



UPPSALA
UNIVERSITET

*Digital Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology 1196*

Reading the Sky

From Starspots to Spotting Stars

URBAN ERIKSSON



ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2014

ISSN 1651-6214
ISBN 978-91-554-9086-7
urn:nbn:se:uu:diva-234636

Dissertation presented at Uppsala University to be publicly examined in Polhemsalen (Å10134), Ångströmlaboratoriet, Uppsala, Thursday, 11 December 2014 at 09:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Associate Professor Edward E. Prather (University of Arizona).

Abstract

Eriksson, U. 2014. Reading the Sky. From Starspots to Spotting Stars. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1196. 229 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9086-7.

This thesis encompasses two research fields in astronomy: astrometry and astronomy education and they are discussed in two parts. These parts represent two sides of a coin; astrometry, which is about constructing 3D representations of the Universe, and AER, where for this thesis, the goal is to investigate university students' and lecturers' disciplinary discernment vis-à-vis the structure of the Universe and extrapolating three-dimensionality.

Part I presents an investigation of stellar surface structures influence on ultra-high-precision astrometry. The expected effects in different regions of the HR-diagram were quantified. I also investigated the astrometric effect of exoplanets, since astrometric detection will become possible with projects such as Gaia. Stellar surface structures produce small brightness variations, influencing integrated properties such as the total flux, radial velocity and photocenter position. These properties were modelled and statistical relations between the variations of the different properties were derived. From the models it is clear that for most stellar types the astrometric jitter due to stellar surface structures is expected to be of order 10 μ AU or greater. This is more than the astrometric displacement typically caused by an Earth-sized exoplanet in the habitable zone, which is about 1–4 μ AU, making astrometric detection difficult.

Part II presents an investigation of disciplinary discernment at the university level. Astronomy education is a particularly challenging experience for students because discernment of the 'real' Universe is problematic, making interpretation of the many disciplinary-specific representations used an important educational issue. The ability to 'fluently' discern the disciplinary affordances of these representations becomes crucial for the effective learning of astronomy. To understand the Universe I conclude that specific experiences are called. Simulations could offer these experiences, where parallax motion is a crucial component. In a qualitative study, I have analysed students' and lecturers' discernment while watching a simulation video, and found hierarchies that characterize the discernment in terms of three-dimensionality extrapolation and an Anatomy of Disciplinary Discernment. I combined these to define a new construct: *Reading the Sky*. I conclude that this is a vital competency needed for learning astronomy and suggest strategies for how to implement this in astronomy education.

Keywords: Astrometry, Astronomy Education Research, Disciplinary Discernment, Extrapolating three-dimensionality, Reading the Sky

Urban Eriksson, , *Department of Physics and Astronomy, Physics Didactics, 516, Uppsala University, SE-751 20 Uppsala, Sweden.*

© Urban Eriksson 2014

ISSN 1651-6214

ISBN 978-91-554-9086-7

urn:nbn:se:uu:diva-234636 (<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-234636>)

To Maria and our children for their patience.

List of papers and conference presentations

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

Papers

- I Limits of ultra-high-precision optical astrometry: Stellar surface structures. *Astronomy and Astrophysics*, 476(3), 1389 -1400.
- II Who needs 3D when the Universe is flat? *Science Education*, 98(3), 31.
- III Introducing the Anatomy of Disciplinary Discernment: An example from Astronomy. *European Journal of Science and Mathematics Education*, 2(3), 167-182.

Reprints were made with permission from the publishers.

Conference Presentations

The following Conference presentations also contributed to the work reported on in this thesis.

Airey, J., & Eriksson, U. (2014a). A semiotic analysis of the disciplinary affordances of the hertzprung-russell diagram in astronomy. Presentation at *The 5th International 360 Conference: Encompassing the Multimodality of Knowledge*. Aarhus, Denmark: Aarhus University. 8 - 10 May.

Airey, J., Eriksson, U., Fredlund, T., & Linder, C. (2014a). The concept of disciplinary affordance. Presentation at *The 5th International 360 Conference*:

Encompassing the Multimodality of Knowledge. Aarhus, Denmark: Aarhus University. 8 - 10 May.

Airey, J., Eriksson, U., Fredlund, T., & Linder, C. (2014b). On the disciplinary affordances of semiotic resources. Presentation at *The First Conference of the International Association for Cognitive Semiotics (IACS)*, Lund, Sweden: Lund University. 25-27 September.

Airey, J., & Eriksson, U. (2014). What do you see here? Using an analysis of the Hertzprung-Russell diagram in astronomy to create a survey of disciplinary discernment. Presentation at *The First Conference of the International Association for Cognitive Semiotics (IACS)*. Lund, Sweden: Lund University. 25-27 September.

Eriksson, U., Linder, C., & Airey, J. (2011). Watching the sky: new realizations, new meanings, and surprising aspects in university level astronomy. In *Science learning and citizenship: Proceedings of the ESERA 2011 Conference*. Lyon, France. 5-8 September.

Eriksson, U., Linder, C., & Airey, J. (2014). Tell me what you see. Differences in what is discerned when professors and students view the same disciplinary semiotic resource. Presentation at *The 5th International 360 Conference: Encompassing the Multimodality of Knowledge*. Aarhus, Denmark: Aarhus University. 8 - 10 May.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2011). Watching the sky: New realizations, new meaning, and surprising aspects in university level astronomy. Poster presentation at *The Foundations and Frontiers of Physics Education Research (FFPER) conference*, Bar Harbor, Maine, USA. 13-17 June.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2012). Who needs 3D when the universe is flat? Poster presentations at the *Gordon Research Conference Astronomy's Discoveries and Physics Education*, Colby College, Waterville, ME, USA. 17-22 June.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013a). Awareness of the three dimensional structure of the Universe. Presentation at *the 21st Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education (SAARMSTE)*, University of the Western Cape, Bellville, South Africa. 14-17 January.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013b). The overlooked challenge of learning to extrapolate three-dimensionality. Presentation at *The*

International Conference on Physics Education. Prague, Czech Republic. 5-9 August.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013c). What do teachers of astronomy need to think about? Presentation at the *Nordic Physics Days*, Lund, Sweden. 12-14 June.

Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2014a). The anatomy of disciplinary discernment—An argument for a spiral trajectory of learning in physics education. Presentation at *The First Conference of the International Association for Cognitive Semiotics (IACS)*, Lund, Sweden. 25-27 September.

Contents

1	Prelude	21
1.1	Introduction and research questions	21
1.2	Who should read this thesis and why?	25
1.3	A note on the language used in this thesis	25
Part I: Stellar surface structures and the astrometric search for exoplanets .		27
2	Introduction	29
3	Optical Astrometry	31
3.1	Science drivers for astrometry	31
3.1.1	Stellar astrophysics	32
3.1.2	Kinematics and dynamics of stellar groups	32
3.1.3	Exoplanets	33
3.1.4	Solar system bodies	33
3.1.5	Reference frames	34
3.2	Classification of astrometric techniques	34
3.3	Basic astrometric data	35
3.3.1	Position	35
3.3.2	Proper motion	36
3.3.3	Parallax	37
3.4	Noise and statistics	38
3.4.1	Random errors in the astrometric data	38
3.4.2	Statistical biases in the use of astrometric data	41
3.5	Astrometric detection of exoplanets	43
3.5.1	Methods for detecting exoplanets	44
3.5.2	Expected astrometric effect of exoplanets	47
3.6	The future: From mas to μ as	51
3.6.1	Gaia: The Billion Stars Surveyor	52
3.7	Astrophysical limitations	55
3.7.1	Circumstellar disks	55
3.7.2	Surface structures	56
3.7.3	Multiplicity	58
3.7.4	Weak microlensing or distortion by gravitational fields	59

4	Astrometric effects of surface structures	62
4.1	Methods of modelling stellar surface structures	62
4.2	The Equivalent ARea Spot (EARS) model	63
4.2.1	Properties of a single spot	63
4.2.2	Multiple spots on a rotating star	64
4.2.3	Theoretical relations used in the model	67
4.2.4	Calculation of the moments	69
4.2.5	Radial velocity	72
4.2.6	Summary of the moments	73
4.3	Monte Carlo simulations	73
4.3.1	The rotating model	74
4.3.2	The static model	76
4.3.3	Results from the simulations	76
4.4	Summary of numerical results	79
5	Impact on astrometric exoplanet searches	80
5.1	Predicted effects of stellar surface structures	80
5.2	Comparison with the effects of exoplanets	84
6	Conclusions	87
6.1	In reflection	88
	Part II: Astronomy Education Research	89
7	Introduction	91
7.1	Astronomy as a science – challenges for learning and understanding	92
7.2	Aim and justification for Part II of the thesis	94
7.3	Research questions	94
7.4	How should Part II of the thesis be read?	95
8	Situating the study – A Review	96
8.1	Physics Education Research	96
8.1.1	PER and Representation Research	98
8.2	Astronomy Education Research	100
8.2.1	Historical development of AER	100
8.2.2	Focal points in Astronomy Education Research	101
8.2.3	Alternative conceptions	104
8.3	Virtual Learning Environments – potent tools for learning astronomy	109
8.3.1	3D Virtual Learning Environments and displays	109

8.3.2	Spatial and learning affordances of Virtual Learning Environments	111
8.3.3	Summary	113
8.4	Three-dimensionality in Astronomy and Astronomy Education	114
8.4.1	Three-dimensionality and Astronomy – ways to represent astronomical objects in 2D	114
8.4.2	Spatial thinking for the purposes of this thesis	115
8.4.3	Relating AER to Spatial thinking	120
8.4.4	Three-dimensionality and Astronomy Education – ways to represents the structure of the Universe for understanding	121
9	Conceptual framing	125
9.1	Introduction	125
9.2	Representations	127
9.3	Building a concept of disciplinary discernment: vision, (visual) noticing, reflection and affordance	129
9.3.1	Vision	129
9.3.2	(Visual) Noticing	130
9.3.3	Reflection	132
9.3.4	Affordance	133
9.4	Summary	134
10	Research Methodology	135
10.1	Introduction	135
10.2	An introduction to the qualitative (interpretative-hermeneutic) research methodology	137
10.2.1	Personal background of the researcher	138
10.3	Method	139
10.3.1	Setting the scene for data collection	139
10.3.2	Video selection and production	141
10.3.3	Data collection	143
10.3.4	Recruiting the participants	144
10.4	Analysis of the data – A hermeneutic approach	145
10.5	Addressing Quality Issues	147
10.5.1	Reliability of Qualitative Research	149
10.5.2	Validity of Qualitative Research	153
10.6	On quality control in this thesis	155
10.6.1	On the reliability of this study	156
10.6.2	On the validity of this thesis	157

10.7	Ethical considerations related to this thesis	158
11	Results – Challenges in learning astronomy	161
11.1	Who needs 3D when the Universe is flat? – Learning to extrapolate three-dimensionality	161
11.1.1	Research Question 2(a): In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?	163
11.1.2	Research Question 2(b): What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?	166
11.2	The Anatomy of Disciplinary Discernment	167
11.2.1	Research Question 3(a): What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?	169
11.2.2	Research Question 3(b): How can this discernment be characterized from an educational perspective?	171
12	Reading the Sky – A way to view learning astronomy	179
12.1	Introducing Reading the Sky	179
12.1.1	Background	180
12.1.2	Building the concept <i>Reading the Sky</i>	181
12.1.3	What is <i>the Sky</i> ?	183
12.2	Defining <i>Reading the Sky</i>	184
12.3	Towards optimizing teaching and learning astronomy	185
13	Implications, Knowledge claims and Future work	189
13.1	Implications – Examples related to my research	189
13.2	Knowledge claims	191
13.3	Future work	192
13.3.1	Short term	192
13.3.2	Long term	192
14	Swedish summary – Svensk sammanfattning	193
14.1	Bakgrund	193
14.2	Syfte	194
14.3	Del I	194
14.4	Del II	197

References	203
Published in Astronomy & Astrophysics	230
Limits of ultra-high-precision optical astrometry: Stellar surface structures	231
Published in Science Education	245
Who needs 3D when the Universe is flat?	245
Published in the European Journal of Science and Mathematics Education	278
Introducing the Anatomy of Disciplinary Discernment: An example from Astronomy	279
Appendix A: Rotating coordinate systems	297
Coordinate systems and coordinates	297
General coordinate transformation	298
Rotation about a single axis	298
A rotating star	300
Appendix B: Copy of the Concession Form Used	303

Glossary

This is a list of pertinent terms used in Part II of the thesis with descriptions of the way in which they have been used. *Italics* terms are further explained within the list.

Word	Explanation
<i>Activities</i>	Actions unique to the discipline, hence part of <i>semiotic resources</i> . For example, looking through a telescope.
<i>Appresentation</i>	‘The mechanism by which aspects which are not technically discernable in a given semiotic resource are ‘read into’ the <i>semiotic resource</i> – a necessary condition for a semiotic resource to acquire an appropriate, disciplinary meaning’ (Airey 2009).
<i>Astronomy</i>	The science of observing and measuring positions, luminosities, motions and other characteristics of objects in the Universe.
<i>Astrometry</i>	The branch of <i>astronomy</i> specifically dedicated to measuring position and motion of astronomical objects.
<i>Astrophysics</i>	The science of modelling phenomena in the Universe. Astrophysicists create physical theories of small to medium-size structures in the Universe.
<i>Cosmology</i>	Creates theoretical models and theories for the largest structures and the Universe as a whole.
<i>Constructivism</i>	Model of learning saying that humans construct knowledge from an interaction between their experience and ideas. This implies that knowledge cannot be transferred to another person.
<i>Disciplinary affordance</i>	The inherent potential of a representation to provide access to disciplinary knowledge (Fredlund et al. 2012).
<i>Disciplinary discourse</i>	The complexity of <i>semiotic resources</i> of the <i>discipline</i> .
<i>Disciplinary discernment</i>	Noticing, reflecting on, and creating meaning from a disciplinary perspective.
<i>Dynamic spatial ability</i>	The ability to handle moving elements, relative velocities and distance judgements.

cont.

Word	Explanation
<i>Experience</i>	This refers to conceptualisation and understanding the world through discernment.
<i>Learning in astronomy</i>	For the purposes of this thesis, learning in astronomy is a function of ‘becoming fluent’ in using disciplinary-specific representations, which, in turn, is a function of the disciplinary affordance of representations.
<i>Modes</i>	A set of socially and culturally shaped resources for making-meaning. (Kress & van Leeuwen 2001).
<i>Multimodality</i>	The understanding that communication involves more than just language. It involves all semiotic resources.
<i>Reading the Sky</i>	The ability to discern <i>disciplinary affordances of the Sky</i> in order to acquire a holistic understanding of the Universe at all levels of scale, dimensions and detail.
<i>Representations</i>	Those <i>semiotic resources</i> that are designed specifically to communicate ways of knowing in a science discipline such as astronomy.
<i>Semiotics</i>	The study of signs and meaning.
<i>Semiotic resource</i>	A term used in social semiotics and other disciplines to refer to a means for meaning making. In astronomy, typical semiotic resources include, mathematics, pictures, graphs, etc.
<i>Spatial affordance</i>	The pragmatic possibilities that technology has for having objects change size and to change the motion and perspective in a given VLE representation.
<i>Spatial thinking</i>	The recognition, consideration, and appreciation of the interconnected processes and characteristics among astronomical objects at all scales, dimensions, and time.
<i>The Sky</i>	The whole Universe at all levels of detail, including all forms of representations describing it.

cont.

Word	Explanation
<i>Variation theory of Learning</i>	Briefly, to learn something requires the discernment of something. Discernment means being able to differentiate amongst the various aspects of some given phenomenon to facilitate a focussing on the most educationally relevant aspects. Without experiencing pertinent patterns of variation there can be no discernment. And without discernment there can be no learning.
<i>Visualisation</i>	A graphical representation either presented static or dynamical in a simulation.

Abbreviations

PAER	Physics and Astronomy Education Research
AER	Astronomy Education Research
PER	Physics Education Research
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
DD	Disciplinary Discernment
ADD	Anatomy of Disciplinary Discernment
DBER	Discipline-Based Education Research

Acknowledgments

This work would not have been possible without the support of my wife, Maria. You have been very understanding and helped push me forward in moments of doubt and held me back when I got carried away too much by my work. The way in which you have taken care of our children, our home and me during these years is admirable, thank you! Hopefully, I will have more time now for all the things I should have done.

I would also like to thank my mother and father for supporting me over the years when I was young. You saw my interest in science and encouraged me to seek knowledge though the years in school and as a undergraduate student. I am grateful for your support and believe Mom is smiling towards me somewhere out there amongst the stars. Love you both!

Special thanks to my supervisor Cedric Linder for his help and advice on this work. The way in which you have taken care of me and supported me is fantastic! I could not have had a better supervisor. Without our discussions and your patience this work could not have been done! As much as this is my work and accomplishment, I owe it all to you. Thank you! John Airey, for your insights and sensitivity to language. I thank you for the discussions and help with the writing. You know that my articles, or rather ‘ours’, and this thesis, improved much with your help. Thanks! Anne Linder, thank you for saving my bacon! And more than once! Your critical eyes are very sharp and have really helped improve all of my work. Also thanks to the rest of the Uppsala PER group. I am privileged to have worked with you all!

In Kristianstad I have the always supportive co-supervisor Andreas Redfors, who has stood up for me over the years. We have had good discussions and you have corrected me when necessary, but always supported me. Actually, it is your ‘fault’ that I am where I am and for that I am grateful. Thank you! Also thanks to the LISMA group, with its diversity of expertise in all the different science and mathematics education fields. I am glad to have such knowledgeable colleagues and look forward to working more closely with you in the future.

Also thanks to my former colleague Jonas Persson, now at Trondheim University, for fruitful discussions on the subjects of math, the Universe, and everything... Maybe some day our roads will cross again with new discussions on astronomy and physics education.

In this work I use a simulation movie ‘Flight to the Virgo Cluster’ constructed by Professor Brent Tully (Tully-Fisher Relation). He has granted me permission to use it as I find suitable.

Urban,

You have my blessings and wholehearted support for your enterprise. I am pleased to have my material used effectively.

Brent Tully.

Finally, special thanks to Kristianstad University who made all of this possible by funding my graduate studies.

1. Prelude

*Though thou art far away, thy rays are on Earth;
Though thou art in their faces, no one knows thy going.*
Egyptian Pharaoh Akhenaten, 'The Great Hymn to the Aten'

1.1 Introduction and research questions

There are few things in the world around us that are constant. Most things change with different time scales, like day and night, the weather, or the seasons, etc. But for most people, no changes in the night sky are in their focal awareness. Being unable to easily discern or experience any changes in the night sky could make it uninteresting to look at. Yet how could one experience any changes if one does not look up and try to observe? This thesis addresses both the possible very small changes of measured stellar positions in the sky, and the experiences that students have when looking at the stars or other astronomical objects in the sky, or at different types of representations of these stars or objects.

For myself, I observed and experienced the amazing change of the phases of the Moon when I was young. I realized that the appearance of the Moon changed overnight and also that the Moon moved(!) across the sky from night to night when observed at the same time, and even, at times, was visible in daytime. This was a profound realization. Since then, I have had many opportunities to experience the night sky, but the deepest impact was made when I visited the Nordic Optical Telescope at La Palma in the Canary Islands. Being there, outside the dome at night in that extremely dark place, it felt like I was able to reach up and touch the sky of stars. Standing there, observing, made me wonder if it was possible to really understand where the stars actually were: How far away? How are they distributed? Do they change position? If so, how much? Would it be possible to see this? Measure it?

After this, my interest in astronomy lead me through different stages in life and now being a physics and astronomy educator and researcher, I have come to understand the importance of experiencing the night sky as a way to create interest and stimulate learning in both physics and astronomy. This type of experience should, of course, be best experienced 'live', at night, but it can

also be experienced in planetariums, or even on a computer, tablet or smart-phone.

Historically, the sky has been seen as something that changes very little. Ancient cultures struggled to understand the celestial motion of the five ‘wandering stars’ (planets, as we call them today: Mercury, Venus, Mars, Jupiter and Saturn). The main problem was a geocentric way of viewing the world, leading to a rather complicated model for describing the heavenly motion of the planets. Ptolemaios summarized this knowledge in the first book on astronomy, *Almagest* (Ptolemy 2nd century C.E.), using many circles to make a geocentric model that could be used to predict the movement of celestial objects. This model lasted until it was eventually questioned by Copernicus (1543). He proposed a much simpler Sun-centred model, for explaining the motion of the planets. However, he made one serious mistake by continuing to think in circular orbits, which actually led to his model being less accurate in predicting the positions of the planets in the sky. Today, after the work of well-known scientists like Galileo Galilei, Tycho Brahe, Johannes Kepler and Isaac Newton, we have a rather good and simple model that uses Newtonian mechanics to describe the main features and behaviour of constituents in the Solar System. The model has been further refined by Einstein’s relativity theory to include relativistic effects of the planets. The most well-known example of where Newtonian mechanics fails in its explanation is in the prediction of the precession of Mercury. However, including Einstein’s theory the model can predict the observed motion extremely well.

The historical development of astronomy mirrors in many aspects the views of the Universe that students may still hold today. The literature reveals (see Chapter 8) that students have conceptions of the Universe that span from almost nothing at all, through scientifically inappropriate conceptions commonly known as alternative conceptions, preconceptions or misconceptions, to scientifically appropriate conceptions¹. An example that highlights this, is a recent study which revealed that about one third of EU citizens, and one quarter of US citizens did not know, or believe, that the Earth orbits the Sun (NSB 2014). This, and many other alternative conceptions on the ways in which the Universe is viewed, are very common, and capture some of the challenges that science educators have to face. Research on students’ conceptions have shown how difficult it is to get students to change to a more scientific point of view, as I will outline in my review in Chapter 8. Therefore, the gap between the theories and observations made by scientists, and the conceptions held by stu-

¹For the purposes of this thesis I will use ‘the term’ alternative conceptions (Driver & Erickson 1983) to describe these scientifically inappropriate conceptions.

dents, is large and presents a considerable challenge for educators to bridge. In this thesis, I address these two aspects – disciplinary knowledge and students’ knowledge – from the perspective of astronomy and physics. The thesis is the result of an awareness that I have built up from many years of teaching astronomy and physics. It starts with the question of where the stars are and ends with questions about what students and educators discern about the stars and other objects in the Universe. The research questions for this thesis are thus related to the multidimensional structure of the Universe and how it can be understood.

The first part of the thesis is about astrometry (‘measuring the stars’) and focuses on modelling the variation in position and motion of stars due to brightness variations from stellar surface structures. Sunspots are one example of variations on the solar surface; and for stars in general we find the same pattern. Of course, it varies very much between different types of stars. The simulations I developed lead to a possibility to statistically predict how the ‘spottiness’ affects both ‘position’ and ‘radial velocity’ of the stars. This is not a ‘real’ variation, but an observed variation that occurs due to the fact that the spots (bright and/or dark) change the brightness distribution of the stellar disc as seen from a distance. As an example, if there are many dark spots on the left side of the star (as seen from Earth) then the photometric centre, or photocentre, seems to shift to the right; the stars seem to be in a slightly different position in the sky. However, this apparent shift is very small, and even with today’s technology, very hard to detect. The same situation occurs for motion in the radial direction. If more bright areas are moving away from us as the star rotates, we interpret this observation as the whole star moving away from us. Both the photocentric motion (sideways) and the radial velocity are virtual motions, but in our detectors we find it hard to separate this from any ‘real’ motion. Interestingly, the results from my simulations and models, when compared with the variations imposed by extra solar planets (exoplanets) gave a surprising result. The signal imposed by an Earth-like exoplanet in the metaphorical habitable zone was of the same order of magnitude as the variations imposed by the brightness variations on the star. This finding makes exoplanet detection using the astrometric method, extremely difficult, if not impossible, for Earth-like exoplanets in the habitable zone. For larger (Jupiter-like) planets this poses no problem since the signal imposed by these large planets will be orders of magnitude larger than that for Earth-like exoplanets.

After developing these asymmetric simulations I found myself again reflecting on how our students think about these issues, so after finishing the Licentiate degree in Lund, I decided to continue the work shifting my focus into

student learning. Fortunately, I found that the Physics Education Research (PER) group in Uppsala was interested in these questions as well and I was able to continue pursuing my research interests there.

The transition from ‘hard-core’ astrometry to educational science was a big step for me to take. Educational science is very different in many ways from natural sciences, especially when it comes to methods for obtaining meaningful data from people. Fortunately, I was not the first to make this transition and there is lots of educational literature describing the methods and theory building needed. Using these new perspectives, I started the second half of my Ph.D. Being situated in higher education and using concepts like variation, discernment, disciplinary-specific representations, etc., to look at student learning, I found that there was surprisingly little research done on student learning framed by representations in astronomy education. However, the literature does describe research done on representations in physics education (and other science areas) however, so I was able to draw on this work for my further studies. I give details of this in my literature review in Chapter 8.

My research focus in astronomy education became being about investigating university students’ discernment when experiencing the Universe. What I mean by discernment is noticing, reflecting and meaning-making (see Chapter 9). However, in my research journey I immediately faced an interesting problem – how do I get the students to discern new things, or old things in new ways, at the university level? Marton and Booth (1997) have argued that to discern ‘things’ the students need to experience specific patterns of variation (Marton & Trigwell 2000; Marton 2014; Ling & Marton 2011; Ingberman et al. 2007). The obvious answer for me was to use simulations; simulations built on computer software that can be manipulated either by the teaching professor² or by the students themselves. The field of science dealing with simulations is also reviewed in Chapter 8 in this thesis.

²In my thesis the designations ‘lecturers’, ‘teaching professors’ and ‘astronomy educators’ are used interchangeably.

The research questions that has guided me through this work are:

1. How large is the astrometric effects of stellar surface structures as a practical limitation to ultra-high-precision astrometry (e.g. in the context of exoplanet searches) and what are the expected effects for stars in different regions of the HR-diagram?
2.
 - a) In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?
 - b) What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?
3.
 - a) What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?
 - b) How can this discernment be characterized from an educational perspective?
4. How can the idea characterized as *Reading the Sky* in this thesis inform the teaching and learning of astronomy?

This thesis starts with astrometry in Part I, where I describe my astrometry work and the outcomes of that. Part II then addresses my astronomy education research (AER) focusing on students' discernment of three-dimensionality.

1.2 Who should read this thesis and why?

The work presented in this thesis is aimed at astronomy/physics educators and researchers. It is also anticipated that staff at science centres and planetariums would benefit from reading this thesis as it addresses learning experiences similar to those offered by these facilities.

1.3 A note on the language used in this thesis

The research focus in my thesis changes from Part I to Part II. In Part I the focus is on the science of astrometry and as such largely decoupled from personal aspects. It is therefore written using passive voice. The second part of the thesis concerns educational science and here the researcher is a crucial part of the interpretation and theoretical construction. Consequently, work in this field is often presented using first person, which I have followed.

Part I:

Stellar surface structures and the astrometric
search for exoplanets

2. Introduction

The Milky Way Galaxy is believed to contain at least 200 billion stars and lots of dust, gas, etc. (see Fig. 2.1). Around one rather ordinary G-type star there is a planet, very small but important for its inhabitants. This particular star and its planet is our home in this vast universe. Observing, and trying to understand, the structure of our Galaxy and the function of its parts is one of the goals of modern astrophysics. Basic questions in this context concern where the stars are and how they move, e.g. their positions, distances and motions. It is the task of astrometry to investigate such fundamental data about the stars in the Galaxy.

Actually, the locations of very many stars in the Galaxy still remain unknown. Today we know the positions of a few million stars¹ but we only know the distances to some 20000 stars with an accuracy of 10% or better, and these stars are mostly our closest neighbours. The basic stellar data obtained with the astrometric method are *parallax*, *position* and *proper motion*. The parallax gives the distance to the star using trigonometry with the distance between the Sun and the Earth as a baseline. The parallax is less than an arc-second even for the nearest stars. The largest parallax survey to date was done by the Hipparcos project² around 1990, and gave a typical accuracy of about 0.001 arcsec (1 milliarcsec = 1 mas).

New instruments have been built and launched into space, which aim for about 100 times higher astrometric accuracy, or about $10\ \mu\text{as}$. These include the space borne ESA project Gaia, and the ground-based ESO VLTI PRIMA interferometer. These developments lead to new kinds of considerations since astrometric methods now approach the fundamental limits for how accurate it is possible to measure stellar positions. The stars themselves set one of these limits, depending on *stellar surface structures* such as spots, plages, faculae, granulation and non-radial oscillations. This limitation turns out to be of great interest especially for exoplanet searchers since the astrometric jitter due to the surface structures of a star could be of the same magnitude as the effect caused by an orbiting Earth-like exoplanet.

¹For example the Tycho-2 Catalogue gives the positions of the 2.5 million brightest stars on the entire sky to about 0.01 arcsec.

²<http://www.rssd.esa.int/Hipparcos/>

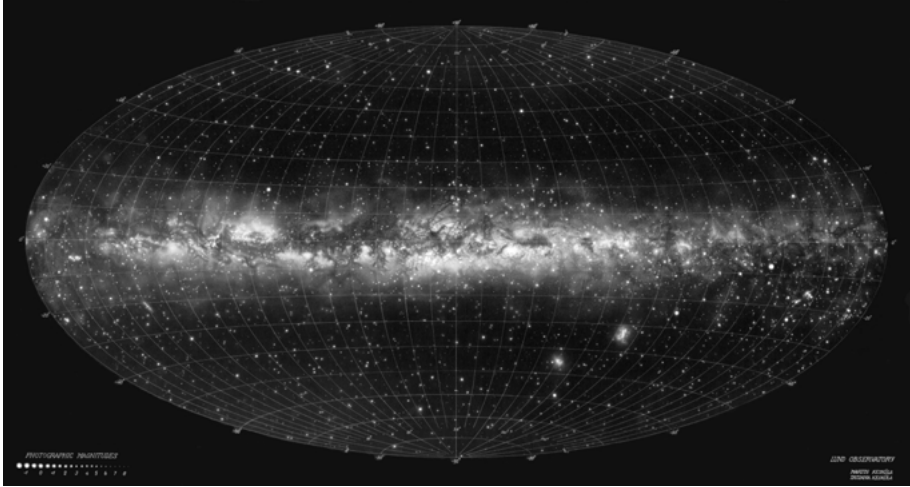


Figure 2.1. The Lund Observatory Milky Way panorama. The original drawing, measuring 2×1 m, was made in 1953–55 by Tatjana and Martin Kesküla under the direction of Knut Lundmark. © Lund Observatory

The overarching research question for Part I of my thesis (Research Question 1) is: How large are the astrometric effects of stellar surface structures as a practical limitation to ultra-high-precision astrometry (e.g. in the context of exoplanet searches) and what are the expected effects for stars in different regions of the HR-diagram?

This part of my thesis will start with an introduction to optical astrometry and exoplanet searches, followed by a presentation of a stellar model for (the astrometric effect of) a spotted surface. By means of numerical simulations I investigated the influence of the spots on the total flux, photocentric displacement, third central moment (of interest for interferometry) and radial velocity of the star. The first three properties are moments of the intensity distribution across the stellar disk and are therefore mutually connected, which makes it likely to find statistical relations between them. This also holds to some extent for the radial velocity effect. The results from the simulations are also contrasted against a theoretical model. Finally, I evaluate the expected astrometric effects for different types of stars, and draw some conclusions concerning the possible detection of exoplanets around these stars.

3. Optical Astrometry

This chapter contains a short introduction to astrometry and astrometric methods. I identify different perturbing sources that can affect the accuracy of astrometric measurements. I also briefly present ongoing astrometric projects.

Astrometry is the part of astronomy that provides the positions, and by extension, the dimensions and shapes of the celestial bodies. Since the positions vary with time, a primary goal is to describe the motions of the bodies. After obtaining this information, the results can be analysed in two different ways.

The kinematic approach: in this case the description of the motion is an objective in itself. One can e.g. relate the components of the stellar motion to intrinsic properties of the star such as its age, spectral type, or chemical composition.

The dynamical approach: this case concerns the understanding of motion in terms of the forces, or potentials, and other circumstances that govern them. Examples are celestial mechanics in the Solar system and dynamical studies of the Galaxy from stellar motions.

In these examples astrometry is a tool to achieve scientific data and one can therefore consider it as an astronomical technique, like photometry, spectroscopy or radio astronomy. A more strict definition of astrometry is that it is the application of certain techniques to determine the geometric, kinematic, and dynamical properties of the celestial bodies in the Universe.

3.1 Science drivers for astrometry

Why study astrometry? One cannot use advanced and costly instruments just to observe objects because they are observable. The instruments of today are much more powerful and sophisticated than before and consequently more expensive. In practice, this leads to a limited number of projects and an increasing need for careful programming of the instruments used for observations. Earlier in history it was considered important and relevant to study every possible object under the justification that the observations might be valuable in the future. Today such reasoning does not work. The overarching question in astrometry today concerns what the use of these observations is and to what

questions they will bring answers. In modern astrometry the question is: – What domains of astronomy need the knowledge of positions, distances, motions of celestial bodies, and for what? Five areas of interest can be identified

3.1.1 Stellar astrophysics

The most important parameter that can be obtained from astrometric measurements is the *parallax*. Trigonometric parallaxes are the basis of nearly all the other methods to determine distances in the Universe. The distance scale is largely based on the principle that two stars having the same physical characteristics, e.g. spectrum, temperature, variability, also have the same luminosity. If the parallax for a star with certain characteristics is known by trigonometric methods, the distance to that star and all similar stars can be determined. Knowing distances is fundamental in stellar astrophysics because it allows converting apparent quantities (such as magnitudes) into intrinsic properties (such as luminosities).

Apart from the parallax, other interesting parameters determined by astrometric techniques are:

- Proper motion, representing the apparent path on the sky.
- Orbital motions of double and multiple stars.
- Non-linear proper motion, which may be the signature of invisible companions.
- The apparent acceleration of stars, which may provide astrometric determination of the radial motion of the star (astrometric radial velocity, Dravins et al. 1999).

3.1.2 Kinematics and dynamics of stellar groups

The important parameters are transverse velocities (obtained from proper motions and parallaxes) and/or radial velocities. They allow one to study the motions in clusters (leading to knowledge on the force field that keep them from disrupting), to detect stellar associations, to analyse the motions within the Galaxy and to derive relations between the kinematic and astrophysical properties of stars which lead to understanding of the dynamics and the evolution of the Galaxy.

3.1.3 Exoplanets

Exoplanets are planets orbiting other stars than the Sun. These are difficult to observe since the light from the central star almost totally blinds out the much fainter reflected light of the planet.

Today there are both indirect and direct methods of detecting exoplanets. The indirect methods all concern studies of the central star and its behaviour due to a planetary companion. Many of the known exoplanets today have been detected indirectly from the radial velocity variations of the star and by transits, but astrometric techniques are expected to become important for exoplanet detection in the next decade. Since this is an important theme of this thesis, the whole of Sect. 3.5 is devoted to the detection of exoplanets.

3.1.4 Solar system bodies

One cannot systematically observe all objects in the solar system. Some are of more interest than others and the following stand out:

1. *The Sun*. Earlier the Sun was very important to observe astrometrically since it defined the equinoxes and this was a difficult task (due to its brightness). Today the reference frame is independent of the location of the Sun and the Solar System (Sect. 3.3.1) and those observations are no longer needed. Two quantities are important for the theory of the internal structure of the Sun and these are the shape and the diameter of the Sun, together with their time variations.
2. *Major planets*. The major planets are important to study for dynamical reasons. The planetary system is a laboratory for weak field general relativity studies. The motion of the planets is the basis of the definition of the dynamical celestial reference frame used until 1997 (FK5¹) and this will be maintained for comparison with the extragalactic reference frame used today. This is a major theoretical objective where very precise observations are needed and it is also required for the preparation and operational fulfilment of space missions.
3. *Dwarf planets*. This relatively newly defined group of objects includes Ceres, Pluto and Charon, Quaoar, Eris, Makemake, etc. Many of these objects are found in trans-Neptunian orbits or in the Kuiper-belt and are of great interest for the studies of the outer solar system, and the formation of planetary systems.
4. *Small Solar System Objects*. These objects include asteroids and comets and are too numerous to be followed with the utmost precision. A small

¹FK5= the fifth fundamental catalogue (Fricke et al. 1988)

number of observations is sufficient to compute ephemerides precisely enough not to lose these objects. Today there are several hundreds of thousands of such objects in the databases. Information on these objects and especially the orbits of the Earth-grazing asteroids are vital for us and our survival.

5. *Planetary satellites.* Every satellite is a particular problem for celestial mechanics and precise measurements of their position and motion are useful for theoretical and practical reasons. In the preparation for space missions to these objects, very accurate ephemerides are needed.

3.1.5 Reference frames

The construction of a non-rotating celestial reference frame is very important for position determination of any objects in the universe. Quasars and remote galaxies are fixed on the sky to better than 10^{-5} arcseconds ($10\mu\text{as}$) per year and therefore these objects are ideal fiducial points for a celestial reference frame. Continuous astrometric observations of these objects giving accurate positions are of utmost interest for constructing a fundamental celestial reference frame. This has indirect effects on all other measurements of motions of celestial bodies, since any rotation of the frame will wrongly be interpreted as a motion or acceleration of the celestial bodies under study. It is the task of astrometry to provide and maintain such a reference frame.

3.2 Classification of astrometric techniques

There are several different kinds of instruments that are used to make astrometric observations from ground and space. Depending upon the field of view and mechanical properties of the instrument, one can distinguish three classes of astrometric techniques. These are complemented by a range of other techniques to obtain additional geometric information about the objects, such as *spectroscopy* (for radial velocity) and *photometry* (e.g., for stellar diameters using lunar occultations or in eclipsing binaries).

Small-field astrometry: here, relative measurements are made within a field of view of a fraction of a degree, often by means of a relatively large telescope. This allows reaching faint objects, but it can only be used to study the internal geometry of small objects (double or multiple stars, clusters etc), or to measure them relative to background objects such as quasars. The main advantage of small-field astrometry is that many of the perturbations affecting the measurements are nearly constant within

a sufficiently small field. The classical instruments for this technique are long-focus, ground-based refractors or reflectors, but the Hubble Space Telescope has also been used for this kind of observations. Optical interferometers, for example, VLTI PRIMA, are examples of small-field astrometry. Typical applications are for determination of (relative) parallaxes and (relative) proper motions.

Large-field astrometry: the prototype instrument is the Schmidt camera, with a field of view of a few tens of square degrees. It is used to determine positions of celestial bodies with respect to reference stars. It is often used to cover a large fraction of the sky with overlapping plates (Eichhorn 1988). This is the classical technique for large-scale surveys of positions and proper motions. A recent version is, for example, the Sloan Digital Sky Survey SDSS (Gunn et al. 2006).

Global astrometry: this aims at observing objects all over the sky and producing a consistent set of positions covering the celestial sphere. This is possible in principle, and nowadays in practice, but only from a satellite where the effects of atmosphere and gravity are eliminated and the entire sky can be reached with a single instrument. Here one finds missions like Hipparcos and Gaia (Sect. 3.6.1).

3.3 Basic astrometric data

3.3.1 Position

The position of a star at a certain time t is by tradition given by two spherical coordinates. There are, however, many different coordinate systems to choose between. Historically, the most commonly used system is the *equatorial system* illustrated in Fig. 3.1. Its origin is usually taken to be the (mean) equator and vernal equinox, γ , at a specified time such as 1950.0 or 2000.0. Coordinates in this system are designated *right ascension* (α) and *declination* (δ).

From 1 January 1998, these systems are superseded by the International Celestial Reference System (ICRS) (Kovalevsky et al. 1989). This is a non-rotating, rigid system linked to extragalactic radio sources. The practical realization of this system is the International Celestial Reference Frame (ICRF), which is primarily based on 212 extragalactic radio sources² (e.g. Ma et al. 1998). The idea is that these sources are so distant that they do not show any

²There are also secondary sources and they are (i) 294 compact sources whose positions are likely to improve when more observations are accumulated and (ii) 102 sources less suited for astrometric purposes, but which provide ties for reference frames at other wavelengths.

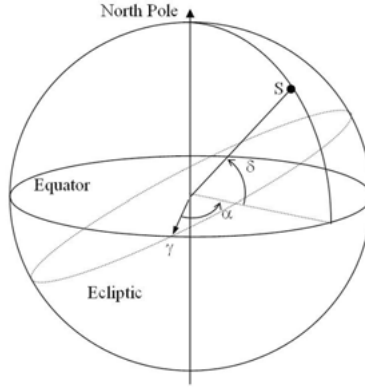


Figure 3.1. The equatorial reference system.

sign of proper motion or change of shape, larger than a few μas . This was determined to be the fundamental reference frame by the 23rd IAU General Assembly in 1997. Although this system is completely decoupled from the rotation of the Earth, the old names for the angular coordinates (right ascension and declination) are retained. The Hipparcos and Tycho Catalogues (ESA 1997) are optical realizations of the ICRS.

Regardless of what system is used, one faces several problems when trying to determine the position of an object. The direction from where the light is emitted is not the same as it appears in the instrument. One only see the apparent deviated direction and this is due primarily to the following causes: the *refraction* of the light beam in the atmosphere, *aberration* due to the motion of the observer and finally *relativistic light deflection* due to the curvature of the space-time (Sect. 3.7.4). In space astrometry the problem with refraction in the atmosphere of course disappears.

3.3.2 Proper motion

Proper motion is the time derivative of the position of the star at an epoch t_0 . In the equatorial system it is composed of two quantities:

$$\mu_\alpha = \left(\frac{d\alpha}{dt} \right)_{t=t_0} \quad \text{Proper motion in right ascension}$$

$$\mu_\delta = \left(\frac{d\delta}{dt} \right)_{t=t_0} \quad \text{Proper motion in declination}$$

where μ_δ corresponds to an actual angle on the sky and μ_α corresponds to the angle on the equator and thus the actual angle on a local small circle is

$\mu_\alpha \cos \delta = \mu_{\alpha*}$ ³. The modulus of the proper motion on the tangential plane to the celestial plane at position α_0, δ_0 will then be

$$\mu = \sqrt{\mu_{\alpha*}^2 + \mu_\delta^2}$$

and its position angle θ is reckoned to be from North towards East.

Notice that this only reflects the motion on the celestial plane at the position of the star. The total motion includes the motion perpendicular to the plane, i.e. the radial velocity component.

3.3.3 Parallax

Perhaps the most important parameter that can be obtained from astrometric measurements is the *parallax*. The principle of parallax measurement is illustrated in Fig. 3.2. As the Earth annually orbits the Sun, the observer's changing position causes an annual shift in the star's measured position, tracing a small ellipse on the sky that reflects the size and orientation of the Earth's orbit as it might be viewed from the star. However, most stars are so distant that their parallaxes are very small and difficult to measure accurately. The nearest known star, Proxima Centauri (α Cen C), has a parallax of 772.33 ± 2.42 mas (Cox 2000). A typical naked-eye star's parallax is about 10 mas. Most of the 118000 parallaxes in the Hipparcos Catalogue are only a few mas in size, barely larger than the errors of measurement.

The distance, r , to a star is related to the parallax, ϖ , by the definition

$$r = \frac{1 \text{ AU}}{\sin \varpi} \approx \frac{1}{\varpi} \quad (3.1)$$

where ϖ is in arcseconds and r in parsec. Differentiating leads to the following for the relative errors:

$$\begin{aligned} dr &= -\frac{d\varpi}{\varpi^2} \\ \Rightarrow \\ \left| \frac{dr}{r} \right| &= \left| \frac{d\varpi}{\varpi} \right| \\ \text{or} \\ \left| \frac{\sigma_r}{r} \right| &= \left| \frac{\sigma_\varpi}{\varpi} \right| \end{aligned} \quad (3.2)$$

From this one see that the relative error in distance is the same as the relative error in parallax. For small parallaxes, with values close to the measurement

³Modern catalogues, such as the Hipparcos and Tycho catalogues (ESA 1997), always give $\mu_{\alpha*} = \mu_\alpha \cos \delta$ rather than μ_α

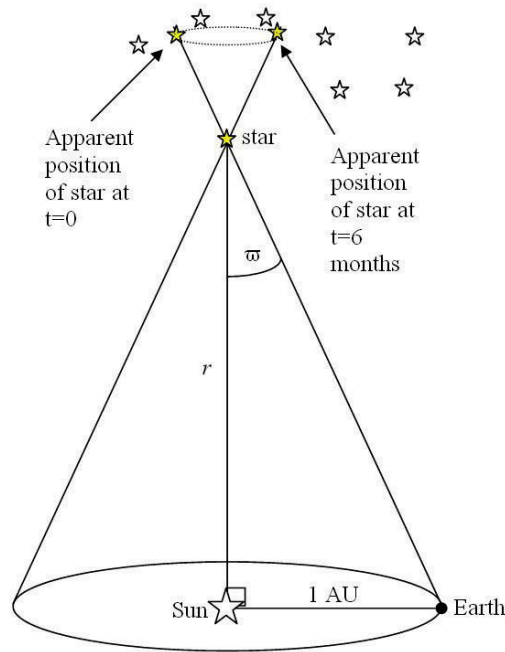


Figure 3.2. Schematic illustration of parallax determination. The apparent motion of the star forms a ‘parallactic ellipse’ and its size is inversely proportional to the distance. Note that the background stars are supposed to be fixed.

error, this leads to very large uncertainties in distance determination and this can be a problematic complication. The ratio $\frac{\sigma_\varpi}{\varpi}$ is an important parameter for the statistical use of parallax (Sect. 3.4.2).

3.4 Noise and statistics

3.4.1 Random errors in the astrometric data

The observed value of, say, a parallax is of course not the same as the true value. The observed parallax is the result of a lengthy data processing chain involving the combination of hundreds or thousands of individual measurements. Each of these measurements is affected by many different kinds of errors. Below follows a summary of the most important ones. Astrometric data contains correlated and uncorrelated instrumental, atmospheric and astrophysical noise.

Photon noise: there are fundamental uncertainties related to the wave/particle nature of light. These can be derived from photon statistics and Heisenberg's uncertainty principle. The latter states that one cannot measure both position, \mathbf{r} , and momentum, \mathbf{p} , of a photon with infinite precision. Lindegren (2005) shows that the resulting relationship between the RMS size of the pupil in the measuring direction, σ_x , and the RMS uncertainty of the measured direction, σ_θ , for the detection of one photon of monochromatic wavelength λ , is given by

$$\sigma_x \sigma_\theta \geq \frac{\lambda}{4\pi} \quad (3.3)$$

For N photons one thus find that

$$\sigma_\theta \geq \frac{\lambda}{4\pi\sigma_x\sqrt{N}} \quad (3.4)$$

The expression for σ_x is different for different shapes of the aperture(s). It is straightforward to derive these expressions for different apertures (Lindegren 1978):

Circular pupil telescope: in this case one find that

$$\sigma_x = \frac{D}{4} \quad (3.5)$$

where D is the telescope aperture.

Rectangular pupil telescope: for a rectangular aperture of length L , σ_x has the form

$$\sigma_x = \frac{L}{\sqrt{12}}. \quad (3.6)$$

For example, the space astrometry mission Gaia have two rectangular primary mirrors with a length of $L = 1.45$ m. This leads to $\sigma_x \approx 0.42$ m. Assuming a wavelength of $\lambda = 550$ nm one find that $\sigma_\theta \approx 10^{-7}$ rad ≈ 20 mas for each photon. To reach $10 \mu\text{as}$ accuracy requires some $N \sim 10^7$ photons, which is not an unreasonable number.

Interferometers: for interferometers, with aperture much less than the baseline B , one find

$$\sigma_x = \frac{B}{2}. \quad (3.7)$$

Atmospheric noise: for details, see, for example, Lindegren (1980) and Shao and Colavita (1992). Briefly, one can notice that for a monopupil telescope the limiting factor is the seeing disk due to the turbulent atmosphere. Then, in the long-exposure limit, one have to replace D in

Eq. 3.5 with Fried's parameter r_0 (the coherence length of the atmospheric wavefront errors; typically 0.1–0.5 m in visual light). For interferometers, the atmospheric disturbance influences the fringes so that instead of (3.4)–(3.7) one has

$$\sigma_\theta = \frac{\lambda}{2\pi B \sqrt{t/t_c}} \frac{1}{\text{SNR}} \quad (3.8)$$

where B is the baseline, t_c is the atmospheric coherence time (a few tens of ms in the near-infrared K band), t is the integration time and SNR is the signal-to-noise ratio per coherence time.

Instrument noise: this primarily originates from three sources: detector noise, mechanical noise, and optical effects (aberrations, distortions, etc.). Today, the sizes of these errors can be made as small as on the order of 1–10 μas in dedicated instruments. For narrow-angle measurements with interferometers one has uncertainties in the delay line, σ_l , and baseline, σ_B , and $\sigma_{\text{sys}} = \sqrt{\sigma_l^2 + \sigma_B^2}$ (Shao & Colavita 1992). The uncertainty in the optical delay line can be expressed as $\sigma_l = \delta l/B$ and for the baseline it can be expressed as $\sigma_B = (\delta B/B)\vartheta$ where ϑ is the angular separation between the target and a reference star. In the case of the optical delay line the uncertainty must be extremely small, of the order of nm, to achieve μas astrometric accuracy, while for the error in the baseline one only need some 50 – 100 μm to achieve μas astrometry. For a space-borne instrument, the spacecraft environment also causes noise. There are several sources that can contribute to the total uncertainty, for example, attitude errors due to solar wind, micro-meteoroides, radiation pressure, etc. In a well-designed instrument these additional sources should be small compared to the photon noise.

Astrophysical noise: this is a main topic of this part of the thesis, see Sect. 3.7 and Ch. 4.

From the above it is clear that in designing space-borne instrument, detailed error models must be developed and the design optimised for every case in order to reach the final accuracy goal. In optical and near infrared wavelengths the ultimate accuracy thus depends mostly on the aperture size and the total number of detected photons from a given source. For ground-based instruments the challenges are largely of a different nature, namely to reduce the atmospheric noise.

3.4.2 Statistical biases in the use of astrometric data

Lies, damned lies and statistics.

Benjamin Disraeli

Because the astrometric data have random errors, their application to astrophysical problems is not always as simple as one might think. Here I mention some of the pitfalls that one may encounter when using parallax data.

Non-linear transformations Assume that the parallax for a star was found to be ϖ with a standard error σ_{ϖ} , and that the probability density function (pdf) of the errors is normal. What can then be said about the distance to the star? After transforming to distances the errors are no longer normally distributed and the derived value for the distance with highest probability will be over-estimated by a factor depending on $\frac{\sigma_{\varpi}}{\varpi}$ (see Kovalevsky & Seidelmann 2004). If $\frac{\sigma_{\varpi}}{\varpi} < 0.1$ this bias is negligible. Otherwise one tends to over-estimate distances calculated from parallaxes.

Malmquist bias This bias, named after the Swedish astronomer Gunnar Malmquist (1893–1982), is a serious problem in survey astronomy. The Malmquist bias is a statistical effect by which the brighter members of a population are over-represented in a brightness-limited sample. Each class of objects has its intrinsic distribution of true absolute magnitudes, as well as other physical quantities, with relevant true mean value M_0 and dispersion σ_M . A way to express this is to say that the Malmquist bias is caused by the fact that systematically brighter objects are observed as distance (and volume) increases, as a result of a combination of the selection and the intrinsic scatter of absolute magnitudes. This leads to a built-in distance-luminosity correlation which is very difficult to unravel. For example, for a flux-limited sample intrinsic properties correlate with distance, thus two seemingly unrelated intrinsic properties will appear to be correlated because of their mutual correlation with distance.

Malmquist bias is defined as *the difference in mean absolute magnitude between the flux-limited (FL) and distance-limited (DL) distributions*. For a uniform space distribution the Malmquist correction is

$$\langle M \rangle_{DL} - \langle M \rangle_{FL} = 1.382 \sigma_M^2 \quad (3.9)$$

A illustrative tool for demonstration of the Malmquist bias is the Spaenhauer diagram showing derived absolute magnitude plotted versus distance (see e.g. Spaenhauer 1978; Butkevich et al. 2005). Fig. 3.3 presents

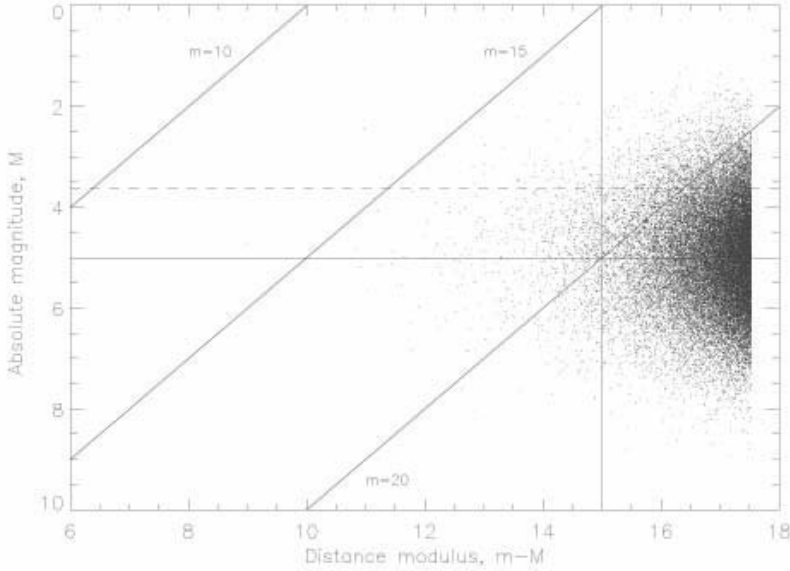


Figure 3.3. A simulation of a uniform space distribution of stars with true absolute magnitude $\langle M \rangle = 5$ mag and dispersion $\sigma_M = 1$ mag plotted against distance modulus $m - M = 5 \log \frac{r}{10 \text{ pc}}$. The diagonal lines represent apparent magnitude. For a distance-limited sample (e.g. the points to the left of the vertical line of $m - M = 15$), the mean absolute magnitude, $\langle M \rangle_{DL}$, equals the true value $\langle M \rangle = 5$ (the solid horizontal line). For a flux-limited sample (e.g. to the left of the diagonal line at $m = 20$), the mean value $\langle M \rangle_{FL}$ is 1.382 mag brighter (dashed horizontal line) as predicted by Eq. (3.9). From the figure one see that in a flux-limited sample only atypically bright objects at the largest distances are seen.

an example of a uniform space distribution of stars with true mean absolute magnitude $\langle M \rangle = 5$ mag and dispersion $\sigma_M = 1$ mag plotted against distance modulus. This simulation shows that there is a offset between the distance-limited and flux-limited mean absolute magnitudes because the bright members are over-represented at large distances.

Finally one should note that an effect that competes with the Malmquist bias is caused by observational errors. The number of objects as a function of apparent intensity $N(s)$, the number count or source count, usually rises steeply towards smaller values of s . There are many more faint objects than bright ones! If one, in compiling a catalogue, in effect draw samples from a number-count distribution, forget those below s_{lim} , and converts the retained fluxes into luminosities, one will deduce an erroneous luminosity distribution function. Adding the effect of ob-

servational errors is the same as to convolve the number counts with the noise distribution. Because of the steep rise in the number counts at the faint end, the effect will be that the final sample is contaminated with faint objects. This can severely bias the deduced luminosity function towards less luminous objects (Wall & Jenkins 2003).

Lutz-Kelker bias It is well known that a systematic error will be introduced when parallaxes are used to calibrate a luminosity system. One tends to overestimate the parallax i.e. underestimate the distances. This bias was first proposed by Lutz and Kelker (1973) and is widely referred to in the literature under the designation *Lutz-Kelker bias*. Assume that one calculates luminosities from observed parallaxes in a narrow range bounded by an upper and a lower limit. Due to measurement errors, stars actually outside the adopted lower limit will then be scattered into the sample and stars inside will be scattered out. But there are more stars outside the boundary than inside (if one assumes the stars to be uniformly distributed in space) and this results in more stars being scattered in than out, and the true average parallax of a sample of stars will thus be smaller than the observed average parallax. The bias is not caused by the use of a lower parallax limit. It exists at all values of parallax and is a consequence of both the errors of observation and the fact that the number density of stars increases towards smaller parallaxes or larger distances. This can be seen in Figure 3.3. The size of the systematic error induced depends only on the ratio $\frac{\sigma_p}{p}$, just as before, but this time the errors point in the opposite direction and we thus tend to underestimate distances due to this effect.

3.5 Astrometric detection of exoplanets

Some 20 years after the first detection of an exoplanet (see Perryman 2014, for an excellent review), the search intensifies all the time and more and more exoplanets are being found. So far most of the exoplanets are detected by indirect methods, mostly by the small variation in radial velocity of the central star caused by the gravitational interaction with one or more orbiting planets. However, many exoplanets have been detected, and still are, with the Kepler data using the transit method (e.g. Koch et al. 2010). There are many possible techniques to detect exoplanets and in this section I summarise the most important techniques, both indirect and direct. I also investigate the expected astrometric effect of exoplanets.

Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated April 2007)
[corrections or suggestions please to michael.perryman@esa.int]

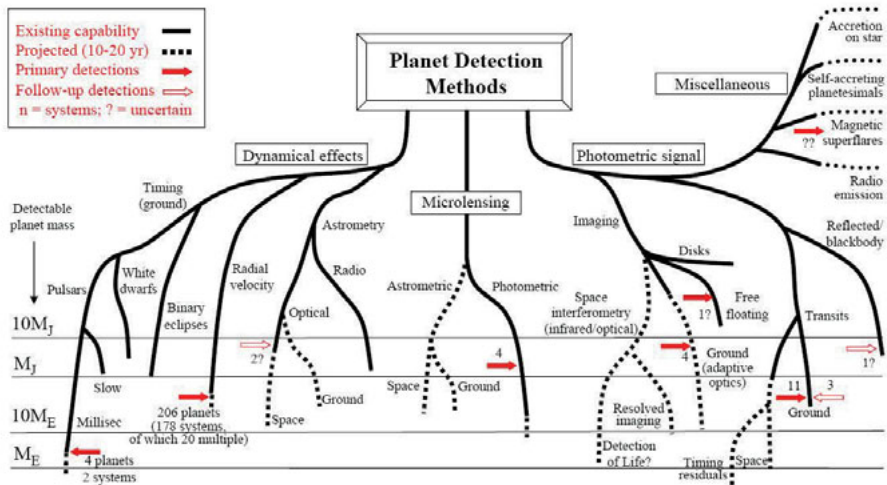


Figure 3.4. Perryman (2000) created a diagram, giving an overview of the present and future methods of detecting exoplanets. This diagram is an updated version from April 2007. A more recent version can be found in e.g. Perryman (2014). The number of detected planets are much larger today, especially those detected by the transit method.
© M.A.C. Perryman

3.5.1 Methods for detecting exoplanets

The many possibilities for detecting exoplanets are schematically described in the ‘Perryman tree’ (Fig. 3.4) where current and future methods/techniques are identified. Below is a summary of the most important methods/techniques divided into two natural groups, the indirect and the direct methods (see also, for example, Fischer et al. 2014; Perryman 2014; Wright & others 2013, for reviews). The **indirect methods** are:

Radial velocity This is the most common way to detect the presence of a planet orbiting a star. The star makes a small orbit around the common centre of mass of the planetary system, leading to a change in its radial velocity. If this is detected and has a periodic pattern, it is a sign of a small companion, e.g. an exoplanet. Up till today this ‘jitter’ can only be detected for planets that are relatively large, i.e. several times the Earth’s mass, and mostly in close orbit around its parent star.

Astrometric This is for me the most interesting technique since it involves the positional changes of a star. One cannot detect any planets using this technique today but in a near future this will change. Gaia and other projects will be able to measure the small ‘jitter’ in position of the central star due to the gravitational interaction with a planet. Gaia (now in orbit) is expected to find many thousands of Jupiter-sized exoplanets. The detection of a habitable Earth-sized exoplanet is a much more difficult task. I will come back to that later.

Transits When a planet transits in front of its parent star, there will be a small drop in the star’s brightness. This drop can be detected and information on the size of the planet can be extracted from the data. Having both the transit and radial velocity information, the planet’s orbit can be determined exactly, and gives us the true mass and size of the planet. More than 600 planets have been detected and confirmed in this manner, however, many are large planets since this method is limited by atmospheric disturbances. With space missions like COROT (Baglin et al. 2002) and Kepler (Koch et al. 2004; Koch et al. 2010) transits by small Earth-like planets have become a reality and the numbers are increasing all the time (see, for example, The Exoplanet TEAM 2014, for an update on current findings). Unfortunately, neither COROT or Kepler is still operational, but others are planned for future missions (e.g. MOST and TESS) (see, for example, Fischer et al. 2014, for a summary)

Microlensing Lensing occurs if a massive object passes between a distant source (star) and the observer. The situation for microlensing occurs if the lensing, massive object does not possess the gravitational field to split the image of the lensed, distant object into separate images. Instead, it refocuses some of the stray light and thus makes the distant source brighter. This is the ideal situation for dwarf stars, like F, G, K and M stars. If one of these stars crosses the line of sight to a distant bright star, it will cause a microlensing event in which the brightness of the distant star rises and then drops back to normal on a time scale of some ten days. If the lensing star has a planetary companion, it too will cause an additional amplification in the source star’s brightness. See Fig. 3.5. This amplification will depend upon the mass of the planet and will thus be a sensitive indicator of the planet’s mass. Even Earth-sized planets should be possible to detect using this technique although there is little hope that any of these planets will ever be seen again.

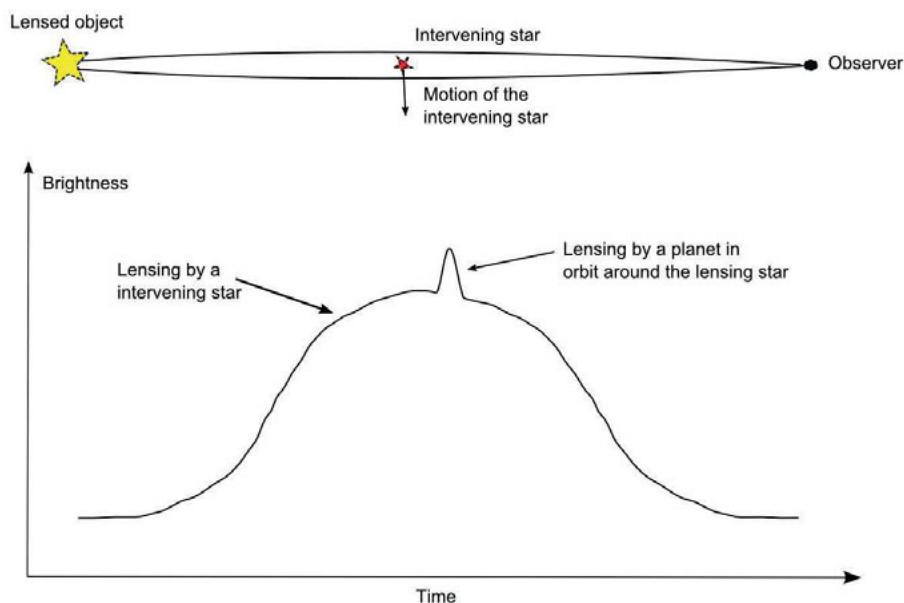


Figure 3.5. Schematic figure describing a microlensing event of a distant star. The brightness first increases and then decreases as the intervening star passes between the distant star and the observer. The planetary companion to the lensing star might also cause a distinct lensing event.

This is an interesting possibility to detect exoplanets but the circumstances required are unusual; only a some 20 planets have been detected in this manner.

The **direct methods** are:

Direct imaging A possibility to detect exoplanets, by using infrared (IR) telescopes like Spitzer, exists due to the fact that the flux ratio between the star and the planet is lower in IR than in visible. So far only few planets have been detected using this method.

Nulling Interferometry Using two or more telescopes and combining the light from them in such way that there is destructive interference on the central star reveals details on the surroundings of the star. Any light reflected on a exoplanet is expected to be seen in the detector since it is offset from the central star and takes a different path through the telescope system. Darwin (e.g. Karlsson et al. 2006) is a future space interferometer using the nulling technique.

Closure phase Closure phase can in principle be used to detect exoplanets. If the flux ratio of a star-planet couple is a reasonable 100 000, the closure phase is of the same order of magnitude, i.e. 1×10^{-5} leading to phase

changes of the order of 0.001° (Monnier 2003a). This is a very small phase change and the question is if it can be separated from the noise induced by many other effects including stellar surface structures.

Polarimetry Light rays emitted by a star are unpolarised but after being reflected on a (exo)planet, the rays are polarised in one preferred direction. A polarimeter is a device capable of detecting polarised light and rejecting unpolarised light. Such devices are under construction and can be used in the future to detect signals originating from exoplanets.

3.5.2 Expected astrometric effect of exoplanets

How large is the astrometric jitter due to exoplanets? From the database *The Extrasolar Planets Encyclopaedia*⁴ (The Exoplanet TEAM 2014) many of the detected planets are large (Jupiter-size) and in close orbit around the central star, even if more and more smaller planets are detected.

So far there has been some detection of Earth-like exoplanet. Earth-like exoplanets will have such a small effect on the central star that they cannot be detected with currently available techniques. Of course, the finding of any planet like the Earth would be a great discovery, and if the orbit is in the habitable zone, it will be even more interesting. The first suspected Earth-like exoplanet ($M_* \approx 5 M_\oplus$) in the habitable zone was found by Udry et al. (2007).

Consider for simplicity a system with a single planet of mass M_p in circular orbit around a star of mass M_* . If a is the semi-major axis of the relative orbit, the star moves about the centre of mass with semi-major axis, or *astrometric signature*,

$$\alpha = \frac{M_p}{M_* + M_p} a \simeq \frac{M_p}{M_*} a \quad (3.10)$$

since $M_p \ll M_*$. For a star of luminosity L_* , the mean distance of the habitable zone is approximately (Kasting et al. 1993; Gould et al. 2003)

$$a = \sqrt{\frac{L_*}{L_\odot}} [\text{AU}] \quad (3.11)$$

For reasonably long-lived main-sequence stars (of spectral type A5 and later), the luminosity scales with mass as $L_* \propto M_*^{4.5}$ (Andersen 1991), and using this one has

$$a = \left(\frac{M_*}{M_\odot} \right)^{2.25} [\text{AU}] \quad (3.12)$$

⁴<http://exoplanet.eu/>

The astrometric signature, α , of a planet in the habitable zone will then be

$$\begin{aligned}
 \alpha &\simeq \frac{M_p}{M_*} a [\text{AU}] \\
 &\simeq \frac{M_p}{M_*} \left(\frac{M_*}{M_\odot} \right)^{2.25} [\text{AU}] \\
 &= \frac{M_p}{M_\odot} \left(\frac{M_*}{M_\odot} \right)^{1.25} [\text{AU}]
 \end{aligned} \tag{3.13}$$

and with $M_\oplus \simeq 3 \times 10^{-6} M_\odot$ Eq. (3.13) becomes

$$\alpha \simeq 3 \times \frac{M_p}{M_\oplus} \left(\frac{M_*}{M_\odot} \right)^{1.25} [\mu\text{AU}] \tag{3.14}$$

The RMS excursion of the star's position on the sky, σ_{pos} , can be obtained by the following reasoning: Assume that the star moves in a circular orbit with radius α making an inclination i to the sky plane. Then the change in position of the star can be expressed in a Cartesian coordinate system as (Binnendijk 1960)

$$\begin{aligned}
 \Delta x &= \rho \sin \theta \\
 \Delta y &= \rho \cos \theta
 \end{aligned}$$

where ρ is the radius vector projected on the sky plane and θ is the position angle. From Fig. 3.6 one also see that

$$\rho \sin(\theta - \Omega) = \alpha \sin \omega \cos i \tag{3.15}$$

$$\rho \cos(\theta - \Omega) = \alpha \cos \omega \tag{3.16}$$

What is then the RMS excursion of the position of the central star? The excursion along an arbitrary direction, s , is given by (see Figure 3.7)

$$\begin{aligned}
 \Delta s &= \Delta x \sin \varphi + \Delta y \cos \varphi \\
 &= \rho \sin \theta \sin \varphi + \rho \cos \theta \cos \varphi \\
 &= \rho \cos(\theta - \varphi)
 \end{aligned} \tag{3.17}$$

Using $\theta - \varphi = \theta - \Omega + (\Omega - \varphi)$ to rewrite 3.17:

$$\begin{aligned}
 \Delta s &= \rho \cos((\theta - \Omega) + (\Omega - \varphi)) \\
 &= \rho \cos(\theta - \Omega) \cos(\Omega - \varphi) - \rho \sin(\theta - \Omega) \sin(\Omega - \varphi)
 \end{aligned} \tag{3.18}$$

Using (3.15) one get

$$\Delta s = \alpha \cos \omega \cos(\Omega - \varphi) - \alpha \sin \omega \cos i \sin(\Omega - \varphi) \tag{3.19}$$

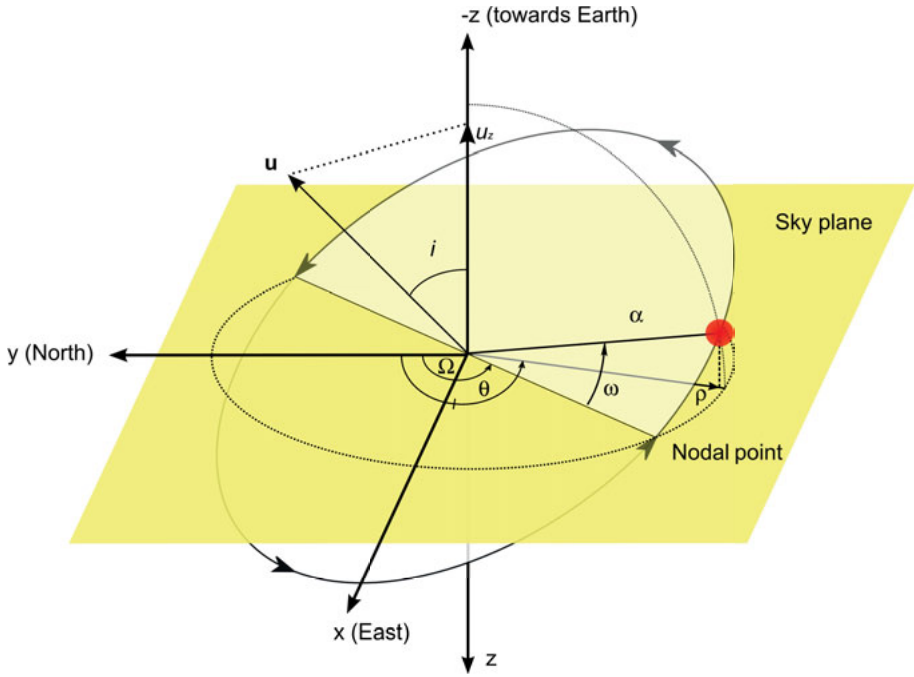


Figure 3.6. Schematic diagrams describing the motion of a star in an inclined orbit around the barycentre. Conventions according to Binnendijk (1960).

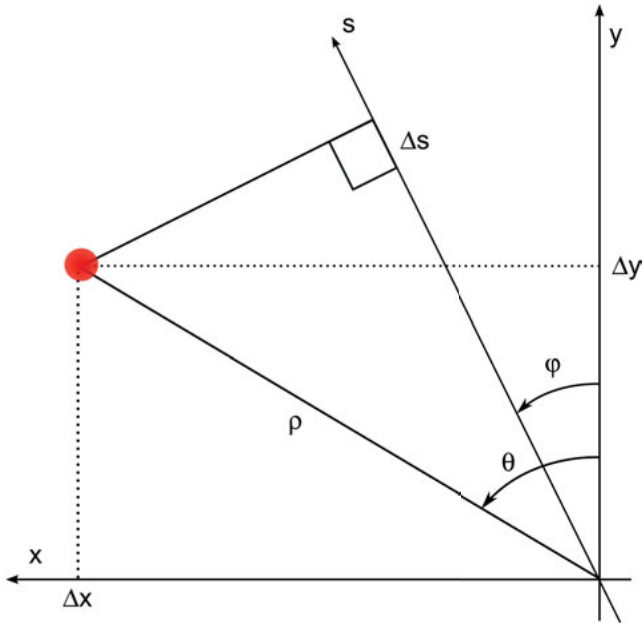


Figure 3.7. The projection of the position of the central star (red) on the arbitrary direction s .

The RMS excursion of the position of the central star is given by $\sigma_{pos}^2 = \langle \Delta s^2 \rangle$ where Δs^2 is

$$\begin{aligned}\Delta s^2 &= (\alpha \cos \omega \cos(\Omega - \varphi) - \alpha \sin \omega \cos i \sin(\Omega - \varphi))^2 \\ &= \alpha^2 (\cos^2 \omega \cos^2(\Omega - \varphi) - \frac{1}{2} \cos i \sin 2\omega \sin 2(\Omega - \varphi) \\ &\quad + \cos^2 i \sin^2 \omega \sin^2(\Omega - \varphi))\end{aligned}\quad (3.20)$$

According to Fig. 3.6 the direction of the rotation axis of the orbital plane of e.g. a planet in $u = (u_x, u_y, u_z)$ compared to the sky plane. The z-axis is pointing away from the observer and the inclination of the system is denoted by i . Ω is the angle between the y-axis and the nodal point. u is then given by $u = (-\sin i \cos \Omega, \sin i \sin \Omega, -\cos i)$. Since there is no preferred direction for u , the expectation values for $\langle u_j^2 \rangle$, $j = x, y, z$, must all be the same, i.e. $\langle u_x^2 \rangle = \langle u_y^2 \rangle = \langle u_z^2 \rangle = \frac{1}{3}$. From this one realises that for a randomly orientated system the expectation value $\langle \cos^2 i \rangle = \frac{1}{3}$ and $\langle \sin^2 i \rangle = \frac{2}{3}$. Since all φ, i, Ω are independent, the expectation value for Eq. 3.20, i.e. σ_{pos}^2 , will be

$$\begin{aligned}\sigma_{pos}^2 &= \langle \Delta s^2 \rangle = \alpha^2 \left(\frac{1}{2} \cdot \frac{1}{2} - \frac{1}{2} \cdot 0 \cdot 0 \cdot 0 + \frac{1}{3} \cdot \frac{1}{2} \cdot \frac{1}{2} \right) \\ &= \alpha^2 \left(\frac{1}{4} + \frac{1}{12} \right) = \frac{1}{3} \alpha^2 \\ \Rightarrow \sigma_{pos} &= \frac{\alpha}{\sqrt{3}}\end{aligned}\quad (3.21)$$

Inserting Eq. (3.14) into Eq. (3.21) gives

$$\sigma_{pos} \simeq \sqrt{3} \times \frac{M_p}{M_{\oplus}} \left(\frac{M_*}{M_{\odot}} \right)^{1.25} [\mu\text{AU}]. \quad (3.22)$$

The resulting photocentric displacement of the central star for Earth-like planets in the habitable zone for different spectral type stars can be found in Fig. 3.8. The RMS variations are very small ($1\mu\text{AU} \sim 150\text{ km}$). Early-type stars, which are not included in this figure, are too short-lived and evolve too rapidly to create a temperature-stable environment for life to evolve over the billions of years required for this process. These stars also emit very much UV light and the effect of high-energy radiation on living organisms is well documented: the energetic rays destroy the molecules upon which life is built. These arguments largely exclude early-type stars from the search of exoplanets.

The situation for late-type stars is better in the sense that the central star radiates little UV and is much more long-lived. The orbital period, comparable to a few years, is acceptable for a search program but the photocentric

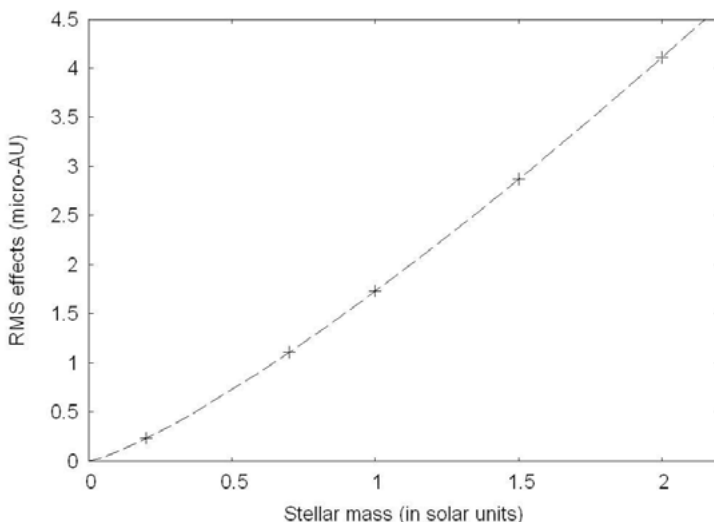


Figure 3.8. Graph of the expected astrometric RMS dispersion for different main sequence stars, in the mass range $0.2\text{--}2 M_{\odot}$, corresponding to spectral classes A–M, caused by an Earth-like (in mass) exoplanet in the habitable zone. The graph is based on Eq. (3.22). Note that $1 \mu\text{AU} \sim 150 \text{ km}$

displacement is very small. Another problem might be that the habitable zone is narrower for cool stars and therefore the probability for finding an Earth-like planet in this zone gets smaller with cooler stars. On the other hand, there are many, many more late-type stars, especially M stars.

In conclusion, if one wants to find Earth-like exoplanets one should look amongst late type stars. The remaining question is if it is possible to detect them at all using astrometric techniques or if this signal will drown in the astrometric noise from its parent star. I will come back to that later.

3.6 The future: From mas to μas

Over the last 30-40 years astrometry has undergone a huge development. Today it is possible to make measurements with accuracies of only a few μas . This is due to mainly two new possibilities: interferometric observations and space astrometry.

Interferometry is an old technique that has recently developed into a practical possibility for optical astrometry, after being a common technique in radio astronomy for a long time. Also interesting is the possibility to get information from interferometry on stellar surface structures (Ludwig & Beckers 2008). This can be done by using the concept of *closure phase* (see e.g. Corn-

well 1989; Monnier 2003b; Perrin & Malbet 2003; van Belle 2008, for good reviews.). Although it is beyond the scope of my thesis to review the field of interferometry and closure phase, I will touch upon it since one important parameter for closure phase is the third central moment of the flux distribution. Closure phase is defined for any constellation of three telescopes as the sum of the phases and for a marginally resolved source, the closure phase can be approximated by (Lachaume 2003)

$$\phi_C = -4\pi^3 M'_3 \cdot u_{12} \cdot u_{23} \cdot u_{31} \quad (3.23)$$

where M'_3 is the third central moment, e.g. the skewness of the image. Since closure phase involves the third central moment of the flux distribution, it becomes interesting to investigate the variation of the third central moment due to stellar surface structures.

Astrometry, on the other hand, which now has the great advantage of having telescopes in space, can make observations much more accurate since one does not need to consider atmospheric refraction and turbulence, nor the rotation of the Earth, although the rotation of the satellite must be accounted for. The possibility to observe the whole sky with a single space-borne telescope gives much better opportunities to calibrate the instrument to high accuracy, hence making very accurate observations.

3.6.1 Gaia: The Billion Stars Surveyor

Gaia⁵ is an ESA space astrometry project that will map the stars in our Galaxy and its neighbours, including the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). It will have a $25 \mu\text{as}$ accuracy for objects up to magnitude $V=15$. It is a global astrometric project in the sense that it will measure object properties continuously as the satellite rotates in a complex manner (the Gaia Scanning Law). The goal is to map the position, radial velocity, proper motion etc. for every object brighter than $V=20$ magnitudes to create a 3D map over our Galaxy. Over one billion objects are expected to be catalogued, including stars, quasars, small solar system objects, and (large) exoplanets.

The scientific results from Gaia are almost inconceivable in extent and implication: detailed information on the structure, dynamics, evolution and history of our Galaxy and beyond, distribution of dark matter, detection of many thousands of exoplanets and solar system bodies, the curvature of space-time in the solar neighbourhood etc. Most important is perhaps the possibility to

⁵<http://www.cosmos.esa.int/web/gaia>

establish a rigorous distance scale framework throughout the Galaxy and beyond.

Gaia is designed with the following considerations in mind:

- Astrometry ($V < 20$)
 - Completeness to 20 mag (on-board detection) $\Rightarrow 10^9$ stars
 - Accuracy:
 - * 5–14 μas at $V = 3\text{--}14$
 - * 9–26 μas at $V = 15$
 - * 130–600 μas at $V = 20$

The high astrometric accuracy leads to very accurate distance determinations e.g.

- * distances with $1\sigma = 1\%$ for 10 million stars out to 2.5 kpc
 - * distances with $1\sigma = 10\%$ for 100 million stars out to 25 kpc
 - * parallax calibration of all distance indicators e.g. Cepheids and RR Lyrae to LMC/SMC
- Radial velocity ($V < 16\text{--}17$):
 - Principles: slitless spectroscopy using Ca triplet (847–872 nm)
 - Application:
 - * Determination of the third component of space motion, perspective acceleration
 - * Possibilities to determine the dynamics of stars, perform population studies, and binary studies
 - * From spectral analysis: stellar chemistry, stellar rotation

Gaia was launched into space in December 20, 2013, and placed in the vicinity of the gravitationally stable second Lagrange point (L2) some 1.5 million km from the Earth on the opposite side relative to the Sun. See Fig. 3.9.

The major scientific goals for the Gaia project (ESA 2014) are (see, e.g., de Bruijne 2012; Perryman et al. 2001, for an overview):

- Mapping the Milky Way galaxy, LMC and SMC
 - Gaia will determine astrometric distances and positions for over one billion stars in our Galaxy, LMC and SMC, leading to a three dimensional map of the Galaxy and its surroundings.
 - Gaia will provide accurate radial velocity and proper motion measurements of all stellar populations leading to knowledge of the velocity distribution for different populations of stars.
 - One of Gaias unique features is the well-defined sampling and subsequent observation of tens of millions of binaries over the entire sky. Gaias strengths is its extreme sensitivity to non-linear (proper) motions. Large fractions of astrometric binaries with periods in the

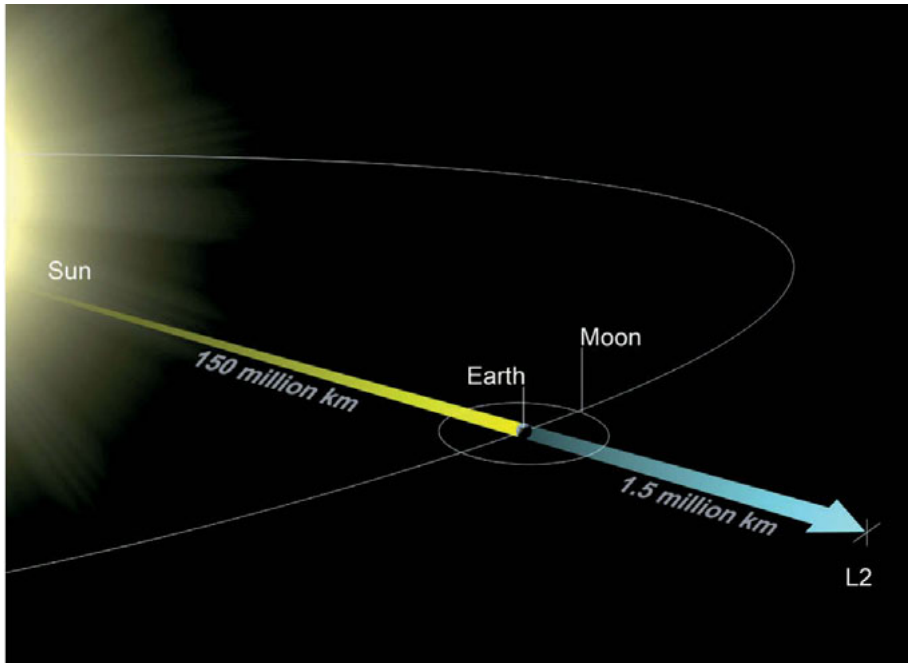


Figure 3.9. Gaia will operate from the gravitationally stable Lagrange point L2 (image: ESA)

range 0.03–30 yr will be recognised immediately. As a result of its aperture size, Gaia will resolve all binaries with separations above some 20 mas which have moderate magnitude differences between the components.

- Knowing the position and motion of the stars leads to information on the spatial and dynamic structure of the Galactic disk and halo. This is essential for stellar and galactic evolution and the formation history of the Galaxy.
- Stellar structure and evolution
 - Gaia will accurately determine the distance to better than 10% for stars out to 25 kpc. Accurate parallax calibrations are obtained for all distance indicators, like Cepheids and RR Lyrae, making distance determinations easier in the future.
 - Physical properties, like (initial) mass functions and luminosity functions, for all type of stars and regions throughout the Galaxy will be obtained. Gaia will also detect and characterise variability for all spectral types. This is important for the possibility of exoplanet detection in the future.
- Solar system bodies detection

- *Small Solar System bodies* is a newly defined group of objects, including asteroids, comets, Kuiper Belt objects etc. Many of these objects will be mapped and their orbits determined.
- Today, some 4000 near-earth objects are known and of them approximately 100 cross the Earth orbit. Gaia is predicted to find a few thousand such objects larger than 1 km. This knowledge is vital for the survival of mankind on the Earth. The detection limit at 1 AU is a few hundred meters, depending on albedo.
- Exoplanets
 - Gaia will monitor hundreds of thousands of F, G and K stars out to ~ 200 pc and is expected to find tens of thousands of Jupiter-sized exoplanets with periods less than 10 years. This also includes determinations of planetary masses and orbits. However, Earth-sized planets are not possible to detect with Gaia.

3.7 Astrophysical limitations to ultra-high-precision astrometry

There exist several astrophysical limitations to ultra-high-precision astrometry. In this section I briefly describe a few of the more important ones, namely circumstellar disks, (stellar) surface structures, (stellar) multiplicity and microlensing phenomena.

3.7.1 Circumstellar disks

Circumstellar disks are extended objects that are also variable on all sorts of time scales due to a range of hydrodynamic, gravitational and magnetic phenomena. Thus precision astrometry will be intrinsically difficult for these objects. Nevertheless it is of great interest to detect the newly formed planets around young stellar objects. A Jupiter-sized planet embedded in a circumstellar disk induces spiral density waves in the circumstellar disk. This leads to a time-variable gravitational pull that makes the central star wobble, causing an astrometric offset. Furthermore, the time-variable asymmetric scattered light from the non-uniform disk, together with the light from the central star, leads to more astrometric shifts. Takeuchi et al. (2005) modelled the size of the errors induced by these phenomena on young solar-like stars in the Taurus-Auriga region ($D \approx 140$ pc, $a = 5$ AU) and found that the gravitational pull of the variable disk is negligible ($< 1 \mu\text{as}$) but the variable disk illumination in-

duces a shift of the order of $10 - 100 \mu\text{as}$, corresponding to a virtual distance of approximately 10 mAU.

3.7.2 Surface structures

Stellar surface structures are phenomena such as *spots*, *flares*, *plages*, *faculae*, *granulation* and *non-radial oscillations*. These phenomena will affect the light-emitting area on the surface of the star by blocking some light or emitting an excess of light in different regions of the star. Spots and plages are fairly stable in position and thus appear to move as the star rotates. Faculae and granulation cells often vary on timescales shorter than the rotation period. All of these phenomena lead to a non-uniform flux distribution and will influence the total flux, the astrometric position of the photocentre, the third central moment (important for interferometry) and radial velocity.

Intuitively, one can understand that if there is a dark spot emerging over the limb on left side of the visible hemisphere, the total flux will successively become smaller until the spot is located at the central line of the star. After that the flux increases again until the spot reaches the limb on the other side of the visible hemisphere. The photocentre will first be shifted to the right as the spot moves from the left limb towards the centre and then to the left as the spot moves towards the right limb. The radial velocity will also change since a loss of light from the left hemisphere will make the other side dominant and since that side is rotating away from the observer, the overall radial velocity will be positive. This will influence the shape of the spectral lines and is used in Doppler Imaging (DI) to create images of the stellar surface (for an introduction see e.g. Gray 2005, p. 496 ff and references therein). The third central moment is more difficult to visualise. The results of these effects on a model star are schematically shown in Figure 3.10. Non-radial oscillations will shift the integrated properties total flux, photocentre position and radial velocity since the shape of the star changes together with its rotation. It is hard to draw any intuitive conclusions concerning the effects of these phenomena and it is not considered any further here.

When addressing surface structures one generally speak of stellar surface structures. There is on the other hand one more aspect: the intrinsic structures of quasars and other Active Galactic Nuclei (AGNs). These objects are very important for astrometric missions since they are used to create the extragalactic reference frame and any uncertainties in the position of these objects due to changes in their structures will limit the possibility for very accurate frame determination. It has been found that quasars can vary in brightness from one day to another and consequently also shift the centre of gravity of

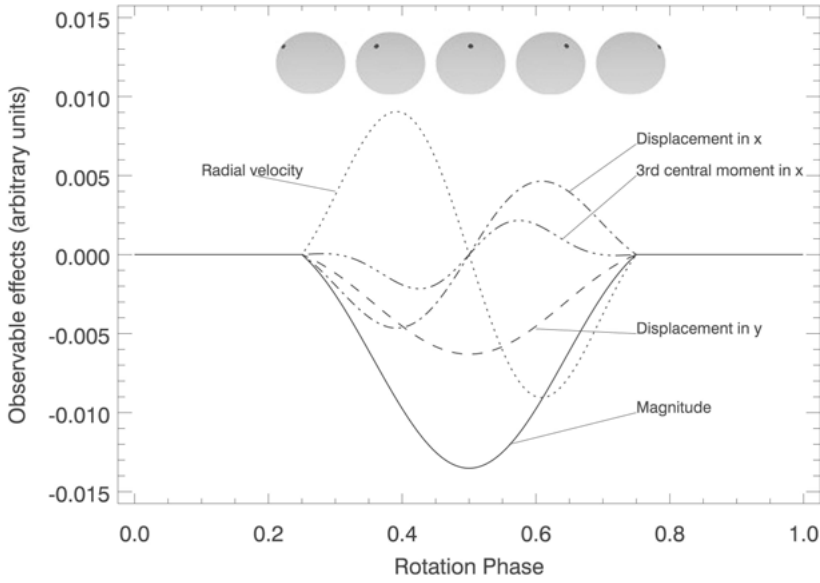


Figure 3.10. This figure shows the effect of one dark spot on flux (mag), photocentric displacement, third central moment and radial velocity as the star rotates about its axis. Here a spot covering 1% of the visible stellar surface is located at 30° latitude on the surface of a star with its rotation axis perpendicular to the line of sight. Note the similarity between the radial-velocity offset and the photocentric offset in y (normal to the rotation axis). This is not a coincidence but a consequence of $(\boldsymbol{\omega} \times \mathbf{r}) \cdot \hat{\mathbf{z}} = y\omega_x - x\omega_y$. The radial-velocity curve resembles the derivative of the light curve, which can also be understood as a consequence of the general formulae. See Chapter 4.

the light on this timescale. This indicates that quasars are very small objects, the emitting diameters are of the order of one light-day, equal to the size of the solar system. There are also many examples of quasars that vary in brightness over longer periods of time, say years, and this indicates that the light emitting source has a size of approximately one light-year. For ‘close by’ quasars this can be a large obstacle for astrometry.

For example, a quasar at 1 billion pc ($z \sim 0.25$) and a diameter of 0.5 parsec (~ 100000 AU) the angular size will be about $100 \mu\text{as}$, and the photocentre may vary on a time scale of the order of a year by a significant fraction of this size. Trying to make accurate parallax determinations using such a reference source inevitably leads to large errors.

3.7.3 Multiplicity

Stars are often gravitationally grouped in pairs or multiples. More than 50% of all stars are believed to belong to systems with two or more members. In general, the multiple systems have a hierarchical structure: a star and a binary orbiting around each other in triplet systems, two binaries orbiting each other in a quadruple system and so on. Thus most multiple systems can be described as binaries with several levels of size. Observationally, there are four main classes of binaries: visual binaries (separated more than 0.1 arcsec), astrometric binaries (only one component visible), spectroscopic binaries (two sets of spectral lines visible or the Doppler shift of the lines varies periodically) and photometric or eclipsing binaries (one component passes in front of the other as they orbit each other).

The following sources of perturbation can be identified:

- Time coverage

It can be difficult to identify a binary system if the time coverage of the orbital period is poor. The orbital motions of the stars can erroneously be taken as an extra proper motion.

- Unresolved binaries

Apart from the cases mentioned above there is also an interesting technique to identify and study the separation of Color-Induced Displacement (CID) stars. This was originally proposed by Christy et al. (1983) and has since then been applied to e.g. the Sloan Digital Sky Survey (SDSS) data (Pourbaix et al. 2004). For any double star and any photometric filter, the position of the photocentre lies between the two components. If the components have different colours, the position of the photocentre will change with the adopted filter as it depends on the ratio of the flux of the components. The CID is thus the change of the photocentre position due to the adopted filter. This effect can only be observed by using different filters and if these binaries are identified by spectroscopic or photometric techniques, the separation can in principle be determined from one single multi-colour measurement as can be done by e.g. Gaia.

- Variability of one or both components in unresolved binaries

If one (or both) of the binary components is a variable, Gaia observations may have technical difficulties and they might erroneously be identified as an eclipsing binary or no binary at all (Halbwachs & Pourbaix 2007). However, there are methods around this problem. For Hipparcos there was a model used in the reduction of the data concerning unresolved binaries including one photometric variable, the so called variability-

induced movers (VIMs). Wielen (1996) showed that the photocenter of a binary, in which one component is variable, moves in a very characteristic manner. For a binary with a fixed geometry, the photocentre moves back and forth on a straight line connecting the two components. The size of this motion depends on the ratio of the flux of the constant star to the average flux of the system times the distance between the stars. It is unfortunately not possible to directly derive the distance between the stars, but an estimate of the smallest distance d_{min} can be obtained. In practice, there is an upper limit and this is set by the accuracy of the instrument; if the separation is large enough the binary will be a visual binary and not an unresolved, close binary. If, on the other hand, the variable star is a Cepheid, with known period-luminosity function, it is possible to derive orbital parameters for the binary (see e.g. Halbwachs & Pourbaix 2007, 2005; Pourbaix et al. 2003).

- More than two components

It is common that there are more than two components, and although the hierarchical structure of such a multiple system makes it possible to treat them as binaries with several levels, it can be difficult to determine the orbital parameters, especially if one or more of the components are invisible.

3.7.4 Weak microlensing or distortion by gravitational fields

When determining the position of a star one use the direction of the beam of light coming from the star. Unfortunately, light does not travel in straight lines but follows null geodesics in the four-dimensional space-time. If a beam of light passes close to a mass it will bend as described by Einstein's general theory of relativity. If one determine the direction of the beam, one will end up with an 'incorrect' position of the star. The total deflection of a ray of light, α , is approximately given by

$$\alpha = \frac{4GM}{c^2 b} \quad (3.24)$$

where GM is the constant gravitation of the deflecting body, and b the impact parameter. (Kovalevsky & Seidelmann 2004; Lena et al. 1998)

An example is the bending of a light beam that travels close to the solar limb. The gravity of the Sun will change the direction of the beam by $1.75''$, making the source of the beam, the far away star, appear in a different direction. For a beam at 90° from the Sun the effect is 4.0717 mas. This effect is well known and easy to compensate for. For gravitational sources **outside**

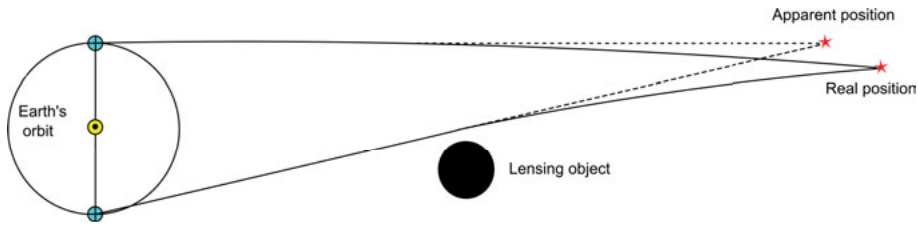


Figure 3.11. The position of a star is altered by a lensing object close to the lines of sight of different epochs. The parallax will appear larger than without the lensing object, and thereby making the star appear closer to the observer. The positional change over time can erroneously be interpreted as an extra proper motion.

the solar system the situation is more problematic since their precise properties remain unknown, such as their masses and locations. Such objects can be brown dwarfs or even black holes.

The conclusion is that one cannot be certain of the exact positions of the stars. More importantly, the gravitational deflection for a given star is constantly changing because of the relative motions of the star, the observer, and the lensing object. This will cause errors also in the measured proper motion and parallax. An example is shown in Fig. 3.11, where the lens makes the apparent parallax of a distant star too large. Sazhin et al. (2001) have investigated the parallax distortion due to the weak microlensing and concluded that it will become important at the $\sim 1 \mu\text{as}$ level.

Microlensing events (causing a change in brightness and an associated astrometric excursion) can only occur in dense regions of stars and the only regions where this could be of any practical significance, are towards the Galactic centre and perhaps the spiral arms. Simulations and analysis of this has been done by Belokurov and Evans (2002) and they conclude that, statistically, these events demand the intervening star to be very close, say about 50 pc, and the source star located at about 300 pc.

Kopeikin and Gwinn (2000) discuss different gravitational sources of astrometric perturbations in the μas and sub- μas region. They conclude that relativistic effects of the space-time curvature must be thoroughly investigated and mention e.g. deflection of light due to gravitational waves originating from binaries, super-massive binary black holes in AGNs or from the early Universe, relativistic effects of secular aberration caused by the circular motion of the solar system with respect to the Galactic barycentre, etc. All these effects are assumed to be important at the sub- μas level and some of the effects are believed to be possible to investigate by techniques such as VLBI, SIM and/or Gaia.

The Solar system is located at a specific position in space-time and without detailed knowledge of the space-time curvature between us and the stars, one cannot know their 'correct' positions. Their astrometric data must therefore be defined by the observed direction of the light beam regardless of the (unknown) space-time curvature outside of the Solar system. The local effects of the Sun and planets are of course known and can be accounted for.

4. Astrometric effects of surface structures

The development of more and more accurate instruments and techniques drives us to begin to consider new sources of perturbations in the astrometric signal. One of these sources is stellar surface structures, for example bright and/or dark spots. The nature of their influence on the photometric and astrometric signals is not well described in the literature. I have investigated these effects both theoretically and by means of simulations. Basically, I have studied the statistical relations between integrated properties such as total flux, location of the photocentre, spatial extension (stellar diameter) and asymmetry or skewness of the image. These are all moments of the flux distribution: total flux is the zeroth moment, photocentre position is the first normalised or reduced moment and, skewness is the third central reduced moment.

In this work it is shown that there are in fact distinct relations between the dispersions of all these properties and also of the radial velocity, which is a combination of first moment terms in x - and y -direction together with the angular rotational velocity.

4.1 Methods of modelling stellar surface structures

There are different approaches to the modelling of a stellar surface. A common approach is to lay a grid over the entire surface and let properties vary between discrete grid elements. As the star rotates, one can calculate the combined effect(s) of the properties of interest for all visible grid elements. This is a very time consuming approach, especially if the stellar surface must be divided into small grid elements. To save computing time one can use a coarse grid but this introduces discretisation errors. There are also difficulties handling large grid elements as they approach the limb. Due to rotation, parts of the element will gradually pass over to the far side of the star, while other parts are still visible to the observer.

An alternative way to model surface structures is to treat most of the surface as ‘blank’, which can be handled analytically, and add to this a limited number of small structures (‘spots’). A large structure can be modelled as many small structures close together, if necessary. The integrated effects are calculated by

summing over all the visible small spots, which may be much faster than summing over a complete grid. The advantages of using small spots or dividing a large structure into small spots are obvious: when modelling such structures one only has to take into account the projection effect as the spot approaches the limb. It is then approximated to disappear over the limb instantaneously.

When modelling starspots I have chosen the latter approach and the model is described in detail in the following sections. The model is built on assuming N spots distributed over a spherical star, where each spot is

- absolutely black,
- small in comparison to the stellar radius,
- of equal size A expressed as a fraction of the total surface¹,
- randomly spread over the entire surface of the star, and
- fixed in position on the surface, while the star rotates.

The star itself is treated as a solid body with a rotation period P about a tilted axis.

4.2 The Equivalent ARea Spot (EARS) model

4.2.1 Properties of a single spot

Dark or bright spots on the surface of a star will affect the integrated properties in different ways. One realises the following:

- The flux from the star is reduced in proportion to the total projected area of the visible spots and varies accordingly. It is therefore possible to find a mean value of the flux but more important is the RMS variation of the flux.
- A black spot on the left side ($-x$) of the star will shift the photocentre position in the $+x$ direction and also cause a positive skewness (third central moment) in the flux distribution along the x -axis. As the star rotates, these properties will shift and especially the RMS variations are of interest here.
- The apparent radial velocity will also shift, depending on whether a dark spot is rotating towards or away from the observer. A dark spot on the side rotating toward the observer will cause the apparent radial velocity to be positive, since more bright area is rotating away from the observer, giving a positive contribution to the radial velocity component.

Of course bright surface structures will lead to similar effects but with the opposite signs. It is therefore straightforward to model this simply by assigning different signs to dark and bright surface structures.

¹The size can alternatively be set to a mean value with a variation

The size of the spots is defined, using the angular radius ρ as seen from the centre of the star, as $A = \sin^2(\rho/2)$, see Fig. 4.1. The assumption that the spots are treated as absolutely black is uncritical if the spot area, A , is treated as an *equivalent area*. This means that the spots are actually treated as points but with properties equivalent to a completely black spot of area A . If one let dark spot areas be positive one can formally treat bright spots as having negative areas. Their contribution to the intensity can then be specified by the following reasoning. Assume that the surface brightness is given by a linear limb-darkening law

$$I(x, y) = (1 - a + a\mu)I_C \quad (4.1)$$

where a is the limb-darkening factor and $\mu = |z|/R$ is the projection factor of a surface element dS when projected onto the sky. $I_C = I(0, 0)$ is the mean intensity at disk centre, where $\mu = 1$.

A spot at (x_1, y_1) has an equivalent area $A = \frac{1}{2\pi R^2} \iint \alpha(x, y) \mu dS$, where α is 0 except close to (x_1, y_1) , where it is some number between 0 and 1, depending on the contrast. In the following simulations maximum contrast is being used for the spots ($\alpha = 1$). For the Sun in visible light, $a \approx 0.6$.

Using this, the surface brightness or intensity can be expressed as

$$I(x, y) = (1 - \alpha(x, y))(1 - a + a\mu)I_C \quad (4.2)$$

This is the *fundamental intensity model* that the rest of the analysis is built upon.

4.2.2 Multiple spots on a rotating star

When describing the spot coverage of a star, a commonly used property is the *spot filling factor*, f . It is interpreted as the fraction of the visible sphere covered by spots. The property varies from $\ll 1\%$ for old, inactive stars to several percent for young, active stars. Saar and Donahue (1997) and Hatzes (2002) used the spot filling factor when modelling the effect of starspots on radial velocity variations. From their models, they derive radial-velocity and position variations that are proportional to $f^{0.9}$ or $f^{0.92}$. However, they do not explain the origin of the power exponents.

What is expected from a statistical point of view? The relation between the total equivalent area of the spots, $A \cdot N$, and spot filling factor, f , is that $f \simeq 2 A \cdot N$. As long as $A \cdot N \ll 1$, all the effects are proportional to A . When addressing the dependence of N one must take into consideration that the spots are randomly spread over the surface and any of the effects will mainly depend on the number of spots k on the visible part of the star at any given time. Statistically, the number of visible spots follows a binomial distribution function

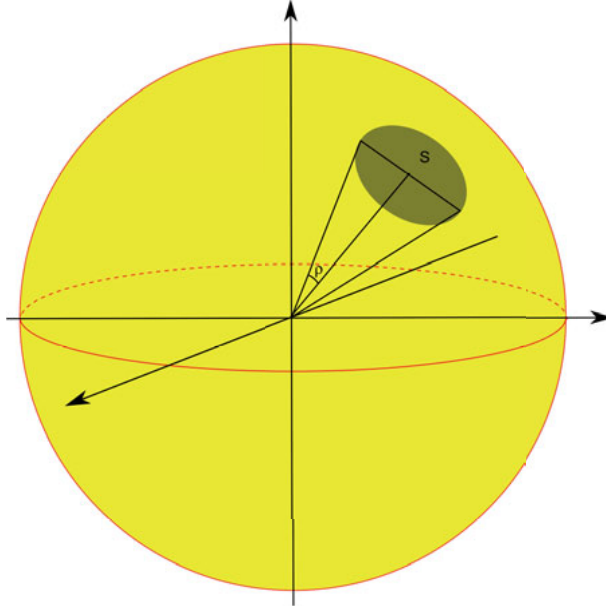


Figure 4.1. Definition of the area of the spot. The spot area is related to the angle, ρ , by $A = \sin^2(\rho/2)$.

with parameters $p = 0.5$ and N . The RMS dispersion of such a distribution is $\sqrt{N}/2$, i.e. one can expect the RMS variations of the integrated properties to be proportional to $A\sqrt{N}$ or

$$\sigma_j \propto A\sqrt{N} \quad \text{where} \quad j = F, m, \text{pos}, v_R \text{ and } \mu_3. \quad (4.3)$$

rather than depending on the spot filling factor, f , or some power of it.

To simulate a spotted star I randomly place N spots of a given size A on the surface of star of radius R and then tilt the rotation axis to a certain inclination i . The position angle ϕ is set to zero (or any other value, even random). To randomly place the spots on the surface demands some considerations for the latitude coordinate. If the spots are distributed uniformly in latitude between $+90^\circ$ and -90° there will be an excess of spots close to the poles, which is unrealistic. We instead use a more realistic distribution, where the probability density is the same for all surface elements

$$\phi = \cos^{-1} (1 - 2 \cdot \text{randomu}(\text{seed}))$$

where ϕ is the colatitude². For the longitude one simply has

$$\lambda = 2\pi \cdot \text{randomu}(\text{seed}).$$

The first problem encountered with a rotating star is the fact that one only sees half of it at any given time. One also realises the need for transforming the spot's position on the star to a fixed coordinate system on the sky, with origin at the centre of the star. Below, and in more detail in Appendix A, I describe how this can be carried out, taking into account the projection effect of the spots as well as the limb-darkening law ($I \propto 1 - a + \mu a$).

When simulating a rotating star I first define two right-handed Cartesian coordinate systems, one that is fixed to the model star $\mathbf{E} = [\mathbf{e}_1 \ \mathbf{e}_2 \ \mathbf{e}_3]$ and one that is fixed onto the sky $\mathbf{Z} = [\mathbf{x} \ \mathbf{y} \ \mathbf{z}]$. I choose the orientation of the star's coordinate system so that the \mathbf{e}_3 axis coincides with the rotation axis. The star rotates with angular velocity ω .

To model a randomly orientated, rotating star the following steps are needed:

1. Place a spot at the coordinates $(r_j, \lambda_j, \phi_j) \rightarrow \mathbf{r}_j$
2. Rotate the model star by the angle $\omega \Delta t$, where Δt is the time step.
3. Transform to new coordinates (x_j, y_j, z_j) .
4. If the spot is visible ($z_j < 0$) it is used in the calculations for the integrated properties.
5. Repeat from 2. until $\omega t = 2\pi$.

In Appendix A an expression is derived for the transformation between the internal, rotating coordinate system of the star and the fixed coordinate system:

$$\begin{bmatrix} x_j \\ y_j \\ z_j \end{bmatrix} = \mathbf{T}(t) \begin{bmatrix} r \cos \phi_j \sin \lambda_j \\ r \sin \phi_j \sin \lambda_j \\ r \cos \phi_j \end{bmatrix} \quad (4.4)$$

where $\mathbf{T}(t)$ stands for the total transformation between the two systems.

The coordinates x_j and y_j are used in the calculations of the moments, but also z_j , since it will help to define which part of the star that is visible to the observer. A negative value of z_j means that the spot is on the side facing the observer and therefore visible. z_j is also used for the projection factor $\mu = \frac{|z_j|}{R}$.

²randomu(seed) is a function returning a list of random number between 0 and 1 with a uniform distribution for different seeds. This is the notation used in the program language IDL (Interactive Data Language) in which I have made the simulations.

4.2.3 Theoretical relations used in the model

Let $I(\mathbf{r}, t)$ be the instantaneous surface brightness of the star at a point $\mathbf{r} = (x, y, z)$ on the visible surface, i.e. the specific intensity in the direction of the observer. I am interested in the integrated properties: total flux $F(t)$, photocentre offsets $\Delta x(t)$, $\Delta y(t)$ in the directions perpendicular to the line of sight, the third central moment³ of the intensity distribution $\mu_3(t)$, and radial velocity offset $\Delta v_R(t)$. These are defined by the following integrals over the visible surface $S (z < 0)$:

$$F(t) = \int_S I(\mathbf{r}, t) \mu \, dS \quad (4.5)$$

$$\Delta x(t) = \frac{1}{F(t)} \int_S I(\mathbf{r}, t) x \mu \, dS \quad (4.6)$$

$$\Delta y(t) = \frac{1}{F(t)} \int_S I(\mathbf{r}, t) y \mu \, dS \quad (4.7)$$

$$\mu_3(t) = \frac{1}{F(t)} \int_S I(\mathbf{r}, t) (x - \Delta x(t))^3 \mu \, dS \quad (4.8)$$

$$\Delta v_R(t) = \frac{1}{F(t)} \int_S I(\mathbf{r}, t) (\boldsymbol{\omega} \times \mathbf{r}) \cdot \hat{\mathbf{z}} \mu \, dS \quad (4.9)$$

where $\mu = \frac{|z|}{R}$ is the projection factor of the surface element dS when projected onto the sky and $\boldsymbol{\omega}$ is the angular velocity of the star (assumed to be rigid). The photometric variation in magnitudes is given by

$$\Delta m(t) = -1.086 \frac{F(t) - \langle F \rangle}{\langle F \rangle} \quad (4.10)$$

where $\langle F \rangle$ is the time-averaged flux and the scale factor 1.086 originates from conversion between change in magnitude and flux⁴.

The expression for the non-normalised central moments in Cartesian coordinates is

$$M'_{mn} = \int_S I(x, y) (x - \Delta x)^{m-n} (y - \Delta y)^n \mu \, dS \quad (4.11)$$

³There are actually four different third moments, involving the powers x^3 , x^2y , xy^2 and y^3 . Only the first is considered here, but similar expressions can be derived for the other three.

⁴The relation between change in magnitude and flux is given by

$$\Delta m(t) = -2.5 \lg \left(\frac{F(t)}{\langle F \rangle} \right)$$

where $m + n = \text{order of moment}$. For the closure phase one needs the third central moments and there are actually four possibilities; $M'_{30}, M'_{21}, M'_{12}, M'_{03}$. Here, this is exemplified by the case where $m = 3, n = 0$:

$$M'_{30} = \int_S I(x, y) (x - \Delta x)^3 \mu \, dS \quad (4.12)$$

It is often useful to have the normalised moments. They are found by dividing the (central) moments by the zeroth moment, e.g. the total integrated flux.

$$F = M_{00} = \int_S I(x, y) \mu \, dS \quad (4.13)$$

Generally, the normalised moments are

$$\frac{M_{mn}}{M_{00}} = \frac{1}{F} \int_S I(x, y) x^{m-n} y^n \mu \, dS \quad (4.14)$$

and the central moments

$$\frac{M'_{mn}}{M_{00}} = \frac{1}{F} \int_S I(x, y) (x - \Delta x)^{m-n} (y - \Delta y)^n \mu \, dS \quad (4.15)$$

In conclusion, one find that

$$F = M_{00} \quad (4.16)$$

$$\Delta x = \frac{M_{10}}{M_{00}} \quad (4.17)$$

$$\Delta y = \frac{M_{01}}{M_{00}} \quad (4.18)$$

$$\mu_3 = \frac{M'_{30}}{M_{00}} \quad (4.19)$$

and, since $\lg x = \ln x / \ln 10$, the relation can be rewritten as

$$\begin{aligned} \Delta m(t) &= -2.5 \lg \left(\frac{F(t)}{\langle F \rangle} \right) \\ &= -\frac{2.5}{\ln 10} \ln \left(\frac{F(t)}{\langle F \rangle} \right) \\ &= -\frac{2.5}{\ln 10} \ln \left(1 + \frac{F(t) - \langle F \rangle}{\langle F \rangle} \right) \end{aligned}$$

In the limit of small changes ($F(t) \approx \langle F \rangle$), one find

$$\Delta m(t) \approx -1.086 \frac{F(t) - \langle F \rangle}{\langle F \rangle}$$

For the radial velocity, Eq. (4.9), the expression $(\omega \times r) \cdot \hat{z}$ is the radial velocity of a point (x, y) on the surface as the star rotates around its axis.

These are the generally applicable theoretical relations and in the following section I will derive numerical relations under the assumption of a spotted star, using the *equivalent area* of a spot as a parameter of the size of the spot.

4.2.4 Calculation of the moments

Zeroth moment or total flux, F

Using the intensity model in Eq. (4.2), the instantaneous total flux is given by

$$\begin{aligned}
 M_{00} = F &= \int_S (1 - \alpha(x, y))(1 - a + a\mu) I_C \mu \, dS \\
 &= \int_S (1 - a + a\mu) I_C \mu \, dS - \int_S \alpha(x, y)(1 - a + a\mu) I_C \mu \, dS \\
 &\approx \pi R^2 \left(1 - \frac{a}{3}\right) I_C - 2\pi R^2 A_1 \mu_1 (1 - a + a\mu_1) I_C \quad (4.20)
 \end{aligned}$$

where $\pi R^2 (1 - a/3) I_C$ is the total flux from an non-spotted star⁵. Let $Q_1 = 2A_1$ be the size of the spot expressed as a fraction of the visible sphere, $2\pi R^2$, then

$$F \approx \pi R^2 \left(1 - \frac{a}{3}\right) I_C - \pi R^2 Q_1 \mu_1 (1 - a + a\mu_1) I_C \quad (4.21)$$

If there are several spots, then the flux will be a sum over the n visible spots (with $z_i < 0$):

$$F \approx \pi R^2 I_C \left(1 - \frac{a}{3}\right) - \pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) \quad (4.22)$$

First moments and photocentric displacement

The first moment in x is

$$\begin{aligned}
 M_{10} &= \int_S I(x, y) x \mu \, dS \\
 &= \int_S (1 - \alpha(x, y))(1 - a + a\mu) I_C x \mu \, dS \\
 &= \int_S (1 - a + a\mu) I_C x \mu \, dS - \int_S \alpha(x, y) \mu (1 - a + a\mu) I_C x \mu \, dS \\
 &\approx 0 - \sum_{i=1}^n 2\pi R^2 A_i \mu_i (1 - a + a\mu_i) I_C x_i
 \end{aligned}$$

⁵See Paper I for the detailed calculations of the total flux.

With $Q_i = 2A_1$ one get

$$M_{10} \approx -\pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) x_i \quad (4.23)$$

The same reasoning for y gives

$$M_{01} \approx -\pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) y_i \quad (4.24)$$

The normalised moments, equal to the photocentric displacements $\Delta x = \frac{M_{10}}{M_{00}}$ and $\Delta y = \frac{M_{01}}{M_{00}}$, can now be expressed as

$$\Delta x = \frac{M_{10}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) x_i}{\left(1 - \frac{a}{3}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i)} \quad (4.25)$$

$$\Delta y = \frac{M_{01}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) y_i}{\left(1 - \frac{a}{3}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i)} \quad (4.26)$$

If all Q_i are small then this can be approximated by

$$\Delta x = \frac{M_{10}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) x_i}{\left(1 - \frac{a}{3}\right)} \quad (4.27)$$

$$\Delta y = \frac{M_{01}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) y_i}{\left(1 - \frac{a}{3}\right)} \quad (4.28)$$

The second moment, M_{20}

The second moment in x is

$$\begin{aligned} M_{20} &= \int_S I(x, y) x^2 \mu \, dS \\ &= \int_S (1 - \alpha(x, y)) (1 - a + a \mu) I_C x^2 \mu \, dS \\ &= \int_S (1 - a + a \mu) I_C x^2 \mu \, dS - \int_S \alpha(x, y) \mu (1 - a + a \mu) I_C x^2 \mu \, dS \\ &\approx \frac{1}{4} \pi R^4 I_C \left(1 - \frac{7a}{15}\right) - \sum_{i=1}^n 2\pi R^2 A_i \mu_i (1 - a + a \mu_i) I_C x_i^2 \end{aligned}$$

thus

$$M_{20} \approx \frac{1}{4} \pi R^4 \left(1 - \frac{7a}{15}\right) I_C - \pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a \mu_i) x_i^2 \quad (4.29)$$

and the normalised moment will be

$$\begin{aligned}\frac{M_{20}}{M_{00}} &\approx \frac{\frac{1}{4}\pi R^4 \left(1 - \frac{7a}{15}\right) I_C - \pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^2}{\pi R^2 I_C \left(1 - \frac{a}{3}\right) - \pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i)} \\ &\approx \frac{\frac{1}{4}R^2 \left(1 - \frac{7a}{15}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^2}{\left(1 - \frac{a}{3}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i)}\end{aligned}\quad (4.30)$$

or, approximately

$$\frac{M_{20}}{M_{00}} \approx \frac{\frac{1}{4}R^2 \left(1 - \frac{7a}{15}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^2}{\left(1 - \frac{a}{3}\right)} \quad (4.31)$$

The third moment, M_{30}

The third moment in x is

$$\begin{aligned}M_{30} &= \int_S I(x, y) x^3 \mu \, dS \\ &\approx 0 - \sum_{i=1}^n 2\pi R^2 A_i \mu_i (1 - a + a\mu_i) I_C x_i^3\end{aligned}$$

thus

$$M_{30} \approx -\pi R^2 I_C \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^3$$

and the normalised moment will be

$$\frac{M_{30}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^3}{\left(1 - \frac{a}{3}\right) - \sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i)} \quad (4.32)$$

or, approximately,

$$\frac{M_{30}}{M_{00}} \approx \frac{-\sum_{i=1}^n Q_i \mu_i (1 - a + a\mu_i) x_i^3}{\left(1 - \frac{a}{3}\right)} \quad (4.33)$$

The third central moment, M'_{30}

The third central moment in x is

$$\begin{aligned}M'_{30} &= \int_S I(x, y) \cdot (x - x_0)^3 \mu \, dS \\ &= \int_S I(x, y) (x^3 - 3x^2 x_0 + 3x x_0^2 - x_0^3) \mu \, dS \\ &= M_{30} - 3M_{20} \frac{M_{10}}{M_{00}} + 3M_{10} \left(\frac{M_{10}}{M_{00}}\right)^2 - \left(\frac{M_{10}}{M_{00}}\right)^3 M_{00} \\ &= M_{30} - 3 \frac{M_{20} M_{10}}{M_{00}} + 2 \frac{M_{10}^3}{M_{00}^2}\end{aligned}\quad (4.34)$$

From this it is clear that one can calculate the third central moment using the non-central moments. Thus,

$$\mu_3 = \frac{M'_{30}}{M_{00}} = \frac{M_{30}}{M_{00}} - 3 \frac{M_{20}}{M_{00}} \frac{M_{10}}{M_{00}} + 2 \frac{M_{10}^3}{M_{00}^3} \quad (4.35)$$

4.2.5 Radial velocity

Assume a spot on the surface of the star associated with the position-vector \mathbf{r} . The rotational velocity of \mathbf{r} will of course be

$$\begin{aligned} \mathbf{v}_{\text{rot}} &= \boldsymbol{\omega} \times \mathbf{r} = \begin{vmatrix} \omega_x & \omega_y & \omega_z \\ x & y & z \\ \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \end{vmatrix} \\ &= \hat{\mathbf{y}}x\omega_z - \hat{\mathbf{x}}y\omega_z + \hat{\mathbf{x}}z\omega_y - \hat{\mathbf{z}}x\omega_y - \hat{\mathbf{y}}z\omega_x + \hat{\mathbf{z}}y\omega_x \end{aligned} \quad (4.36)$$

Since the $+z$ -axis points away from the observer, the *radial velocity*, v_r , of the spot will be the z -component of \mathbf{v}_{rot} :

$$\begin{aligned} v_r &= (\boldsymbol{\omega} \times \mathbf{r}) \cdot \hat{\mathbf{z}} \\ &= (\hat{\mathbf{y}}x\omega_z - \hat{\mathbf{x}}y\omega_z + \hat{\mathbf{x}}z\omega_y - \hat{\mathbf{z}}x\omega_y - \hat{\mathbf{y}}z\omega_x + \hat{\mathbf{z}}y\omega_x) \cdot \hat{\mathbf{z}} \\ &= \omega_x y - \omega_y x \end{aligned} \quad (4.37)$$

and the overall change in radial velocity due to the spots will be

$$\Delta v_r = \omega_x \Delta y - \omega_y \Delta x \quad (4.38)$$

The radial velocity can thus be expressed as a combination of the first two normalised moments of the intensity distribution together with the components of the angular velocity. If the $+y$ direction coincides with the projection of the rotation vector $\boldsymbol{\omega}$ onto the sky, then $\omega_x = 0$, $\omega_y = \omega \sin i$, and $\omega_z = \omega \cos i$ where $\omega = 2\pi/P$.

4.2.6 Summary of the moments

The calculations lead to expressions all including the common part $K_i = Q_i \mu_i (1 - a + a \mu_i)$ and inserting this into the derived expressions, together with the convention of expressing x_i, y_i as fractions of the stellar radius R , leads to

$$M_{00} = \pi R^2 \left(1 - \frac{a}{3}\right) I_C - \pi R^2 I_C \sum_{i=1}^n K_i \quad (4.39)$$

$$M_{10} = -\pi R^3 I_C \sum_{i=1}^n \left(\frac{x_i}{R}\right) K_i \quad (4.40)$$

$$M_{01} = -\pi R^3 I_C \sum_{i=1}^n \left(\frac{y_i}{R}\right) K_i \quad (4.41)$$

$$M_{20} = \frac{1}{4} \pi R^4 \left(1 - \frac{7a}{15}\right) I_C - \pi R^4 I_C \sum_{i=1}^n \left(\frac{x_i}{R}\right)^2 K_i \quad (4.42)$$

$$M_{30} = -\pi R^5 I_C \sum_{i=1}^n \left(\frac{x_i}{R}\right)^3 K_i \quad (4.43)$$

$$M'_{30} = M_{30} - 3 \frac{M_{20} M_{10}}{M_{00}} + 2 \frac{M_{10}^3}{M_{00}^2} \quad (4.44)$$

These expressions have a form that directly makes them useful in the following simulations. Remember that they represent the instantaneous values of the quantities. The time dependence follows from the rotation of the star, i.e. when modelling a rotating star one must calculate these moments for every rotation phase until a whole revolution is completed.

The assumptions made correspond to what I call the *Equivalent ARea Spot* (EARS) model. This model will be used in Monte Carlo simulations in the following section.

4.3 Monte Carlo simulations

Modelling stellar surface structures and their influence on the integrated properties of interest is straightforward using the expressions derived above. The inclination and position angle can be chosen arbitrarily but it is not very interesting to seek the detailed relationships between the integrated properties for a certain configuration. More interesting are the relationships between the statistical properties. One therefore needs to perform Monte Carlo simulations of a large number of randomly oriented model stars and calculate the statistics of the integrated properties. Actually, simulations based on the EARS model were made in two different ways, using a rotating and a static model.

4.3.1 The rotating model

I randomly place a number of spots of given size A (dark and/or bright) on the surface of a model star and tilt its axis to a (random) inclination i and position angle φ . For each model star, the integrated properties as functions of the rotational phase are calculated and the results are saved in a matrix. The results from such calculation for an individual model star with only one spot can be seen in Figure 3.10.

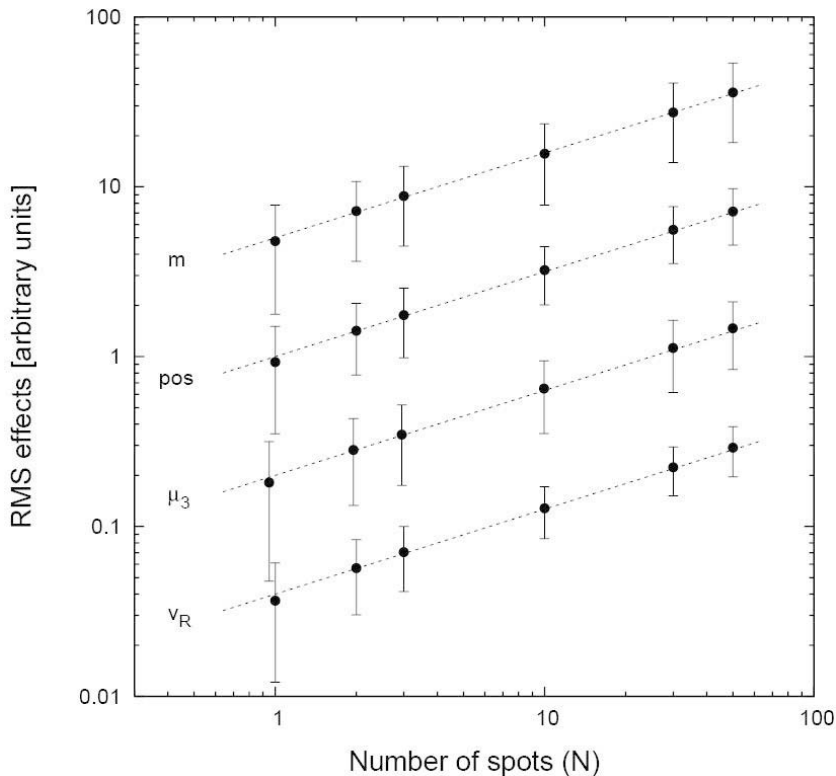


Figure 4.2. Results of Monte Carlo simulations of a rotating star with different number (N) of spots of size $A = 0.0025$. The different graphs represent from top to bottom σ_m , σ_{pos} , σ_{μ_3} and, σ_{v_R} , expressed on an arbitrary scale. Dots and error bars represent mean value and dispersion of the σ values for a set of simulations with a given N . The dashed lines have slopes 0.5, corresponding to $\sigma \propto \sqrt{N}$.

After performing a complete revolution of the model star I calculate the RMS dispersions⁶, $D[M_{mn}]$, for the integrated properties saved in the matrix and the procedure is repeated for a large number of model stars. The analysis is based on the statistics of these RMS values.

⁶Note that I use the notation $D[M_{mn}]$ for the dispersion of the moments M_{mn} .

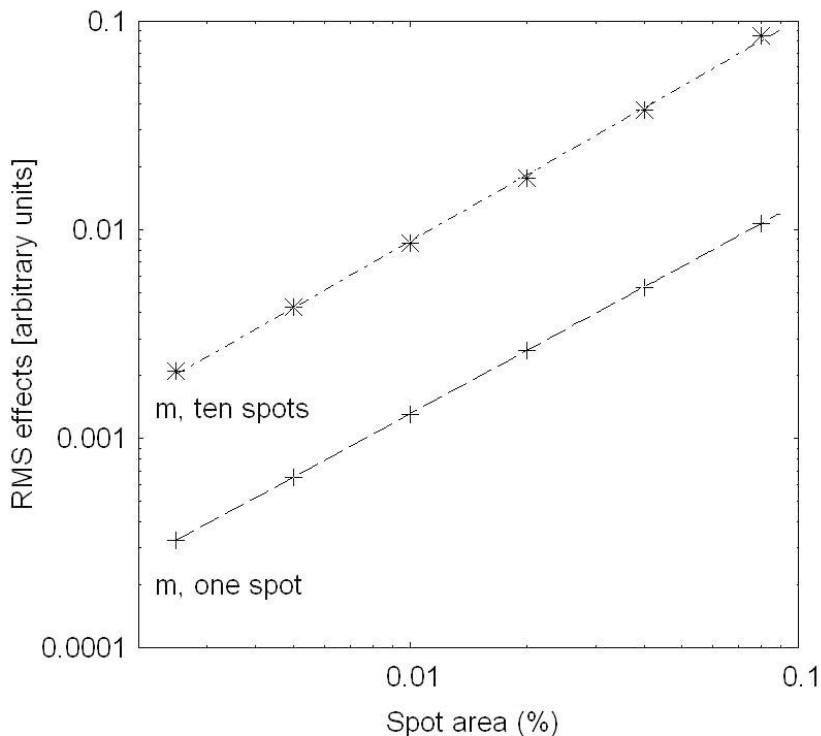


Figure 4.3. Results of Monte Carlo simulations of the effect of varying spot size clearly show that the RMS dispersion of the magnitude, σ_m , is proportional to the spot size, $\sigma_m \propto A$, as predicted. The upper graph represents the case σ_m with ten spots. The lower graph represents the case for only one spot. In both cases the spot size varies from 0.0025 to 0.08 of the total surface area. The slopes of the dashed lines are 1, corresponding to a linear relationship. The same linear relation is found for the other dispersions.

Using the programming language IDL, I made many simulations of different scenarios, e.g. using $A = 0.0025$ (equivalent to a spot radius of 5.73°), $N = 1, 2, 3, 10, 30, 50$ and a limb-darkening factor $a = 0.6$ together with a random orientation of the rotation axis. The results can be seen in Figure 4.2. One clearly sees that there are indeed very simple relations between the RMS dispersions of the integrated properties and that they are proportional to \sqrt{N} . The same patterns are found for any other set of input parameters.

Simulations also show that the RMS dispersions are proportional to the spot size, as predicted. This can be seen in Figure 4.3.

The conclusion from these simulations is that the RMS dispersions of the integrated properties confirms the predicted relationship from the binomial distribution; $\sigma \propto A \cdot \sqrt{N}$.

4.3.2 The static model

Simulations are also made using a ‘static’ model, i.e. where the star does not rotate. Here, I simply simulate a large number of independent realisations of the spotted surface, calculate the intensity moments for each realisation, and compute the RMS dispersions among the realisations. The orientation of the rotation axis does not matter in this case.

In the rotating model, each new phase can be considered as a new set of spot placements and it would therefore seem that the resulting statistics for the rotating and static models should be the same (except for the radial-velocity effect, which can only be obtained in the rotating model). I did find small differences in the statistics between the two models, but they are of little practical consequence.

The static model should give results more in line with the analytical model presented in the appendix of Paper I. It also more closely resembles the simulations made by Svensson and Ludvig (2005) and Ludwig (2006), who considered the photometric and astrometric jitter caused by granulation.

4.3.3 Results from the simulations

The rotating and static models were used to simulate many different scenarios. The statistical results were also compared with the theoretical predictions from the analytical model described in Appendix A of Paper I.

For the rotating model, I simulated 1 000 stars with randomly placed spots of size $A = 0.0025$ using the procedure described earlier in this section. Each rotation of an EARS-model star was divided into 200 phases, and for each rotation-phase the integrated properties were calculated. Simulations were performed with 1, 2, 3, 10, 30 and 50 spots. In the EARS-model simulations one could choose between dark, bright or dark and bright spots in any required statistical proportions.

For the static star model I simulated 10 000 cases, using the same spot area and number of spots as in the EARS-model simulations. In these simulations, the inclination is of course irrelevant. Simulations were made for the following cases:

1. Simulation of 1000 rotating stars with a varying number of dark (or bright) spots and a randomly orientated rotation axis.
2. Simulation of 1000 rotating stars with a varying number of dark (or bright) spots and an inclination of $\pi/2$ of the rotation axis.

3. Simulation of 1000 rotating stars with a varying number of dark and bright spots, with a probability of 0.50, and a randomly orientated rotation axis.
4. Simulation of 1000 rotating stars with a varying number of dark and bright spots, with a probability of 0.50, and an inclination of $\pi/2$ of the rotation axis.
5. Simulation of 10 000 static stars with a number of dark (or bright) spots
6. Simulation of 10 000 static stars with a number of dark and bright (50/50) spots.

For case 1 I find:

$$\sigma_m \simeq (1.17 \pm 0.60) \cdot A\sqrt{N} \quad (4.45)$$

$$\sigma_{\text{pos}} \simeq (0.57 \pm 0.25) \cdot A\sqrt{N} \cdot R \quad (4.46)$$

$$\sigma_{\mu_3} \simeq (0.22 \pm 0.09) \cdot A\sqrt{N} \cdot R^3 \quad (4.47)$$

$$\sigma_{v_R} \simeq (0.51 \pm 0.26) \cdot A\sqrt{N} \cdot R\omega \quad (4.48)$$

where $\sigma_{\text{pos}} = \sigma_{\Delta x} = \sigma_{\Delta y}$ and where the values after \pm show the RMS dispersion of the proportionality factor found among the different simulations. Similar results are obtained for Case 2–4 but for Case 5–6, the radial velocity is omitted since there is no rotation. These results are then used to calculate the numerical factors between the RMS dispersions of the integrated properties. The results are presented in Table 4.1.

A useful and striking consequence of the results from the simulations is that from a measurement of any of the four dispersions I can *statistically* predict the other three dispersions, under the assumption that one know the stellar radius and rotation period and that the effects are indeed caused by stable stellar surface structures on a rotating star. Most important is perhaps that it is not necessary to know A or N in order to do this. If e.g. the photometric

Table 4.1. Results from simulations for different types of models. Case 1–4 are from the rotating model, Case 5–6 from the static model and Case 7 is the predicted result from the analytical model in Appendix of Paper I. In Case 5–7 no rotation is present and therefore no radial velocity dispersion.

Case	$\frac{D[M_{10}]}{RD[M_{00}]}$	$\frac{D[M'_{30}]}{R^3D[M_{00}]}$	$\frac{\sigma_{\text{pos}}}{R\sigma_m}$	$\frac{\sigma_{\mu_3}}{R^3\sigma_m}$	$\frac{\sigma_{v_R}}{R\omega\sigma_m}$	Comments
1	0.53	0.20	0.49	0.19	0.43	Rotating, dark spots, random i
2	0.47	0.18	0.42	0.16	0.47	Rotating, dark spots, $i = \pi/2$
3	0.54	0.20	0.49	0.19	0.43	Rotating, dark and bright spots, random i
4	0.40	0.15	0.37	0.14	0.46	Rotating, dark and bright spots, $i = \pi/2$
5	0.49	0.15	0.45	0.14	–	Static, dark spots
6	0.41	0.15	0.38	0.14	–	Static, dark and bright spots
7	0.409	0.151	0.376	0.139	0.307	Analytical model

dispersion is known, the result from Case 1 will be

$$\sigma_{\text{pos}} \simeq 0.49 R \sigma_m \quad (4.49)$$

$$\sigma_{\mu_3} \simeq 0.19 R^3 \sigma_m \quad (4.50)$$

$$\sigma_{\nu_R} \simeq 0.43 R \omega \sigma_m \quad (4.51)$$

When comparing the results in Table 4.1 with the results derived from the analytical model in Paper I, the results are deviating except in Case 4 and 6. The numerical factors from the simulations are some 30–40% larger than according to theory for the first and third case. One common property for these two cases is the random inclination of the rotation axis and here is a clue to understanding why they deviate. First, the photometric variability is systematically smaller in these experiments. This could indeed be the case in many experiments, for instance when the star is seen at a small inclination (nearly pole-on), in which case the rotating model could give a small photometric effect coupled with significant variation of the photocentre. By contrast, the analytical model allows no such ‘singular’ cases. Secondly, the statistical model is built on the assumption that there is a mean intensity ($\pi R^2 I_C (1 - \frac{a}{3})$) and a variance, i.e. one need *both black and bright spots* to fulfil this assumption. Since calculations are made for the relative properties $D[M_{10}]/RD[M_{00}]$ and $D[M'_{30}]/R^3 D[M_{00}]$, one realises that if $D[M_{00}]$ gets smaller, both relative properties consequently get larger. As shown earlier, the expectation value for the variance for $\sin i$ is $\langle \sin^2 i \rangle = \frac{2}{3}$ and since $D[M_{00}]$ depends on the inclination one can statistically say that $D[M_{00}] \propto \sqrt{\langle \sin^2 i \rangle} = \sqrt{\frac{2}{3}} \approx 0.816$ leading to some 18% smaller values for $D[M_{00}]$, on average. When dividing the integrated properties by $D[M_{00}]$, some 22% larger values for the relative properties are obtained. This largely explains the deviations in the results of the simulations from the results of the statistical model.

In conclusion, the analytical model works well for small intensity variations like granulations, small spots, faculae etc. For a more realistic case (a randomly oriented, rotating star with stellar surface structures), the analytical model may underestimate the effects by some 20–30%.

4.4 Summary of numerical results

The numerical and analytical models show that there are indeed distinct statistical relations between the dispersions of the integrated properties. It is also noted that there is a considerable scatter between the different realisations, amounting to about 50% RMS about the mean RMS effect. Thus, any prediction based on either model is only valid in a statistical sense, with considerable uncertainty in any individual case. Nevertheless, the overall agreement between the results of these very different models suggests that the statistical relations amongst the different effects have a fairly general validity. The expressions for σ_{v_R} are the least general in this respect, as they obviously break down if the structures change on a time scale smaller than the rotational period, or if the surface structures themselves have velocity fields.

This research has shown that from knowledge of e.g. the photometric dispersion, it is possible to derive statistical relations for the remaining dispersions:

$$\frac{\sigma_{\text{pos}}}{R\sigma_m} \approx 0.43 \pm 0.06 \quad (4.52)$$

$$\frac{\sigma_{\mu_3}}{R^3\sigma_m} \approx 0.16 \pm 0.03 \quad (4.53)$$

$$\frac{\sigma_{v_R}}{R\omega\sigma_m} \approx 0.45 \pm 0.02 \quad (4.54)$$

where the values after the \pm are the maximum deviations of different models from the mean value. These relations can be compared to the results from the analytical model:

$$\frac{\sigma_{\text{pos}}}{R\sigma_m} = 0.376 \quad (4.55)$$

$$\frac{\sigma_{\mu_3}}{R^3\sigma_m} = 0.139 \quad (4.56)$$

$$\frac{\sigma_{v_R}}{R\omega\sigma_m} = 0.307 \quad (4.57)$$

The conclusion is that the theoretical statistical model gives a lower limit to the effects of stellar surface structures and that the results from the simulations are perhaps more realistic.

5. Impact on astrometric exoplanet searches

This chapter summarises and discusses the results presented in Paper I.

The ongoing Gaia mission is expected to reach accuracies of just a few μas . This turns out to be close to and sometimes even lower than the predicted effects of stellar surface structures, which are therefore a source of perturbations or ‘jitter’ in the astrometric signal. One of the goals of this research project was to quantify the expected effects for stars in different regions of the HR-diagram. This was done using the theoretical considerations and Monte Carlo simulations described in the previous chapter. Thus, the more easily observed photometric or radial velocity variations could be used to predict the astrometric jitter caused by stellar surface structures. Closure phase, through its connection to the third central moment of the brightness distribution, was also found interesting since this observable contains information about asymmetries on the stellar surface, resulting from e.g. stellar surface structure.

Interestingly, it was found that the astrometric jitter due to stellar surface structures and the variations induced by exoplanets are of a similar magnitude, especially for stars with low photometric variability. This motivated a deeper investigation of the statistical astrometrical effect of exoplanets in the context of exoplanet searches.

5.1 Predicted effects of stellar surface structures

The analysis in Chapter 4 resulted in a number of statistical relations between the RMS dispersions of the different integrated properties. Using e.g. the variations in the photometric signal as a observable, relations like Eqs. (4.52)–(4.54) and Eqs. (4.55)–(4.57) can now be applied on real stars in different regions of the HR-diagram. The analysis is made for pre-main sequence stars (PMS stars), main-sequence stars (MS stars), giant and supergiant stars. There are however groups of stars that must be excluded from this analysis and these are pulsating stars and certain peculiar stars. The photometric and radial velocity variations for these stars have very different origins and are therefore not correctly represented by the present models.

A first overview of stellar variability can be found in the results from the Hipparcos project. Eyer and Grenon (1997) analysed the photometric variability throughout the HR-diagram for the stars in the Hipparcos catalogue

(Fig. 5.1). Highly stable areas (dark blue in the diagram) exist in many areas of the HR-diagram, both among early, intermediate and late spectral types. The instability strip, extending from around F0V to F8II and above is clearly seen. The most stable stars are B8-A3 IV and V (on the blue side) and G8II to G8V (on the red side of the instability strip), with a variation of less than 2 mmag. From G8 to M2V the variability increases due to the development of activity and star spots. However, more and more accurate data for individual stars are being produced all the time, but Eyer and Grenon's analysis is found useful, since it covers most categories of stars.

The literature was searched for more detailed investigations of photometric and radial-velocity variability in the different spectral and luminosity classes and the results are summarised in Table 5.1 (for details, see Paper I). The astrometric RMS dispersions were calculated using three different formulae:

$$\sigma_{\text{pos}} \simeq 0.376R\sigma_m \quad (5.1)$$

$$\sigma_{\text{pos}} \simeq 0.195P\sigma_{v_R} \quad (5.2)$$

$$\sigma_{\text{pos}} = (300 \mu\text{AU}) \times 10^{1-\log g} \quad (5.3)$$

where R is the radius, P the rotation period and g the surface gravity of the star (in cm s^{-2}). Eq. (5.3) is taken from Svensson and Ludwig (2005). The astrometric jitter is consistently expressed in linear units, using the astronomical unit AU, mAU (10^{-3} AU) or μAU (10^{-6} AU). This eliminates the dependence on the distance to the star, while providing simple conversion to angular units: 1 μAU corresponds to 1 μas at a distance of 1 pc.

Eq. (5.1) is based on the analytical model and probably gives realistic order-of-magnitude estimates for the astrometric jitter although one realises that the proportionality factor might be a little low compared to the EARS-model simulations. Eq. (5.2) is also based on the theoretical model and, as before, the proportionality factor might be a little low. This formula is however only valid if the radial velocity is rotationally modulated. Since pulsations, non-radial oscillations, convection and many other effects may cause radial-velocity variations without a corresponding astrometric effect, these estimates are upper limits. Nevertheless, rotational modulation is important among active (young) main-sequence stars and M dwarfs, and for these objects the formula may provide correct order-of-magnitude estimates. Eq. (5.3), with $\log g$ taken from Cox (2000), is derived from the inverse relation to surface gravity g found by Svensson and Ludwig (2005) for a range of hydrodynamical model atmospheres. Although the authors warn that sphericity effects may render an extrapolation of this relation to supergiants very uncertain, one has applied it to all the stellar types in Table 5.1. Since it only includes the random effects

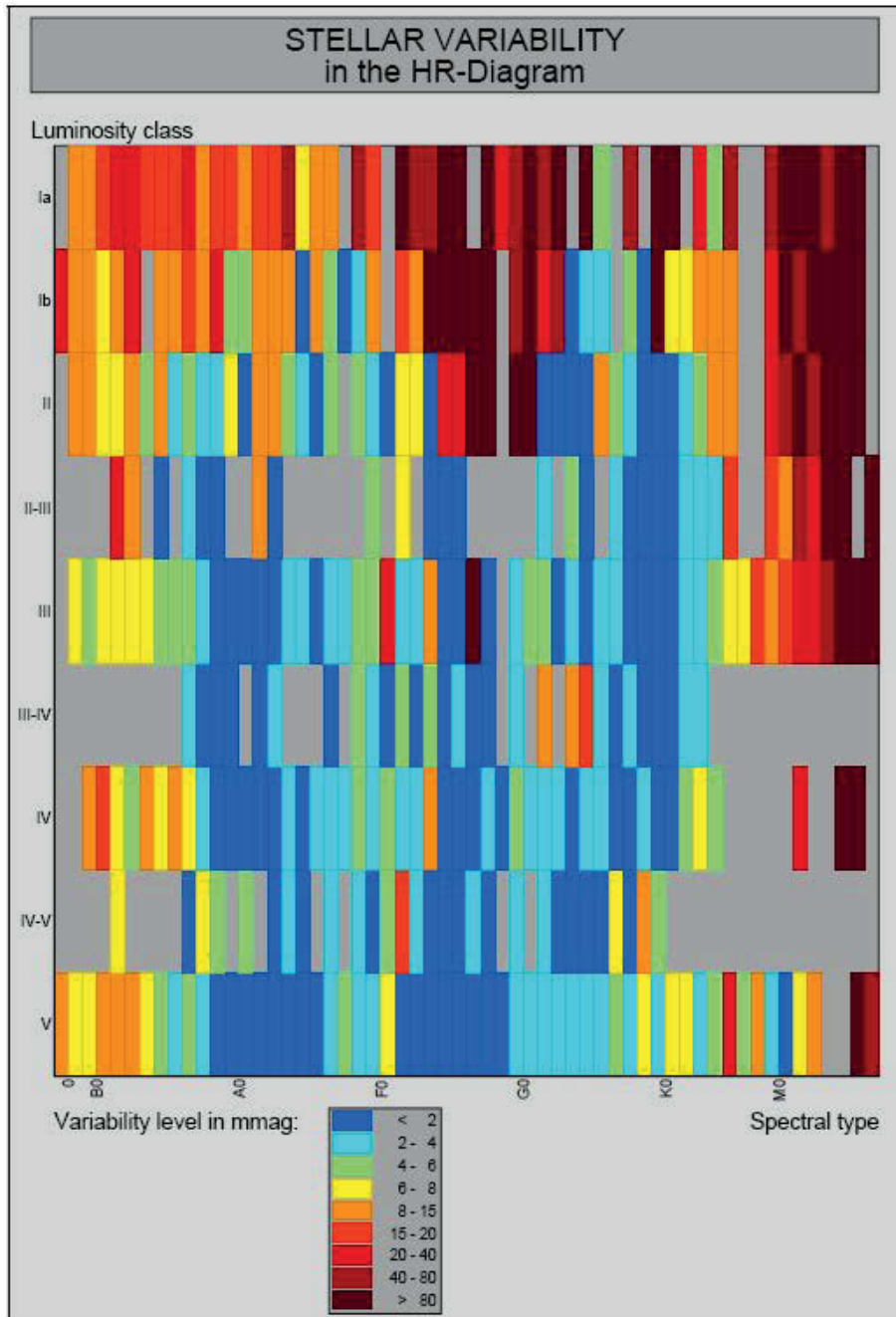


Figure 5.1. Stellar variability in the HR diagram. Stars in different bins are labelled with the mean intrinsic scatter. © ESA SP-402 (Eyer & Grenon 1997)

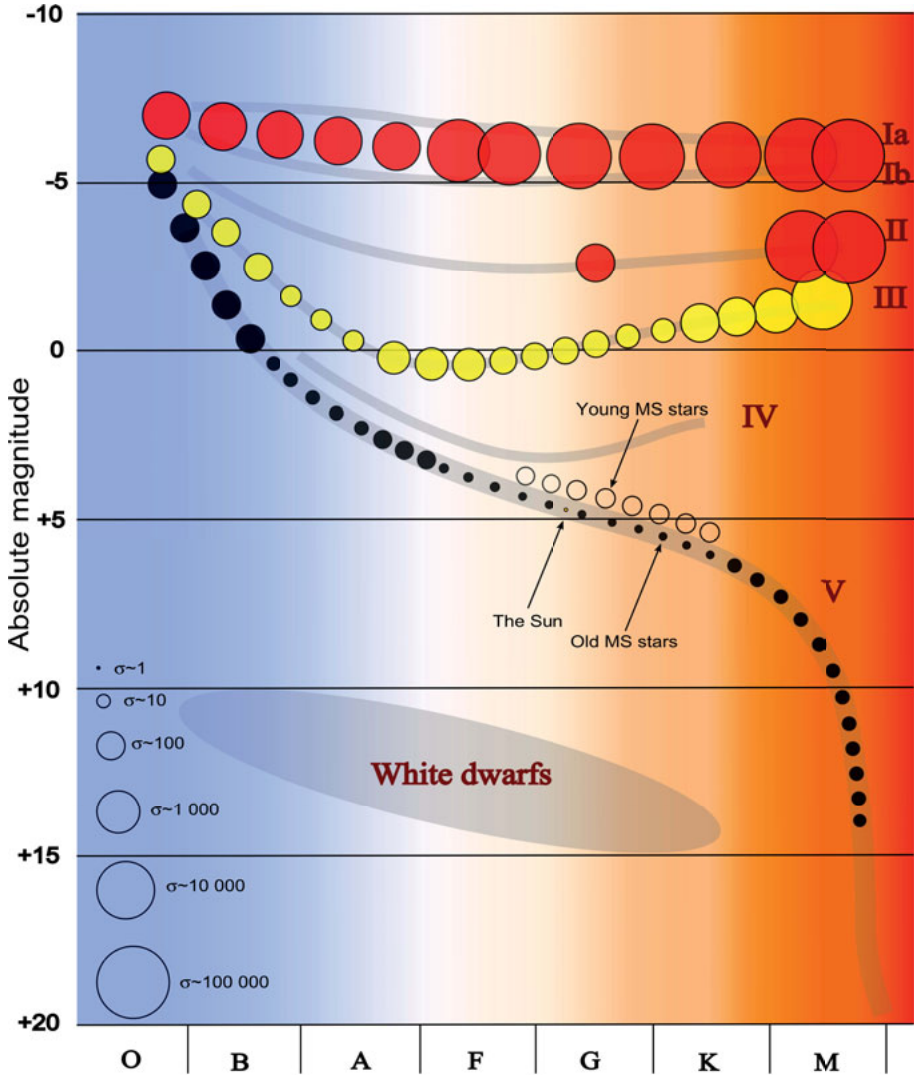


Figure 5.2. HR diagram visualising the astrometric RMS dispersion in different sub-groups of spectral and luminosity classes. The diameter of the circles are proportional to $\log \sigma_{\text{pos}}$ and data are from Eriksson and Lindegren (2007). The dispersions are in μAU .

of stellar granulation, the formula represents a lower limit to the expected astrometric jitter.

In Table 5.1, stars having similar properties are binned together and the uncertainty will be fairly large. If the likely mechanisms of the variability are considered, it is nevertheless possible to make some quantitative conclusions. These are visualised in Fig. 5.2, showing the astrometric RMS dispersion for stars in different regions of the HR diagram. For main-sequence A to M stars, the expected level of astrometric jitter is generally in the range 2–20 μAU , probably depending mainly on the level of stellar activity; old, inactive stars should have less jitter (2–5 μAU). The Sun appears to be more stable than the typical old, solar-like star, but not by a large factor. It is intriguing that our Sun appears to be the photometrically most stable star in the literature. The most stable giant stars are the late F to early K types, where the expected astrometric jitter is of order 25 μAU . Late-type giants and supergiants have σ_{pos} of a hundred to several thousand μAU .

5.2 Comparison with the effects of exoplanets

We have seen that both stellar surface structures and exoplanets can cause astrometric jitter of comparable size. In Sect. 3.5.2 I found that potentially habitable Earth-like exoplanets are mainly expected around late type main-sequence stars (A–M), in the mass range 0.2–2 M_{\odot} . The astrometric signature of such planets ($\sqrt{3}$ times the RMS dispersion in Fig. 3.8) is $\lesssim 7 \mu\text{AU}$. Clearly, it will be very difficult to detect the planetary signal if the jitter caused by surface structures is much greater than this number.

In reality the detection probability is a complicated function of many factors such as the number of observations, their temporal distribution, the period and eccentricity of the orbit, and the adopted detection threshold. Moreover, it is very likely that the star has multiple planets, some of which may be much heavier than the looked-for Earth-like planet. The detection is then further complicated by the superposition of several different periodicities.

Sozzetti (2005) made numerical simulations to investigate the astrometric detection of exoplanets by projects like Gaia under relatively idealised conditions. Assuming an orbital period shorter than the mission length, it was found that the single-epoch measurement error must be smaller than about half the astrometric signature α . Since the single-epoch measurement error consists of all the noise contributions including surface-structure effects, one conclude that astrometric detection is only possible if

$$\sigma_{\text{pos}} \lesssim 0.5\alpha \quad (5.4)$$

where σ_{pos} is the jitter caused by the surface structures, and then only if other noise sources are even smaller.

Comparing with the estimates of σ_{pos} from Table 5.1 it is seen that Earth-like exoplanets in the habitable zone may only be detected by astrometric techniques if they orbit unusually stable main-sequence stars, like the Sun. For most old, solar-type stars the expected astrometric jitter is just about the limit of the criterion (5.4), making detection difficult if not impossible. On the other hand, the vast majority ($> 90\%$) of the exoplanets already detected by the radial-velocity method produce astrometric wobbles that are significantly greater ($\alpha \gtrsim 10 \mu\text{AU}$). Astrometric observations of these stars would be highly interesting for obtaining independent information about the systems, in particular orbital inclinations and unambiguous determination of planetary masses. Exoplanets of about $10 M_{\oplus}$ orbiting old F–K main-sequence stars in the habitable zone might generally be astrometrically detectable ($\alpha = 20\text{--}50 \mu\text{AU}$) with Gaia.

Table 5.1. A summary of typical photometric and spectroscopic variability for different stellar types, and inferred levels of astrometric jitter (σ_{pos}), using Eqs. (5.1), (5.2) and (5.3). The jitter is estimated in three different ways: from the photometric variability, using Eq. (5.1) [this will overestimate the jitter if part of the variability is due to radial pulsation]; from the radial velocity variability, using Eq. (5.2) [this method will overestimate the jitter if the variability is not caused by rotational modulation]; and from the surface gravity, using Eq. (5.3) [this only includes jitter caused by granulation, and is therefore a lower limit]. References to typical observed quantities are given as footnotes. Radii and $\log g$ (not shown) are taken from Cox (2000).

Type	σ_m [mmag]	σ_{v_R} [m s ⁻¹]	R [R_\odot]	P [d]	σ_{pos} (5.1) [μ AU]	σ_{pos} (5.2) [μ AU]	σ_{pos} (5.3) [μ AU]
Main-sequence stars:							
O–B7V	10 ^c		7		120		0.3
B8–A5V	<2 ^c		2.5		<9		0.2
A6–F0V	2–8 ^c		1.6		5–20		0.1
F1–F8V	<2 ^c	3–100 ^m	1.3	3 ^b	<5	1–30	0.1
F9–K5V (young)	5–15 ^{a,d,k}	16 ^j	1	10 ^a	10–25	18	0.1
F9–K5V (old)	1–3 ^{a,d}	3–5 ^k	1	25 ^a	2–5	8–14	0.1
G2V (Sun)	0.4 ⁱ		1	25 ^b	0.7		0.1
K6–M1V	10 ^c	5 ^m	0.6	40 ^a	10	20	0.1
M2–M9V	20 ^l	10 ^m	0.3	0.2–2 ^l	10	0.2–2	0.04
Giants:							
O–B7III	4–8 ^c		10		70–140		1
B8–A7III	<4 ^c		5		<35		1.5
A8–F6III	5–20 ^c		5		50–200		2
F7–G5III	2–6 ^c	<20 ^f	7	10 ^b	25–75	<25	5
G6–K2III	<2 ^{c,g}	20–30 ^{e,f,n}	15	30 ^b	<50	60	20
K3–K8III	5–10 ^{c,h}	20–100 ^{e,f,n}	25		200–500		50
M0III	20 ^{c,h}	30–150 ^{e,f,n}	40		1400		150
M5III	100 ^{c,h}	50–300 ^{e,f,n}	90		16000		
Bright giants and supergiants:							
O–A1a,b	4–40 ^c		30		200–2000		25
F1a,b	20–100 ^d		100		4000–20 000		100
GII	2–10 ^c		30		100–500		40
G–K1a,b	10–100 ^c		150		3000–30 000		250
M1a,b,II	~100 ^c		500		~100 000		300–3000

References: ^aAigrain et al. (2004), ^bCox (2000), ^cEyer & Grenon (1997), ^dFekel et al. (2004), ^eFrink et al. (2001), ^fHekker et al. (2006), ^gHenry et al. (2002), ^hJorissen et al. (1997), ⁱLanza et al. (2004), ^jPaulson et al. (2004), ^kRadick et al. (1995), ^lRockenfeller et al. (2006), ^mSaar et al. (1998), ⁿSetiawan et al. (2004)

6. Conclusions

At present, and for the foreseeable future, stars are still unresolved, or just marginally resolved, objects that can only be observed by their disk-integrated properties like intensity, astrometric position, closure phase and radial velocity. There are many sources of perturbations that can affect the signals from the moment the light leaves the object until it reaches the detectors in our instruments and becomes a measurable quantity. In Part I of my thesis, I have presented several of these sources and discussed their significance for future astrometric missions, in particular, the effects of stellar surface structures.

From both theoretical considerations and numerical simulations, I have answered research question (1): How large is the astrometric effects of stellar surface structures as a practical limitation to ultra-high-precision astrometry (e.g. in the context of exoplanet searches) and what are the expected effects for stars in different regions of the HR-diagram? In answering this question I have derived a set of statistical relations among the integrated properties and found that they all were proportional to $A\sqrt{N}$, where A is the relative area of the surface structures and N is the number of structures on the stellar surface. This led to the conclusion that expressing the other effects in terms of the photometric variation, cancels the dependence of $A\sqrt{N}$, leaving me with a set of simple relations i.e. Eqs. 4.52–4.57 in this work and Eqs. 12–18 in Paper I.

When applying these relations to real, ordinary stars, using observed photometric and/or radial velocity variations, I conclude that the astrometric jitter ranges from about $1 \mu\text{AU}$ for stars like the Sun, to several μAU for most main-sequence stars, some tens of μAU for giant stars and up to several mAU for supergiant stars.

Exoplanets will also cause a variation in the position of the photocentre, and the corresponding dispersion is easily calculated. Applying this to Earth-like exoplanets in the habitable zone, one found that the astrometric jitter is only a few μas . As a consequence of the size of the astrometric jitter, one can only expect to detect Earth-like exoplanets, using astrometric techniques, if they orbit stars that are unusually stable for their type, similar to our Sun. The situation for larger exoplanets is much better. Planets heavier than $10 M_{\oplus}$ located in the habitable zone can readily be astrometrically detected around ordinary main-sequence stars, if other noise sources are sufficiently small.

More investigations are needed concerning the other perturbing sources affecting the disk-integrated properties. Multiplicity and weak microlensing need to be investigated from a statistical point of view since these perturbations are likely to become problematic when striving for nanoarcsecond astrometry in the future. On the other hand, some of these perturbations will perhaps be the signal in future astrometric projects that will help us to understand more about the stars and the stellar environment.

6.1 In reflection

Since 2007 when I finished my licentiate degree in Lund and Paper I was published, much has happened concerning astrometry. At the time of writing this thesis Paper I has been cited 21 times and particularly interesting is the work by Makarov et al. (2009). The authors were clearly initially suspicious of my results presented in Paper I, however, they developed a similar code and found similar results. Using photometric data from, for example, space-borne instruments with less photometric noise, they found that the noise in the other parameters was also reduced. In effect, they argued for lower levels of astrometric noise for real stars than those presented in my paper (I), and argued for astrometric detection of Earth-like exoplanets. However, the empirical relationship derived in Paper I is still valid.

In 2009 I was an invited speaker at the conference *Towards other Earths*¹, Porto, Portugal, where I presented the results from my astrometry research. At that time, μ as astrometry was still in the future and detection of especially Earth-like exoplanets using astrometric techniques, seemed distant. This situation still holds today, even though there is now talk of nanoarcsecond astrometry as a possibility in the future.

December 20, 2013, Gaia was launched and has now spent almost one year in space. After calibration and testing, observations are now on-going and data is being collected. Many interesting publications are to be expected, but most importantly the generation of the much coveted 3D map of the Galaxy. The possibilities of such a map for the teaching and learning of the 3D structure of the Universe is the motivation for Parts II of this thesis.

¹<http://www.astro.up.pt/investigacao/conferencias/toe2009/>

Part II:
Astronomy Education Research

7. Introduction

*‘Space is big. Really big.
You just won’t believe how vastly, hugely, mind bogglingly big it is.
And so on.’*
Douglas Adams, *‘The Hitchhikers Guide to the Galaxy’*

While investigating the details of star spots and their influence on astrometry, and at the same time teaching physics, astronomy, astrophysics and astrobiology, I came to realize that appreciating the nature of students understanding of phenomena related to these topics is a really important aspect for teachers in these areas. This realization shifted my focus from astronomy and astrometry into the field of physics and astronomy education research (PAER). I have found that opening the door into the ‘inner Universe’ of students is as interesting and exciting as the real, or ‘outer Universe’. The connection between the ‘outer’ and ‘inner’ Universe goes through sense/perception via vision. One aspect of this is what I call *disciplinary discernment*, which concerns the discernment of ‘disciplinary affordances’ (Fredlund et al. 2012) of representations used by the discipline, through noticing, reflecting and meaning-making from the disciplines perspective. It is around this concept that Part II of my thesis will revolve. Further details of disciplinary affordances and disciplinary discernment are given in Chapter 9.

7.1 Astronomy as a science – challenges for learning and understanding

The night sky could be seen as a dark, and perhaps even frightening place as the only objects that are visible are the moon and the bright dots commonly called stars. Even this is not something that everyone has the possibility of seeing as they may live in large, highly polluted cities. The increasing problem of ‘light pollution’ (Riegel 1973) is another limiting factor for accessing the night sky. Others may look with interest, but their general knowledge about the Universe, is often very poor (see, for example, Comins 2001; NSB 2014). I have found this to be true from my experience when presenting numerous shows to over 35 000 visitors at Kristianstad University’s planetarium. I came to realize that most of the visitors are unable to identify more than one or two constellations in the sky: usually only the Big Dipper and/or possibly Orion. This nature of the Universe as being a physical presence and yet intangible and unfamiliar to many people presents a challenge for astronomy educators.

Astronomy as a science discipline is considered by many to be an integral part of physics; others consider it to be only closely related to physics. Regardless of the perspective taken there are some profound differences between physics and astronomy, particularly when looking at them from an educational standpoint. While physics uses design experiments to create, explore and verify proposed models, astronomy has to take a somewhat different approach. In astronomy one cannot create a desired experiment in the same way as can be done in physics. The astronomical distances and objects of interest are too enormous to even contemplate such a scenario. Also, the astronomical time scales are such that it is instantaneously possible to observe a multiplicity of time intervals, a dynamic not possible in a conventional physics experiment on Earth.

Astronomers study the Universe by collecting data made up of electromagnetic waves, with frequencies and wavelengths ranging from gamma rays to radio waves. In other words, astronomers ‘utilize observational data as a primary source of evidence’ (Gray 2014, p. 3) for their scientific activities. From observations of different stars, together with knowledge about physics, astrophysicists begin to model stellar evolution from a statistical perspective and make predictions based on these models, which they can then test against different time domains. Astronomy can be seen to be similar to other sciences, like palaeontology, cosmology, and evolutionary biology, where direct experimentation is usually not possible (Gray 2014). These science disciplines are sometimes referred to as historical sciences, which are contrasted to the exper-

imental sciences, like physics and chemistry. For the historical sciences Gray concludes:

‘Thus, the quality of this research is often based on the adequacy of the explanation [...] rather than successful prediction since it is based on the study of complex and unique entities (e.g., the big bang) that have a low probability of repeating exactly (if at all). [...]. In addition, reasoning in historical sciences consists largely of explanatory or reconstructive reasoning compared to predictive reasoning from causes to effects as is found in the experimental sciences ’ (Gray 2014, p. 5).

From this positioning it is reasonable to argue that astronomy belongs to the historical sciences, at least in part. The uniqueness of astronomy as a historical science lies in the sheer size of the four space-time dimensions: the three space dimensions plus the time dimension. Learning about astronomy thus manifests as learning to understand and appreciate the vastness of the Universe as a function of its 3D structure. This is not easy as we cannot easily ‘see’ the Universe, so the kind of experience that is called for to promote learning and understanding about the Universe is largely ‘missing’ from everyday life and needs to be created for astronomy education purposes.

As will become evident from my analysis in Chapter 11, university students often have great difficulty in making the kind of extrapolations that translate into them being able to ‘see’ the 3D structure of the Universe. In this thesis I argue that the difficulty of becoming aware of the Universe as a 3D structure has a lot to do with the limitations of our brain to directly experience the Universe as a 3D place. Much of this inability to ‘see’ the Universe as a 3D phenomenon is rooted in people only experiencing it as a curved 2D roof over their heads. Historically, astronomers even talked about fixation stars being situated on a sphere at the rim of the solar system to explain what they could see. Most of us will never, except for maybe a handful of astronauts, be in a position where we will be able to directly experience the Universe as something other than 2D. From our perspective on the surface of the Earth, we never experience anything else but the flat, or at best slightly curved, surface of the Earth. Therefore, it is unrealistic to expect people to have an awareness of the deep structure and components of the Universe. Even the planets, which are introduced in the early years of the school science curricula, are seldom recognizable in the night sky and although they are often modelled showing their relationship to the Earth and the Sun this does not seem to translate to an appreciation of the 3D nature of the Universe. It is easy to imagine students looking at the night sky and asking themselves: if the Moon is supposed to be smaller than the planets then where are the bigger planets?

The Universe is a vast place and it is hard for people to recognize or understand these large distances. Our brain uses many different inputs, for example, travel time, features along the way, route-segmentation, travel effort, etc. for making distance determination (see, for example, Montello 1997) but these offer no help when dealing with large astronomical distances. This is one of the fundamental learning challenges that emerge in my analysis.

7.2 Aim and justification for Part II of the thesis

Part II of my thesis aim to fill a gap in the physics and astronomy education research. I report on the experiences that university students have regarding the structure of the Universe when trying to read the sky. This is done using an accredited simulation of our Galaxy (Tully 2012), which presents new possibilities for learning.

I make the case that *Reading the Sky* is a concept that can be used to model an important competence in physics and astronomy education: the ability to discern the disciplinary affordances of representations as part of achieving the intended understanding of the three-dimensional structure of the Universe. I do this by combining findings and discussions from Papers II and III. Paper II addresses the ability to extrapolate three-dimensionality from 2D visual input, and how this ability can be described by different categories of multidimensionality discernment. Paper III describes a consequential theoretical framework for the development of discernment of the disciplinary affordances of representations, what I have characterized in terms of what I call an Anatomy of Disciplinary Discernment (ADD).

7.3 Research questions

The research that I report on in this part of the thesis consists of four empirical questions: (2a,b) and (3a,b), and one theoretical question (4). The research questions are:

2. a) In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?
b) What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?
3. a) What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?

- b) How can this discernment be characterized from an educational perspective?
- 4. How can the idea characterized as *Reading the Sky* in this thesis inform the teaching and learning of astronomy?

7.4 How should Part II of the thesis be read?

Part II of the thesis is divided into the following chapters. After this introduction, Chapter 8 provides the relevant background aspects of physics and astronomy education research. Since I am particularly interested in the use of simulations, this includes a review of pertinent simulations work and finally, I review the astronomy education literature on three-dimensionality. Chapter 9 outlines the conceptual framing used in this Part II of the thesis. Here, all the theoretical concepts that I use are explained. The next chapter (Chapter 10) is devoted to research methodology, and here I describe the approach taken for the research reported on. Here, weight is given to the way the data was analysed. Next come the results of my research, which are summarized in the Chapter 11. These results led me to the construction of the concept of *Reading the Sky*, which is thoroughly developed and discussed in Chapter 12. In Chapter 13 I discuss implications of my findings important for teaching and learning astronomy. This chapter is also used to explain what my PAER knowledge claims are. Here I also discuss the kind of future work that I am planning to develop in relation to its relevance for PER and AER. Finally, there is a Swedish summary at the end (Chapter 14).

8. Situating the study – A Review

This chapter provides a review of research reported on in the field of physics and astronomy education (PAER)¹ that is pertinent to the work that makes up Part II of my thesis. The chapter begins with an introduction to Physics Education Research (PER) and then moves on to Astronomy Education Research (AER), acknowledging that there is much in the PER literature that is also applicable to AER. The AER section is further divided into an overview of AER research, and then two sections particularly pertinent to this thesis; a review of research dealing with Virtual Learning Environments (VLE) as a tool for learning astronomy, and a review of research on dimensionality in AER.

8.1 Physics Education Research

PER is today internationally taken to be a relevant and authentic part of the broader physics and astronomy research community. This means that PER researchers are most often physically situated within university departments of physics and physics and astronomy. PER researchers, as ‘discipline based education researchers’ (National Research Council 2012), need to be experts in the subject of physics and related subjects such as astronomy, engineering and education. Such a background is vital when it comes to looking at issues relating to the teaching and learning of physics. Thus, PER is a field of research focused mainly on two things: ‘understanding’ how students experience learning physics and how to optimise that, and how ‘teaching’ physics can be best coordinated to achieve that optimisation.

¹The notations PAER and AER are used interchangeably by people doing astronomy education research within physics departments (for example, see the Rutgers PAER group) and people doing astronomy education research in astronomy departments, centres for astronomy and/or astronomy education (for example, see the University of Arizona’s Center for Astronomy Education). I will mainly use AER in this thesis.

In an effort to better understand how students think about physics, different theoretical approaches have been introduced in PER work. Examples of these theoretical approaches include Epistemology (e.g., Lemke 2007; Linder 1992a; Koponen & Mäntylä 2006), Ethnography (e.g., Bailey et al. 2010; Blown & Bryce 2010; Bryce & Blown 2012b), Grounded theory (e.g., Taber 2000), Phenomenology (e.g., Arons 1982; Ornek 2008), Phenomenography (e.g., examples in Marton & Booth 1997; Linder & Marshall 2003), Variation theory (e.g., Ingerman et al. 2009; Fraser & Linder 2009; Linder & Marshall 2003), Multimodality (e.g., Jewitt 2003; Kress et al. 2001; Lemke 2009; Tang & Moje 2010; Tang et al. 2011, 2014), or cognition (e.g., Beilock & Fischer 2013). From the work within these different fields, the body of knowledge concerning how students think about physics has increased substantially over the past 20 years.

Following PER, educational research that is situated in a discipline has come to be known as Discipline-Based Education Research (DBER). The National Research Council (NRC) 2012 has identified a common set of educational challenges that span across many science disciplines. In so doing, the NRC uses PER to illustrate how DBER is producing useful practical teaching knowledge. One example from Docktor and Mestre (2014) relevant to my research is the differences identified between students and experts when solving problems with respect to the representations being used. Expert thinking is suggested to be more oriented around visual attributes than mathematical formulations. In addition, both the American Journal of Physics (May, 2014) and the Journal of Research in Science Teaching (August, 2014) recently devoted issues addressing questions about how to combine educational research from different sciences to promote interdisciplinary learning. For example, concerning similarities between physics and biology modelling (Hoskinson et al. 2014) and, chemistry, life sciences and physics concerning the concept of energy (Becker & Cooper 2014; Dreyfus et al. 2014).

Several good reviews of PER have been done over the years by, for example, Redish (2003); Thacker (2003); Beichner (2009) and Cummings (2011). There are also web resources (e.g. PER-Central², ComPADRE³) that provide excellent access to the many parts of PER, and in fact PAER, work and I will incorporate discussion on these resources in the sections that follow.

Although now somewhat dated, I would like to highlight the still highly regarded and extensive review of PER by Lillian McDermott and Joe Redish (1999). The authors identified and categorised different research fields within

²<http://www.per-central.org>

³<http://www.compadre.org>

PER, ‘to contribute to the establishment of a research base’ (p. 755) using extensive examples from the literature. Their categorisation is still valid today, although with the further developments in the field it is now possible to identify many more categories. Figure 8.1 shows the categories identified by McDermott and Redish (1999) on the right hand side. The figure gives an indication of the considerable research that had been done on conceptual understanding up to that time, and a large body of work in this area has continued up to the present. On the left hand side of the Figure I show how my work can be seen to fit into Representations, a contemporary category of investigation in the PER field.

8.1.1 PER and Representation Research

The different fields within PER, as identified by McDermott and Redish (1999), also illustrated in Figure 8.1, continue to attract attention from researchers, but there are also other emerging fields within PER that have recently been attracting attention. For my thesis, the most important of these falls under the broad heading of ‘Disciplinary-specific Representations’.

‘[R]epresentations are constructed from a collection of signs’ (Linder 2013, p. 43) and are made up of different modes or semiotic resources (Airey & Linder 2009; Airey 2009). In physics, these are often multimodal and consist of items such as written and spoken language, gestures, simulations, mathematical symbolism, diagrams, pictures, images, graphs, etc. These representations are used in the ‘disciplinary discourse’ (Airey & Linder 2009; Airey 2009) of physics (and astronomy) community to communicate disciplinary knowledge and share meaning. To learn to think like a physicist students need to learn to recognise and work with the ways that representations coordinate and function together (see, for example, Fredlund et al. 2012; Kohl et al. 2007a; Maries 2013; Rosengrant et al. 2007; Van Heuvelen 1991). Consequently, the use of multiple representations plays a crucial role in the teaching and learning of physics (e.g. Airey & Linder 2009; Kohl et al. 2007b,a; Prain et al. 2009). This thrust of research is becoming increasingly recognised as a critical aspect in the teaching and learning of physics. Hence, the literature on representations in PER has grown extensively over the years. For example, Kohl & Finkelstein (2008); Linder (1992b); Podolefsky & Finkelstein (2006, 2008); E. Prather (2005) on the role of representations in learning physics, Lemke (1998, 2007, 2009) on the importance of multiple representations, Bransford et al. (2000) in relation to learning, Etkina et al. (2006); Kozma et al. (2000) on the role of representations and tools in laboratory and experimental de-

sign, Maries (2013); Rosengrant et al. (2006) on multiple representations and physics problem solving.

As a representation, the language of physics has steadily gained more attention for its importance regarding the provision of access to learning and understanding physics (Airey 2009; Lemke 1990; Tang et al. 2011; Yore & Treagust 2006). This area is seen to be strongly related to scientific literacy and the work of Lemke (for example, 1990; 1995; 1998). Physics as a science discipline uses many words to help represent physical properties. However, these words often have different meanings in everyday life, for example, work, force, power, heat, etc., hence they contribute to the construction of alternative conceptions by the students (see, for example, Arons 1997; diSessa et al. 2004; Brookes & Etkina 2009; Itza-Ortiz et al. 2003). An interesting astronomy related example is the use of fields in physics. In astronomy and physics, it is used in the description of e.g. electromagnetic fields and gravitational fields, which are three-dimensional vector fields. These are to be contrasted against, for example, everyday knowing about football fields and crop fields, which usually are two-dimensional in nature. Hence, an ‘unpacked’ (Fredlund et al., in review) use of the word field may reinforce alternative conceptions for students entering the discipline of astronomy (Airey 2009). The lack of disciplinary unpacking in the language used to communicating physics to students is of great concern and has been studied by a number of researchers (e.g. Brookes & Etkina 2009; Itza-Ortiz et al. 2003; Lemke 1990; Touger 1991; Wellington & Osborne 2001). For two good summaries of pertinent work see Brookes (2006; 2007, and references therein).

Another theme in research involving representations has come from the development of computers. Physics education researchers started to see possibilities in using interactive approaches to enhance learning. This came with the increasing development of user-friendly interfaces of computers for creating new educational virtual learning environments. In PER, this sparked a new thrust of research, and the usefulness and affordances of these new resources are increasingly being studied. For example, simulations of different kinds, for instance the PhET Interactive Simulations⁴ are finding their way into many courses in both introductory physics and more advanced courses (see, for example, Jimoyiannis & Komis 2001; Kohnle et al. 2013; Hazelton et al. 2013; McKagan et al. 2008; Podolefsky et al. 2010). The types of multimedia representations used in these resources have been found to be effective for improving learning outcomes in many cases (see, for example, Jimoyiannis & Komis 2001; Khatri et al. 2013; Kohnle et al. 2013; Lindgren et al. 2013). In

⁴<http://phet.colorado.edu>

this developing field more research is needed to ascertain the pros and cons of using these representations (see, for example, Podolefsky 2013) and what challenges they present (see, for example, Hegarty 2011). In Sections 8.2.2 and 8.2.3 I review the field of virtual learning environments and their usefulness in education from an astronomy education perspective.

8.2 Astronomy Education Research

Since the main focus of this thesis lies within the field of astronomy, a closer look at research done specifically in Astronomy Education is needed. I start with an overview giving a short historical background, then I address some of the focal points of work done in AER that includes looking at the issue of alternative conceptions in astronomy, and then move forward with a discussion on virtual learning environments and dimensionality, which are new and under-researched fields within the discipline.

8.2.1 Historical development of AER

AER is a field that has grown extensively over the last two decades. It has its roots in Physics Education Research (PER) and much of the PER work has applicability in astronomy education. One of the first researchers to address the understanding of astronomical phenomena was Piaget (1929, 1930) when he described children's ideas about the shape of the Earth and the cause of night and day. For decades, Piaget's work was very influential and pioneering in many aspects, especially in the area of understanding how phenomena around us get constructed. Other early researchers doing pioneering work in the field have been Joseph Nussbaum (Nussbaum & Novak 1976; Nussbaum 1979), Stella Vosniadou (Vosniadou 1991; Vosniadou & Brewer 1992, 1994), John Baxter (Baxter 1989) and Yrjö Engeström (Engeström 1991).

Early reviews of the research carried out in astronomy education were done by Adams & Slater (2000); Bailey & Slater (2003); Bailey et al. (2004); Bailey (2011). Then, in 2010, Lelliott and Rollnick carried out a comprehensive audit of the field where they categorised and ordered strands that they could identify within AER. They referred to these as the focal points in AER, see Figure 8.2 and Section 8.2.2. Over the years, many papers have been published addressing students' alternative conceptions of astronomy (also referred to as misconceptions or preconceptions in the literature) and these are discussed in Section 8.2.3.

8.2.2 Focal points in Astronomy Education Research

Much of the research in AER identified by the earlier reviewers mentioned above, followed by Lelliott and Rollnick's review in 2010, involves investigating conceptions related to the Earth and/or the Moon. As can be seen from Figure 8.2 a large part of these studies fall under the broader characterisation 'Astronomy taught in schools' and 'Gravity', a category under 'The Science of Astronomy', reflecting how the work has predominantly been done in the educational context of young students' (up to age16).

The research strand exploring ways of conceptualizing 'the Earth' is perhaps the oldest research strand within AER, and generally the data source for this research has been young students conceptions of the shape of the Earth. For example, see Baxter (1989); Jones et al. (1987); Nussbaum & Novak (1976); Nussbaum (1979); Panagiotaki et al. (2009); Sneider & Pulos (1983); Schoultz et al. (2001); Sharp & Sharp (2007); Vosniadou & Brewer (1992, 1994).

Conceptions concerning 'day and night' cycles have also been well studied. An important finding regarding this research thread is that it is possible to distinguish three different mental models (intuitive, synthetic and scientific) in students thinking about day and night (see, for example, Bakas & Mikropoulos 2003; Baxter 1989; Bryce & Blown 2012a; Jones et al. 1987; Trumper 2001a,b; Vosniadou 1991; Vosniadou & Brewer 1992, 1994). Also, the older the studied students were the better the understanding they displayed. At the same time it needs to be noted that only two thirds of university level science students studied were found to provide satisfactory explanations regarding day and night cycles (see, for example Bakas & Mikropoulos 2003; Mant & Summers 1993; Mant 1995; Schoon 1992; Trumper 2000, 2001a,b). Similar results have been found for adults in the general population (see, for example, Heywood et al. 2013; Parker & Heywood 1998).

Conceptions and ideas concerning 'seasons' have also been widely reported on, and often form part of studies on the day and night cycles mentioned above. It is commonly found that seasons are phenomena that present conceptual challenges for students across all levels of astronomy education. Almost all such studies have identified the alternative conception that has become widely known as the 'distance theory', where 'winter' translates into the Earth being farther away from the Sun than in the 'summer' (see, for example, Bakas & Mikropoulos 2003; Kikas 1998; Sadler 1998; Schoon 1992; Trumper 2001a,b; Tsai & Chang 2005; Plummer & Maynard 2014). This alternative conception is also commonly found even amongst schoolteachers (see, for example, Atwood & Atwood 1996; Mant & Summers 1993; Mant 1995;

Ojala 1992; Parker & Heywood 1998). In some studies the students have been found to mention the Earth's tilt when attempting to provide an explanation for seasons, but typically little or no further explanation was provided (see, for example, Baxter 1989; Dunlop 2000; Roald & Mikalsen 2001). Sneider et al. (2011) gives a comprehensive overview of the historical development of this topic and concludes that one of the reasons for this being so difficult for students to appropriately conceptualise is that it requires substantial 'spatial' reasoning skills.

Another well-researched thread in AER focuses on students' ideas about the 'Earth-Sun-Moon System', which includes a lot of work done investigating students' ideas on the phases of the Moon. This research has shown how it is very common to 'see' the phases of the Moon as resulting from the Earth casting its shadow on the Moon. See, for example, studies with younger students, Baxter (1989); Dove (2002); Dunlop (2000); Engeström (1991); Isik-Ercan et al. (2012); Jones et al. (1987); Pena & Gil Quilez (2001); Schoon (1992); Stahly et al. (1999); Taylor & Grundstrom (2011); Trumper (2001a,b); K. C. Trundle et al. (2007); K. Trundle et al. (2008), and for university students, Mulholland & Ginns (2008); Comins (2001); Schneps (1989). The general finding in these studies is that the participants struggled with conceptualising and understanding how the Earth-Sun-Moon are related to each other in terms of their relative motions, sizes and distance. However, this research has also found that what is commonly referred to as 'scaffolding' (originally coined by D. Wood et al. (1976)) of the learning experience, helps students to create a more coherent understanding of the Earth-Sun-Moon system and the phases of the Moon (Barnett & Morran 2002; Chen et al. 2007; Hudgins et al. 2006; K. C. Trundle et al. 2007).

'Gravity' has been the second most popular strand researched in AER and has been studied at all levels. The concept has been used to study, *inter alia* 'falling body' thought experiments on the Earth versus on the Moon and other places, and different conceptions associated with this. Here, a clear bridging between PER and AER can be identified, for example, gravity is an important part of mechanics PER work (e.g. Sharp & Sharp 2007). The PER mechanics work research is situated both at school level, see for example Berg & Brouwer (1991); McDermott (1984); Noce et al. (1988); Sneider & Pulos (1983); Treagust & Smith (1989); Watts & Zylbersztajn (1981), and university level, for example, Watts (1982); K. E. Williamson & Willoughby (2012). From these studies it is clear that students from all educational levels, and even some teachers (mainly the primary level), hold many different alternative conceptions about the concept of gravity.

Students and teachers ways of making sense of ‘The Solar system’ have not been as extensively studied in AER, but some of the studies that have been done indicate that students struggle with connecting gravity to the motion of the planets (for example, see, Treagust & Smith 1989). Other studies indicate that about half of 10-11-year-olds hold alternative conceptions about the solar system (Sharp 1996; Sharp & Kuerbis 2006)). Similar results have been found for primary school teachers (Mant & Summers 1993; Mant 1995).

When addressing issues related to Stars and the Sun not many studies are to be found in the literature, and most of those found address ideas about what stars are and what they look like (e.g. Agan 2004; Bailey et al. 2009; Sharp et al. 1997; Sharp 1996) and how they move across the night sky as viewed from the reference frame of the rotating Earth (e.g. Bailey et al. 2009; Bailey, Johnson, et al. 2012; Baxter & Preece 2000; Dove 2002).

Students ideas on ‘Cosmology’ is a relatively new research thread within AER and, as Pasachoff (2002) has argued, there is a need for studies about how students make sense of cosmological issues in relation to recent findings in the scientific field of cosmology. Here, research into conceptions about the Big Bang (e.g. Bailey, Coble, et al. 2012; Hansson & Redfors 2006, 2007; E. E. Prather et al. 2009, 2003; Wallace et al. 2011a,b, 2012a,c,b), has shown how up to 80% of students harbour alternative conceptions about what the Big Bang was, how it happened and where.

The young field of ‘Astrobiology’ has stimulated interest and generated a slowly growing body of research on the ways of conceptualising astrobiology (see, for example, Hansson & Redfors 2013; Offerdahl et al. 2002). This research captures the very diverse conceptions held by students.

Finally, the important category of ‘Size and Distance’ requires more attention and, as such, is included in my research. This research thread is strongly connected to the challenges around issues of discernment and three-dimensionality in astronomy education. Research that has been done in the AER category of ‘Size and Distance’ includes, for example, Coble et al. (2013) who found that the undergraduate students in their sample succeeded fairly well at tasks involving relative distances, but struggled with absolute distances. This is in line with the results of a survey on senior high school students done by Trumper (2001b), and by a study carried out by Agan (2004) concerning students’ conceptions about stellar distances. Coble et al. (2013) also found that the students had difficulties in conceptualising the Solar system with any sophistication, and at larger distances the students had problems in visualizing galactic structures, such as halos. However, it was also found that students’ conceptual understanding of the hierarchical structure of the Universe

increased over a semester of teaching. With those few examples from the literature, it is easy to concur with Lelliott and Rollnick that:

‘...there should be a greater focus on the teaching of distance and size to help explain astronomical phenomena. Although very few studies focused on this big idea, it is crucial to so much of astronomy, from the size of the Earth and the solar system to their relationship to the rest of the galaxy and the Universe. Not only is this concept under-researched, but it is under-taught.’
(Lelliott & Rollnick 2010, p. 1791)

8.2.3 Alternative conceptions

Everyone constructs their own conceptions about astronomy and other phenomena. These conceptions often turn out not to match the scientific way of conceptualizing phenomena; this is referred to in the literature as having constructed ‘alternative’, or ‘mis-’, conceptions and often referred to a ‘alternative conceptions’ when discussing what students bring with them into class. These alternative conceptions are very common at all levels.

The AER literature contains numerous examples of studies concerning alternative conceptions in the field, and below I highlight those dealing with university students and adults; the studies most relevant for my work.

A well-known example illustrating the persistence of alternative conceptions is the video ‘A private Universe’ (Schneps 1989). In this video MIT students, on their graduation day, were asked to explain why we have seasons. Only two (2) out of 27 could give an answer that was scientifically correct.

Neil Comins, in his book ‘Heavenly Errors: Misconceptions about the Real Nature of the Universe’ (2001) provides numerous examples of alternative conceptions that undergraduate students hold in relation to stars, galaxies, and the Universe. For example: ‘Stars really twinkle’, ‘Black holes are huge vacuum cleaners, sucking everything in’, ‘Pulsars are pulsating stars’, ‘All stars are yellow’, ‘Stars last forever’, ‘The galaxy, the solar system, and the Universe are all the same thing’, ‘Gravity is the strongest force in the universe’, ‘The universe is static or unchanging’, and ‘The Earth is at the centre of the universe’. Although Comins does not investigate these conceptions more extensively, he highlights how alternative conceptions are very common when it comes to understanding astronomy and the astrophysical processes involved.

A particularly interesting thread of research, which has relevance for my research, has been done by Favia et al. (2013, 2014). They have worked extensively on finding and analysing what they refer to as ‘misconceptions’ held by introductory level university astronomy students. In their first paper (2013),

these authors use item response theory (IRT) to explore alternative conceptions concerning topics relating to galaxies. They found ‘that the concept of galaxy spatial distribution presents the greatest challenge to students of all the galaxy topics’ (p. 1). This kind of result supports the research focus in my thesis by reinforcing that extrapolating three-dimensionality is one of the essential factors for successfully learning astronomy. Favia and his co-authors also investigated 215 common alternative conceptions held by this group of students ($N=639$) to look for correlations amongst the conceptions. They used a new instrument that probed whether or not a student believed any of the conceptions presented to them in a survey. This promising work is ongoing and the authors’ aim is to group different conceptions in order to propose an optimal teaching sequence for teaching concepts within the different areas in astronomy (Favia et al. 2014).

Many alternative conceptions may originate from the representations used in student literature and from earlier teaching in astronomy that tried to represent different aspects of the Universe, but failed to do so in ways that promoted scientifically sound meaning-making (see, for example Sadler 1996; Vosniadou & Brewer 1992, 1994). Such ‘traditional’ representations have by necessity two-dimensional (2D) semiotic structure as they are presented in, for example, images and diagrams and other 2D teaching material (for example commonly used textbooks such as Freedman et al. 2010; Jackson 1891). The literature reports that 2D representations can be seen to contribute to misleading and encouraging the construction of alternative views by children (Ojala 1997; Price & Lee 2010; Vosniadou 1991) and older students’ alternative conceptions (Parker & Heywood 1998; Pena & Gil Quilez 2001). Trying to build an understanding of the complex Universe using alternative conceptions about the Earth, Moon and Sun, etc., will most likely lead to further conceptual problems, as Sadler (1996, p. 55) argues: An ‘understanding of science may be constructed much like astronomy’s cosmic distance scale; accurate measures of more and more distant objects are dependent on the ways in which we measure closer objects. It may be impossible for students to acquire powerful scientific ideas without great attention to the basics’. Teaching astronomy in a traditional way using an orchestration of 2D representations, such as images, photographs, diagrams, 2D animations, etc., turns out to be highly problematic in terms of being able to effectively help students come to understand challenging astronomical concepts and their functional use in making sense of the complexity of the Universe.

Bruce and Blown (2012b) investigated the general astronomy knowledge of people aged between 3 and 80 sampled in both China and New Zealand ($N_{total} = 993$) and found that their knowledge was generally unsophisticated.

Many were found to have developed alternative conceptions similar to those of Favia et al. (2013, 2014) described earlier. Bruce and Blown (2012b) also found that the astronomical knowledge sophistication of the people in the study increased with an education in astronomy. They identified this increase in astronomy knowledge in groups that they characterized as novice and expert (see definitions in Bryce & Blown 2012b, p. 554)). Their definitions of novice and expert can be interconnected with educational levels in most cases, although they found some overlap between different educational groups. Their results resonate with my results reported on in this thesis.

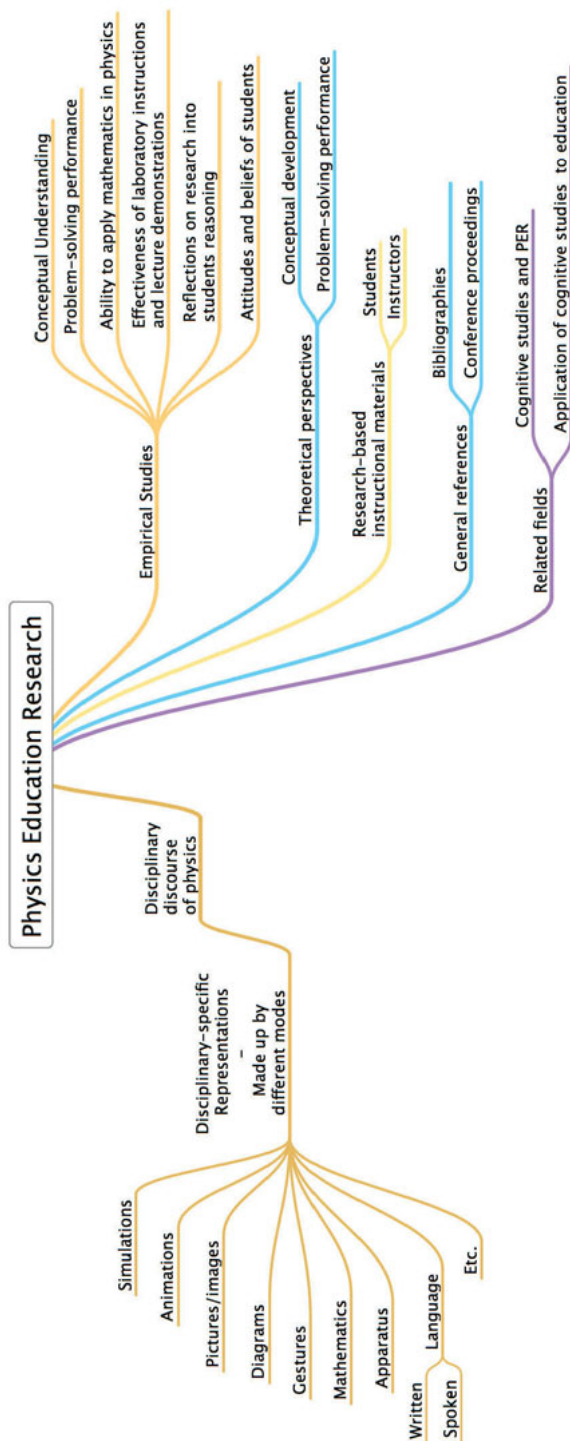


Figure 8.1. Illustrating PER: Broad categories adopted from McDermott and Redish (1999, to the right), illustrating PER papers over the past decades, divided into categorised and sub-categories, together with other, more recent categories identified in the literature regarding ‘Disciplinary-specific Representations’ (cf. Airey & Linder 2009, to the left).

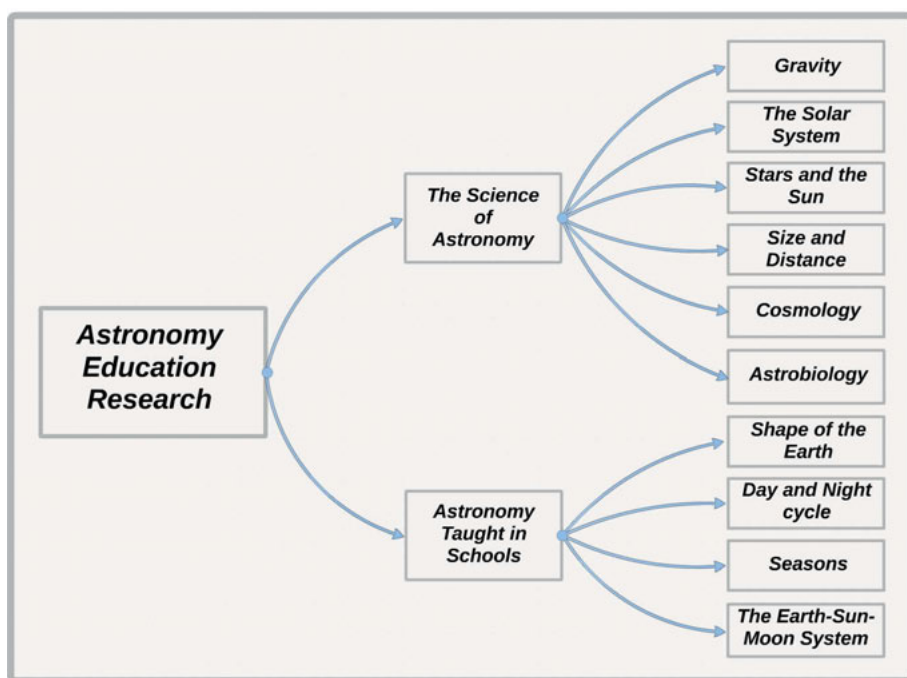


Figure 8.2. These categories are a conglomerate of those identified by Lelliott and Rollnick (2010) and Bailey and Slater (2003) as representing ‘Focal Points’ in astronomy education.

8.3 Virtual Learning Environments – potent tools for learning astronomy

As a way to help students come to understand the grandeur and complexity of the multidimensional Universe, different learning environments can be used. A learning environment could be any environment where learning can take place: in lecture-rooms, laboratories, coffee-room, at home, etc. Virtual learning environments (VLEs) are powerful learning environments created using multimedia tools. These environments offer potential for learning through their use and way of presenting different disciplinary-specific representations using visualisation (Sterman 1994). They can be adapted to particular circumstances and suited to particular tasks or purposes. They have been found to offer new possibilities for students to learn about the 3D structure of the Universe in ways that otherwise would be difficult, if not impossible to visit, similar to the microcosmos, or any imaginary world (see Lipşa et al. 2012).

The potential of VLEs has not been extensively studied from an astronomy learning perspective, but the field of VLEs builds on research on multimedia teaching and learning, a developing field with a growing research body (see, for example, Ainsworth 2006; Mayer 2009). I will discuss multimedia learning in detail in Chapter 9. Acknowledging the pedagogical benefits of using VLEs, I have chosen to use an example of such a VLE, a highly regarded astronomical simulation (Tully 2012), in my research reported on in Part II of this thesis. In the papers that this part of the thesis is built upon I did not discuss the research done in the field of VLEs, however I present a review of the research field in this chapter. The following two sections provide an overview of pertinent research on the use of multidimensional VLEs, and their learning affordances, as they apply to my work (Sections 8.3.1 and 8.3.2 respectively).

8.3.1 3D Virtual Learning Environments and displays

The real world is 3D, however the textbooks and video displays that are usually used to represent the world to students are 2D representations. This potentially leads learners to construct conceptions that are inaccurate and oversimplified from a scientific point of view (Marr & Nishihara 1978). Since the 1800's attempts have been made to overcome such difficulties in educational settings by trying to facilitate the experience of three-dimensionality; from the earliest attempts by Wheatstone (1852) using stereoscopy, to the more modern stereoscopic displays, usually using 3D glasses of different types. Currently, even more advanced displays are being developed that do not require glasses to be used (Lee 2013). However, the literature on the learning possibilities of

stereoscopic representations is limited (see, for example, Price & Lee 2010; Rutten et al. 2012). Furthermore, from the literature it is seen that astronomy, being intrinsically 3D (or even 4D), poses special demands on learners as it involves extreme distances, translations, and relative motion of objects in a 3D Universe (Barab et al. 2000; Hansen et al. 2004a,b; Keating et al. 2002; Parker & Heywood 1998; Plummer 2014). Thanks to today's powerful computers, 3D VLEs, which are being extensively used in computer games, open up possibilities for learning situations. However, the educational and pedagogical benefits are not well known, especially when it comes to the benefits that emanate particularly from the 3D aspects of VLEs. It has been found that the cognitive load (Chandler & Sweller 1991) increases when using 3D VLEs and that students need time to practice to come to terms with these learning environments, especially concerning proper use and interpretation of different depth cues to support the extrapolation of three-dimensionality (Hegarty 2011; Hubona et al. 1999; Price & Lee 2010). This is an issue, which is further developed in my thesis.

The literature identifies three important aspects to take into account when considering the pedagogical benefits of 3D VLEs: Three-dimensionality, smooth temporal changes and interactivities (Dalgarno & Lee 2010). Here, the sensation of 3D is found most important but also the experience of smooth temporal changes, meaning that the VLE must be experienced as realistic⁵. This means that while moving around in the VLE the changes of perspective must be experienced as very smooth, hence making it look realistic. Finally, the possibilities to interact with the VLE, or other 'players' or learners in it, are found important (Dalgarno & Lee 2010).

The literature identifies three properties of 3D VLEs that can be related to conceptual learning. These are 'representational fidelity' (Dalgarno & Lee 2010; Zeltzer 1992), 'immediacy of control' (Hedberg & Alexander 1994; Whitelock et al. 1996), and 'presence' (Hedberg & Alexander 1994; Slater & Wilbur 1997; Whitelock et al. 1996). Representational fidelity relates to how well the VLE resembles reality, i.e. how realistic it is experienced by the user. Dalgarno and Lee (2010) argue that the two most important visual aspects of the representational fidelity are realistic display of the environment and smooth display of view changes and object motion. This relates to the possible experiences a user can have of VLEs. An example could be a virtual journey into space where the more photographic the quality of the display is, together with smooth temporal changes, the more realistic the experience. Another aspect of the fidelity of representation is the consistency of object

⁵However, realism in this perspective does not necessarily mean photorealism.

behaviours. In the case for Dalgarno and Lee, when several users are in the same virtual environment, they can act and interact and the responses must be realistic. In my case, I argue that the behaviour, looks and position of virtual objects in the VLE must obey the fundamental laws of physics for them to be experienced as realistic. Immediacy of control, also referred to as immersion, 'is a description of a technology, and describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant' (Slater & Wilbur 1997, p. 3). This means that the system generates a 3D representation that appears to surround the user from a physical point of view and at the same time offers control of the environment through view control, navigation, and object manipulation. This is considered important from a learning perspective since knowledge construction is enhanced by embodied actions (Dede 1995; Dall'Alba & Barnacle 2005) together with vision (Polanyi 1965). 'Presence is a state of consciousness, the (psychological) sense of being in the virtual environment' (Slater & Wilbur 1997, p. 4). Presence thus refers to the participant experiencing the VLE as more realistic than the surrounding real world, hence experiencing the displayed environment as a place visited rather than just an image seen. Obviously, presence and immersion are closely related and different authors use these two expressions interchangeably to describe the same thing, i.e. the subjective perception of 'being there' (Dalgarno & Lee 2010). In conclusion, 'immersion relies on the technical capabilities of [the] technology to render sensory stimuli, whereas presence is context dependent and draws on the individual's subjective psychological response' (Dalgarno & Lee 2010, p. 13).

8.3.2 Spatial and learning affordances of Virtual Learning Environments

Affordance (see Section 9.3.4) is often considered to be a problematic term in education. However, the Virtual Learning research community commonly uses the term in different contexts. Important for this thesis are 'spatial affordance' and 'learning affordance'. Hence, I review and define these two concepts below.

VLEs in general, and 3D simulations in particular, do not in and of themselves cause learning to occur. However, these environments can be used to make certain tasks possible, those that may lead to learning benefits. The pragmatic possibilities that technology has for having objects change size and to change the motion and perspective in a given VLE representation are termed 'spatial affordances' (cf. Bower 2008). Once the technological tools are being

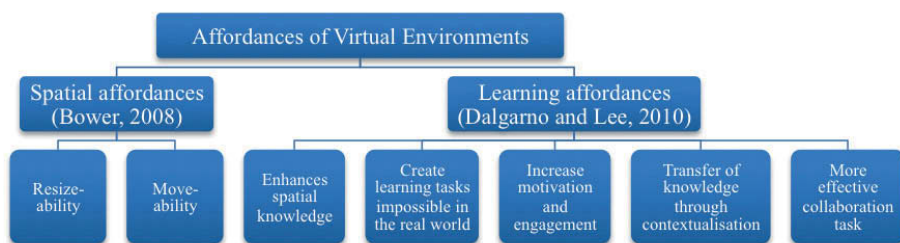


Figure 8.3. Different affordances of VLEs as listed by Bower (2008) and Dalgarno and Lee (2010)

used in teaching, one needs to investigate what learning is being ‘afforded’ by their use. Such learning affordances ‘represent the theoretical learning benefits of 3-D VLEs [...]. It is the tasks, activities and underpinning pedagogical strategies supported or facilitated by the technology rather than the technology itself that have an impact on learning’ (Dalgarno & Lee 2010, p. 17-18). See Figure 8.3 for an overview.

Dalgarno and Lee (2010) identified five learning affordances for 3D VLEs. The first of these is that 3D VLEs can be used to facilitate learning tasks that lead to the development of enhanced spatial knowledge representation of the explored domain. This is extremely important from my perspective since I am interested in students’ discernment, which involves the extrapolation of 3D. Second, 3D VLEs can be used to facilitate experiential learning tasks that would be impractical or impossible to undertake in the real world. Research on students’ experiences of the microcosmos using 3D simulation software, suggests that VLEs are ‘most useful when they embody concepts and principles that are not normally accessible to the senses’ (Winn & Jackson 1999, p. 7). Other studies have found that students develop a deeper understanding of the microcosmos from interacting with a VLE, in an effort to allow students to experience being inside a quantum atom. It was especially important how ‘realistic’ the VLE was experienced and also how well it gave a sense of ‘being there’, i.e. ‘presence’ (Kontogeorgiou et al. 2008). The findings from the research done on using simulations to visualize the microcosmos as a tool for promoting student learning (cf. Rundgren & Tibell 2009) is relevant for my work because it is equally impossible to access the macrocosmos. We cannot experience the 3D structure of the Universe when watching the night sky; it is simply not accessible to our senses. Thirdly, Dalgarno and Lee (2010) identify that 3D VLEs can be used to facilitate learning tasks that lead to increased intrinsic motivation and engagement. A virtual journey into space potentially provides a vivid and inspirational experience unlike what many

students have seen before (Slater & Wilbur 1997). The fourth learning affordance for 3D VLEs that Dalgarno and Lee (2010) identify is that 3D VLEs can be used to facilitate learning tasks that lead to improved transfer of knowledge and skills to real situations through contextualisation of learning. This means that when a student experiences a realistic simulation of the Universe, it opens up new possible ways of thinking for the student when the student combines prior knowledge with the new experience and tries to describe it in new ways (Marton & Booth 1997; Webb 2005). An example could be seeing the Orion constellation change shape as the simulation changes the perspective and gives a view of Orion from different angles and distances, revealing features in new ways. The fifth learning affordance identified by Dalgarno and Lee (2010) is that 3D VLEs can be used to facilitate learning tasks that lead to richer and/or more effective collaborative learning than is possible with 2D alternatives. This involves other participants, and interaction, when using the VLEs.

A third important affordance of VLEs for this thesis is the temporal affordance of a VLE. For example, in a simulation, as in most human social activities, the tempo is too high for us to discern or notice all things; the amount of information present simultaneously is simply too large. This could potentially lead to ‘cognitive overload’ (Mayer & Moreno 2003; Mayer 2009; Lowe 2003; Tasker & Dalton 2008) making the students ‘miss the point’. However, when things are slowed down, or stopped at intervals and different segments re-played, they can discern much more. This is an important aspect to consider in a teaching and learning situation, which uses multimedia as this generates conditions for the learners to discern many things in a simulation (Lemke 2007; Mayer 2009).

8.3.3 Summary

I have reported on research dealing with the properties of VLEs, together with the different affordances of VLEs, which I have found very useful when considering conceptual learning in astronomy. As will become evident in the following section, VLEs are being used in astronomy education and so the growing research reported on in the literature regarding their usefulness, limitations and possibilities for learning astronomy is important. However, considering the current very fast development of VLEs, where software developers can deliver astronomical simulation software that takes into consideration many of the aspects described earlier, the pedagogical aspects of using these VLEs for learning astronomy needs further consideration, especially in understanding what these VLEs afford for the students.

8.4 Three-dimensionality in Astronomy and Astronomy Education

An extension of the research on representations has recently emerged in the area of 3D models, both static and computer simulated. It is within the area of 3D representations that my thesis research in PAER is primarily situated.

Earlier, I argued that astronomy is unique as a science. It is very complex and intrinsically 3D (or 4D, when including time) and this constitutes a major challenge to students entering the discourse of astronomy. The most common experiences that any person could have from looking at the sky, or at images representing part of the sky and objects in the Universe is essentially 2D, so the educational challenge lies within moving from these 2D experiences to a 3D (or 4D) understanding of the Universe. This is what I call *Reading the Sky* and I will address this in detail in Chapter 12.

The complex educational challenges raised by the 3D nature of the Universe are similar to many of the difficulties in representing dimensionality in, for example, chemistry, geoscience, and engineering, which can thus also benefit by the use of virtual environments like simulations and animations (see, for example, Sterman 1994). Today, the development of technology potentially offers new ways to experience the Universe as 3D by moving through computer simulations of the Universe. These developments offer a leap forward in the teaching and learning of astronomy, where students now can be given experiences (almost) similar to real observations of the Universe. Since experiences are key to constructing new understandings, such 3D representations potentially offer great possibilities, but also present challenges (Wickens et al. 1994). Moving from 2D to 3D can thus be said to be a paradigm shift in astronomy education, similar to what has taken place in many other science disciplines, such as physics (Kuhn 1970). In this chapter I will first shortly address the difficulties in representing astronomical data in different scientific and useful ways. After this, I will review the literature addressing the use of 3D representations in astronomy education.

8.4.1 Three-dimensionality and Astronomy – ways to represent astronomical objects in 2D

Representing 3D objects using 2D representations is not something that is done easily, especially in astronomy. The need to move from a spherical, real, 3D-oriented set of data taken from telescopes, to a flat, 2D image or representation of the astronomical objects under investigation could be computationally demanding (see, for example, Borne 2010). Stretching the image, and flat-

tening it, in different ways to make it suitable for merging with other data taken in the same stellar neighbourhood is problematic as it involves translations, line of sight rotations, windowing transformation, and perspective transformations. Clark (2014) describes how these computations lead to issues where the boundary conditions and coordinate transformations must carefully be taken into account. The computations eventually lead to a possible 2D representation of the astronomical objects under study. However, thanks to the nature of the data, it may be possible to visualize the data from different directions, hence offering a possibility to explore and experience the astronomical objects from different directions (Lipša et al. 2012), to possibly allow for extrapolating three-dimensionality by the observer.

Researchers have developed methods for representing depth in flat, 2D images, and, especially in planetary astronomy and geography, height can be visualized using colour to code the third dimension on, for example, maps (Card et al. 1999). This can be seen, for example, in images representing different formations on other planets, like Mars, or moons like Titan, see Figures 8.4 and 8.5. This works well if the objects have a surface that can be visualized. However, using colours to indicate height could also be a source of student's alternative conceptions, as in the case where students are used to using red or blue to represent temperature and when these colours are used in coding a map to visualize height (Cid et al. 2009). There are many studies detailing how disciplinary experts make and use such representations routinely to explain aspects of different ideas (for example, see Anderson & Leinhardt 2002). In fact, it is often found that these experts have lost the ability to see things as a novice might see them (Bransford et al. 2000). For the experts, what might be obvious and simple in a representation might not be discernible at all for novices (Rapp 2005). This is an aspect that my research also addresses (see Papers II and III).

8.4.2 Spatial thinking for the purposes of this thesis

Some researchers suggest that experiencing 3D must involve spatial ability. However, since '[n]o consensus exists for categorization of measures of spatial ability' (Linn & Petersen 1985, p. 1479), I have taken spatial ability to fall outside the scope of my thesis and, as such, is not dealt with in my analysis. On the other hand, taking a fine grained perspective, aspects in my results could be seen to have similarities to what Hunt et al. (1988) began referring to as '*dynamic spatial ability*' (the ability to handle moving elements, relative velocities and distance judgements—see Section 11.1). Thus, for purposes of my thesis I am going to focus on what the National Research Council (2006)

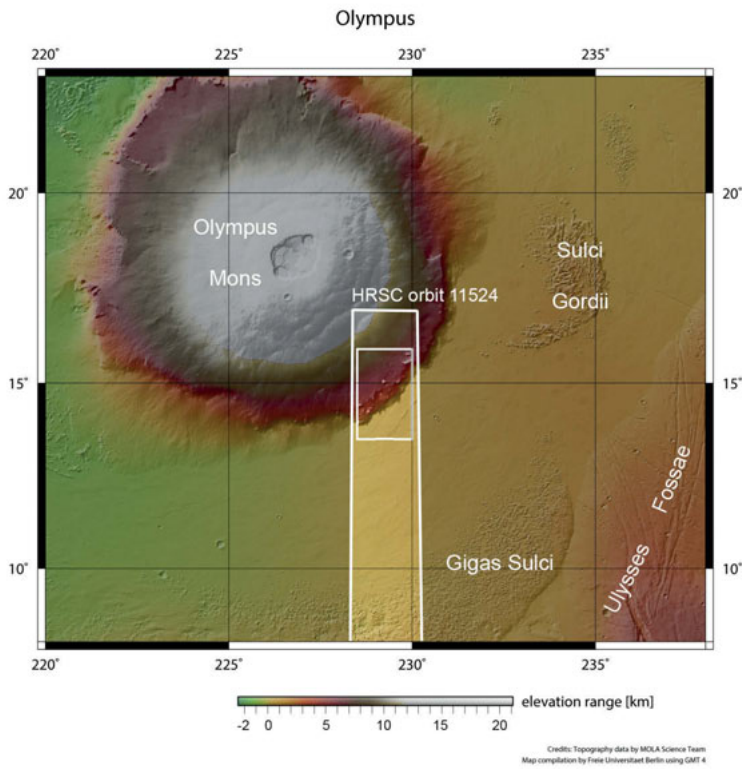


Figure 8.4. Image representing Olympus Mons on Mars. Here, colour is used to represent different heights. Image credits: NASA/MGS/MOLA Science Team

define as ‘spatial thinking’. I do this because, in this thesis I suggest that spatial thinking, in terms of being able to extrapolate three-dimensionality, is very important for learning astronomy.

One of the most cited reports dealing with the various components of spatial thinking that relates to teaching and learning, how education can foster it, and its implication for improving education and science learning is the ‘Learning to think spatially’ (National Research Council 2006). Here, the authors call for the need for students to be ‘spatially literate’ (Christopherson 1997) through the development of ‘appropriate levels of spatial knowledge and skills in spatial ways of thinking and acting, together with sets of spatial capabilities, have the following characteristics :

1. the habit of mind of thinking spatially.
2. practice spatial thinking in an informal way.

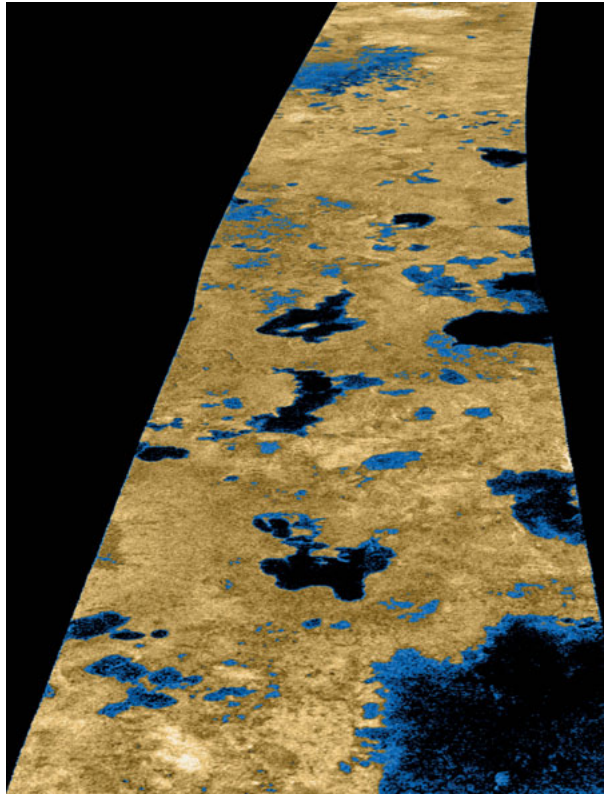


Figure 8.5. Image representing the landscape on Titan, with lakes and land, using colour to code height. Image credits: NASA/JPL/USGS

3. adopt a critical stance to spatial thinking.'

(National Research Council 2006, p. 4)

The National Research Council continue to argue that the 'basis for spatial thinking is the structure of space and the operations that we can perform on and in that structure' (p. 36) and that the 'key to spatial thinking is a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning' (p. 5). These three elements are referred to as follows:

1. **'Space** – the relationships among units of measurement (e.g., kilometers versus miles), different ways of calculating distance (e.g., miles, travel time, travel cost), the basis of coordinate systems (e.g., Cartesian versus polar coordinates), the nature of spaces (e.g., number of dimensions [two- versus three-dimensional]).
2. **Representation** – the relationships among views (e.g., plans versus elevations of buildings, or orthogonal versus perspective maps), the effect of projections (e.g., Mercator versus equal-area map projections), the principles of graphic de-

sign (e.g., the roles of legibility, visual contrast, and figure-ground organization in the readability of graphs and map.

3. **Reasoning** – the different ways of thinking about shortest distances (e.g., as the crow flies versus route distance in a rectangular street grid), the ability to extrapolate and interpolate (e.g., projecting a functional relationship on a graph into the future or estimating the slope of a hillside from a map of contour lines), and making decisions (e.g., given traffic reports on a radio, selecting an alternative detour).’

(National Research Council 2006, p. 12-13)

By taking these three elements into consideration, and following the example given by Kerski (2008), I define spatial thinking in an astronomy context to be *the recognition, consideration, and appreciation of the interconnected processes and characteristics among astronomical objects at all scales, dimensions, and time*. This definition captures what students need to understand in terms of astronomical concepts and objects and how these are connected theoretically and spatially, how to spatially represent these concepts and objects, and how to reason about these competently from a disciplinary perspective.

Spatial thinking thus comprises broad sets of interconnected competencies that can be taught and learned and has become increasingly more important for science education. For example, in physics it is important when reasoning about motion through space (e.g. Kozhevnikov & Thornton 2006), in chemistry it is important to reason about molecular structure and its connection to chemical properties (e.g. Tasker & Dalton 2006, 2008; Stieff 2011), in engineering it is vital to be able to visualise constructions (Sorby 2009), and in geology the reasoning about physical processes involved in landscape formation (e.g. Orion et al. 1997; Kali & Orion 1996). In science, the use of spatial representations (such as images, models, maps, animations and simulations) has become increasingly more important as the amount of scientific data, collected with modern data-collecting technology, has increased tremendously (Card et al. 1999; Linn & Petersen 1985). Thus, ‘we have gone from a problem-rich, data-poor world to one that is both data-rich and problem-rich, but is currently lacking the capacity to bring data to bear on solving problems. The solution to problems will depend on the capacity to process, analyse, and represent the vast quantities of data that we can gather and store’ (National Research Council 2006, p. 32). Present (and future) development of computer technology drives this development rapidly forward, towards better, faster and more realistic computer-based representations. There are today different research communities that are focusing on how to best use visualisations to reveal patterns in complex data sets. These can be gathered under the multidisciplinary field known as ‘Visual Analytics’, which focuses on how to use dynamic visuali-

sations to support analytic thinking with large data sets (e.g. Card et al. 1999; Thomas & Cook 2005). This development highlights the growing need for students to develop spatial thinking, especially in science (National Research Council 2006).

Several longitudinal studies have found that students who are talented in spatial thinking statistically account for the variation in who chooses to study science (Hegarty 2014; Shea et al. 2001) and, at the same time it is being claimed that it is this ‘skill’ that determines how far a student will progress in science education (Gardner 1993). Spatially thinking has been shown to be particularly predictive for success in science education at the higher level (see, for example, Pallrand & Seeber 1984), for the pursuit of scientific occupations (Wai et al. 2009), and for creative accomplishments (Kell et al. 2013).

An interesting alternative to spatial thinking is the concept of visualisers (Richardson 1977; Pashler et al. 2008; Kozhevnikov et al. 2002, 2005). It refers to people being visualisers and, as such, two separate kinds can be identified; ‘*Object visualizers* use imagery to construct vivid detailed pictures of static objects (e.g. a rabbit visualized with color, texture, size and a specific orientation and environmental context). *Spatial visualizers* excel at representing relations among objects as well as dynamic transformations of objects. The kind of visualization most important to scientists is the latter kind – spatial visualization’ (Newcombe & Stieff 2012, p. 958). Being a ‘spatial visualizer’ corresponds with how I see spatial thinking from an astronomy educator perspective and thus, I feel, does not offer a better way to theorize what it means to think spatially.

From my discussion in this section, it could be reasonable to conclude that the more one learns within a science discipline, the better ones spatial thinking becomes, and the better visualiser one is. However, it is also found that disciplinary experts in different fields of science, technology and mathematics (STEM) *do not report* extensive use of spatial thinking in problem-solving (Uttal & Cohen 2012). This may seem surprising and even paradoxical from the discussion that I have presented above. Obviously, being a disciplinary expert does not mean that only spatial thinking is necessary: ‘Expertise in STEM reasoning is best characterized as a complex interplay between spatial and semantic knowledge’ (Uttal & Cohen 2012, p. 162). Therefore, the educational background of these experts makes it possible for them to use other semantic knowledge to solve problems and ‘see’ solutions in an almost automatic manner (Eberbach & Crowley 2009; Schneider & Shiffrin 1977). There are findings in the literature to support this from chemistry (e.g. Stieff 2004); radiology (e.g. Lesgold et al. 1988; B. P. Wood 1999), and geometry (e.g. Koedinger & Anderson 1990), but none reported from astronomy.

There is, however, one noteworthy discovery related to spatial thinking and spatial structures that is worth mentioning here, since it deviates from the reported expert/novice pattern above: the discovery of the structure of DNA by disciplinary experts James Watson and Francis Crick, supported by Rosalind Franklin and Maurice Wilkins (Watson & Crick 1953). There is, however, one noteworthy discovery related to spatial thinking and spatial structures that is worth mentioning here, since it deviates from the reported expert/novice pattern above: the discovery of the structure of DNA by disciplinary experts James Watson and Francis Crick, supported by Rosalind Franklin and Maurice Wilkins (A. I. Miller 1984), since no other disciplinary knowledge could be used to solve such a problem.

As the historical example above highlights, discussions about spatial thinking are often centred around the fact that data is presented in 2D and that it might be the ways in which different representations are displayed that ‘matters’ educationally: the design of visual-spatial displays, and especially complex displays like simulations and animation⁶, have been found important for learning science in general (Hegarty 2011) and, as I suggest in this thesis, astronomy in particular.

8.4.3 Relating AER to Spatial thinking

In the previous section, for the purposes of my thesis, I defined spatial thinking as the recognition, consideration, and appreciation of the interconnected processes and characteristics among astronomical objects at all scales, dimensions, and time. From this point of view, spatial thinking can be taken to be very important in many different areas and subjects. However, given the current and growing possibilities of computer based teaching material, little impact of such material on learning astronomy is found in the literature. Moreover, it is taken for granted that the students need to be able to think spatially (see, for example, Heyer et al. 2013) to understand the enormous 3D Universe, from the essentially 2D input that is available.

Furthermore, it is not clear from the AER literature what the required spatial thinking entails and what it could be used for (hence the development of my definition). On the other hand, experienced astronomy teachers repeatedly observe that students possessing high levels of spatial thinking generally succeed better in astronomy courses than those with lower levels of spatial thinking (Heyer et al. 2013). The lack of literature concerning the connection between

⁶Here, we find commercial astronomical software like Starry Night, Star Walk, Planet Walk, Google Earth, Uniview, etc., used on computer, tablets or smart-phones

astronomy education and spatial thinking is troublesome but there is a growing interest from the AER community to investigate this (see, for example, Heywood et al. 2013). This concern was recently identified and highlighted by the National Research Council 2012 in the USA:

Considering that astronomy requires learners to imagine a three-dimensional dynamic universe of galaxies and orbiting planets by looking up at a flat sky, it would be reasonable to assume that spatial thinking is an active area of inquiry in astronomy education research. However, systematic research on spatial thinking in astronomy is very limited. Studies are under way to examine the relationships between spatial thinking and astronomy knowledge, but their results have not yet been published in peer-reviewed journals. (p.112)

The work presented in this thesis thus adds what I believe to be valuable new momentum to the research body concerning teaching and learning astronomy and its connection to spatial thinking.

Having introduced my definition of spatial thinking, I can now return to my review discussion on three dimensionality in AER.

8.4.4 Three-dimensionality and Astronomy Education – ways to represents the structure of the Universe for understanding

A majority of the frequently used representations in astronomy education are 2D such as diagrams, plots, or images, used to help students better understand fundamental processes and underlying structures of the Universe. In astronomy education there is an implicit and untested assumption that students need to, and will be able to, conceptually extrapolate 3D representations from these 2D images through spatial thinking; however, this is often not the case (Hansen et al. 2004a,b; National Research Council 2006; Parker & Heywood 1998; Sorby 2009; V. M. Williamson & Abraham 1995). To help students appreciate the 3D nature of the Universe, Virtual Learning Environments (VLEs), as discussed in Section 8.3, can be used, and the simulation video (Tully 2012) that I used in the work in this thesis is an example of this. These VLEs dynamically introduce students to the structure and complexity of the Universe in pseudo-3D, which is otherwise impossible using other representations (Gilbert 2008; Mikropoulos & Natsis 2011; Webb 2005). However, little is known about the learning possibilities that such a collection of representations can present to ‘reflective learners’ (Linder & Marshall 2003) and how the ability to extrapolate three-dimensionality is related to the level of disciplinary knowledge of the students. In fact, very little evidence is found in the literature to support

this connection (Hegarty 2011; Heyer et al. 2013). Furthermore, what can be found in the literature is most often related to spatial thinking, and not, as I suggest in this thesis that it has to do with how the 2D input from vision can be used to extrapolate an experience of depth, what I call *extrapolating three-dimensionality* (see Paper II and Chapter 11).

Most of the research literature on students understanding of astronomical 3D structures focuses on the Earth-Sun-Moon connection, day and night, phases of the Moon, and seasons, as discussed in Section 8.2.2. Research on students at all levels shows that it is difficult for students to understand the 3D structure of the planetary system in general, and the Earth-Moon connection in particular (Lelliott & Rollnick 2010). However, when students engage in modelling these phenomena, using either physical objects (balls, etc. (Vosniadou 1991)) or computer simulations, the level of understanding increases (Barab et al. 2000; Barnett et al. 2005; Keating et al. 2002). Vosniadou (1991) reported on a survey describing the mental models that students at all levels of education, and even adults, were having concerning the shape of the Earth, day and night, the Moon, the Sun, and the stars and found that they was surprisingly poor. She could identify three distinct mental models for the students: intuitive, scientific and synthetic. She suggests that to improve the level of understanding, teachers should use 3D models (balls and lamps) to emphasize the correct model and thereby change the students' mental models to a scientific model. This need was also identified by Parker and Heywood (1998) who found a number of key features which the students needed to be confronted with and made aware of. The first two of which were 'spatial awareness' and 'two-and three-dimensional reasoning', both of which could be referred to as spatial thinking. These referred to the problems the students were having relating to experiencing, or being aware of, the three-dimensional structure of the planetary system. In the first case, 'there is the generic problem of spatial awareness in relating to position in space of the observer and the observed objects' (Parker & Heywood 1998, p. 515). In the latter case, they found that the students had great difficulties in moving from two-dimensional representations of the solar system to three-dimensional representations, especially when considering the movement of these celestial bodies from different perspectives.

With more powerful computers available in schools and social settings today, students can access computer modelling software more easily, and by creating and engaging with these models the students may develop a more sophisticated, scientifically correct understanding of the dynamic structure of the celestial bodies. In the literature there are many examples of the possibilities for 3D modelling software to construct 3D models of the Earth-Sun-Moon system

in elementary, primary and secondary school, as well as at undergraduate level (cf. Barnett et al. 2001; Barnett & Morran 2002; Barnett et al. 2005; Mintz et al. 2001; Plummer & Maynard 2014; Trumper 2000; Yair et al. 2001, 2003; Yu & Sahami 2008). This literature describes how students can develop sophisticated understandings of astronomy concepts concerning the Earth-Moon connection and the solar system by using 3D VLEs. A common argument is that the use of software helps students reconstruct their knowledge on the structure of the solar system and perceive it as a 3D place. One example of this is the Virtual Solar System (VSS) project (Barab et al. 2000), where large groups of undergraduate students used software to model the solar system. The students used the VLE to create and develop their own models throughout an inquiry-based course with great success. Students developed their understanding especially for: 1) astronomy conceptual knowledge in general, 2) changing the frames of reference by jumping around on and between different objects in the solar system and, 3) the dynamical processes in the solar system. Barab et al. argue that through ‘this process, concepts (plane of the ecliptic, relative scale, mathematical formulas, line of nodes) become living phenomena that are actualized and not simply realized’ (p. 751).

In two papers Hansen et al. (2004a,b) investigated the impact of 3D modelling on non-science major students understanding of astronomy. They conducted both qualitative and quantitative investigations to learn what differences there might be between students taught in traditional large-lecture formats and students taught in a project-based introductory astronomy course (VSS, see above). Here, just as in many other cases, the students in the project-based classes used computer software to develop and use models of the solar system (VSS) in problem solving. The authors investigated both spatial knowledge (distance, perspective and relative displacement) and declarative knowledge (properties, facts, and figures regarding celestial objects) through interviews and a survey. Their prime goal was to assess students’ conceptual understandings and especially looking for instances where students referred to their 3D models in their explanations. The results from their investigation showed that, first, students using 3D modelling software developed a scientifically sound conceptual understanding of especially the dynamical astronomical phenomena but did not necessarily improve their declarative knowledge, and second, students developed the ability to change reference frames using 3D modelling software much more, compared to the students in the traditional large-lecture classes.

There is an interesting study by Joseph (2011) in which he investigated the educational benefits of using stereoscopic visualization technology in a course with university level astronomy students and found that this technology was

highly appreciated by the students. They used the technology to explore the solar system and the local group of galaxies and these students scored much higher in 'post-tests' than those students taught using a 'static information presentation' method, corresponding to using 2D representations. Although some aspects of the technology and teaching method could be improved, this study indicated that the use of 3D modelling software is beneficial compared to teaching methods using only 2D representations.

Very few studies have been conducted studying students' ideas about stars, star formation, relative scale of objects in the Universe, and the arrangement and abundance of these objects (Bailey et al. 2009; Simonelli & Pilachowski 2003). Again, these studies revealed that a large majority of students had alternative conceptions that were neither scientifically correct nor complete. None of the categories found revealed any real awareness of the structure of the Universe, such as stars and their properties (colour, energy production, size, state, age, distances, etc.), and planets. The students were mixing scales, especially when talking about the solar system versus our galaxy. Only some 15% of the students gave answers related to distance or location.

The issue of using 2D representations where 3D representations are needed is also a problem for astronomers when publishing their work Barnes and Fluke (2008). Many journals will only accept 2D images, however, the American Journal of Physics accepts videos and simulations to support claims made in articles published in that journal, and others are likely to follow.

9. Conceptual framing

9.1 Introduction

In this chapter I present the conceptual framing for Part II of this thesis. I begin by posing the question: How can learning that is framed by representations be characterized for astronomy education? This could be approached from several ways. For my thesis, I am drawing on a social semiotic perspective (Kress 2009). Here, learning is taken to be the construction of meaning from representations (see, for example, Kress 2009). This perspective on learning is a function of ‘becoming fluent’ in using disciplinary-specific representations, that is achieving ‘fluency’ in a disciplinary discourse (Airey & Linder 2009). This, in turn, is a function of the ‘disciplinary affordance’ of representations (Fredlund et al. 2012). Such learning is made possible by experiencing pertinent patterns of variation; patterns that facilitate noticing educationally critical aspects (Marton & Booth 1997; Marton & Pang 2013). The parts of this perspective on learning are discussed throughout this chapter as part of the constitution of my conceptual framing.

The following uses the concept of energy to illustrate what achieving a basic ‘fluency’ in part of the disciplinary discourse of astronomy/physics calls for:

‘Students need to be taught, in each separate kind of physical instance of “energy”, how to measure “energy” differently, how to use the word “energy” to refer to specifically different aspects of a system or phenomenon, how to write equations that apply to that type of system, how to draw diagrams for it; and then they need to be taught how to move back and forth among the different verbal, mathematical, visual, and operational representations for “energy” in each case, and then further how to integrate and construct equivalences between each different pair of types of cases. *They need to gradually build up an abstract concept of energy, for there is nothing there to “leap” to until they have learned how to construct the necessary equivalences.*’ (Lemke 1998 p. 4, emphasis added)

From this illustration an appreciation can be obtained for how such a trajectory of learning would involve achieving familiarity with the representations that are needed to construct a holistic understanding. For astronomy and physics students, the ability to be able to move coherently between multiple

representations and perspectives has been shown to be a necessary (though not sufficient) condition for successful learning (Airey & Linder 2009). For students to become successful in this learning process, specific ‘patterns of variation’ in the ways that representations get used to communicate disciplinary knowledge and practices are also required (Marton & Booth 1997; Marton 2014). These patterns of variation present learning opportunities that contribute to building abstractions and construct references across representations, exposing the underlying structure of the subject (Ainsworth 2008; Spiro & Jehng 1990). However, despite the potential fruitfulness of applying the Variation Theory of Learning to physics and related engineering educational practice (for example, see, Bernhard 2010; Fraser & Linder 2009), as Vince and Tiberghien (2002, p. 51) have observed, ‘establishing relevant relations between the physics model and the observable objects and events is a very difficult task’. Thus, suitable scaffolding has to be generated to help guide the process of learning using existing disciplinary knowledge and familiar representations (Lindstrøm & Sharma 2009; Podolefsky & Finkelstein 2008). This is not a straightforward task for astronomy teachers. When studying images representing different astronomical objects, the large amount of information present often contributes to students not discerning the educationally critical aspects (Elby 2000; Stansfield 1976). Students tend to focus on the most compelling visual attributes and thereby neglect other important aspects of visual representations (cf. Podolefsky & Finkelstein 2008). And there is a further compounding factor: many important aspects are not immediately discernible in disciplinary representations; they are only ‘implicitly’ present (Elby 2000), that is, they are ‘appresent’ (Linder 2013; Marton & Booth 1997). Competently discerning educationally relevant aspects through vision is a complicated process, but it is this discernment (or lack of it) that constrains the experience students can have of the Universe.

Building on this perspective of how learning astronomy can be made possible, I now introduce the parts of the conceptual framing that I called on to answer my Research Questions 2-4: representations and disciplinary discernment.

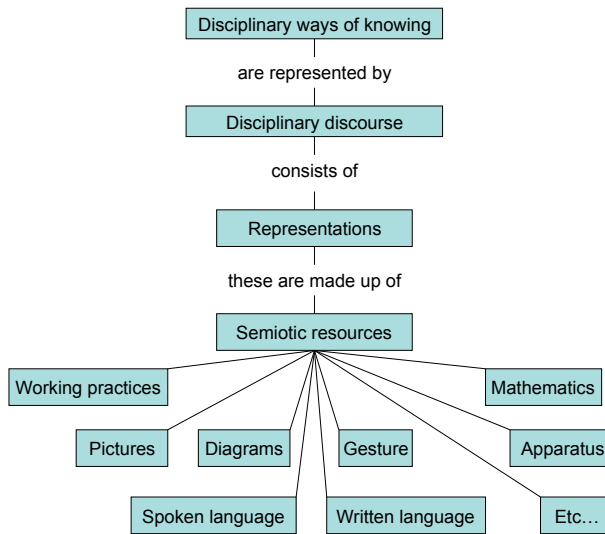


Figure 9.1. How the relationship between representations and semiotic resources are conceptualized for this thesis (After Airey & Linder 2009, p. 29).

9.2 Representations

In this section, I will describe what is meant by representations. I will then use this frame to discuss visualization and the dimensionality of representations.

In their most basic form, representations are semiotic resources that we use to constitute our communication practices in astronomy/physics (for example, see, Lemke 2001, 2005).

This perspective is comes from the field of ‘social semiotics’ (e.g., Kress 2010). I draw on it because it offers a fruitful way to capture meaning-making practices that shape our access to discernment (visual noticing and making sense of that noticing – see later) in a disciplinary context – disciplinary discernment – such as astronomy/physics. Examples of the forms of representation that we use in astronomy/physics are diagrams, graphs, mathematical formalism, signs, written language, spoken language, visual simulations, and the working practices of the discipline. For the purposes of my thesis, I have adapted Linder and Airey’s (2009 p. 90) ‘[d]iagram of the relationship between disciplinary ways of knowing and the modes of disciplinary discourse’ to illustrate the relationship between representations and semiotic resources, see Figure 9.1.

These modes in Figure 9.1 have specific communication potentials (Airey 2009) and as such they are ‘particularly suited for specific representational and communicational tasks’ (Kress 2010, p. 28), i.e., each mode has ‘different possibilities for representing disciplinary ways of knowing’ (Airey & Linder 2009, p. 2). These modes can be more meaningfully referred to as semiotic resources (Halliday 1978; Airey 2009).

The semiotic resources specific to the disciplinary discourse of astronomy are the representations, tools, and activities that are used to communicate the ways of knowing of astronomy (see Figure 9.1). In this thesis, representations are central to meaning-making through disciplinary discernment and thus could also be referred to as ‘artefacts that symbolize an idea or concept in science’ (Tang et al. 2014, p. 2; also see Blown & Bryce 2010; Clark 2014; Jackson 1891; Taylor & Grundstrom 2011; Yu & Sahami 2008). The representations that I was interested in for the research in Part II of my thesis were those that are available in simulations (such as stars, nebulae, clusters, colours). In contrast to a still image, a simulation uses a sequence of spatially represented elements in time, which provide the possibility of experiencing a variety of critical patterns of variation and for my research these are embedded in motion parallax.

My research interest was grounded in a search for a better understanding of what students discern from representations. While Elby’s (2000) work in this area gave consideration to what caught students’ attention, my interest was in what came next; after something gets noticed, what sense gets made of it? I used this interest to define *disciplinary discernment* in terms of noticing, reflecting on, and creating meaning from astronomy/physics perspective. As part of illustrating how I developed this idea, I provide discussion on vision, noticing, reflection and affordance in this chapter.

9.3 Building a concept of disciplinary discernment: vision, (visual) noticing, reflection and affordance

To use a magnifying glass is to pay attention, but isn't paying attention already having a magnifying glass? Attention by itself is an enlarging glass.

(Bachelard 1994, p.158)

9.3.1 Vision

In astronomy, perception is dependent on vision. It is through vision that one perceives and experiences the Universe. An important aspect of this perception is the ability to make distance determinations. Here, people use two different methods: binocular vision and monocular vision (Blake & Wilson 2011; Gibson 1950; Gregory 1966; Howard 2002). In the next section I describe these 'types' of vision (also see Paper II).

Binocular vision and monocular vision

Binocular vision uses the concept of parallax for distance determination. By viewing the same object from two different positions it is possible to discern the shift in the position of the object, compared to more distant objects, and thereby estimate the distance to the object. This is referred to as stereopsis in the literature (Gibson 1979; von Noorden 1996). Unfortunately, it only works over short distances, due to the small separation between our eyes. When looking at a nearby object the eyes will point slightly inwards and make a small angle, referred to as the parallax angle. Human physiology puts a threshold on the smallest parallax angle that can be appreciated by our eyes and this translates to the maximum distance of about 200 meters. Beyond this distance, binocular vision can no longer be used for distance determination. 'However, we perceive depth, and the relative positions of objects in space, for even the most distant objects. Thus, stereopsis is not the only mechanism for perceiving depth' (Hubona et al. 1999, p. 218). Monocular vision works as the next mechanism used to determine distance by comparing distant objects with some accessible reference objects or cues. These cues need to be familiar objects to function as cues. For example, when looking over a landscape one may see a car in the distance. Since the size of cars are known to most people, the car can be used to make estimates on how far away we are, or how big objects in the landscape next to it may be. Obviously, these estimates will be subject to large errors. Precision can thus be increased by a third powerful depth cue: motion. 'Everyday perceptual experiences occur within a context of nested motions. Moving eyes, and moving objects, provide powerful perceptual cues

about the environmental and spatial properties of perceived objects' (Hubona et al. 1999, p. 218). This can be obtained by, for example, moving ones own head or the whole body to make more accurate distance determinations in ones' surroundings. This involves relative motion that offers perspective changes where one views an object from different positions in space, similar to the situation for binocular vision, and is often referred to as motion parallax (Nawrot & Joyce 2006; Rogers & Graham 1979). In fact, it is the same technique that astronomers use in distance determinations to nearby stars, see Part I, Section 3.3, of this thesis.

However, in astronomy, the distances involved are extremely large and humans become restricted to monocular vision for any distance determination, but since cue material is missing when observing the night sky, astronomical distance determinations become physiologically impossible (B. W. Miller & Brewer 2010). The only available alternative then becomes using motion parallax, but even this is of course restricted since humans cannot travel around in space over large astronomical distances. Fortunately, computer simulations offer a realistic alternative in this perspective and therefore I have used simulations for my data collection in Part II of the thesis (cf. Wickens et al. 1994).

The next disciplinary discernment attribute that I need to discuss is what I call 'noticing' (meaning visual noticing). Noticing is something that is necessary but not sufficient for disciplinary discernment to take place.

9.3.2 (Visual) Noticing

Seeing on a conscious level where one focuses on a particular object calls for it to catch one's attention – 'noticing' that particular object (Polanyi 1965; Mason 2002). For example, when a person sees a 'shooting star' in the night sky such seeing may be solely at the level of 'caught my attention'. Much more than such noticing is needed to see it as a meteoroid 'burning up' due to the friction supplied by our atmosphere. Since learning in astronomy gets triggered by some event that gets noticed, the noticing must be through the visual perceptual system (Latour 1986). While humans are monitoring their environment all the time, very little of this is in one's 'focal awareness' (Marton & Booth 1997). It is what is in our focal awareness that I am calling noticing.

To notice something means to be able to distinguish something from the background or surroundings. However, 'we notice all the time, but on different levels' (Mason 2002, p. 33), and most of what we notice is quickly 'lost' from accessible memory. This is referred to as 'ordinary noticing' by Mason. When we notice and remember, then the noticing remains in our focal awareness by a 'marking' and may even be 'recorded', either as an 'inwardly mental note'

or as an ‘outwardly note’. This leaves it available for the meaning-making reflection process to occur. Mason describes this as follows:

To *mark* something is to be able to re-mark upon it later to others. *Marking* signals that there was something salient about the incident, and re-marking about it to someone else or even yourself makes the incident more likely to be available for yet further access, reflection and re-construction in the future. Thus *marking* is a heightened form of noticing. (p. 33)

(Visual) noticing in astronomy education contexts will be different for different people depending on their background and past experiences and their disciplinary and educational levels (Latour & Woolgar 1979). Lindgren & Schwartz (2009) refer to this as *the noticing effect*, define as follows:

‘A characteristic of perceptual learning is the increasing ability to perceive more in a given situation. Experts can notice important subtleties that novices simply do not see. This literature helps explain how people can come to perceive what they previously could not, and how *the ability to notice often corresponds to competence in a domain.*’ (p.421, emphasis added)

The complexity of noticing extends to the understanding of ‘novices’ who:

‘fail to notice the right things. Instead, they notice many irrelevant features and behaviors that fail to forge connections or to support deeper understanding of complex phenomena. Disciplinary knowledge, however, can filter, focus, and foster understanding.’ (Eberbach & Crowley 2009, p. 49)

It is, however, difficult to prepare to notice relevant things. To circumvent this difficulty Mason (2002, p. 75) suggest two strategies: 1) continuing to work on sharpening sensitivities, and 2) imagining yourself acting in a fresh way in a typical situation. These require both persistence and commitment in the act of noticing (which could be difficult for a student who is continuously experiencing new things through education). To overcome this educational challenge, the ‘Variation Theory of learning’ (Marton & Booth 1997; Marton 2014) can be used to introduce relevant patterns of variation into the experience of noticing. By learning through experiencing relevant patterns of variation a student can be seen to become more competent and to develop a ‘professional vision’ (Goodwin 1994), which in turn facilitates the possibility of further, in-depth noticing.

Next, I discuss the role of reflection in making meaning of what gets noticed in my definition of disciplinary discernment

9.3.3 Reflection

In choosing to draw on the idea of reflection in my definition of disciplinary discernment I was very much aware of the ‘uses and abuses’ of the construct in the educational literature (Fendler 2003; Hatton & Smith 1995).

John Dewey originally conceptualized the idea of reflection describing it in terms of:

‘Active, persistent and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it and the further conclusions to which it tends, constitutes reflective thought.’ (Dewey 1933, p. 9)

Dewey’s model of reflection has two integral components. Firstly, ‘a state of doubt, hesitation, perplexity, mental difficulty, in which thinking originates’, and secondly, ‘an act of searching, hunting, inquiring, to find material that will resolve the doubt, settle and dispose of the perplexity’ (Dewey 1933, p. 12). Here, the need ‘for the solution of a perplexity, is the steadying and guiding factor in the entire process of reflection.’ (p. 14). Donald Schön became well known for his development of Dewey’s ideas to create an epistemology of professional practice based upon the notion of reflection-in-action that involves having a ‘reflective conversation’ with the puzzling situation (Schön 1983). Such reflection must be different for different persons; an ‘expert’ can be expected to evoke different reflections to that of a ‘novice’. What is also important for my definition of discernment is how Schön draws on Dewey’s idea of ‘transaction’ to characterize the interdependent relationship between the knower and the known as follows (Schön 1983):

‘The inquirer’s relation to this situation is transactional. He shapes the situation, but in conversation with it, so that his own models and appreciations are also shaped by the situation. The phenomena that he seeks to understand are partly of his own making; he is in the situation he seeks to understand’ (p. 150).

In summary, after noticing something that is puzzling or intriguing and thus having it in one’s focal awareness, reflection on that noticing is how meaning-making takes place. It happens through a metaphorical entering into a ‘conversation’ with that puzzling/intriguing situation.

Before proceeding I need to address the natural question, ‘is this noticing and reflection not what scientific observation is about?’ In a sense it certainly is. However, there many aspects of what an astronomer observes that are not *visually* directly observable. For example, our scientific observations of the interior of a gamma ray source do not come from direct visual observations (for other examples and philosophical discussion, see Shapere 1982). The

distinction between what can be *visually* observed and what gets observed through other means (for example, radio telescopes) captures the essence of what I am calling *disciplinary discernment*, which is specifically about what is visually seen and reflected on.

In my work I have associated my idea of competence with Fredlund et al.'s (2012) notion of 'disciplinary affordance'. This is integrally related to the definition of disciplinary discernment that I constructed. Hence, the idea of 'affordance' needs to precede my drawing-together discussion on disciplinary discernment.

9.3.4 Affordance

The concept of *affordance* is used today in many different educational settings. However, the meaning of affordance is still under debate in the literature. Although clearly defined in the Oxford English Dictionary, its use in educational literature typically gets seen as being problematic because it gets directly linked to the work of Gibson (1977, 1979) and his conflict with Norman (1988) over what the meaning of the term should be in the field of psychology. In the social semiotics field Kress (e.g. 2010) has used the affordance to fit into his framing of 'multimodality':

'Modal affordance refers to the potentialities and constraints of different modes – what it is possible to express and represent or communicate easily with the resources of a mode, and what is less straightforward or even impossible – and this is subject to constant social work. From this perspective, the term 'affordance' is not a matter of perception, but rather refers to the materially, culturally, socially and historically developed ways in which meaning is made with particular semiotic resources' (MODE 2012).

Fredlund et al. (2012) refer to: the 'potential of a representation to provide access to disciplinary knowledge' (p. 658). In so doing Fredlund et al. are noting that the affordances of different disciplinary representations are what determines the role they can play in disciplinary communication. The ability to discern these affordances from representations and use them in the sharing of knowledge thus becomes critical for anyone entering a discipline – they constitute the 'language' of the discipline. Thus for the purposes of my thesis learning is a function of 'becoming fluent' in using disciplinary-specific representations, which, in turn, is a function of the disciplinary affordance of representations. This is the grounding for my definition of discernment: noticing, reflecting on, and creating meaning from a disciplinary perspective.

9.4 Summary

The conceptual framework presented in this chapter describes how I have characterized a perspective on learning in astronomy that is framed by representations. I used this framing in the analysis, to discuss the results and to answer my theoretical research question (4): How can the idea characterized as Reading the Sky in this thesis inform the teaching and learning of astronomy?

10. Research Methodology

The harmony of all the details with the whole is the criterion of correct understanding. The failure to achieve this harmony means that understanding has failed.
Gadamer (2004, p.291)

10.1 Introduction

The purpose of this chapter is to provide an overview of the kind of qualitative research framing that I used for the studies reported on in Part II of my thesis: an interpretative-hermeneutic based framing. This particular methodological framework was chosen as a function of its appropriateness for my education research questions, which are:

2.
 - a) In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?
 - b) What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?
3.
 - a) What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?
 - b) How can this discernment be characterized from an educational perspective?
4. How can the idea characterized as *Reading the Sky* in this thesis inform the teaching and learning of astronomy?

A strong background in astronomy and astronomy education is critical if a set of 'credible' (Lincoln & Guba 1985) interpretations is to be constructed when doing AER. This means that the analytic outcomes from my research must present some kind of congruency with what other astronomy educators know and have experienced (see, Merriam & Associates 2002).

Consideration of my research questions illustrates how Part II of my thesis is framed around the notion of discernment, which I defined earlier in Chapter 9 (and in my papers II and III). My empirical analysis (RQ 2-3) focuses on

interpreting (understanding) the discernment that university students and their lecturers have when looking at the sky using a simulation lens. Then, my theoretical analysis (RQ 4) focuses on generating an idealized way to bring out the educational implications of these results. In order to carry out this research I needed to find an appropriate methodology in which to situate it. After an extensive reading of the literature, following the likes of Merriam (2009), I chose to frame my work within the interpretative thread of educational research that is grounded in the basics of hermeneutics.

Hermeneutics has its historical origins in determining the meaning and understanding of religious texts and today is a rigorous discipline in its own right. In the context of educational research hermeneutics provides an ontological, epistemological and methodological grounding (cf. Butler 1998) for qualitative interpretative research, thus the name interpretative-hermeneutic is often used in the literature (for example, see Crotty 1998). A full review of hermeneutics is beyond what is needed for this thesis and furthermore, such reviews already exist, for example, Gadamer (2004); Seebohm (2004); and Stanford University's Encyclopaedia of Philosophy – <http://plato.stanford.edu/entries/hermeneutics/>.

Ontologically, hermeneutics portrays realities being

‘the hermeneutic perspective posits that realities are constructed from multiple, intangible mental constructions that are socially and experientially based, local and specific in nature, and dependent on their form and content on the individual persons or groups holding the constructions.’ (Butler 1998, p. 294)

Epistemologically, hermeneutics sees using a particular framework to construct a particular interpretation (understanding) of the experience of others constitutes a legitimate knowledge claim (Butler 1998; Lincoln & Guba 1985). And, methodologically

‘the variable and personal nature of social constructions suggests that individual constructions can be elicited and refined only through interactions between and among investigator and respondents. These constructions are interpreted using hermeneutical principles and concepts that inform conventional qualitative techniques and are compared and contrasted through a dialectical interchange. It is the task of the researcher as a human instrument to reconstruct the social world of the phenomena under study utilising his/her own idiographically informed interpretations.’ (Butler 1998, p. 294)

What Butler refers to as a ‘dialectical interchange’ is a method of iteration that consists of a constant comparative, cyclical procedure that continuously

moves between a construction of understanding between the ‘parts’ and the ‘whole’ until ‘saturation’ is reached (Lincoln & Guba 1985, p. 350), meaning that no further interpretation gets constructed (see Sections 10.2 and 10.5).

Using this background I now introduce the qualitative (interpretative-hermeneutic) research methodology I used for Part II of my thesis.

10.2 An introduction to the qualitative (interpretative-hermeneutic) research methodology

What is meant by qualitative research that is underpinned by an interpretative - hermeneutic perspective? The best way for me to answer this question is to characterize my research as having an epistemological grounding that portrays knowledge as a human construction, and an aim that is to establish a new understanding of discernment (in terms of my understanding of astronomy and my experience in astronomy education). In other words, my research falls into the broad ‘what, why’ and ‘how’ category of research rather than the ‘how many, how much’, and ‘how generalizable’ category (the former falling into the more interpretative research orientation and the latter falling into the more positivist orientation, which focuses on producing verified and generalizable facts rather than understandings) (Robson 2011).

Qualitative research that aims at constructing understanding using interpretative - hermeneutic methodological points of view has a variety of different orientations. Some of the most familiar being ethnography, discourse analysis, conversation analysis, case studies, hermeneutics, phenomenology, phenomenography, thematic analysis, grounded theory and narrative studies. Common to these research orientations is an analytic approach that involves extensive iteration between ‘parts’ of and the ‘whole’ of a given data segment; a procedure commonly known as ‘making constant comparisons’ (for example, see Blanche et al. 2006; Denzin & Lincoln 2011; Robson 2011; Stiles 1993). What aspects of interpretative-study methodology get to be used and how it gets to be used is very much a function of appropriateness in relation to a given research question (Robson 2011). I describe these aspects for my study in full in Section 10.6 of this chapter.

Qualitative interpretative-hermeneutic studies, because of the complexity involved and because of the nature of their aims, often do not involve a large number of participants and hence the kinds of results, generalization potential and conclusions that they generate call for a different set of quality benchmarks than other more positivist research requires. In the early 1980’s Lincoln and Guba (1985) made a ground breaking epistemic case for such alternatives

in their book *Naturalistic Inquiry*. How I dealt with quality issues for my studies is discussed in Section 10.8 of this chapter.

How does research in astronomy education fit into interpretative studies? Getting to construct an appropriate disciplinary understanding is an essential part of astronomy education. Thus, research that looks at understanding how, for example students, conceptualize, discern, make sense of, see, visualize, extrapolate and so on, aspects of astronomy becomes critically important for informing the teaching and learning of astronomy. At the same time astronomy, as a natural science, has some particular qualities that make the construction of disciplinary understanding particularly challenging, not only for students studying astronomy, but also for astronomers. One of the most important of these is that astronomers' research mainly involves observing different phenomenon 'as they happen' rather than in designed set-up experiments such as those one would find at CERN (European Organization for Nuclear Research). Since much of the data is captured 'as things happen' there is little opportunity for a 'repeat experiment', and often no hypothesis exists before the data is collected. For the analysis, astronomers familiarize themselves with the data in detail, and then begin a process of data reduction using appropriate 'cleaning out' measures. This process involves iterative cycles, which slowly reveal relative relevance and irrelevance in the data. Through this iterative processing interesting questions and answers begin to emerge (see, for example, Bailey et al. 2010; Lena et al. 1998; Martin & Brouwer 1992; Wall & Jenkins 2003). This process has many structural similarities to the interpretative-hermeneutic interactive process that I used for Part II of my thesis. In both cases the strength of the research is partially a function of the background of the researcher. However, in the case of the qualitative (interpretative-hermeneutic) research a further set of attributes is needed to constitute a strong background; knowledge and experience of the given educational setting, and insight into the experience of learning in such settings.

10.2.1 Personal background of the researcher

Throughout my undergraduate studies I had an intensely keen and growing interest in astronomy and so took several extra astronomy courses. After graduating with a Bachelor's degree in physics and mathematics, I started my professional teaching career. After teaching mathematics, physics and astronomy in adult education for five years, I got a position at Kristianstad University, where I taught physics and astronomy for engineers and in-service and pre-service teacher programmes. As a result of my interest in astronomy, I was given the opportunity to continue to study astronomy and this led to me com-

pleting a licentiate degree (Ph.Lic.) in astrometry (Eriksson 2007). Since then my teaching assignments have shifted towards teaching astronomy for student teachers. I currently do this utilizing both regular and online facilities. I also began to run Kristianstad University's planetarium (using an Inflatable Starlab dome and Digitarium software), which, over the years has attracted more than 35 000 visitors. At about the same time, I became responsible for the Kristianstad University Observatory, which I now use to create visually rich learning experiences for my students. Some of this activity has been directed at local schools whose pupils have been invited to visit the observatory to get to know the night sky better.

My many encounters with students, pupils, and others created an interest in what people get to notice from the sky, itself, and from different astronomy representations – such as astronomical images, animations, simulations – and what sense they get to make from this noticing (what I call discernment in this thesis). So, when I got given the opportunity to continue with my Ph.D. research I immediately began to engage with questions related to my notion of disciplinary discernment.

10.3 Method

In this section I outline how I chose the material that I used for my data collection, how the data collection was done, and how I used the kind of qualitative (interpretative-hermeneutic) methodology that I introduced in this chapter to obtain the analytical outcomes that I report on for my Research Questions 2-4 in Chapter 11.

10.3.1 Setting the scene for data collection

The data collection involved using a video simulation of travelling through our Galaxy and beyond in conjunction with a survey that I made available online. The methodology that I chose for my data collection was derived from my interest in discernment that I described earlier. The survey needed to appropriately capture the participants' descriptions of their discernment when engaging with the video (see Section 10.4.2). Since capturing differences was an important part of my research design, I used the web platform to make it possible to easily collect data from a wide variety of educational settings. Obtaining a good variation in descriptions does not necessarily mean that the number of participants needed to be large. For instance, more useful variation could be obtained from five very different descriptions of discernment than

from twenty very similar descriptions (Marton & Booth 1997). I aimed at getting about 100 participants and got 137 drawn from across a wide variety of universities situated in North America, Europe, Australia and South Africa.

There are a number of issues to consider when choosing a survey as the preferred data collection format (Robson 2011). Conventionally, surveys use a fixed design, collect a small span of data from a large number of participants, and are directed at a particular population of people. This was not exactly the case for my survey: I used a flexible design that focused on obtaining a rich variation in discernment description, and collected a large amount of data from a limited number of profiled participants. Surveys have a number of research advantages and disadvantages. These are described as follows by Robson (2011):

Disadvantages

1. Data gathered using respondents are affected by the characteristics of the respondents.
2. Respondents may not report their thinking accurately.
3. Surveys typically have a low response rate and since one does not know the non-respondents it may be difficult to know if the sample is representative.
4. Respondents may not treat the survey seriously, and one may not be able to detect this.
5. Ambiguities in, and misunderstandings of, the survey questions may not be detected.

Advantages

1. Simple and straightforward approach.
2. Adapted to collect generalisable information from most populations.
3. Effective way to collect large amounts of data.
4. Often the only way to retrieve data from people spread over large areas/countries.
5. It allows anonymity, which may encourage frankness. (p.233)

I addressed the issues raised by these advantages and disadvantages as follows: The first four listed disadvantages were alleviated by having an influential person at each of the participant universities present my research case to the 'purposeful sample' of potential participants. Since the qualities of the answers were extremely good, I assumed that the people who participated did so with a positive mindset. The response rate was close to what I had hoped for and an excellent spread of international participants was obtained. To address the last disadvantage in the Robson list, I used very straightforward questions (see Section 10.4.3).

To optimise the advantages of using a survey, I examined other online surveys to learn how to formulate a clear and straightforward strategy for the construction, testing, and subsequent re-construction phases of the survey. My final design of the online survey really functioned well in that the quality of the data collected allowed me to answer all of my first four research questions. Finally, I believe that anonymity was clearly an integral part of the research design and added encouragement to answer the questions in a honest, diligent and thoughtful way.

The development of the survey went through several stages. In summary, these were:

1. Questions were developed with a view to obtaining as much worthwhile data as possible from the participants.
2. These questions were trialed on a group of students in a pre-test. As part of the trial process the participants were given the opportunity to comment on their experience of the questions.
3. The results were analysed and changes were made where needed to improve the survey. These were all minor. There were also changes made connected to the length of the video selections (see Section 10.4.2). These changes were then trailed on a new group of students.
4. These trial results were then analysed and discussed with my supervisors. Consequently, some limited changes were then made that I felt would further improve the survey. This modified version of the survey was subject to re-trial with a small, new group of students.
5. After the results were analysed and discussed only very minor changes were needed. These mainly focused on coherence issues.
6. Then the pen-ultimate survey was given to a selection of interested professors of astronomy. All recommendations from them were incorporated into the survey. Again, these were minor.
7. After this final modification of the survey my supervisors and I considered it ready for use.

10.3.2 Video selection and production

To be able to investigate what students discern from a simulation that exposes a viewer to the structure of the Universe by taking them on a journey through space (Research Questions 2 and 3), I started to search for an appropriate simulation that would provide an effective tool to use in conjunction with my survey described in the previous section. As I mentioned earlier in Chapter 8, simulations have been found to be useful not only as a learning resource but

also for spatial training and evaluation (Cohen & Hegarty 2014). As discussed in the literature, my simulation of choice would need to offer the following:

- interactivity to permit the user to pause, adjust presentation pace, rewind and restart the simulation (Merkt et al. 2011; Schwan & Riempp 2004; Sweller & Chandler 1994),
- multidimensionality experiences through motion parallax (Hubona et al. 1999; Nawrot & Joyce 2006; Rogers & Graham 1979),
- appropriate disciplinary representations (Airey & Linder 2009; Airey 2009), which are used in ways that generate educationally pertinent patterns of variation (see discussion in Chapter 9).

Furthermore, certain cues that were considered to be undesirable were purposely *not* offered, for example,

- tick-marks for distances, or scale,
- labels for represented objects (Wickens et al. 1994),
- narration that explained what was displayed (cf. Ainsworth 2008),
- other sounds, like music (Mayer 2003; Sweller & Chandler 1994).

Furthermore, the simulation would need to be experienced as going on a ‘realistic’ journey through our Milky Way galaxy and beyond to present different educationally critical characteristic features and phenomena of the Universe (for example, different types of nebulae, stellar nurseries, star cluster, supernova remnants, stars of different types, constellations, galactic features (giant molecular clouds etc.) and the grand structure of the Milky Way). Since the simulation would be presented in 2D on flat monitors, it needed to be able to offer the kind of motion parallax that could provide what is needed to attain a sense of structural 3D. Also, all objects needed to be displayed and positioned as accurately as possible from an astronomical point of view.

I searched for such a simulation on the Internet and in the literature and found a highly regarded simulation that had all the required features. It was called *Flight to the Virgo Cluster* and was created by astronomer Brent Tully (2012). As part of the refinement of my research design other simulations were then compared with Tully’s. After extensive comparisons, Tully’s simulation remained the best choice. I then contacted Brent Tully explaining what I wanted to do and he gave me permission to use the simulation as I wished for my research.

The astronomical objects displayed in the Tully video were carefully examined by experienced astronomers and they confirmed my legitimacy and accuracy evaluation. I also asked Brent Tully to ratify this judgement, which he immediately did in a highly professional precise way (Tully, personal communication, 2013). The section of the simulation that I then chose to use for my simulated journey that started in the vicinity of the Earth, and then

proceeded through the stellar neighbourhood and different nebulae and other formations, and finally out of the galactic plane to give a grand overview of the Milky Way Galaxy and its surroundings (the simulation journey then continues through intergalactic space, passing by a number of galaxies, until it reaches the huge elliptic galaxy M87, which is visible from Earth in the direction of Virgo). Although visually extensive, the simulation running time is only a few minutes long.

In the production of the survey the part of the simulation chosen to be included was cut into shorter pieces, or clips. This was done because simulations like the one chosen for this research project, include huge amounts of information, so keeping what should be salient to the user ‘alive’ called for a careful ‘multimedia evaluation’ of the visual experience. In other words, the idea of limiting the focus of the clips was to make sure that ‘cognitive overload’ (Mayer & Moreno 2003) did not become a limiting factor for the quality of the data collected.

The piloting process that I carried out led to the following ‘segmenting principle’ being taken into account: ‘People learn better when a multimedia message is presented in user-pace segments rather than as a continuous unit’ (Mayer & Moreno 2003, p. 175). This principle has been shown to be most significant when the material is complex, presented with a fast pace, and the learner is relatively inexperienced with the material. When presented with long sequences, participants will be much more likely to just focus on parts of the sequence rather than the whole sequence. Presenting smaller segments at a time, similar to ‘modular presentations’ (e.g. Gerjets et al. 2004), enhances the possibility for a participant’s focus to be sharpened and learning to take place (Mayer & Moreno 2003). Thus, the part of the Tully simulation that I used was sliced into seven short clips, each having a limited number of educationally critical characteristic features/phenomena. The clips lasted on average about 15 seconds and the participants were also given unlimited review access. The aim was to have the clips form part of the survey in a coherent way. All of this was evaluated through the piloting process described earlier. A detailed description of the different clips can be found in Paper II of my thesis.

10.3.3 Data collection

The online aspects of presenting the survey were taken care of using a survey creating tool that is commonly used in educational contexts in the Nordic countries: <http://hkr.itslearning.com/test/r.aspx?XS=rsyzzasemogy>. Participating in the online survey started with agreeing to the ethical conditions described later in this chapter. After this the participants were asked to

provide some relevant demographic data (gender, educational level, etc.). The survey then moved on to the simulation clips described earlier. After the presentation of each of the clips, the same two open-ended discernment questions were asked. During the piloting process these questions had been refined, making them more straightforward by eliminating any ambiguity and/or misunderstanding. The final wording was:

1. Please write what comes to mind when you watch this clip, like things you noticed, sudden new realizations or connections, surprising or confusing things.
2. What, if any, 'I wonder . . . ' questions did this clip raise for you? If you have not noticed something new, feel free to say so.

In accordance with the 'segmenting principle' discussed above (Mayer & Moreno 2003), the individual clips could be re-played as many times as wanted by the participants while they answered the clip questions. At the end of the complete clip-question sequence, a number of follow-up clarification questions were asked. The clarification questions were used to further address aspects that the participants may have discerned in the simulation clips and which they were subsequently thinking about in retrospect. After completion of the data collection, the data analysis process started, see Section 10.5.

10.3.4 Recruiting the participants

To be able to collect the kind of data that I needed required a widely situated group of participants to 'smooth out' regional differences and at the same time give access to a good variation in the data. As already described, the data was collected using the online survey that I developed, so the participants would need to have access to, and be familiar with, computers in their 'natural setting' (in this case the educational setting they found themselves in) (Blanche et al. 2006). There was a need for 'minimum disturbance' to the natural setting (i.e. for the participants to be able to work comfortably, without any form of hindrance, influence or coercion) for me to be able to make legitimate interpretations of the participants' responses. Since the overarching research interest for Part II of my thesis concerned the development of disciplinary discernment in relation to university astronomy education, I needed participants that spanned the entire university experience from first-year introductory students to graduate students, to people teaching astronomy. In other words, I wanted all participants to be actively engaged with astronomy/physics. Also, to reduce possible effects from local educational settings and syllabi, the participants needed to come from a wide variety of educational contexts. In order to do this, astronomy educators at large universities and respected centres

Table 10.1. *Summary of participants in terms of self-reported location in the higher educational system. Note that when collapsing the introductory students with the first-year students, this group will have 59 participants.*

Educational level	Number of participants
First-year undergraduate students	36
Post-first-year undergraduate students	22
Graduate students	11
Lecturers/professors	39
Extramural students	20
Others	9
Total	137

for astronomy studies around the world were contacted. They were asked to help me attract a ‘purposeful sample’ (Robson 2011) by encouraging the cadre of participants that I wanted, both students and faculty, to participate in the study. In all, this resulted in 137 participants, 79 men and 58 women, from the US, Canada, Australia, South Africa, and five countries in Europe. Towards achieving the ‘wide variation of educational setting’ requirements, the undergraduate students were initially divided into three groups: introductory (or extramural), first-year undergraduate and post-first-year undergraduate students. Due to similarities found in the data, the first two groups were later merged into one group of first-year undergraduate students. The distribution of the participants can be found in Table 10.1. From this table it is clear that the two largest groups are first-year undergraduate students and lecturers/professors.

The ‘Others’ group are staff working at science centres or planetaria. As such these are difficult to categorise, and they were not used for addressing Research Question 2b in Part II in my thesis (and in Paper II). However, they were used for the remaining analysis and discussion.

10.4 Analysis of the data – A hermeneutic approach

The analysis that this Part II of the thesis is built upon focuses on the ‘lived’ discernment of the participants as a function of watching the Tully simulation. As outlined earlier, the qualitative data analysis in this thesis was grounded in an interpretative-hermeneutic approach. The iterative aspect, which derived from the hermeneutic influence that I discussed earlier, is often characterized as the ‘constant comparison approach’ (CCA) (Glaser & Strauss 1967). To achieve a holistic understanding, the analytic process must continuously move between a construction of understanding between the ‘parts’ and the ‘whole’,

in an iterative way, until the process no longer generates any development of the holistic understanding ('saturation', see Lincoln & Guba 1985). This is the cyclic way that I worked: first, finding significant parts of description, then through these parts starting the construction of an understanding of the 'whole' and vice-versa.

By iterating between 'parts' and 'wholes' while all the time looking for possibilities for reformulation, it became possible to eventually reach a holistically sound outcome. Through this process a hierarchy of aspects, or categories, emerged allowing me to create a structural model of the derived understandings of the phenomenon, which I have characterized as discernment in this thesis (and in Papers II and III).

What follows is an in-depth illustration of how I engaged with the data. I began with familiarizing myself and then immersing myself in the data to begin a process of coding by tagging similar pieces of textual segments of descriptors (attributes) as part of starting the construction of categories. So, the categories were being initially developed *in vivo*. Essentially I was coding the data by consciously not taking on any assumed *a priori* knowledge about the nature of what the emerging categories might be or should be. To achieve this mindset I iteratively made the data 'lead the way' as the 'descriptor-builder' (cf. Glaser & Strauss 1967). After this iterative working through the process of (re)sorting, (re)coding, (re)characterizing, (re)amalgamating, (re)classification, a set of final categories started to emerge (Basit 2003; Lincoln & Guba 1985; Strauss & Corbin 1998). I continued with the process, until 'saturation' was reached, meaning that the iteration process stopped generating changes in the analysis. Along the way my categories captured more and more discernment detail, which is often referred to in the literature as a process of re-contextualization or recreating the 'whole'.

When I began the analysis process described above, I did it 'manually', meaning that I literally cut the descriptions from photocopies of the survey answers and iteratively worked with them and the complete answers in the iterative way described. Once I understood the process I felt able to re-start the analysis using the widely accredited NVIVOTM computer analysis program without it being a 'black box' experience. The 'manual' process not only allowed me to attain a really good conceptualization of the analysis process, but the emerging results allowed me to give, or not give, credence to outcomes that were produced by the analytic software.

NVIVOTM is a retrieve, code and theory-building tool, developed specifically for, *inter alia*, the kind of qualitative analysis I was completing. NVIVOTM can analyse data in two general ways. Either the coding can be done automatically using the software's search functions, or manually. In my case, I drew

on my earlier manual analysis. This also provided a way of furthering the trustworthiness quality aspect of the data that I discuss in Section 10.6.

To further illustrate how I engaged with the data, consider the illustrative example given in Figure 10.1. In the figure, which shows an excerpt taken from the NVIVO™ coding process, only text related to the emerging category *Motion* is shown in ‘bold’. In this selection of the data set the following sub-categories were identified: Rotation, Movement, Acceleration, and Speed. These sub-categories are all part of the discernment category *Motion* (In Paper II, the *Motion* category is more thoroughly defined).

10.5 Addressing Quality Issues

As for any research methodology, there are quality issues that one needs to take into account. In traditional quantitative research these fall under the broad headings of ‘Reliability’, ‘Validity’ and ‘Generalizability’. For example, the following general classes of reliability are often referred to in quantitative research: Inter-Rater or Inter-Observer Reliability, Test-Retest Reliability, Parallel-Forms Reliability, and Internal Consistency Reliability (e.g. Robson 2011). For qualitative research that has the researcher seeking understanding, not facts and generalisations of these Lincoln and Guba (1985) made a compelling case for a set of alternative constructs under the theme of what they termed ‘Trustworthiness’. These are ‘Credibility’ (a reflection of confidence in the the outcomes), ‘Transferability’ (a reflection on how the outcomes may have applicability in different contexts), Dependability (a reflection on how the outcomes are consistent and could be obtained again) and, ‘Confirmability’ (a reflection on how ‘neutral’ the outcomes may be in terms of researcher bias, motivation, or interest). However, there are today qualitative research methodology publications that still build their discussions using traditional headings of; ‘Reliability’, ‘Validity’ and ‘Generalizability’. For example, ‘Reliability refers to the trustworthiness of observations or data; validity refers to the trustworthiness of interpretations or conclusions’ (Stiles 1993, p. 601). ‘The validity and reliability of a study determines the types of inferences a researcher can make, whether they be statistical, causal or construct inferences or generalizations’ (Nilsen 2014, p. 56). ‘Generalisability’ (or Lincoln and Guba’s notion of transferability) refers to the extent to which the findings of the enquiry are more generally applicable outside the specifics of the situation studied (Robson 2011). Since such usage has the possibility of broaden appreciation of the issues at hand, for the purposes of my discussion I will follow the example given by Stiles (1993) who built his perspective on quality control

ID	Now follow the movie, cut into seven clips. Together wit...	Clip 2/Watch this clip and answer the q...	Clip 3/Watch this clip and answer th...	Clip 4/Watch this clip and answer the questions b...
96	<p>1 no</p> <p>2 things coming toward me</p> <p>3 not sure</p> <p>4 could blue shift be observed in the video? I couldn't tell. Is the observer moving? Is it time progression or spatial movement in a static background?</p>	<p>1 I was wondering what was coming towards me - the gaseous blob - it seems to be a size I wasn't expecting (smaller than expected). Why are things turning?</p> <p>1. I'm moving towards a big cloud of gas. Maybe it's a galaxy?</p> <p>2. I don't understand what you mean by implications, exactly. I'm assuming that I'm moving, but it could be that everything is moving toward me.</p> <p>3. Nope. I guess I'm wondering what the survey is about.</p>	<p>1 I'm moving past one big gas cloud and toward another.</p>	<p>1 seemed to pass through the blob more quickly</p> <p>2 either that thing is spatially smaller compared to distances between other objects or the speed of observer changes there, possibly more gravitational force?</p> <p>3. I would want to know what of those implications might be reasonable</p>
97	<p>are things moving towards me or me to them? What's flying past?</p>	<p>1. Yes, in space.</p> <p>2. I saw stars speeding by me, so I guess I was moving very fast.</p> <p>3. I'm moving through space?</p> <p>4. Nope.</p>		
98	<p>The video makes it look like the viewer is moving forward, and stars are passing by</p>	<p>it looks like we are going to collide with something, maybe a nebula</p>		<p>1. Again, I'm passing out of one red gas cloud and going towards another. Red means that it's not very warm, I guess, compared to something burning blue or white.</p> <p>2. I'm moving?</p> <p>3. No.</p>
99			<p>1) I wonder if the straight cloud in the distance is the Milky Way galaxy. There is a second object and we are moving closer to it.</p> <p>2) I think we are going to pass through a different object - the video stopped right before we hit it.</p> <p>3) I wonder if this second object is similar to the one we passed (the other one looked like a nebula, but I'm not sure about this one)</p>	
100	<p>It looks like we are turning about our axis as we travel, and that we are moving</p>	<p>Again rotating as we move, this time with a galaxy in the background and a gas cloud of some sort that we travel by</p>	<p>Again traveling by two gas clouds,</p>	<p>through a cloud and toward another,</p>

Figure 10.1. Excerpts from the data to illustrate the NVIVO™ coding process. The sub-categories Rotation, Movement, Acceleration, and Speed, are grouped together under the discernment category *Motion*. Published with permission from Science Education.

using a interpretative-hermeneutic approach. The following sections give an outline of these pertinent quality issues from a general perspective and then in Section (quality control i this thesis) I discuss these, and other aspects, are handled in my thesis.

10.5.1 Reliability of Qualitative Research

‘Reliability’, in qualitative research is about procedural trustworthiness, which concerns how repeatable the observations are and whether a researcher’s report reflects what another competent researcher would have seen if observing the same data. For my thesis work this encompasses questions about how different participants describe their discernments of the same scenario and how these differences get interpreted (made sense of/understood) from an astronomy and teacher-of-astronomy perspective. Also, ‘characteristically qualitative trustworthiness issues arise because words do not mean the same thing to everybody and because events look different from different perspectives’ (Stiles 1993, p. 602). As recognition of such issues certain strategies need to be considered to ensure the quality of qualitative research (see Table 10.2).

Table 10.2. *Summary of strategies to ensure reliability in qualitative research (Stiles 1993, p. 602-607).*

Disclosure of Orientation	‘First, good practice recommends disclosure by the investigator of his or her expectations for the study, preconceptions, values, and orientation’.‘Despite inevitable limitations (e.g., investigators’ limited insight or inability to articulate relevant preconceptions), these disclosures can help readers infer the observations’ meaning to the investigator, and they indicate a starting point for gauging how the study changes the theory’ (p. 602).
---------------------------	--

cont.

Table 10.2. *Summary of strategies to ensure reliability in qualitative research (Stiles 1993, p. 602-607).*

Explication of Social and Cultural Context	Here, the investigators social and cultural background must be explicitly clarified, ‘by stating shared viewpoints and relevant values as well as the circumstances under which data were gathered’. ‘A goal of the explication, like the goal of personal disclosure, is to orient readers to the perspectives from which phenomena were viewed and to remind them that this research, like all research, derives from a particular perspective.’ (p. 603). This is in line with the hermeneutic methodology, as described earlier, to ‘understand the cultural forms through which ‘truths’ are accomplished’ (Silverman 1989, cited in Stiles 1993, p. 603).
Description of Internal Processes of Investigation	An important part of the investigation is the ‘progressive subjectivity’ (Guba & Lincoln 1989) which acknowledges how the investigation affects the investigator. Here, one states what was difficult, surprising, if the data made you change your mind, etc. in order to ‘illuminate the context of the substantive interpretations.’(p.603). This becomes increasingly important in qualitative research as the addressed topics often are personally significant to the investigator, hence reasonably changing the investigator as a person as he or she is conducting the research. ‘Good practice dictates that these processes be shared with the readers, as they constitute a part of the meaning of the study’s observations and interpretations’ (p. 604).
Engagement With the Material	In qualitative research immersion with the material is an important part of both the data collection and the analysis. The danger of being too engaged with the material, and hence possibly affect the outcome, must be balanced by disclosure in ‘revealing internal processes in ways that permit readers to assess (and perhaps compensate for) the distortions’ (p. 604).

cont.

Table 10.2. *Summary of strategies to ensure reliability in qualitative research (Stiles 1993, p. 602-607).*

Iteration	‘Good practice favors recycling- repeated encounters of theories or interpretations with the participants or the text. At the simplest level, recycling may involve checking the accuracy of empathy by reflecting the investigator’s understanding to participants during interviews’ (p.605). Obviously, these are two slightly different aspects. The first aspect concerns how the investigator repeatedly confronts the participants with his or her interpretation of what has been said earlier in order to clarify, correct, or negotiate the meaning. The second aspect concerns how investigator’s doing qualitative research engage in ‘an extended ‘dialogue’ with their texts (tapes, transcripts), which includes reading, conceptualizing, rereading, and reconceptualizing’ (p. 605). This empathy means that ‘interpretations change and evolve as they become infused with the observations’ (p. 605).
Grounding of Interpretations	In order for the reader to understand the linking between interpretations and the observations made, one needs selected text that is salient to the interpretations made during the iterative encounters with the material (cf. Hammer & Berland 2014). This concerns what often is referred to as ‘confirmability’ (Lincoln & Guba 1985). Interpretations are grounded in particular setting and contexts, based on observations that are difficult, if not impossible, to repeat exactly. Therefore, it is important to provide the reader with enough material to confirm the interpretations made through inspection of the data. However, this could be problematic as it could concern ethical issues, feasibility, or the type of data that is gathered.

cont.

Table 10.2. *Summary of strategies to ensure reliability in qualitative research (Stiles 1993, p. 602-607).*

Ask ‘What’, Not ‘Why’	It is important to ask questions that the participants can answer. In most cases, it is the investigator that should make the interpretations and not the participants. To avoid difficulties, it is important to ask the right questions. For example, when presented with a picture or video of something, people may not know why things are as they are presented, but they do know what they believe they see. Therefore, ‘what’-questions are better than ‘why’-questions: “What’ questions elicit material of which clients have direct knowledge. ‘Why’ questions often elicit half-baked theories or post hoc justifications for what clients think or do’ (p. 607, emphasis added). However, ‘why’-questions can be asked if there is an interest in peoples theories, believes, etc.
-----------------------	---

10.5.2 Validity of Qualitative Research

As in quantitative research, in interpretative research the ideas behind the notion of ‘validity’ are extremely important as they reflect whether or not ‘an interpretation is internally consistent, useful, robust, generalizable, or fruitful’ (Stiles 1993, p. 607). However, the literature dealing with validity in qualitative research is very diverse bringing out many different aspects. In Table 10.3 I summarise parts that are relevant for my thesis.

Table 10.3. *Summary of different types of validity issues in qualitative research.*

Triangulation	Most often this refers to looking at the ‘research approach from more than one perspective, theory, participant, method or analysis’ (Robson 2011, p. 553). There are different types of triangulation in qualitative research to ensure validity (Blanche et al. 2006): ‘data triangulation’ (use as many data sources as possible), ‘investigator triangulation’ (use as many researchers as possible in the analysis, also called confirmability (Lincoln & Guba 1985)), ‘theory triangulation’ (use multiple perspectives to interpret a single set of data), ‘methodological triangulation’ (use multiple methods to study a single problem), and ‘interdisciplinary triangulation’ (using finding in other disciplines to compare with).
Coherence	This refers to the apparent quality of the interpretation itself – ‘the ability to accommodate the answers to the questions of interest [...] and make then intelligible therein’ (Blanche et al. 2006, p. 383). It includes internal consistency, which refers to whether the interpretation is a casual one or not. ‘Coherence goes beyond simple matching of data with hypothesis to a resonance throughout a network of stated and implied understandings and values’ (Stiles 1993, p. 609). Thus, the ‘interpretation of a text or phenomenon/actor’s ‘thought’ must present a unified picture and not be contradictory’ (Butler 1998, p. 292).

cont.

Table 10.3. *Summary of different types of validity issues in qualitative research.*

Uncovering; Self-Evidence	In the process of evaluating interpretations it is important to ask if ones researcher questions have been answered.
Testimonial Validity	This refers to the ‘ability to demonstrate that the research was designed in a manner which accurately identified and described the phenomenon to be investigated’ (Robson 2011, p. 546). One way to achieve this is checking with the participants if ones interpretations accurately describes the experience the participants had. This is also referred to as credibility in the literature and can be addressed using e.g. triangulation (Blanche et al. 2006). However, if the data is in written text, it might not be possible to address this particular validity.
Consensus Among Researchers; Replication	This refers to the process of checking and cross checking interpretations with other researchers. This is similar to the ‘investigators triangulation’ mentioned earlier. Consensus can then be claimed ‘within a small but highly informed community’ (Stiles 1993, p. 612)
Reflexive Validity	‘Reflexive validity refers to how the theory – or the researcher’s forestructure or way of thinking – is changed by the data. The underlying notion is that interpretation is in a dialectical relationship with observation’ (Stiles 1993, p. 612). This is particularly clear in the iteration process, since the cyclical working back and forth with data should gradually change the interpretation. Again, this carries similarities to natural sciences where scientists usually work to elaborate or extend others work and understanding towards <i>paradigms</i> , instead of testing theories by trying to <i>falsify</i> them (Kuhn 1970).

In qualitative research, it is the researchers responsibility to seek and justify the constructs that they use to make a case for the quality of their research outcomes. This I do in the next section by first discussing some general issues regarding the quality control in the thesis and then give specific details of how reliability and validity are addressed in the thesis in relation to the issues raised in Tables 10.2 and 10.3.

10.6 On quality control in this thesis

As described earlier, I used an online survey as my data collection tool for the research reported on in my thesis. There are likely differences in how participants answer a question in a naturally occurring, contextually grounded conversation versus on an online survey. As such, my research design carries challenges associated with the reliability and the validity of the outcomes of the research. However, it was to some extent possible to avoid, or at least minimise, some of these challenges by situating the survey in a familiar context and discourse, and by using simple questions (cf. Robson 2011). I say this because there was no sign in the data or survey comments that any of the participants felt bored, distracted, unable to see relevance, or were generally uncomfortable with their engagement with the survey. The use of a simple layout and straightforward questions, and short simulation clips, made the survey accessible, understandable and interesting for all the participants. Furthermore, the quality and form of the data clearly indicated that all the participants understood what was being asked from them and that they took the task seriously and conscientiously. This indicates that there were few, if any research-disturbing ‘internal validity’ problems (cf. Robson 2011).

There was, however, one issue that could have affected the reliability of my data. It concerned to what extent the participants felt a high degree of authentic involvement in the research endeavour. This is a well-known issue when surveys are used for data collection (Robson 2011), and maybe more so in the case of online surveys. As such, the issue could be seen as introducing a limitation to my research. Furthermore, the length of the survey and the time it took on average to complete could have been an issue. However, I could not find any trace of these issues in the data or survey comments.

To address the idea of generalisability as a quality construct for qualitative research, I am drawing on the work of Stake and Trumbull (for example, Stake & Trumbull 1982), who introduced the idea of ‘naturalistic generalization’. They do this by arguing that generalizability comes from studies being ‘planned and carried out in such a way as to provide a maximum of vicarious experience to the readers who may then intuitively combine this with their previous experiences’ (p. 1). I have done this in this thesis by providing extensive detail of the planning, method, the analysis and the results obtained. To complete this ‘thick description’ (Geertz 1973), I need to add some further detail about the participants and how they responded to the study: my research design called for a ‘purposeful sampling’ (for example, see Patton 2002), which is essentially a non-random sampling approach aimed at accessing a specific group in order to obtain the ‘information-rich data’ that is envisaged as being

of central importance in the research aim. In my study, the desired ‘sampling’ outcome was difficult to directly ‘control’. This is because I had no direct selection avenue available to me regarding exactly which students and which faculty ended up taking the survey. Therefore, the ‘sampling’ could be considered to contain both purposeful and random aspects. However, the ‘sampling frame’ (Robson 2011, p. 261) for my study was defined in terms of students and faculty situated in university level astronomy/physics. I aimed at getting at least 100 participants and ended up with 137. Their personal profiles ranged from novice to expert and their educational contexts were spread across nine countries around the world. The encouragement to participate came from influential leaders in these contexts who explained the ‘what and why’ of my research to the potential participants in their particular educational setting. This ‘sampling’ provided me with extremely rich and useful data. This means that both the engagement with the survey and the spread in the participants’ background, particularly educational level, turned out to be very good for the purpose of my study. In the data I collected I could not detect any traces of difference between the participants as functions of educational settings, or gender.

10.6.1 On the reliability of this study

I will now address detailed issues concerning reliability, or procedural trustworthiness by referring to those presented in Table 10.2.

Starting with the issue of ‘Disclosure of Orientation’, I recognized that how I chose to collect the data – through an online – could potentially create some limited possibilities for directing the data collection. Once the survey was piloted and the final design obtained then I asked my contacts to bring it to the attention of the purposeful sample of students and colleagues that I wanted to take the survey. After this I could only wait for the data to arrive in the database and hope that everything worked as I wanted it to. No problems arose here.

On the issue of ‘Explication of social and cultural context’, I recognized the importance of my background as an astronomer and as an astronomy teacher for how the study was designed, how the data was collected and how it was analysed. I argue that it was my strengths in these areas that were critical for the success of my research. This was partially because it required a disciplinary expert to find the appropriate simulation to use and to appreciate how it could be used for obtaining high quality data from a ‘purposefully sampled’ set of participants.

‘Progressive subjectivity’ acknowledges that the data might have affected my analysis. However, I would argue that through the extensive piloting that formed an integral part of developing the survey, the possible progressive subjectivity became very limited. There was one aspect that I found in the data that did surprise me and did initially start to influence me. This was finding how little disciplinary knowledge some participants used in their discernment descriptions. This made me think about the importance of how we educate our astronomy students and how poor this education could be. It was this negative feeling that at first crept into my manual analysis and it took a lot of effort initially to distance myself from this negative evaluation mindset. This quickly became easy when the analysis of this data led to the emergence of a baseline category that was outside of my disciplinary discernment categories. This issue also formed part of the possible danger of becoming too engaged with the data. Once I had overcome the progressive subjectivity issue, I found that my personal background enabled me to lift the data out of such restraints as I found myself becoming increasingly analytic and less evaluative.

Concerning the issue of ‘iteration of interpretation’ in the data analysis, the ethical guarantees of anonymity created almost no possibility to come back to the participants to discuss my analysis with them. However, I was able to do this in my piloting stages and found that no analytic issues arose in my discussion with those participants.

For the ‘Grounding of interpretations’, I believe that I have provided sufficient illustrative analysis and information on how I have come to my reported conclusions for a reader to come to appreciate my engagement with the data. This is done both in my thesis and in Papers II and III. I thus would argue that the grounding of the interpretations I have made are both substantial and clear.

Finally, when addressing the reliability of the data from the perspective of ‘asking the right type of questions’, I followed the guidelines in the literature and asked specifically for ‘what’ the participants discerned and not ‘why’ they did so. It was then my job as a researcher to interpret the participants’ descriptions of discernment.

10.6.2 On the validity of this thesis

Deliberation on whether the interpretations and results from this study can be effectively argued to be ‘internally consistent, useful, robust, generalizable, or fruitful’ (Stiles 1993, p. 607) was my central validity concern. To make a case that I had achieved the needed validity as it applied in my qualitative research studies, I looked at the different issues outlined in Table 10.3 when giving consideration to my research design and the analysis of my data. For example,

I used ‘investigator triangulation’ to validate the coding, (sub-)categories and themes. In order to enhance the confirmability four independent researchers were asked to examine subsets of the data for consistency. Different cases were cross-checked and discussed amongst the researchers until agreement was reached about the coding process for the (sub)categories and themes. ‘Coherence’ was addressed by continuously checking the interpretations made with the original data. The emerging categories and themes were discussed and were found not to be contradictory but to present unified interpretations of the expressed meanings in the data. Also, the interpretations made were continuously checked against the research questions for Paper II and Paper III. ‘Testimonial validity’ (credibility) turned out to be a difficult issue to substantially address because the data came in written text from an online survey. One of the reviewers for Paper II raised the issue of my apparent willingness to ‘trust’ the authenticity of the descriptions of discernment that were given by the participants. My response to the journal editor was that while it was possible that some of the descriptions I received were not authentic this was not evident in any of the data or survey comments and none of the categories formed could be related directly to any particular data source. And since it was unlikely that similar deceptions were being constructed across nine educational settings I treated the data descriptions as being authentic (Robson 2011; Stansfield 1976). Also during the piloting procedures, the responses from the participants involved in the piloting were used to refine the research design and survey. The different recommendations in the literature (e.g. Robson 2011) were also taken into account. I believe that these efforts made the study credible with regards to the outcomes obtained. Finally, in considering ‘reflexive validity’, I started the analysis with an open mind. I purposefully entered the process without any pre-defined categories or themes in mind that could have directed my analysis in any particular direction. These emerged from the data analysis.

In conclusion, from all of what I have discussed regarding quality issues, I argue that the trustworthiness quality requirements have been well met.

10.7 Ethical considerations related to this thesis

The ethical considerations that are called for in educational research are governed by both national and international laws, regulations, and guidelines. A collection of resources concerning ethical considerations can be found at the web page CODEX¹. For example, the ‘Code of conduct for social science

¹<http://www.codex.uu.se/index.shtml>

research' by UNESCO (de Guchteneire 2006) has an excellent set of suggested guidelines for protecting the individual when conducting social science research. Many countries have developed their own versions of ethical considerations related to different research areas. When doing research 'on people' in 'educational science' contexts, the Swedish Government has published regulations to protect the individual. For my study, one of the most important is the 'Personuppgiftslagen' (PUL), which is about what information concerning individual citizens gets made available for others to use. There are other Swedish ethical guidelines to take note of when doing research in education contexts. For example, researchers in such contexts must follow 'The Act concerning the Ethical Review of Research Involving Humans (2003:460)' (The Ministry of Education and Cultural Affairs 2003). Here, there are rules that must be applied for all research done on individuals. I have taken cognizance of all of these in my research. In particular I gave attention to:

- the overall plan for the research
 - the purpose of the research
 - the methods that will be used
 - the consequences and risks that the research might entail
 - the identity of the responsible research body
 - the fact that participation in the research is voluntary, and
 - the right of the research subject to cease participating at any time
- (The Ministry of Education and Cultural Affairs 2003, §16)

The actual survey included a consent form (given in Appendix B) that explained what this study was about and how I intended to follow the regulations. If the participants accepted these conditions they were asked to click on the 'accept' button before they could start taking the survey. The complete consent detail is given.

As stated in the form, the data that I gathered was treated confidentially and no identifying features were used in any publications, presentations, etc. I alone have access to the code key that could identify personal aspects of a participant. No details of even the particular universities where the participants studied or worked has been provided. Finally, following Kalleberg et al. (2010, §8 and §10), more 'delicate issues' were also given consideration. For example, using the Internet as a way to collect data could possibly allow the data, or parts of it, to be searched for using different search engines, and then used. This would not be acceptable from an ethical perspective and therefore I chose a survey tool that is not 'searchable' over the Internet. Also, Internet users often use pseudonyms for their identity on Internet and therefore, even

if a participant used an obvious pseudonym or nickname, I still changed it to something else so that it could not be traced back to a particular participant.

Through the above, I believe that I have taken into account all ethical considerations to protect the participants.

11. Results – Challenges in learning astronomy

In this chapter I briefly summarise Papers II and III in order to highlight the most significant aspects of my results. These are important because they constitute the foundation for how I propose a new model for the teaching and learning astronomy based on learning to extrapolate three dimensionality and on achieving competence in disciplinary discernment.

11.1 Who needs 3D when the Universe is flat? – Learning to extrapolate three-dimensionality

As is evident from my literature review (Chapter 8), there is a great deal of literature showing a multiplicity of learning challenges that physics and astronomy present to students. In astronomy, a significant challenge revolves around learning to extrapolate three dimensionality as part of coming to understand the 3D structure of the Universe. Hence, the aim of Paper II was to explore the development of the ability to extrapolate three-dimensionality by analysing what astronomy/physics students and teaching professors discerned when engaging with a simulated video fly-through of our galaxy and beyond. The analysis involved investigating, describing and comparing the ability of students and teaching professors to extrapolate from two-dimensional visual input to the three-dimensional Universe. This ability is considered by many to be central to the learning of astronomy; however, very little research exists to support this claim (Heyer et al. 2013). The basic problem is that people do not have the ability in their surrounding landscape to determine distances by visual means for distances larger than a few kilometres. When looking up at the sky, the ability to directly determine distances and hence get an appreciation of the three-dimensionality of what is seen is completely lost in the sense that it is not directly possible. This is due to: 1) the astronomical distances involved, and 2) the lack of familiar cues to support distance determination.

However, it is possible to offer experiences that could potentially help students to begin to appreciate the 3D nature of the night sky by using simulations in combination with the needed motion parallax. In Paper II, I therefore set

out to capture the kinds of meaning that a purposeful selection of participants generated from what they noticed (discerned) of multidimensionality when watching a simulation that offered extensive experience of motion parallax. The following research questions guided me in this task (these are given as Research Questions (2a) and (2b) in Chapters 7 and 10 of the thesis):

2. a) In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?
- b) What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?

As described in the Methodology chapter, an on-line survey was developed and the data that was collected through the survey (137 participants) was analysed using an interpretative-hermeneutic approach. The analysis was broadly thematized in two ways. Firstly, in terms of what was noticed, and secondly, in terms of what meaning that noticing generated, both as a function of multidimensionality. Table 11.1 (similar to Table 2 in Paper II) details the six categories, which are characterized in terms of *Advances three-dimensionality awareness*, *Growth of three-dimensionality awareness*, *Emergence of three-dimensionality awareness*, *Relative size awareness*, *Distance contemplation*, and *Motion identification*. Table 11.1 also provides detail of the analytic parts underpinning the construction of the six outcome categories and their respective boundary conditions. Thus, Table 11.1 also illustrates: 1) the noticing and meaning that underpins the categories, 2) the central characteristics these categories capture, and 3) characteristic contemplation questions that are addressed. These six categories have distinctive connections to multidimensionality and I propose a hierarchy to describe this, see Table 11.2 or Table 3 in Paper II).

The proposed hierarchy of multidimensionality was constructed out of the content of the discernment descriptions. There were two aspects to this, the disciplinary content and the direct and indirect dimensionality content. Examples of the disciplinary content include stars and galaxies, astrophysical constructs, and recognition and naming. Such discernment is further addressed in Paper III. Examples of dimensionality content include descriptions embedded in flat, extended objects and descriptions embedded in attributes of higher domains of dimensionality, for example, curvature attributes. The six categories could be clustered into three groups as a function of one-to three-dimensionality. All of the categories, except the baseline *Motion identification* category, are embedded in disciplinarity; thus, I have called them categories of

disciplinary discernment. The characteristics of both these categories and dimensionality clusters are described in detail in Paper II (p. 424-431), together with illustrative descriptions from the participants.

Although the discernment related to the one and two-dimensionality clustering is interesting in itself, the focus for this thesis has been on the three-dimensionality cluster. This is because I believe that the ability to discern three-dimensionality is crucial for achieving a holistic understanding of the Universe and it is thus a necessary attribute for my concept of *Reading the Sky* (see Section 12.2). An example of the importance of three-dimensionality extrapolation in astronomy given by Merali (2013).

‘In a higher-dimensional universe, a black hole could have a three-dimensional event horizon, which could spawn a whole new universe as it forms . . . the event horizon of a 4D black hole would be a 3D object – a shape called a hypersphere.’
(p.1)

11.1.1 Research Question 2(a): In terms of dimensionality, what do astronomy/physics students and professors discern when engaging with a simulated video fly-through of our galaxy and beyond?

In answering Research Question (2a) I found that the ability to extrapolate three-dimensionality varied with the broad educational levels that I had chosen to ‘sample’, see Figure 11.1 (similar to Figure 5 in Paper II). The trend was very clear: there was a steady increase in the descriptions of three-dimensional discernment across educational levels, from undergraduate study to graduate study to teaching professor. I interpret this as evidence that the ability to extrapolate three-dimensionality is linked to educational level. Put simply, approximately half of the first-year undergraduate students made no reference to three-dimensional discernment. The results also show that the ability to extrapolate three-dimensionality increases rather slowly with increasing educational level. This suggests that meeting the challenge of developing the ability to extrapolate three-dimensionality requires much longer engagement than the literature has suggested to date (cf. Cohen & Hegarty 2014; Hegarty et al. 2007; Hegarty 2014; Plummer 2014; Tversky et al. 2002; Uttal et al. 2013). My results indicate that without teaching and learning insight and purposeful curriculum design it may take several years for astronomy students to develop this ability (see my discussion in Paper III).

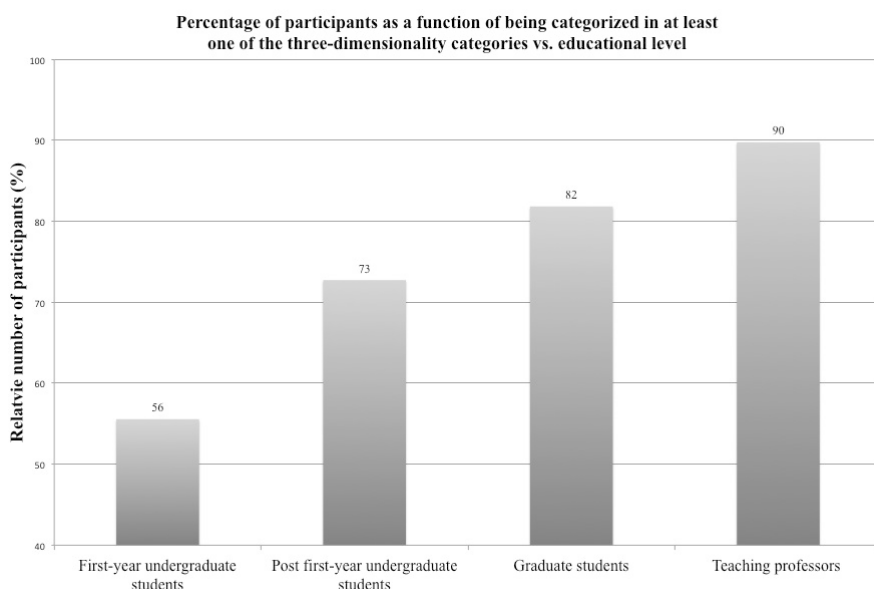


Figure 11.1. Discernment related to three-dimensionality for the different groups of participants.

I also found interesting differences between what the students and teaching professors discerned in terms of three-dimensionality. The three-dimensional cluster contains three distinct categories, but it was not common to find descriptions that belonged to all three categories in the first-year undergraduate group (see Figure 11.1). They focused much of their attention on non-disciplinary characteristics; discernment related to the more disciplinary sophisticated categories – *Emergence of three-dimensionality awareness* and *Advanced three-dimensionality awareness* – was largely missing. What was most accessible for all participants was discernment that related to the *Growth of three-dimensionality awareness* category, which is also closely related to the role motion parallax plays in creating such awareness. To explore this further, I compared the relative number of participants in each category and found that these two categories stood out from the rest: *Motion identification* and *Growth of three-dimensionality awareness*, see Figure 11.2 (or Figure 6 in Paper II). Since the details for these categories cannot be discerned without the motion parallax that is offered by the simulation, I propose that three-dimensional discernment is strongly influenced by the participants' level of physics/astronomy education.

When students start their university education in astronomy, given the parallax experience needed to extrapolate dimensionality, the majority appear to

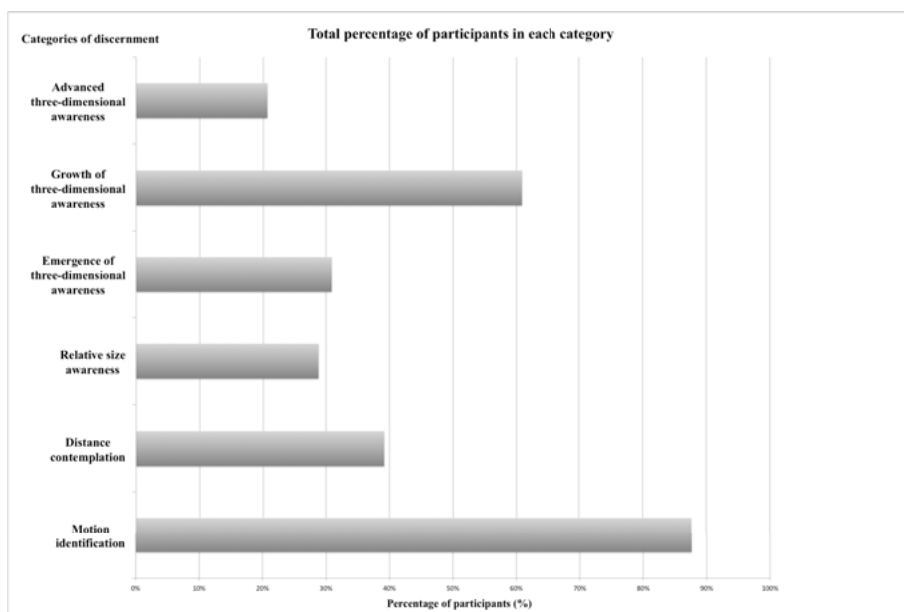


Figure 11.2. Total percentage of participants in each discernment category.

have not yet developed sufficient disciplinary knowledge to be able enable them to effectively discern three-dimensionality related beyond the growth stage shown in Figure 11.2. Thus, as their disciplinary knowledge increases, they need to be simultaneously learning to extrapolate (cf. Barnett et al. 2005; Hansen et al. 2004a,b; Hegarty 2014; Joseph 2011; Parker & Heywood 1998; Plummer 2014; Sorby 2009).

Extrapolating three-dimensionality could be referred to as an ability that is part of spatial thinking. It refers to the ability to extrapolate depth, and hence project the 3D nature of something from a visual 2D input, which could be either presented in static manner (such as an image of a nebula) or dynamically (through, for example, a simulation). These visual inputs have been referred to as visualisations (see, for example, Gilbert 2008; Latour 1986; Ramadas 2009; Uttal & O'Doherty 2008). From this perspective, visualisations are representations that 'highlight the portions of the information that the designer intends for the learner to see and hence support both learning among novices and new discoveries among experts. They allow us to perceive, and to think about, relations among items that would be difficult to comprehend otherwise' (Uttal & O'Doherty 2008, p. 53). However, visualizations '[do] not guarantee that a student will comprehend the intended relationship between the 'visualization' and what it stands for (the referent)' (Uttal & O'Doherty 2008, p. 54). The results from Paper II, that illustrate how students and teaching professors

do not discern the same things from an identical set of visualisations, clearly confirm these difficulties.

Earlier, in Section 8.4.2, I introduced the idea of *dynamic* spatial ability (Hunt et al. 1988; Law et al. 1993; D'Oliveira 2004), which involves the ability to handle moving elements, relative velocities and distance judgements. My view of extrapolating three-dimensionality includes more than is generally attributed to dynamic spatial ability: specific disciplinary knowledge about basic attributes such as size, shape, texture, and distance and an understanding of how these can be represented is also included.

In Chapter 8 I discussed how the National Research Council (2006) made a case that the 'key to spatial thinking is a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning' (p. 5), this coincides with what I have found to be important for extrapolating three-dimensionality. The first concept, space itself, primarily carries similarities to my categories *Motion identification*, *Distance contemplation*, and *Growth of three-dimensionality*, since it involves distance estimates. The second concept, representations, carries similarities to *Relative size awareness* and *Emergence of three-dimensionality* as it involves relationships within and amongst astronomical objects and how they are represented and located in space. The last concept focuses on reasoning and is a demanding task. It needs to involve disciplinary knowledge and, when combining this with the other concepts, carries similarities to the most advanced category in my hierarchy, the *Advanced three-dimensionality* category.

11.1.2 Research Question 2(b): What can this discernment reveal about the ability to extrapolate three-dimensionality in terms of broad educational levels?

As discussed earlier, the ability to extrapolate three-dimensionality, as part of spatial thinking, is important for the effective learning of astronomy. Therefore, I suggest that it must become an integral part of astronomy education.

My results from Paper II show that traditional astronomy education eventually does enable disciplinary discernment and the emergence of three-dimensionality awareness (evidenced by most professors and many of the graduate students in my study). Drawing on these results and the work of Airey & Linder (2009), I propose that it would be fruitful for teachers of astronomy to see effective learning in their classrooms in terms of becoming 'fluent' in the disciplinary discourse of astronomy and part of achieving such fluency calls for hands-on experiences with representations (visualisations) of parts of the Universe.

So, I argue that what is needed is much more than just sharing the needed disciplinary knowledge with students. Rather, what is required is the construction and enactment of meaningful scaffolding experiences to enhance developing the ability to extrapolate three-dimensionality. The situation becomes more complicated when one considers that these educational experiences are largely missing from astronomy education resources available today. Different experiences that incorporate physical models and simulations are needed to extend discernment possibilities (see Table 11.2). These include simulated travelling that can generate the motion parallax needed to create experiences that facilitate extrapolating three-dimensionality. Students would then be given the opportunity to appropriately discern the needed disciplinary knowledge.

Thus, my categories of disciplinary discernment offer a distinct potential for optimising learning and I suggest that using my categories presents a useful tool to evaluate simulations and to find out where students are in their three-dimensionality awareness at any given time (cf. Ausubel et al. 1978).

11.2 The Anatomy of Disciplinary Discernment

The results reported on in Section 11.1 (and Paper II) and complementary research that I carried out (see my list of conference presentations given at the start of my thesis), indicated that simulations have unique potentials for teaching and learning in astronomy because of their ability to make information on the three-dimensional nature of the universe available to students. Building on this, it became an insightful exercise to explore the disciplinary discernment reported on by university astronomy/physics students (whom can be thought of as novices) and lecturers (whom can be thought of as experts) when engaging with the same highly regarded educational simulation. The following research questions guided me in this task. These are taken from Paper III and are given as Research Questions (3a) and (3b) in Chapters 7 and 10 of the thesis:

3. a) What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?
- b) How can this discernment be characterized from an educational perspective?

Before proceeding to a discussion of these two research questions I need to discuss some general aspects from Papers II and III even though this will result in some necessary repetition.

I define *disciplinary discernment* in Paper II as: *noticing something* (Lindgren & Schwartz 2009; Mason 2002), *reflecting on it* (Dewey 1997; Schön 1983), and *constructing meaning* (Marton & Booth 1997) from a *disciplinary perspective*. This construct is central for all of my thesis work, and in Paper III (p. 168-170) I revisit the concept (see also Chapter 9) to expand on it as part of my creating my Anatomy of Disciplinary Discernment taxonomy. The essence of the ADD is learning to focus discernment only on those things that are seen as being relevant by the discipline; put simply, students need to learn what is important and what is not important for the discipline in a given situation (Lindgren & Schwartz 2009). Making this distinction ‘visible’ to students can be accomplished through the Variation Theory of Learning (Ling 2011; Marton & Booth 1997; Marton & Tsui 2004; Marton 2014). Variation theory claims that in order to discern, people need exposure to experiences of appropriate patterns of variation set against a background of sameness. In teaching, such experiences are considered what is necessary to enable people to discern more in a given situation, and hence to begin to develop professional vision (Goodwin 1994). Being able to make such discernment needs both disciplinary knowledge and experiences, and can be referred to in terms of achieving disciplinary competence, and my Anatomy of Disciplinary Discernment from Paper III (see Figure 11.3) can be used to effectively describe it. This process characterises the kind of changes in thinking about learning (cf. Mason 2002) that become the ‘seeds’ needed to construct new meaning from new educational experiences, or re-constructing earlier experiences to make sense of them in new, more disciplinary appropriate, ways (Marton & Booth 1997).

The purpose of Paper III was to study a particular competence important for education in general, but for physics and astronomy in particular, namely what students and lecturers discern from the same disciplinary semiotic resource. Lecturers often assume that their students ‘see’ the same things that they ‘see’ in a representation Northedge (2002), but my research has vividly illustrated I find how this is not the case. The results of my research led me to propose the notion of an Anatomy of Disciplinary Discernment (ADD) – see Figure 11.3 – as an overarching fundamental aspect of disciplinary learning that is a function of disciplinary representations. The ADD is a hierarchy of what is focused on and how that gets interpreted in an appropriately disciplinary manner. I also use my results to go on to propose that the ADD could be used to assess student competence development in a powerful new way. In so doing I claim that the most important roll of the teacher should be thought of in terms of helping students by educational design and practice to move across the levels in the ADD (see Figure 11.5, or Figure 2 in Paper III).

For students entering a new discipline, the appropriate disciplinary interpretation of any given representation is often largely inaccessible (Linder 2013). Here, with its many disciplinary-specific representations, astronomy is found to stand out as a particularly challenging discipline for students. In the literature it has been claimed that simulations have the potential to provide a unique way of representing certain aspects of astronomy to promote learning. I therefore chose to investigate what astronomy students and lecturers discern from one a simulation video that vividly represents many different astronomical objects and processes as one moves through the Milky Way galaxy and beyond.

I now turn to answering the research questions 3(a) and 3(b). To answer these, data was collected and analysed using the method described in the earlier in the Methodology chapter (10) and also in detail in Papers II and III. The method is not repeated here, however, I need to point out the small change that took place for Paper III where a slightly different structure of the ‘purposeful sample’ was created. I decided to combine the two earlier groupings, ‘Introductory students’ and ‘First-year undergraduate students’, into one large group of first-year undergraduate students. I did this because the students in these two groups reported similar discernment and hence the analysis yielded identical categories for both.

11.2.1 Research Question 3(a): What is the discernment reported by university students and lecturers of astronomy when they engage with the same disciplinary representations?

For the question 3(a) five categories emerged from my analysis. These categories characterized the discernment reported by the participants. The categories were found to be hierarchically ordered in what I came to call the *Anatomy of Disciplinary Discernment* (ADD). From Paper III, I now repeat the five categories.

Non-disciplinary Discernment

Discernment is here restricted to noticing different disciplinary representations presented in the simulation, but usually without being able to identify what they are. Typically this noticing comes with questions such as ‘What is that?’. As such, no disciplinary knowledge can be traced back to the noticing, the participants’ attention is simply caught by the representation. Thus, this category functions as a pre-entry level, forming the baseline category for any discernment.

Disciplinary Identification

Discernment at this level involves naming, or recognising, the most salient disciplinary objects in the representation and represents the first sign of disciplinary discernment. The category involves the identification of parts and distinguishing what these are from a disciplinary perspective. If a representation is associated with a name, there must be some meaning connected to that name. The noticing starts to shift from a questioning ‘What is that?’ to a declarative ‘That is...’. From my astronomy perspective this category reveals reflective awareness of the sameness and differences (Marton & Booth 1997) in the structural components of the Universe and how these are represented in the simulation clips.

Disciplinary Explanation Discernment at this level involves explaining or assigning disciplinary meaning to the disciplinary objects that have been discerned, i.e., ‘discovering’ the disciplinary affordances¹ of the representations. This category reflects a transition from the ‘What’ perspective towards a ‘Why’ perspective. The category is characterized by the use of disciplinary knowledge in order to interpret what is seen in terms of astronomical properties and astrophysical processes. It therefore represents a major step in disciplinary discernment, where disciplinary knowledge is used to interpret the different representations to construct an understanding of why things appear as they do in the simulation. The disciplinary affordances of representations are thus beginning to be ‘discovered’ by the participants.

Disciplinary Appreciation In this category, discernment involves analysing and acknowledging the value and appropriacy of the disciplinary affordances of the representation. It reflects a more advanced level of disciplinary discernment because it entails a bringing together of all the previous categories in order to generate a more holistic view of the galaxy. In my study the category includes the bringing together of different representations of stellar objects and how they work at different levels of detail, i.e., discerning the representations of the ‘parts’, and what these are intended to afford, and bringing them together for an understanding of the ‘whole’ and vice versa. This calls for the ability to discern and analyse the disciplinary affordances of the representations at all levels. Such ability makes it possible to appreciate the simulation in different ways.

¹Here I use the Fredlund et al. (2012) definition of disciplinary affordance of a given representation: ‘the inherent potential of that representation to provide access to disciplinary knowledge. Thus, it is these disciplinary affordances that enable certain representations to become legitimate within a discipline such as physics’ (p. 658). The ADD encapsulates the increasing complexity of the intended meaning of representations – a representation’s disciplinary affordance.

Disciplinary Evaluation This category characterises the most advanced level of disciplinary discernment that I identified. The discernment involves analysing and critiquing the representation used for an intended affordance through an identification of the limitations in a given representation. Such critique can involve both positive and negative aspects. This kind of discernment demands high levels of disciplinary knowledge along with an understanding of the pedagogical value of the resource in the teaching of the discipline.

This brings me to an additional comment on the ADD: the categories in the ADD can be seen as being a hierarchy of the discernment that characterizes the ways in which the disciplinary affordances of a given representation may be discerned, see Figure 11.3. This discernment involves accessing disciplinary knowledge to assign meaning to a representation. Therefore, disciplinary knowledge can be said to be the decisive factor for disciplinary discernment. The unit of analysis for the ADD is thus *the discernment of disciplinary affordances of the representations*. One would expect that the higher the educational level the more the disciplinary discernment, which is what I found in my data, see Figure 11.4 (or Figure 1 in Paper III).

11.2.2 Research Question 3(b): How can this discernment be characterized from an educational perspective?

My ADD can be used to contribute to a new educational perspective for AER. I propose that by combining the ADD with Bruner's (1960) 'Spiral curriculum' idea, and Hattie's (2009; 2012) idea of 'Visible learning', important ways of improving the teaching and learning astronomy can be suggested.

Bruner's 'Spiral curriculum' idea involves information being structured so that complex ideas can be taught at a simplified level first, and then re-visited at more complex levels later on. However, Bruner's idea does not address how this could be achieved for a complex subject such as astronomy. By taking the 'spiral' idea and combining it with the ADD, I propose that a way to achieve this is to see learning as the growth into the discipline, see Figure 11.5. For each turn in the spiral, the student's disciplinary discernment would ideally cross a category boundary and move to the next level of the ADD. This takes place alongside the disciplinary knowledge increasing through successful learning. As such, the proposed framework provides a model for how to organise teaching and how to help students to construct new knowledge. Essentially this involves providing the students with opportunities to 'discover' the disciplinary way of organising and categorizing things rather than just being given the ways by teachers. Guided by disciplinary knowledge, framed as concepts acquired in different contexts, and transferred to new contexts, dis-

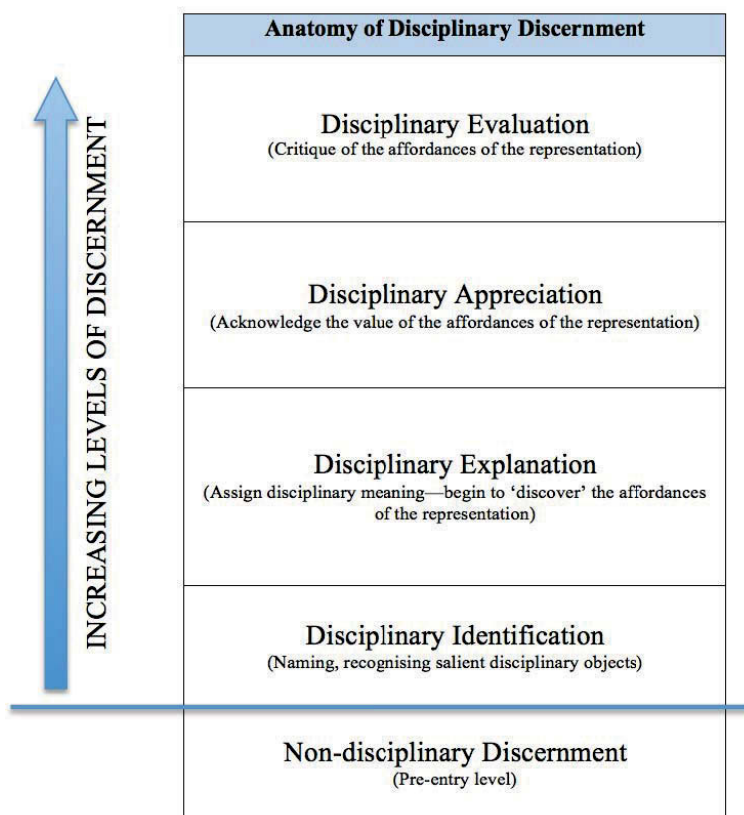


Figure 11.3. The Anatomy of Disciplinary Discernment.

disciplinary discernment from representations enacts meaningful learning. The power of this kind of learning is that it can be used to create a deeper, more holistic, expert-like, understanding of the Universe (cf. Bruner 1961).

The ADD is a framework describing *what* and *how* different disciplinary representations should be discerned in a disciplinary manner. Here, I find it useful to frame disciplinary discernment in terms of ‘competence’. The reason for this is that the ADD can be used to describe the differences between students (‘novices’) and lecturers (‘experts’) in terms of disciplinary discernment².

²See the definition of ‘novice’ and ‘expert’ in Bryce & Blown (2012b, p. 554)

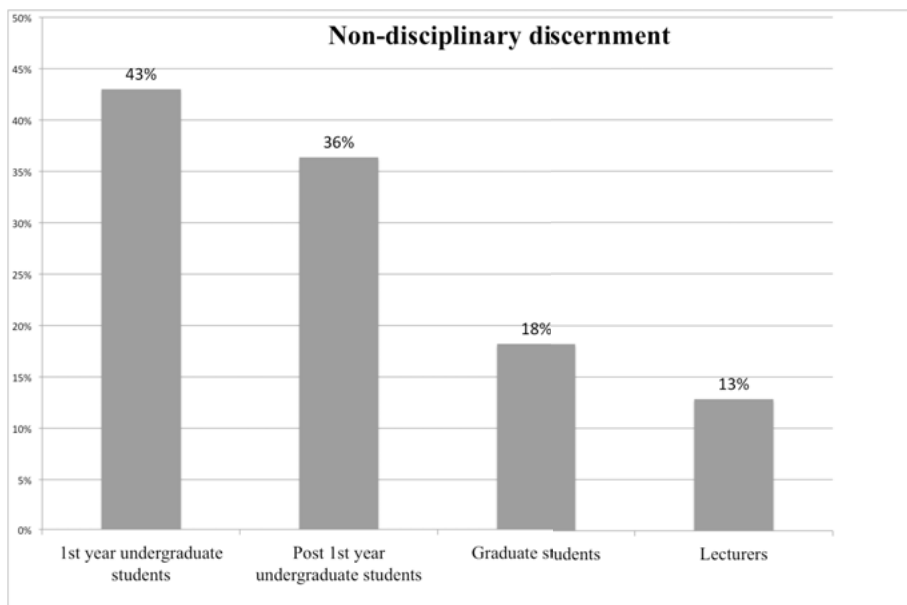


Figure 11.4. The percentages of participants who provided descriptions of discernment, illustrating how less attention gets paid to non-disciplinary characteristics as the education level increases.

Disciplinary experts have developed competences in applying different strategies to interpret discerned details from different representations (Ertmer & Newby 1996), and these experts have hence developed competence similar to Goodwin's (1994) 'professional vision'. The disciplinary experts are 'sensitivity to patterns of meaningful information that are not available to novices' (p. 33 Bransford et al. 2000). The disciplinary experts can both evaluate and criticise representations in a relatively unproblematic manner (Eberbach & Crowley 2009; Schneider & Shiffrin 1977), whereas the students often focus on the 'wrong things'. This can be clearly seen in the results presented in Paper III and shown in Figure 11.4.

Differences in what novices and experts discern from disciplinary-specific representations in the astronomy discourse have been widely studied in AER. One common conclusion has been that novices and experts discern very different things in those representations (see, for example, Bryce & Blown 2012b; Sadler 1996; Uttal & O'Doherty 2008; Eberbach & Crowley 2009). 'To the expert user or professor, the intended purpose of the 'visualization' [including many representations], and its relation to the referent, is obvious. [...] But to novices, the relations that are so obvious to the expert, may be totally opaque' (Uttal & O'Doherty 2008, p.55). In fact, it is often found that

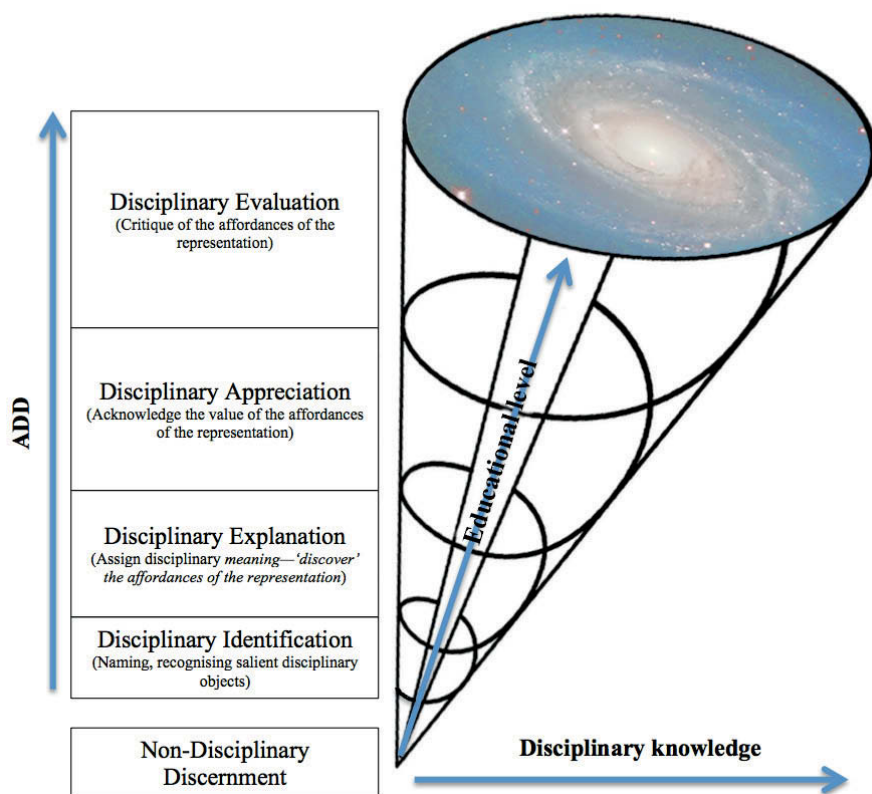


Figure 11.5. Merging the Anatomy of Disciplinary Discernment and the Spiral curriculum. Through the iterative revisiting of different material, disciplinary knowledge increases (illustrated by the width of the spiral) together with the ability to discern disciplinary affordances of representations. This reflects the movement upward through the proposed levels of the ADD.

disciplinary experts have lost the ability to see things as students might see them (Bransford et al. 2000), and do not even ‘recall their [own] prior, non-scientific conceptual frameworks’ (Sadler 1996, p.56). By learning to discern critical features in representations, a novice can eventually become an expert (cf. Podolefsky & Finkelstein 2008). Using the ADD to frame their teaching could help experts to pay attention to the students’ competence in discerning disciplinary-specific representations, and thereby increase the students’ disciplinary knowledge (Linder et al. 2014). Let me give an illustrative example of this process: A friend who has lived most of his life in the Southern Hemisphere points to a group of stars in the night sky which he, throughout his whole life, has believed to be the Southern Cross. A disciplinary expert (an astronomer) from the northern hemisphere, who is with him at the time and

who has never seen the Southern Hemisphere night sky before, quickly discerns that what is being pointed to is the incorrect set of stars. The astronomer proceeds to point to the correct group of stars and gives a comprehensive explanation that enables a new informed disciplinary discernment.

To highlight the complexity of the challenge involved in achieving competence in disciplinary discernment, I give the following example: In the discourse of astronomy and stellar astrophysics, one of the most common disciplinary-specific representations is the Hertzsprung-Russel (HR) diagram, which includes much disciplinary-specific information and knowledge, both ‘presented’ and ‘appresented’ (Linder 2013), see, for example Figure 11.6 taken from Part I of my thesis. The disciplinary affordances of this particular representation are extensive (Airey & Eriksson 2014a). To interpret and understand the HR-diagram, the students need to be discursively fluent in many parts of the astronomy discourse (obviously, this representation has little meaning for anyone outside the discipline).

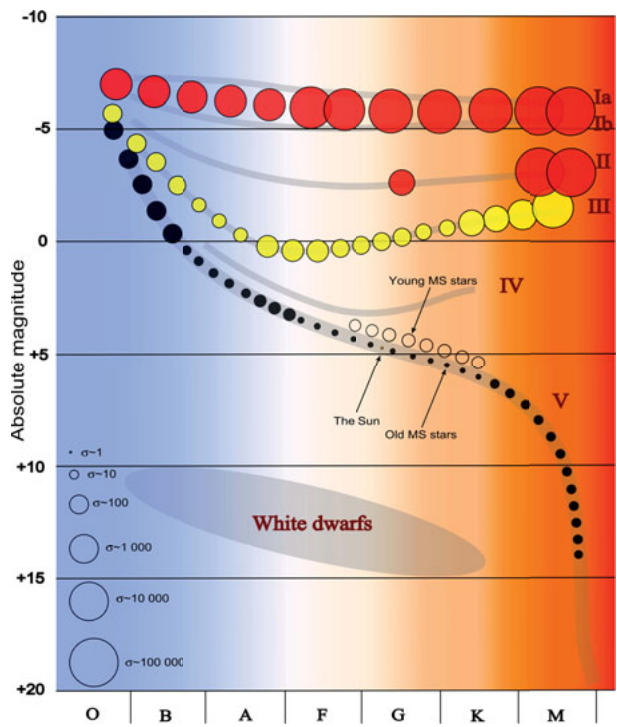


Figure 11.6. Illustrative example of an HR-diagram representing the astrometric RMS dispersion (σ_{pos}) in different sub-groups of spectral and luminosity classes. The diameters of the circles are proportional to $\log \sigma_{pos}$ and data are from Eriksson & Lindegren (2007). The dispersions are in μAU .

However, I believe that it is a teacher's responsibility to provide the scaffolding to increase the students' disciplinary discernment. Here, Hattie's ideas of visible learning becomes useful: 'It is teachers seeing learning through the eyes of students [and,] the greatest effects on student learning occurs when teachers become learners of their own teaching, and when students become their own teachers' (Hattie 2012, p. 14). So, by being aware of the ADD and its levels, the spiral curriculum concept, and visible learning, the role of the teacher is to *help students cross category boundaries in the ADD*. Teachers need to find out where their students are in the ADD (cf. Ausubel et al. 1978) and then guide them to move through each step in the 'ladder', starting at the bottom with everyday noticing and motion identification where their attention is being caught (Eberbach & Crowley 2009), and then moving towards increased disciplinary discernment following each step in the ADD. It is only then that a student can truly be empowered to grow in the discourse of astronomy. Thus, modelling of the role of the teacher as one of increasing disciplinary knowledge by facilitating boundary crossing in the Anatomy of Disciplinary Discernment as part of making learning 'visible' in astronomy, is a major contribution of the work presented in this thesis and provides an answer to Research Question 3(b).

Table 11.1. *Analytic parts underpinning the construction of the outcome categories and their respective boundary conditions.*

Category	Discernment detail		Central manifestation characteristics	Contemplation questions that they ask...
	What is noticed?	What meaning is assigned?		
Advanced three-dimensionality awareness	The 3D structure of different objects and how these are displayed and change due to the motion parallax.	An awareness of what the motion parallax does to reveal the 3D structure of different objects, revealing a holistic understanding of the three-dimensionality of the universe.	Macroscale three-dimensionality	Would the universe really look like this? I don't think so . . .
Growth of three-dimensionality awareness	Change of the looks of objects and constellations due to motion parallax, or thought on what this motion does for the way the objects look.	The motion parallax affects the position and shape of different objects due to the spatial distribution of the objects	Reflective musing	If I was looking from another position, how would the object look?
Emergence of three-dimensionality awareness	The internal and external structure of different astronomical objects	Astronomical objects have detailed internal and external structures and properties, including depth to some extent.	Seeing smaller parts within bigger parts. Microscale three-dimensionality	I wonder what that object is made of and how it is constructed?
Relative size awareness	Different objects are noticed and compared based on their relative size	Comparison between sizes of different objects in a search for cues on size.	Comparing sizes	I wonder how big that object is compared to something I know?
Distance contemplation	Distance travelled, distance between stars or other objects, scale (or lack of scale)	Astronomical distances are very big and difficult to appreciate since cues are missing.	Bringing the extensiveness of the galaxy into focal awareness	I wonder how far we've travelled? Or how big the distances are between . . . ?
Motion identification	Movement, speed, acceleration	Motion through space at high speed and possibly also accelerating.	Detecting motion	We are moving, but where?

Table 11.2. *Summary of the hierarchy of disciplinary discernment related to multidimensionality, both categories of discernment and clustering of these into 1-3 dimensionality. It is important to point out that the derived categories do not represent individual participants because descriptions from any one of the participants could help make up more than one category.*

Disciplinary discernment	Analytic outcomes: Categories of discernment ordered hierarchically	Clustering of categories as function of 1-3 dimensionality
	Advanced three-dimensionality	Three-dimensionality
	Growth of three-dimensionality	
	Emergence of three-dimensionality	
	Relative size awareness	Two-dimensionality
	Distance contemplation	One-dimensionality
Baseline category	Motion identification	

12. Reading the Sky – A way to view learning astronomy

‘You see, but you do not observe. The distinction is clear.’
Sherlock Holmes, in *‘A Scandal in Bohemia’*,
Arthur Conan Doyle (1891)

‘A lily is more real to a naturalist than it is to an ordinary person. But it is still more real to a botanist. And yet another stage of reality is reached with that botanist who is a specialist in lilies.’
Nabokov (1962).

12.1 Introducing Reading the Sky

This chapter addresses Research Question 4: How can the idea characterized as Reading the Sky in this thesis inform the teaching and learning of astronomy? The answer to this theoretical question consists of a set of suggestions that I argue are important educational conclusions arising from the results and discussions presented earlier in the thesis and in Papers II and III. The answer presented is thus a theoretical framework for describing disciplinary discernment from an astronomy learning perspective. This is embedded in a new construct that I call *Reading the Sky*, which, as a ‘generative metaphor’ (Schön & Argyris 1978; Schön 1983, 1991, 1979) aims to generate new perceptions and novel ways to attain a competency. For this purpose, I draw on David Dubois’ definition of competency:

‘Those characteristics—knowledge, skills, mindsets, thought patterns, and the like—that when used whether singularly or in various combinations, result in successful performance’ (Dubois 1998, p. v).

I conclude that the competency of *Reading the Sky* is vital for efforts aimed at optimizing the improvement of astronomy education.

12.1.1 Background

Metaphorically, to *read* something has many meanings and applications. For example, cultural geographers commonly talk about ‘reading the landscape’ (e.g. Brierley et al. 2013; J. Duncan & Duncan 1988; N. Duncan & Duncan 2010; Wylie 2007), and ecology educators talk about ‘reading nature’ (Magntorn 2007).

In cultural geography reading the landscape concerns the ability to ‘see’ the landscape in the kind of disciplinary way that facilitates the generation of insightful understanding. Hence, the usage of the term calls for a disciplinary understanding of the ‘language’ of landscapes (Wylie 2007). Put another way, ‘reading the landscape’ metaphorically symbolizes the interpretation of a given piece of landscape from observations as if one was reading the ‘text’ of cultural geography ‘language’. I interpret such use of ‘reading the landscape’ as an example that vividly captures how disciplinary-specific representations get used to share perceptions, knowledge and meaning-making.

In cultural geography the landscape is seen as ‘being *always already* a representation’ (Wylie 2007, p.68), which is visually three-dimensional in nature. This is my framing for making my case for the idea of *Reading the sky*. Consider the resemblances between the notions of ‘reading the landscape’ and *Reading the Sky*: both the landscape and the sky need to be observed and to make sense of those observations they need to be ‘read’ using an appropriate disciplinary ‘language’ (cf. Ainsworth & Labeke 2004). Learning such ‘language’ is essentially what the educational endeavour is about in any discipline.

In the context of cultural geography, ‘*reading*’ refers largely to knowledgeable field observations, and where the landscape is a book in the broadest sense’ (Wylie 2007, p.71, emphasis added). As such, cultural geographers ‘see’ landscapes as representations that are also to be interpreted rather than just described. Since the ability to read a landscape must vary, the interpretations of what is observed must vary: ‘There is no single, “right” way to read a landscape’ (Brierley et al. 2013, p. 603). However, the educational literature in cultural geography offers little guidance on how ‘fluency’ in reading the landscape can be educationally achieved. The same has been true for reading the sky in astronomy.

The educational framing for ‘reading nature’ by Magntorn (2007) in ecology education is, however, more developed and I thus found this framework to be a good starting point to establish my framing of *Reading the Sky*. Magntorn describes how *reading nature* involves two important elements: first, discernment, which he defines as being ‘able to see things in nature and to discern the differences and similarities between objects in nature’ (p. 17) and second, dis-

cussion, which for him is effective communication using disciplinary-specific multimodal representations. These two aspects are interconnected with ‘outdoor experiences’ and ‘theoretical knowledge’ regarding, for example, organisms, processes, and abiotic factors, i.e., becoming ‘fluent’ in the ‘disciplinary discourse’ of ecology (cf. Airey & Linder 2009). Furthermore, Magntorn frames his findings in terms of what he calls ‘competence’, which he characterizes in terms of content knowledge and its associated attained proficiency. In so doing, Magntorn proposes a revised Structure of Observed Learning Outcomes (SOLO) taxonomy (Biggs & Collis 1982; Dart & Boulton-Lewis 1998). This revision describes different levels of sophistication concerning *reading nature* from an ecology education perspective. These levels are used to classify students’, and teachers’, ability to *read nature*, and to discuss critical aspects for learning to read nature.

The idea of *reading* that I have just unpacked easily incorporates my concept of disciplinary discernment and the ability to extrapolate three-dimensionality. However, as opposed to the SOLO, or Bloom’s, taxonomies my framework of *Reading the Sky* is grounded in disciplinarity.

12.1.2 Building the concept *Reading the Sky*

In astronomy, the importance of *Reading the Sky* has not been addressed or quantified. As I indicated in the section above, I am now doing this from a disciplinary discernment perspective. Through my experiences of teaching physics and astronomy and carrying out research in astronomy education, I have become fascinated by what observers actually believe that they ‘see’ – observe, discern, or *read* – when watching the ‘real sky’, visual simulations of the Universe, and other astronomy representations. The disciplinary ability to ‘read’ the Sky is very complex in nature and so I will now propose how *Reading the Sky* should be quantified and used as an effective astronomy education tool. Through my research process two competencies were identified as being important for *Reading the Sky*: disciplinary discernment and extrapolating three-dimensionality (both depending on the competency of handling disciplinary knowledge in appropriate ways using disciplinary-specific representations). Of course, these competencies can only be theoretically separated; in practice they are intertwined with disciplinary knowledge, theory, and practice (Eberbach & Crowley 2009). *Reading the Sky* opens up a new way to expand disciplinary discernment through an inclusion of how I have defined spatial thinking (in an astronomy education context spatial thinking is the recognition, consideration, and appreciation of the interconnected processes and character-

istics among astronomical objects at all scales, dimensions, and time – see Section 8.4.2).

The discernment of relevant structural components (the ‘parts’) of the Universe and how they interact through different processes, involves looking at, reflecting on, and constructing meaning, in relation to the whole of the Universe. It involves observations and measurements, which have great importance for all of astronomy in general, and for astrometry in particular. Therefore, *Reading the Sky* is my bridge between the two parts in this thesis. At the same time, since it is people making and interpreting these observations, they cannot be absolutely objective. The dark sky, distant light, colours, odours and fragrance from afar, the silhouette of the horizon, sound, etc. collectively contribute to what gets ‘read’ by an observer. In all scientific activity this is phenomenon is known, for example, the natural scientist Alexander von Humboldt wrote about in his *Aspects of Nature* as early as 1849. The challenge lies in only observing the relevant features (Shapere 1982) and the challenge behind that is knowing what these relevant features are and/or how to recognise what these are. This becomes increasingly more important in situations where we need to rely heavily on our eyes to make observations (Latour 1986), as is the case in my construct of *Reading the Sky*. From an epistemological point of view, all knowledge or well-grounded belief, rests on experience; experience that is gained through direct sense-perception, in this case, vision. Furthermore, since none of us have identical prior knowledge, different people discern identical things differently (Goodwin 1994; Chapter 9). Again this is not a new idea, it is well known that Socrates used this to argue that our senses cannot access reality in any direct way – ‘sense-perception is notoriously untrustworthy’ (Shapere 1982, p. 508). At the same time, an image of a galaxy taken by a CCD-camera through a telescope is also only a representation of the ‘real’ object. This kind of representation gets built on chains of representations that have been coordinated by many people, often over a long time period (Fredlund et al. in review). These kinds of representations have an intended signification, which is made up by an enormous number of ‘disciplinary affordances’ (Fredlund et al. 2012). Typically, only a subset of the disciplinary affordances will be discerned by students (and even their teaching professors). In my results I refer to this as the ‘discerned disciplinary affordances of the representation’.

Part of the reason for the limitations to what a novice (and expert) can discern from disciplinary representations comes from ‘cognitive load theory’ (see, for example, Mayer & Moreno 2003), which is about the possibilities and the limitations of our cognitive system. Cognitive load theory portrays the amount of information that can be perceived through vision as being not

only limited per se, but also limited by information perceived by our other senses. This becomes a particularly important consideration when choosing to use simulations that attempt to realistically represent aspects of nature as a teaching tool. Here, there is a potential risk of students missing educationally relevant aspects because of cognitive overload (Mayer & Moreno 2003; Mayer 2009) or, by only focussing on the most visually compelling things, which might not be relevant for the task at hand (Elby 2000; Marton & Booth 1997).

I have taken all of this into account when developing my construct of *Reading the Sky*. The construct builds on appreciating how disciplinary knowledge relates to actual observations (Part I of the thesis) as a function of discerning the disciplinary affordances of representations used in the disciplinary discourse of astronomy (Part II of the thesis). Through this, *Reading the Sky* can be seen to relate to Roberts (2007) Vision I (literacy in the products and processes of science) and Vision II (literacy in the science-related situations) notion of scientific literacy.

For people not in the field of astronomy or having a strong personal interest in astronomy, the general level of astronomical knowledge *Reading the Sky* can be expected to be low (see Chapter 8). However, for university students taking courses in astronomy, *Reading the Sky* becomes a competency that needs to be striven for; the framing of *Reading the Sky* provides a research-informed link between observations and the meaning-making that gets constructed from those observations.

12.1.3 What is *the Sky*?

At this point in my discussion I need to turn to further explaining what I mean when I refer to *the Sky*:

The Sky is the whole Universe at all levels of detail, including all forms of disciplinary-specific representations, and other semiotic resources, describing the Universe, at all scales, its properties, but also the processes involved in their interaction with the surrounding, at local scale and large scale.

This highlights the size of the challenge at hand; to be able to competently get to ‘see’ the whole Universe, its parts, and how they interact. Obviously, from an educational point of view, the competency to read the sky must be seen against the educational aims of a given educational context. For most students, it will begin with local observations of day and night skies. During the day, the Sun and the Moon could be visible. At night the Moon, planets, stars, nebulae, and galaxies could be visible. Observing the night sky in a planetarium

or through a simulation on a computer, tablet, or smart-phone, could educationally enhance such observations. My point is that the aim of astronomy courses should be set against being able to ‘read’ *the Sky* sufficiently well in terms of the aims and objectives of the course. This can be seen as achieving a designated level of ‘literacy’ in the relevant parts of the disciplinary discourse of astronomy applicable to a given course. In this way, achieving competency in *Reading the Sky* involves traversing my adaption of Bruner’s model of the spiral curriculum (see Figure 12.3), which in turn has similarities to the historical development of today’s accepted astronomical view (Gooding 2006; Gray 2014; Hoskin 1996, 1999; Kuhn 1970; Leverington 2013).

12.2 Defining *Reading the Sky*

When young Eduard asked his father why he was so famous the answer he received was:

‘When a blind beetle crawls over the surface of a curved branch, it doesn’t notice that the track it has covered is indeed curved. I was lucky enough to notice what the beetle didn’t notice.’

From Max Flückiger (1974), Albert Einstein in Bern, Switzerland

My formulation of the *Reading the Sky* begins with Figure 12.1, which illustrates how I grounded the idea in the results of Paper II (extrapolating three-dimensionality) and Paper III (disciplinary discernment). I go on to propose a definition of *Reading the Sky* that brings together the extrapolation of three-dimensionality and disciplinary discernment:

Reading the Sky is the ability to discern disciplinary affordances of the Sky in order to acquire a holistic, three-dimensional, understanding of the Universe at all levels of scale, dimensions and detail.

Reading the Sky observations would include what one can notice using telescopes, by looking at spectra from stellar objects, from photos of the sky and from discipline-based representations. All these use the naked eye as a ‘detector’. Discernment is constructed from these observations through a meaning-making process that calls for a ‘fluency’ (Airey & Linder 2009) in disciplinary discourse, which is linked to spatial thinking (see Chapters 8 and 9). Becoming part of the discourse of astronomy thus involves being able to ‘fluently’



Figure 12.1. The foundations of *Reading the Sky* as defined and discussed in the text.

‘read’ *the Sky* by interpreting, understanding and using the different representations that astronomers use to communicate disciplinary knowledge as part of developing a discursive identity (cf. Allie et al. 2009)). Using this disciplinary discourse perspective, *Reading the Sky* calls for the two abilities, ‘disciplinary discernment’ and ‘extrapolating three-dimensionality’ to be linked to ‘observations and experiences’ and ‘disciplinary knowledge’ in order to be able to ‘see’ through vision, and ‘interpret’ through the affordance of disciplinary-specific representations, the Universe. This is illustrated in Figure 12.2.

In the next section, I propose using *Reading the Sky* in two ways. Firstly, to characterize what is needed to link *extrapolating three-dimensionality* and *disciplinary discernment* to *disciplinary knowledge* as part of informing the optimization of the teaching and learning astronomy (see Figure 12.3 and Section 12.3). Secondly, for *Reading the Sky* to characterize a competency that astronomy education should be achieving at much earlier stages than is currently taking place – as shown in Figure 11.1).

12.3 Towards optimizing teaching and learning astronomy

In Section 8.4.2, in order to suggest that the ability to extrapolate three-dimensionality in astronomy be linked to attaining competence in spatial thinking, I developed the following definition of spatial thinking: *the recognition, consideration, and appreciation of the interconnected processes and characteristics among astronomical objects at all scales, dimensions, and time*. To develop the ability to extrapolate three-dimensionality calls for careful consideration by an astronomy teacher about how to meaningfully achieve this.

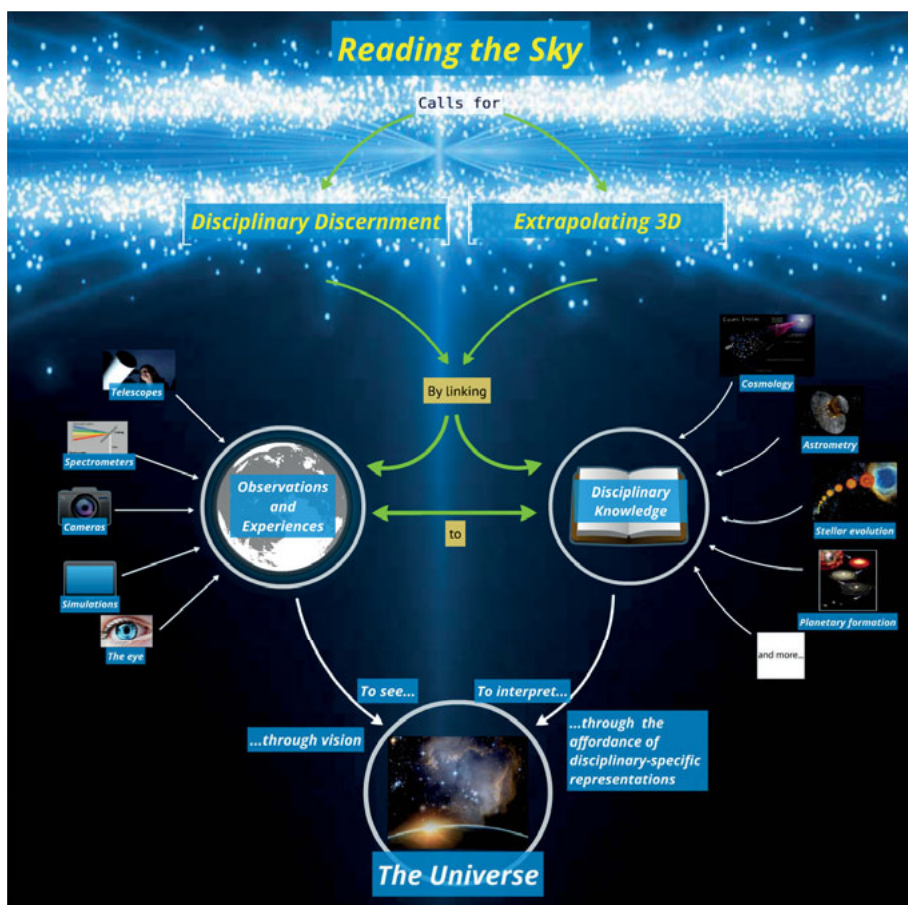


Figure 12.2. Concept map illustrating *Reading the Sky*.

From the results of Paper II I argued that simulations that promote the extrapolation of three-dimensionality have the distinct possibility to help students build the curriculum-intended level of understanding of the three-dimensional Universe. However, the ability to extrapolate three-dimensionality depends strongly on the role that the representations play in the simulation to provide the needed motion parallax. The findings of Paper III led me to further argue that the role of the teacher is also to generate the scaffolding needed to help the students *cross over category boundaries* in the ADD.

So, the tailoring of teaching sequences to provide students with opportunities to develop their abilities concerning thinking spatially in terms of extrapolating three-dimensionality through disciplinary discernment is educationally critical. The role of the teacher needs to be much more than a 'guide' that takes the students through the simulation. What is needed is a teaching mindset that

takes the students ‘on an excursion into the target discourse arena, gradually shifting the frame of reference until it corresponds well enough to allow sense to be made within the specialist discourse’ (Northedge 2002, p. 263). This requires a teaching approach that ‘signals’ the mapping between disciplinary-specific representations without over-burdening the students by making the task too complex (Ainsworth 2008). Hence, such a teacher, by making boundary crossing in the ADD hierarchy possible (see Figure 11.5), will be tailoring their teaching to provide the necessary scaffolding to help students to learn to extrapolate three-dimensionality as a function of developing spatial thinking.

Thus, I suggest an adaption to the spiral curriculum approach (see Figure 11.5) by including a third axis; extrapolating three-dimensionality. This is shown in Figure 12.3. The reason for doing this is to visually bring to the fore how Disciplinary Discernment and Disciplinary Knowledge are necessary but not sufficient abilities for the creation of an optimal spiral of teaching and learning for astronomy.

Further, set against the idea of achieving competency in *Reading the Sky*, I would argue that the three intertwining abilities in my proposed spiral of teaching and learning, provide the essential grounding for the generation of the scaffolding needed to optimize the teaching and learning of astronomy.

From my experience, the traditional astronomy teaching focuses on achieving learning disciplinary knowledge and practices. As such, it assumes that the kind of educational challenge that my research has brought to the fore gets taken care of as a natural part of the associated learning. Consideration of Figure 11.5 clearly shows this is not a valid educational assumption. Therefore, teacher awareness is needed about the crossing of category boundaries in all ‘dimensions’ in the ‘spiral of teaching and learning’ (see Figure 12.3) as a significant step to establish learning that increases in sophistication as educational experience progresses. This is not straightforward, since what is obvious for teachers may not even be discernable for students in or entering into the discipline of astronomy (See, for example, Paper II & III, Bransford et al. 2000; Northedge 2002; Rapp 2005; Tobias 1986). Thus, the role of the teacher is critical here and I suggest that Hattie’s (2009; 2012) idea of visible learning offers a pragmatic way to think about the crossing of category boundaries in all ‘dimensions’ in my ‘spiral of teaching and learning’. ‘It is teachers seeing learning through the eyes of students [and,] the greatest effects on student learning occurs when teachers become learners of their own teaching, and when students become their own teachers’ (Hattie 2012, p. 14).

In conclusion, my construct *Reading the Sky* (Figure 12.2), together with my ‘spiral of teaching and learning’ (Figure 12.3) presents a holistic visualization of my theoretical framework, which answers my fourth research question.

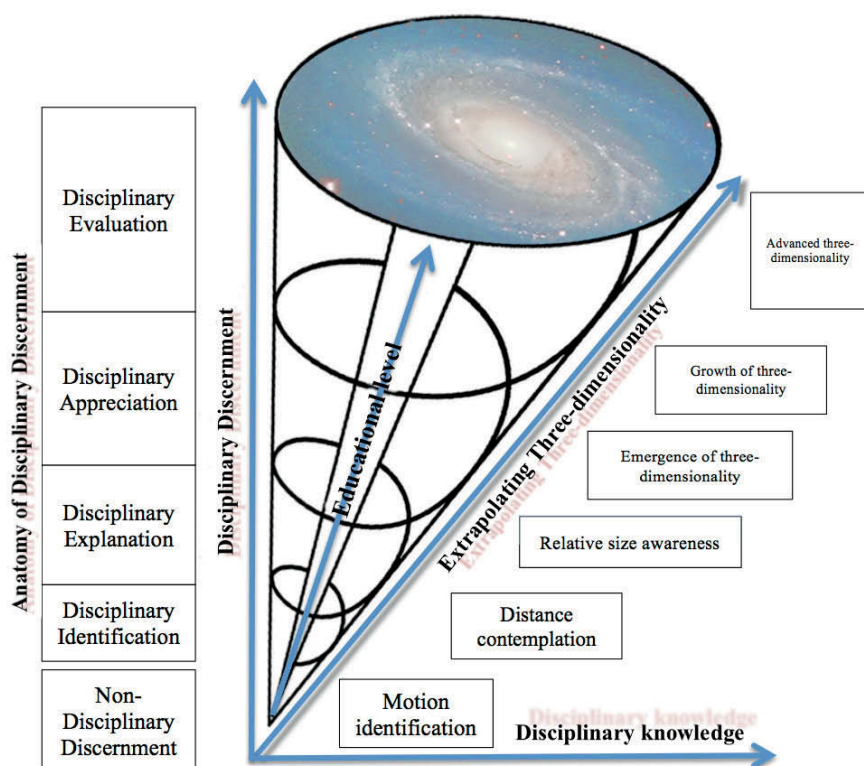


Figure 12.3. This idealised representation illustrates *Reading the Sky* as constituted by three abilities: Disciplinary discernment, Extrapolating three-dimensionality, and Disciplinary knowledge. I refer to this three-dimensional space as the ‘spiral of teaching and learning’. Since these abilities are intertwined with each other, there are numerous possible learning trajectories for the teacher to consider.

I have argued that this framework should be seen by teachers of astronomy to offer a new way of having students’ learning trajectories become part of the disciplinary discourse of astronomy: students need to learn to ‘read’ *the Sky*, or else they will only see and not discern.

13. Implications, Knowledge claims and Future work

13.1 Implications – Examples related to my research

In the papers that my thesis is based upon I discuss implications in relation to their findings. My aim here is to further this discussion by drawing on a brief overview of some of the observational astronomer, Tycho Brahe's, achievements.

Tycho Brahe, 1546 – 1601, working from 'Uraniborg' on the island of Ven between Sweden and Denmark, may well have been the best astronomer of his time in terms of his scientific approach. Brahe is well known for achieving an exceptional level of scientific precision in his measurements of stellar positions. The level of precision that he attained is even more notable considering that he was using his eyes as his detector. The precision in Brahe's data was of the order of $\sigma_{pos} = 0.5 - 3$ arcseconds, taking systematic errors into account (Rawlins 1993). Brahe needed to have exceptional competency in *Reading the Sky* in order to achieve his ground-breaking discerning and measuring of the positions of stars and planets.

Nicolas Copernicus' earlier idea of 'heliocentrism' (Copernicus 1966), having the Sun as the centre of the known Universe with the planets orbiting around it, had spread across Europe (see, for example, Hoskin 1999; Leverington 2013). Copernicus' idea had a particular implication that concerned discernment of the motion of stars; If the Earth was indeed moving around the Sun, with the stars situated on a spherical trajectory far away from the Sun, it would be possible to measure small changes in their relative positions as the Earth moved around the Sun (through parallax motion). Brahe did not agree with Copernicus' idea that the Earth was orbiting the Sun for several reasons. If it was correct, he argued, then he would be able to measure the stellar parallax that would result in such a system. Brahe attempted to do this, but his many measurements and calculations did not lead to anything and today we know why: the parallax angles were too small for him to detect using his eyes as a detector with the size of the Earth's orbit around the Sun. He was very close to being able to do so, for example, he could almost have seen motion parallax for the nearby star 61 Cygni, which has a parallax of 0.314 arcseconds (Allen & Cox 2000). Brahe took his results to be observational evidence

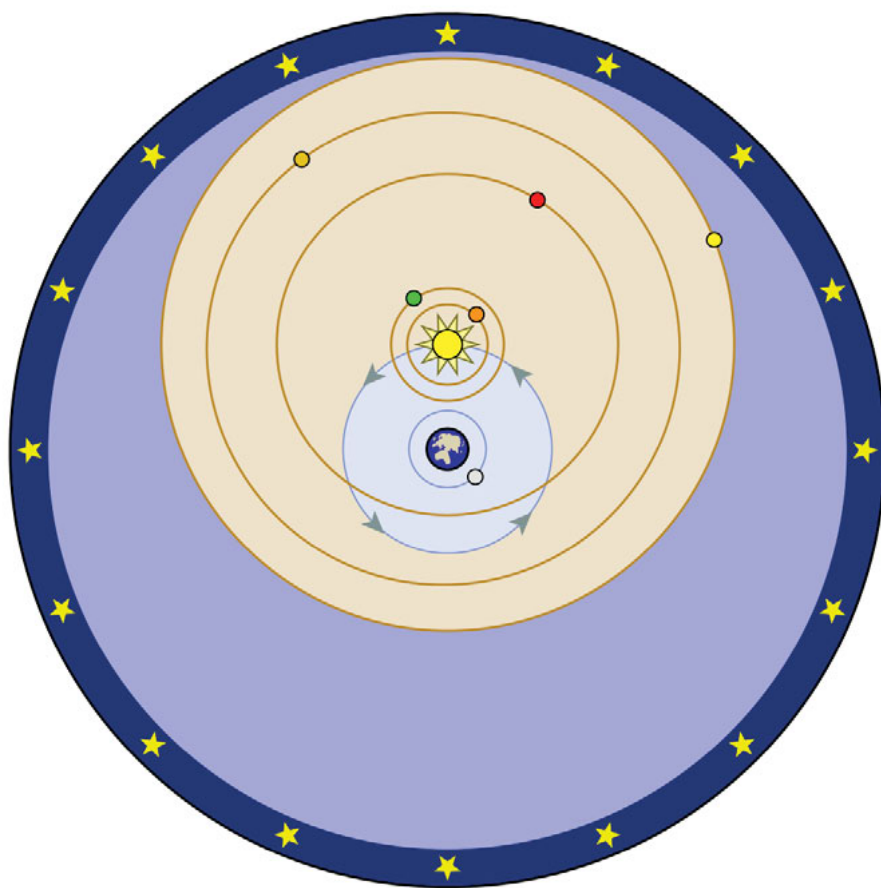


Figure 13.1. This representation shows the Tychonian system, referred to as a geoheliocentric system in which the Sun and Moon orbited the Earth, while the other planets orbited the Sun.

that the stars were at equal distance from the Earth and therefore concluded that the Earth did not move, or orbit the Sun.

From this work, Brahe constructed a new geoheliocentric model of how the Universe worked (see Figure 13.1). In terms of *Reading the Sky*, for his time, Brahe was clearly operating at the most advanced levels of disciplinary discernment and disciplinary knowledge. However, the level of extrapolating three-dimensionality that he was able to operate at was limited due to what he had available to use to make his measurements – his instruments, his eyes and the size of the Earth’s orbit around the sun. This is why the selection of the video simulation was so critical for my study; it had to provide an experience

of motion parallax that could remove the kind of limitation that Tycho Brahe experienced.

13.2 Knowledge claims

My Ph.D. has contributed to the following fields of research: firstly, to disciplinary knowledge within the field of astrometry, and secondly, to astronomy education research situated in higher. In detail:

1. The models that I derived for estimating astrometric noise have been shown to be important for the development of μ as astrometry and highly relevant for exoplanet research (Paper I). In the near future, I anticipate hearing much more about the relevance of this branch of research in relation to the findings from Gaia project.
2. I presented a new way to think about students' ability to extrapolate three-dimensionality (Paper II). Astronomy is in many aspects unique as a science with its huge astronomical distances and time lines. Discernment of these aspects needs to be incorporated into curriculum design and I suggested a new way to address this challenge. It is not trivial; students need to be offered experiences and scaffolding to be able to learn to discern and build their three-dimensionality awareness, using motion parallax.
3. I consider the Anatomy of Disciplinary Discernment in Paper III to be my most significant contribution to the field of PAER. Differences in astronomical competency, which are captured by differences in making the relevant and appropriate disciplinary discernments, are educationally reflected in the different levels of the ADD. Thus, incorporating the ADD into Bruner's spiral curriculum presents a pragmatic teaching model that aims to provide the kind of scaffolding needed to facilitate crossing over of the category boundaries in the ADD. This offers a new way to see teaching and learning in astronomy; a way based on disciplinary discernment of representations. Although I used a video simulation to exemplify this, I argue that the findings are equally relevant and applicable for other types of representational experience in astronomy/physics education.
4. Finally, I believe that the notion of achieving a competency in Reading the Sky has the potential to work as an overarching model for teaching and learning astronomy. Reading the Sky characterizes what is needed to link extrapolating three-dimensionality and disciplinary discernment to disciplinary knowledge as part of informing the optimization of the

teaching and learning astronomy. These three skills constitute a three-dimensional ‘space’ in which learning astronomy takes place through different learning trajectories. Based on the proposed ADD spiral curriculum model in Paper III, I argue that teaching should be crafted in such a way that material is revisited with increasing depth following a ‘spiral of teaching and learning’ astronomy. This should be done in such a way that crossing the category boundaries becomes a functional and realizable aim.

13.3 Future work

13.3.1 Short term

I have started designing a project related to the ADD. This work focuses on the HR-diagram vis-à-vis disciplinary discernment assumptions. The HR-diagram is considered to be central to all stellar astrophysics; what makes it educationally challenging is that to ‘read’ it incorporates a great many counter-intuitive aspects. The project will aim to capture, as a function of the ADD, the learning challenges that students face when experiencing such a representation. And I envisage the outcomes being able to inform the teaching of stellar astrophysics.

Another project that I intend to do in the short term is an exploring of what narration is needed to optimize the possibility of learning to extrapolate three-dimensionality while watching a simulation that aims to enhance discernment of important aspects of the Universe.

13.3.2 Long term

Here I propose investigating that particular aspect of astronomy education that no one has addressed before in detail from the point of view of disciplinary discernment: Time – the fourth dimension.

Time is a difficult construct to deal with in almost in every aspect of astronomy. When making observations one is essentially looking back in time, which is very counter intuitive. Also, every object in the Universe moves in relation to other objects, i.e. the position of every object in the Universe is time-dependent. Therefore, the fourth dimension is also a most suitable educational context for the continuation of the research I have done so far. Its clear connection to both astrometry and astronomy education makes it a particular interesting context.

14. Swedish summary – Svensk sammanfattning

Att läsa himlen – från stjärnfläckar till stjärnobservationer

14.1 Bakgrund

Att betrakta natthimlen kan vara en stor upplevelse. Den ser ju så oföränderlig ut, men ändå spännande för många studenter. Att observera stjärnor och planeter är en gammal vetenskap, som kopplar ihop två intressanta delar. Dels astrometri, ‘att mäta stjärnorna’ och dels hur vi människor uppfattar var stjärnorna och allt annat som finns i universum är. Båda dessa används för att skapa en uppfattning om universums 3D struktur.

Denna avhandling är delad i dessa två delar. Första delen berör vetenskapsområdet astrometri, där jag undersöker och bestämmer variationen i stjärnors ljusstyrka, läge, och rörelse, genom inverkan av stjärnfläckar, dvs mörka (eller ljusa) områden på stjärnors yta. Denna fläckighet kommer att påverka nämnda parametrar så att en stjärna kommer att se ut att förändra sitt läge på himlen, samt hur den rör sig. Dessa effekter är virtuella, dvs stjärnan kommer inte att varken förändra sitt läge eller sin rörelse, men fläckarna har den inverkan på ljuset som vi observerar från stjärnor.

Den andra delen av avhandlingen handlar om studenters, och deras lärares, upplevelser och uppfattningar om universum struktur. Vad urskiljer (discern) de när de tittar på en sk. representation av något astronomiskt objekt? Och hur kopplar det till deras 3D uppfattning om universums struktur?

14.2 Syfte

Syftet med avhandlingen är att beskriva hur universitetsstudenter och deras lärare uppfattar universums 3D struktur. Detta undersöker jag dels från ett ämnesdisciplinärt håll (astrometri) och dels från ett astronomididaktiskt håll. Forskningsfrågorna som jag berör är:

Astrometri:

1. Hur stora är de astrometriska effekter som uppkommer pga av fläckar på stjärnors ytor och hur kan de vara begränsande för ultrahög precision inom astrometri (storleksordningen mikro-bågsekunder = μas) och hur påverkar de möjligheterna att detektera exoplaneter för stjärnor i olika delar av HR-diagrammet?

Astronomididaktik (Astronomy Education Research):

Först behandlar jag fyra empiriska frågeställningar (2a,b) and (3a,b). Baserat på svaren från dessa frågor adresserar jag slutligen en teoretisk fråga (4):

2.
 - a) I termer av dimensionalitet, vad lägger astronomi/fysik studenter, och deras lärare, märke till när de ser på en simulering av en resa genom vår galax?
 - b) Vad kan denna urskiljning säga om deras förmåga att extrapolera tre-dimensionalitet?
3.
 - a) Vad lägger dess två grupper märke till när de ser disciplinära representationer hämtad från astronomin diskurs?
 - b) Hur kan man karakterisera denna urskiljning från ett utbildningsperspektiv?
4. Hur kan begreppet *Läsa Himlen* användas för att förbättra undervisningen och lärandet inom astronomi?

14.3 Del I

Första delen av avhandlingen behandlar alltså stjärnor och deras fläckighet. Precis som solen har fläckar, har sannolikt de flesta andra stjärnor också fläckar i varierande grad. Dessa fläckar kommer att leda till att ljusstyrkan från en stjärna varierar och fläckarna kommer därmed att påverka både läget i sidled och rörelsen i radiell led, genom att tyngdpunkten för ljusfördelningen ändas med rotationen av stjärnan. Dessa rörelser är sannolikt inte så stora men påverkar noggrannheten med vilken vi vill kunna bestämma läge och radial rörelse (sk radialhastighet). Antag till exempel att det finns ett antal mörka fläckar på vänstra delen av en stjärna sett från jorden. Då kommer man att uppfatta att tyngdpunkten för stjärnans ljusfördelningen är något förskjutet till höger. Denna effekt är så liten att den i princip inte går att detektera med

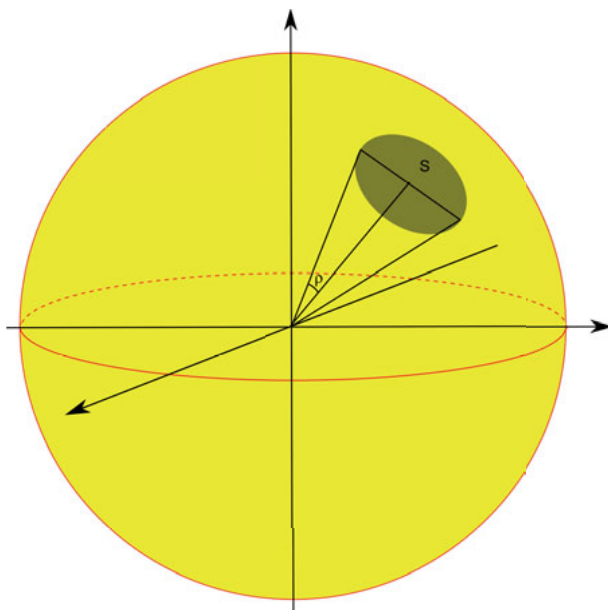


Figure 14.1. Så här kan en stor fläck se ut. Fläckens area är proportionell mot vinkeln, ρ , genom $A = \sin^2(\rho/2)$.

de instrument som finns idag, men inom en snar framtid förväntas man kunna mäta läget med sådan noggrannhet att denna effekt får betydelse. En likartad situation uppkommer för radialhastigheten. Antag att stjärnan roterar så att de mörka fläckarna rör sig från vänster mot höger. Då kommer det inledningsvis var mer lysande yta som är på väg bort från betraktare och man kommer att uppfatta att stjärna verkar vara på väg bort. När sedan fläckarna har passerat mitten på stjärnan sett från betraktare, kommer mer lysande yta att rotera mot betraktare än från och man uppfattar det som om stjärnan är på väg mot oss. Figur 14.1 illustrerar hur en stjärna med en fläck ser ut och Figure 14.2 vilken effekt en mörk stjärnfläck har på de olika parametrarna.

Alla dessa effekter är dock virtuella, dvs det är ingen verklig rörelse, men de går inte att skilja från 'riktig' rörelse på ett enkelt sätt. Därför är det viktigt att ta reda på hur stor denna effekt är för olika stjärnor, speciellt i ljuset av att man är intresserad av att leta exoplaneter runt dessa stjärnor. Exoplaneterna påverkar också stjärnas läge och radialhastighet och det är därför möjligt att det blir problem när man skall försöka hitta dessa exoplaneter. Det visar sig att effekten av stjärnfläckar på typiska 'bra' stjärnor för exoplanet-letare är av samma storleksordning som signalen från jordlika exoplaneter på 'lagom' avstånd från dess stjärna.

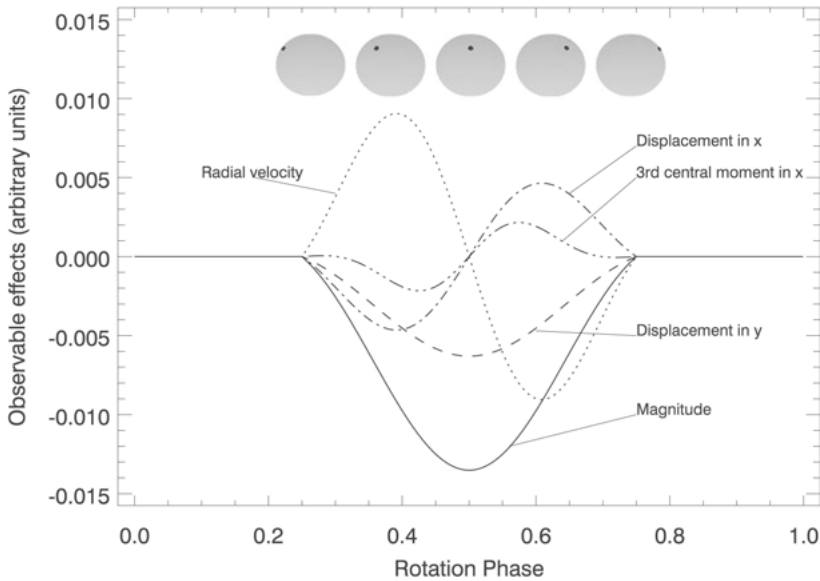


Figure 14.2. Figuren visar en fläck, som täcker 1 % av den synliga ytan, belägen på ytan av en stjärna. Denna fläck flyttar sig runt stjärnan med stjärnans rotation. Detta kommer då att påverka totala ljusstyrkan, positionen (i x- och y-led) samt radialhastighet, m.m. Kurvorna visar hur de olika parametrarna kommer att varia med rotationen.

För att undersöka detta har jag gjort en mängd simuleringar över fläckiga stjärnor, både för roterande stjärnor och statiska stjärnor. Ur dessa simuleringar framkommer ett antal samband som uttrycker det statistiska bruset (variansen) som fläckar skapar på astrometriskt viktiga parametrar, så som ljusflödet (fotometri) (σ_m), position (σ_{pos}), radialhastighet (σ_{v_R}), samt även en annan parameter viktig för interferometriska undersökningar av stjärnor (σ_{μ_3}). Dessa är sedan kontrasterade mot en teoretisk modell. Det visar sig finns samband mellan dessa parametrar, vilket leder till att om man kan bestämma den ena, t.ex. σ_m , så kan man enkelt uppskatta de andra också. Genom att använda det fotometriska bruset, som är känt för många stjärnor, kan man skapa ett HR-diagram som illustrerar t.ex. det astrometriska bruset (Figur 5.2)

När man sedan jämför detta astrometriska brus med det brus som en exoplanet skapar när den går runt sin stjärna, finner man att effekten av jordlika exoplaneter ofta är av ungefär samma storleksordning, eller mindre, vilket gör att det kan bli problematiskt att detektera en sådan exoplanet med astrometrisk

metod. Risken är att signalen från exoplanetens inverkan helt drunknar i bruset som stjärnfläckarna skapar.

Dock finns det hopp om att faktiskt kunna testa detta med det nyligen uppskjutna teleskopet Gaia. Detta kommer att mäta läget av ca en miljard stjärnor i vår galax väldigt nog och många gånger, vilket kommer att göra att man kommer att kunna detektera en mängd exoplaneter, dock sannolikt inga jordlika exoplaneter, då dessa som sagt skapar en för liten signal för att kunna säkert detekteras.

14.4 Del II

När jag under åren ägnat mig åt astrometrisk forskning samtidigt som jag har undervisat i astronomi och fysik, samt givit massor av planetarievisningar, har jag mer och mer funderat över vad studenterna ser när de betraktar en astronomiska representation av the 'yttre' universum. Det kan vara t.ex. ett diagram, en bild, stjärnhimlen i planetariet eller den riktiga, ett 'orrery', eller en simulering. Det har varit uppenbart att de inte sett samma sak som jag har sett, och mina funderingar gick åt att försöka beskriva vad de la märke till i dessa representationer, dvs vad deras 'inre' bild av the 'yttre' universum var. Vägen från det 'yttre' till det 'inre' går via perception och synen. Mot denna bakgrund vill jag alltså ta reda på och beskriva vad deras disciplinära urskiljande (disciplinary discernment) är när de betraktar astronomiska representations. Disciplinärt urskiljande avser att lägga märke till något (notice), reflektera över detta (reflection), för att skapa mening (meaning-making) utifrån ett disciplinärt perspektiv. Alla representationer har en mängd 'disciplinära affordanser'. Detta kan tolkas som 'potentialen hos en viss semiotisk resurs att erbjuda tillgång tillämneskunskaper' (Fredlund et al. 2013). I mitt fall är den semiotiska resursen en simulering, *Flight to the Virgo Cluster*, gjord av den välkända kosmologen Brent Tully (2012), och beskrivande en resa genom vår galax Vintergatan med ett antal passager förbi typiska objekt i galaxen (stjärnor, stjärnbilder, nebulosor, supernovarester, stjärnhopar, stora molekyllära moln, samt hela Vintergatan). Utifrån denna simulering, som ett exempel innehållande en mängd representationer av astronomiska objekt, formulerade jag de forskningsfrågor som styrte mitt arbete.

Jag började med att angripa forskningsfrågorna 2a och 2b, som båda handlar om multidimensionalitet. I litteraturen kring lärandet om astronomi framgår det att man länge misstänkt att för att lyckas bra med sina astronomistudier, så måste man ha ett utvecklat *spatialt tänkande*, dvs ha lätt för att för sitt inre 'se' hur objekt ser ut i 3D utifrån en 2D representation. Dock har man inte

beskrivit detta på ett tillfredställande sätt. Jag kallar denna egenskap för att *extrapolera tre-dimensionalitet* utifrån en tvådimensionell representation. För att kunna ta reda på detta konstruerade jag en web-baserad undersökning, ett formulär, där deltagare kunde se korta avsnitt av nämnd simulering och skriva ner vad de tänkte på när de såg den, vad de la märke till, sådant som gjorde att de fick nya tankar kring något astronomiskt, eller sådant som gjorde dem förvånade eller förbryllade. Dessutom bad jag dem skriva ner vilka, om några, frågor som dök upp i deras huvud när de såg simuleringsavsnitten.

Jag spred detta formulär till astronomer världen över och fick in svar från sammanlagt 137 personer från USA, Kanada, Sydafrika, Australien, samt fem länder i Europa. Som önskat var det stor spridning bland dessa avseende utbildningsnivå, från sådana som läste introduktionskurser i astronomi till doktorander, samt en mängd professorer, se Tabell 10.1. De erhållna data från dessa deltagare analyserades sedan med en standardiserad metod som används inom kvalitativa forskning (hermeneutik) för att finna kategorier som beskriver deltagarnas upplevelser. Det framgick snabbt att deltagarna hade sett massor av saker och speciellt intressant med anledning av forskningsfrågorna 2a och 2b, var sådant som kunde härledas till multidimensionalitetstankar. Kategorierna, dess innebörd, och deras inbördes ordning i förhållande till en-, två-, och tredimensionalitet finns i Tabell 11.1 och 11.2.

Det visar sig att spatialt tänkande avseende tredimensionalitet är svårt för studenterna, speciellt förstaårsstudenterna, medan det verkar vara en egenskap som professorerna besitter i stor grad, vilket framgår av Figur 11.1. Det som verkar vara lättast att urskilja i detta avseende är det som perspektivförändringen ger när man färdas genom rymden i simuleringen (Effekten kallas *rörelseparallax*, och avser förändringar av ett 3D föremåls utseende beroende på relative rörelse). Men att sedan gå vidare och dra några längre slutsatser utifrån detta verkar vara svårare för studenterna. Professorerna däremot visat prov på 'professionellt seende' (Goodwin 1994), och kan ganska lätt tolka intrycken. Detta gör att jag drar slutsatsen att disciplinärt urskiljande är starkt kopplat till den vetenskapliga utbildningsnivån. Det betyder att studenterna 'lär sig' att urskilja mer saker genom sin utbildning och då kan de urskilja mer i de representationer som används inom disciplinen, vilket leder till djupare förståelse om universums 3D struktur.

Under arbetet med att kategorisera svaren från deltagarna enligt ovan, så uppkom det fler kategorier som visade sig mycket intressanta. Dessa kategorier kom att handla om disciplinärt urskiljande på en annan nivå än 'bara' avseende spatialt tänkande. Det gjorde att jag angrep material med utgångspunkt i forskningsfrågorna 3a och 3b. Genom noggrann analys av data fann jag att det kunde användas för att karaktärisera hur disciplinärt urskiljande avseende

representationer kan beskrivas. Jag beskriver även detta med en hierarki som jag kallar anatomin över disciplinärt urskiljande (the anatomy of disciplinary discernment (ADD)), se Figur 14.3. Den kan beskrivas med fem steg, där det lägsta steget inte innehåller något disciplinärt urskiljande (non-disciplinary discernment). Övriga steg är *disciplinärt identifierande* (att kunna namnge och känna igen typiska disciplinära objekt), *disciplinär förklaring* (att kunna tilldela disciplinär mening åt objekt och processer, dvs att börja upptäcka affordancerna i representationerna), *disciplinärt uppskattande* (att kunna uppskatta värdet av affordancerna som representationerna erbjuder), samt *disciplinärt utvärdera* (att kunna kritisera och se begränsningar i representationernas affordancer). Dessa kategorier beskriver väl hur disciplinärt urskiljande kan beskrivas samt också att det finns en stark koppling till disciplinär kunskap, dvs disciplinär utbildningsnivå. Jag beskriver dessa som sammantvinnade i en spiral (Bruner 1960), en metafor för hur man genom disciplinärt urskiljande också skapar förutsättningar för mer disciplinär kunskap, men att denna kunskap också skapar förutsättningar för mer urskiljande när man sedan ser samma eller liknade representationer igen, se Figur 14.4. Det blir då också extra tydligt att disciplinärt urskiljande är starkt kopplat till disciplinär kunskapsnivå, dvs utbildningsnivå, något som också framkommer tydligt i analysen.

Den viktigaste slutsatsen från denna undersökning är att det som krävs för att man skall bli en del av den disciplinära diskursen, är att 'klättra' uppåt, över kategorigränserna i denna ADD. Det är här som lärarens roll i denna process tydliggörs. Det är lärarens uppgift att se till att först identifiera var studenterna är i denna ADD och sedan hjälpa dem att komma över kategorigränserna genom att noggrant utveckla undervisningssekvenser som stöder detta.

Slutligen, och som ett svar på den sista forskningsfrågan (4), har jag valt att kombinera dessa två koncept som presenterats i vars en artikel (Paper II och III). Med utgångspunkt från begreppet att *Läsa* något, och då inte text i en bok, utan t.ex. att *läsa landskapet* (see, till exempel, Wylie 2007) eller att *läsa naturen* (Magntorn 2007), har jag valt att på motsvarande sätt beskriva disciplinära urskiljande på himlen som att *läsa himlen* (*Reading the Sky*). Detta har dock en vidare betydelse eftersom jag i begreppet *himlen* lägger in alla de representationer som används inom astronomidisciplinen. Det betyder att *läsa himlen* innebär att kunna göra disciplinära urskiljande som innefattar både disciplinära urskiljande avseende representationer och tredimensionalitet. För att kunna detta krävs *upplevleser och observationer*, för att genom synen *se*, och genom disciplinära representationer *tolka*, universum för att skapa en holistisk bild av hur universum ser ut och fungerar, se Figur 14.5.

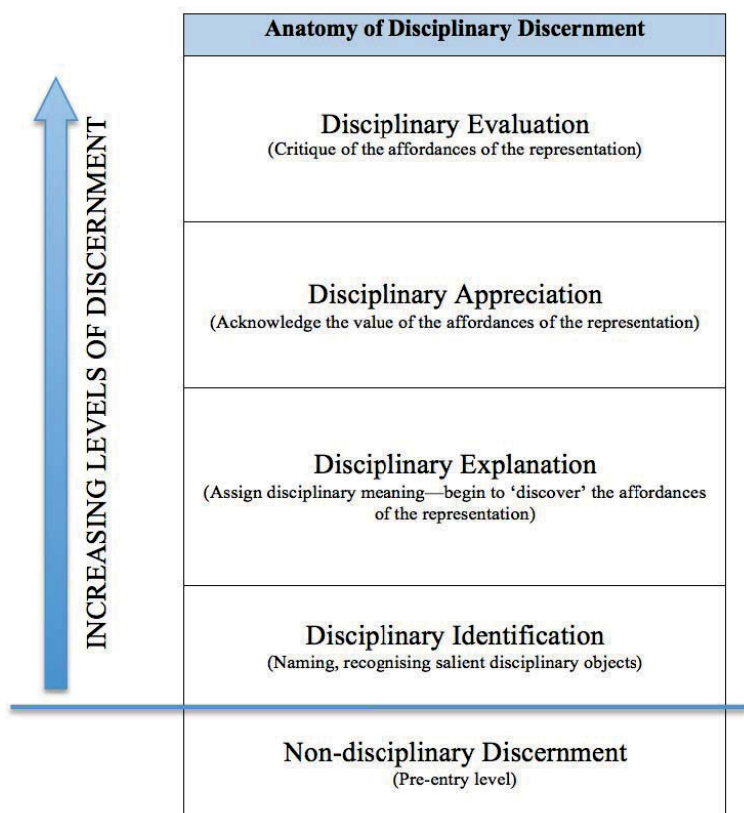


Figure 14.3. Anatomien över disciplinärt urskiljande.

Detta begrepp sammanfattar denna avhandling genom att det kopplar disciplinära kunskaper (Del I) till astronomididaktik (Del II) på ett sätt som inte tidigare är gjort. Detta begrepp fångar också de kompetenser som en astronomistudent måste utveckla, disciplinärt urskiljande från representationer, spatialt tänkande i form av extrapolering av tredimensionalitet, samt disciplinär kunskaper. Detta göra att lärarens roll blir tydligare i att undervisningen måste utformas så att den hjälper studenterna att klättra uppåt i de beskrivna hierarkierna. Läraren bör alltså börja med att ta reda på var studenterna är i dessa hierarkier, och sedan, genom att se sin egen undervisning genom studenternas ögon, göra så att de blir sina egna lärare och därmed själva bygger en förståelse för astronomi och universum (cf. Hattie 2009).

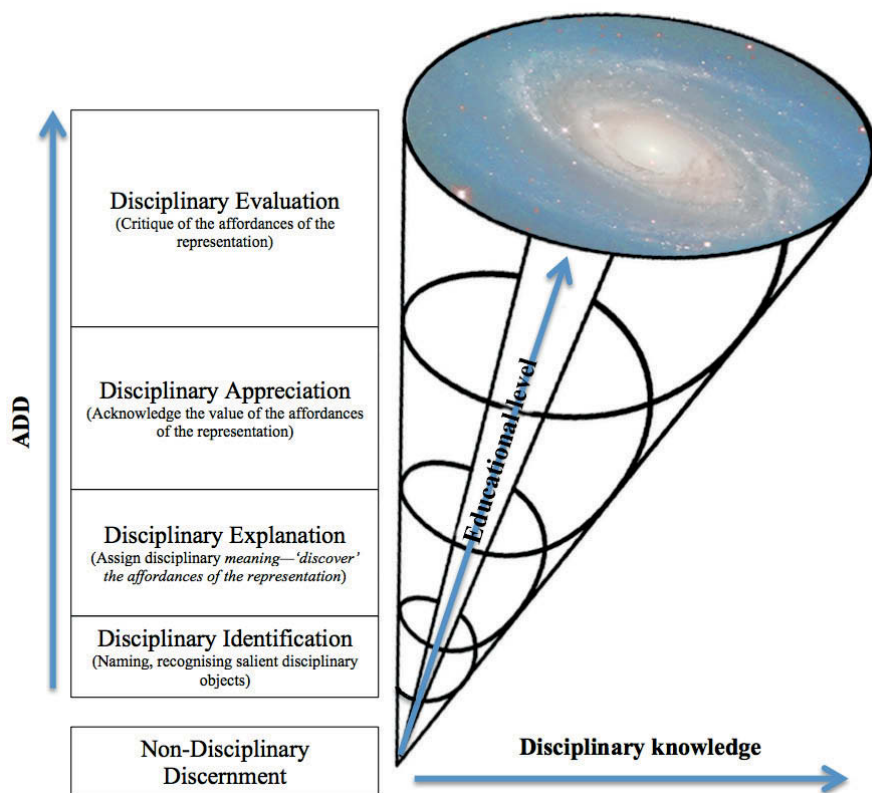


Figure 14.4. Anatomien som beskriver disciplinärt urskiljande samt Spiralen (Bruner 1960). Genom att iterativt återkomma till olika undervisningsmaterial ökas det disciplinära kunnandet (illustrerat med vidden på spiralen spiral) tillsammans med förmågan att urskilja disciplinära affordancer hos representationer. Detta speglar förflyttningen uppåt genom de föreslagna nivåerna i ADD.

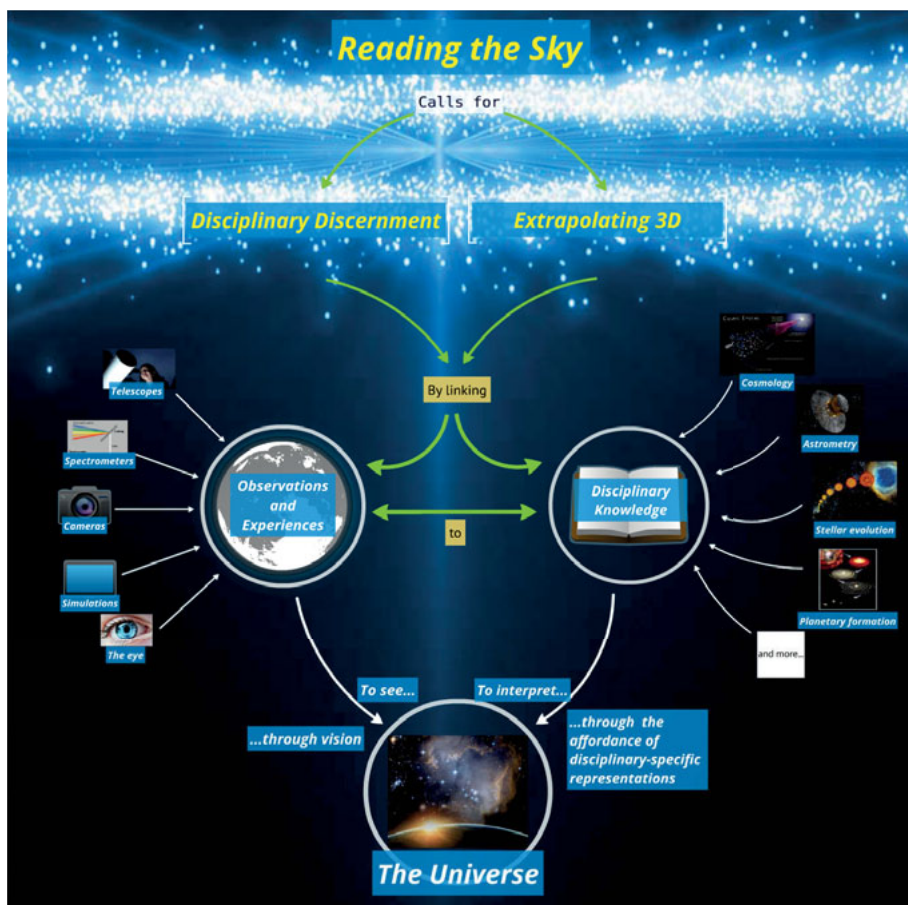


Figure 14.5. Concept map som illustrerar begreppet *Reading the Sky*.

References

- Adams, J. P., & Slater, T. F. (2000). Astronomy in the national science education standards. *Journal of Geoscience Education*, 48(1), 39–45.
- Agan, L. (2004). Stellar ideas: Exploring students' understanding of stars. *Astronomy Education Review*, 3(1), 77-97.
- Aigrain, S., Favata, F., & Gilmore, G. (2004, February). Characterising stellar micro-variability for planetary transit searches. *A&A*, 414, 1139.
- Ainsworth, S. (2006). Deft: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, 16(3), 183–198.
- Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (Vol. 3, p. 191-208). Springer Netherlands.
- Ainsworth, S., & Labeke, N. V. (2004). Multiple forms of dynamic representation. *Learning and Instruction*, 14(3), 241 - 255.
- Airey, J. (2009). *Science, language and literacy – case studies of learning in swedish university physics*. Unpublished doctoral dissertation, Uppsala University.
- Airey, J., & Eriksson, U. (2014a). A semiotic analysis of the disciplinary affordances of the hertzsprung-russell diagram in astronomy. In *The 5th international 360 conference: Encompassing the multimodality of knowledge* (p. 22). Aarhus, Denmark: Aarhus University.
- Airey, J., & Eriksson, U. (2014b). What do you see here? Using an analysis of the Hertzsprung-Russell diagram in astronomy to create a survey of disciplinary discernment. In (pp. 52–53). Lund, Sweden: The first Conference of the International Association for Cognitive Semiotics.
- Airey, J., Eriksson, U., Fredlund, T., & Linder, C. (2014a). The concept of disciplinary affordance. In *The 5th international 360 conference: Encompassing the multimodality of knowledge*. Aarhus, Denmark: Aarhus University.
- Airey, J., Eriksson, U., Fredlund, T., & Linder, C. (2014b). On the disciplinary affordances of semiotic resources. In *Book of abstracts : The first conference of the international association for cognitive semiotics (iacs), september 25-27, 2014 lund university* (pp. 54–55).
- Airey, J., & Linder, C. (2009). A disciplinary discourse perspective on university science learning: Achieving fluency in a critical constellation of modes. *Journal of Research in Science Teaching*, 46(1), 27-49.
- Allen, C. W., & Cox, A. N. (2000). *Allen's astrophysical quantities*. Springer.
- Allie, S., Armien, M. N., Burgoyne, N., Case, J. M., Collier-Reed, B. I., Craig, T. S., ... Wolmarans, N. (2009). Learning as acquiring a discursive identity through

- participation in a community: improving student learning in engineering education. *European Journal of Engineering Education*, 34(4), 359-367.
- Andersen, J. (1991). Accurate masses and radii of normal stars. *A&A Rev.*, 3, 91-126.
- Anderson, K. C., & Leinhardt, G. (2002). Maps as representations: Expert novice comparison of projection understanding. *Cognition and Instruction*, 20(3), 283-321.
- Arons, A. B. (1982). Phenomenology and logical reasoning in introductory physics courses. *American Journal of Physics*, 50(1), 13-20.
- Arons, A. B. (1997). *Teaching introductory physics*. New York: John Wiley & Sons.
- Atwood, R. K., & Atwood, V. A. (1996). Preservice elementary teachers' conceptions of the causes of seasons. *Journal of Research in Science Teaching*, 33(5), 553-563.
- Ausubel, D. P., Novak, J. D., & Hanesian, H. (1978). *Educational psychology: A cognitive view*. New York: Rinehart & Winston.
- Bachelard, G. (1994). The poetics of space: The classic look at how we experience intimate spaces. *Trans. Maria Jolas. Boston: Beacon Press*.
- Baglin, A., Auvergne, M., Barge, P., Buey, J.-T., Catala, C., Michel, E., . . . COROT Team (2002, January). COROT: asteroseismology and planet finding. In B. Battrick, F. Favata, I. W. Roxburgh, & D. Galadi (Eds.), *Stellar structure and habitable planet finding* (Vol. 485, p. 17-24).
- Bailey, J. M. (2011). *Astronomy education research: Developmental history of the field and summary of the literature*.
- Bailey, J. M., Coble, K., Cochran, G., Larrieu, D., Sanchez, R., & Cominsky, L. R. (2012). A multi-institutional investigation of students' preinstructional ideas about cosmology. *Astronomy Education Review*, 11(1), 010302-21.
- Bailey, J. M., Johnson, B., Prather, E. E., & Slater, T. F. (2012). Development and validation of the star properties concept inventory. *International Journal of Science Education*, 34(14), 2257-2286.
- Bailey, J. M., Prather, E., & Slater, T. (2004). Reflecting on the history of astronomy education research to plan for the future. *Advances in Space Research*, 34(10), 2136 - 2144.
- Bailey, J. M., Prather, E. E., Johnson, B., & Slater, T. F. (2009). College students' preinstructional ideas about stars and star formation. *Astronomy Education Review*, 8(1), 010110-17.
- Bailey, J. M., & Slater, T. F. (2003). A review of astronomy education research. *Astronomy Education Review*, 2(2), 20-45.
- Bailey, J. M., Slater, T. F., & Slater, S. J. (2010). *Conducting astronomy education research: A primer*. Macmillan.
- Bakas, C., & Mikropoulos, T. (2003). Design of virtual environments for the comprehension of planetary phenomena based on students' ideas. *International Journal of Science Education*, 25(8), 949-967.
- Barab, S. A., Hay, K. E., Barnett, M., & Keating, T. (2000). Virtual solar system

- project: Building understanding through model building. *Journal of Research in Science Teaching*, 37(7), 719-756.
- Barnes, D. G., & Fluke, C. J. (2008). Incorporating interactive three-dimensional graphics in astronomy research papers. *New Astronomy*, 13(8), 599 - 605.
- Barnett, M., MaKinster, J. G., & Hansen, J. A. (2001). *Exploring elementary students' learning of astronomy through model building-modeling the solar system*.
- Barnett, M., & Morran, J. (2002). Addressing children's alternative frameworks of the moon's phases and eclipses. *International Journal of Science Education*, 24(8), 859-879.
- Barnett, M., Yamagata-Lynch, L., Keating, T., Barab, S. A., & Hay, K. E. (2005). Using virtual reality computer models to support student understanding of astronomical concepts. *Journal of Computers in Mathematics and Science Teaching*, 24(4), 333-356.
- Basit, T. N. (2003). Manual or electronic? the role of coding in qualitative data analysis. *Educational Research*, 45(2), 143-154.
- Baxter, J. H. (1989). Children's understanding of familiar astronomical events. *International Journal of Science Education*, 11(5), 502-513.
- Baxter, J. H., & Preece, P. F. (2000). A comparison of dome and computer planetaria in the teaching of astronomy. *Research in Science and Technological Education*, 18(1), 63-69.
- Becker, N. M., & Cooper, M. M. (2014). College chemistry students' understanding of potential energy in the context of atomic-molecular interactions. *Journal of Research in Science Teaching*, 51(6), 789-808.
- Beichner, R. J. (2009). An introduction to physics education research. In C. Henderson & K. A. Harper (Eds.), *Getting started in per* (Vol. 2). College Park, MD.
- Beilock, S., & Fischer, S. (2013). From cognitive science to physics education and back. In *Physics education research conference 2013* (p. 15-18). Portland, OR.
- Belokurov, V. A., & Evans, N. W. (2002, April). Astrometric microlensing with the GAIA satellite. *MNRAS*, 331, 649-665.
- Berg, T., & Brouwer, W. (1991). Teacher awareness of student alternate conceptions about rotational motion and gravity. *Journal of Research in Science Teaching*, 28(1), 3-18.
- Bernhard, J. (2010). Insightful learning in the laboratory: Some experiences from 10 years of designing and using conceptual labs. *European Journal of Engineering Education*, 35(3), 271-287.
- Biggs, J. B., & Collis, K. F. (1982). *Evaluating the quality of learning. the solo taxonomy*. New York: Academic Press.
- Binnendijk, L. (1960). *Properties of double stars; a survey of parallaxes and orbits*. Philadelphia, University of Pennsylvania Press.
- Blake, R., & Wilson, H. (2011). Binocular vision. *Vision Research*, 51(7), 754-770.
- Blanche, M. J. T., Blanche, M. T., Durrheim, K., & Painter, D. (2006). *Research in*

- practice: Applied methods for the social sciences*. Juta and Company Ltd.
- Blown, E., & Bryce, T. G. K. (2010). Conceptual coherence revealed in multi-modal representations of astronomy knowledge. *International Journal of Science Education*, 32(1), 31-67.
- Borne, K. D. (2010). Astroinformatics: data-oriented astronomy research and education. *Earth Science Informatics*, 3(1-2), 5-17.
- Bower, M. (2008). Affordance analysis—matching learning tasks with learning technologies. *Educational Media International*, 45(1), 3-15.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn*. Washington, DC: National Academy Press.
- Brierley, G., Fryirs, K., Cullum, C., Tadaki, M., Huang, H. Q., & Blue, B. (2013, 10). Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography*, 37(5), 601-621.
- Brookes, D. T. (2006). *The role of language in learning physics*. Unpublished doctoral dissertation, Rutgers University.
- Brookes, D. T., & Etkina, E. (2007). Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning. *Physical Review Special Topics-Physics Education Research*, 3(1), 010105.
- Brookes, D. T., & Etkina, E. (2009). “force,” ontology, and language. *Phys. Rev. ST Phys. Educ. Res.*, 5, American Physical Society.
- Bruner, J. S. (1960). *The process of education* [Book]. Harvard University Press.
- Bruner, J. S. (1961). The act of discovery. *Harvard educational review*.
- Bryce, T. G. K., & Blown, E. J. (2012a). Children’s concepts of the shape and size of the earth, sun and moon. *International Journal of Science Education*, 1-59.
- Bryce, T. G. K., & Blown, E. J. (2012b). The novice-expert continuum in astronomy knowledge. *International Journal of Science Education*, 34(4), 545-587.
- Butkevich, A. G., Berdyugin, A. V., & Teerikorpi, P. (2005, September). Statistical biases in stellar astronomy: the Malmquist bias revisited. *MNRAS*, 362, 321-330. doi: 10.1111/j.1365-2966.2005.09306.x
- Butler, T. (1998). Towards a hermeneutic method for interpretive research in information systems. *Journal of Information Technology (Routledge, Ltd.)*, 13(4), 285.
- Card, S. K., Mackinlay, J. D., & Shneiderman, B. (1999). *Readings in information visualization: using vision to think*. Morgan Kaufmann.
- Chandler, P., & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and Instruction*(8), 293-332.
- Chen, C.-H., Yang, J.-C., Shen, S., & Jeng, M.-C. (2007). A desktop virtual reality earth motion system in astronomy education. *Educational Technology & Society*, 10(3), 289–304.
- Christopherson, J. T. (1997). The growing need for visual literacy at the university. In *Visionquest: Journeys toward visual literacy*. Cheyenne, WY.
- Christy, J. W., Wellnitz, D. D., & Currie, D. G. (1983). Detection of double stars

- with the two-color refractometer. *Lowell Observatory Bulletin*, 9, 28-35.
- Cid, X. C., Lopez, R. E., & Lazarus, S. M. (2009). Issues regarding student interpretation of color as a third dimension on graphical representations [Journal Article]. *Journal of Geoscience Education*, 57(5), 372-378.
- Clark, D. L. (2014). An efficient astronomical image representation for solar system object searches. *Publications of the Astronomical Society of the Pacific*, 126(935), 70-78.
- Coble, K., Camarillo, C. T., Trouille, L. E., Bailey, J. M., Cochran, G. L., Nickerson, M. D., & Cominsky, L. R. (2013). Investigating student ideas about cosmology I: Distances and structure. *Astronomy Education Review*, 12(1), 010102.
- Cohen, C. A., & Hegarty, M. (2014). Visualizing cross sections: Training spatial thinking using interactive animations and virtual objects. *Learning and Individual Differences*, 33(0), 63 - 71.
- Comins, N. F. (2001). *Heavenly errors: Misconceptions about the real nature of the universe*. New York: Columbia University Press.
- Copernicus, N. (1543). *De revolutionibus orbitum coelestium*.
- Copernicus, N. (1966). *De revolutionibus orbium caelestium: libri vi. norimbergae, i. petreum, 1543*. Culture et Civilisation.
- Cornwell, T. (1989). The applications of closure phase to astronomical imaging. *Science*, 245(4915), 263-269.
- Cox, A. N. (2000). *Allen's astrophysical quantities, 4th ed.* AIP Press, 2000. Edited by Arthur N. Cox. ISBN: 0387987460.
- Cummings, K. (2011). A developmental history of physics education research. In *Second committee meeting on the status, contributions, and future directions of discipline-based education research*.
- Dalgarno, B., & Lee, M. J. W. (2010). What are the learning affordances of 3-d virtual environments? *British Journal of Educational Technology*, 41(1), Blackwell Publishing Ltd.
- Dall'Alba, G., & Barnacle, R. (2005). Embodied knowing in online environments. *Educational Philosophy and Theory*, 37(5), 719-744.
- Danby, J. M. A. (1988). *Fundamentals of celestial mechanics*. Richmond, Va., U.S.A. : Willmann-Bell, 1988. 2nd ed.
- Dart, B., & Boulton-Lewis, G. (1998). *Teaching and learning in higher education*. LLC, PO Box 605, Herndon, VA 20172-0605: Stylus Publishing.
- de Bruijne, J. (2012). Science performance of gaia, esa's space-astrometry mission. *Astrophysics and Space Science*, 341(1), 31-41.
- Dede, C. (1995). The evolution of constructivist learning environments: immersion in distributed virtual worlds. *Educational Technology*, 35(5), 46-52.
- de Guchteneire, P. (2006). *Code of conduct for social science research*. UNESCO. Retrieved from http://www.unesco.org/new/fileadmin/MULTIMEDIA/HQ/SHS/pdf/Soc_Sci_Code.pdf
- Denzin, N., & Lincoln, Y. S. (2011). *Qualitative research* (4th ed.). Los Angeles: Sage.

- Dewey, J. (1933). *How we think*, revised edition. *Boston: DC Heath.*
- Dewey, J. (1997). *How we think*. Courier Dover Publications.
- diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, 28, 900.
- Docktor, J. L., & Mestre, J. P. (2014). A synthesis of discipline-based education research in physics. *PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH*, 10(020119).
- D'Oliveira, T. C. (2004). Dynamic spatial ability: An exploratory analysis and a confirmatory study. *The International Journal of Aviation Psychology*, 14(1), 19-38.
- Dove, J. (2002). Does the man in the moon ever sleep? an analysis of student answers about simple astronomical events: A case study. *International Journal of Science Education*, 24(8), 823-834.
- Dravins, D., Lindgren, L., & Madsen, S. (1999, August). Astrometric radial velocities. I. Non-spectroscopic methods for measuring stellar radial velocity. *A&A*, 348, 1040-1051.
- Dreyfus, B. W., Gouvea, J., Geller, B. D., Sawtelle, V., Turpen, C., & Redish, E. F. (2014). Chemical energy in an introductory physics course for the life sciences. *American Journal of Physics*, 82(5), 403-411.
- Driver, R., & Erickson, G. L. (1983). Theories-in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education*, 10, 37-60.
- Dubois, D. (1998). *The competency casebook*. Amherst, MA: HRD, & Silver Spring MD: International Society for Performance Improvement.
- Duncan, J., & Duncan, N. (1988). (re)reading the landscape. *ENVIRONMENT AND PLANNING: SOCIETY & SPACE*, 6(2), 117-126.
- Duncan, N., & Duncan, J. (2010). Doing landscape interpretation. In D. Delyser, S. Herbert, & S. Aitkin (Eds.), *Handbook of qualitative research in human geography* (pp. 225-248). London: SAGE.
- Dunlop, J. (2000). How children observe the universe. *Publications of the Astronomical Society of Australia*, 17(2), 194-206.
- Eberbach, C., & Crowley, K. (2009). From everyday to scientific observation: How children learn to observe the biologist's world. *Review of Educational Research*, 79(1), 39-68.
- Eichhorn, H. (1988). The Development of the Overlapping-Plate Method. In S. Debarbat (Ed.), *Iau symp. 133: Mapping the sky: Past heritage and future directions* (p. 177).
- Elby, A. (2000). What students' learning of representations tells us about constructivism. *The Journal of Mathematical Behavior*, 19(4), 481-502.
- Engeström, Y. (1991). Non scolae sed vitae discimus: Toward overcoming the encapsulation of school learning. *Learning and Instruction*, 1(3), 243-259.
- Eriksson, U. (2007). *Stellar surface structures and the astrometric search for*

- exoplanets*. (Unpublished licentiate thesis, Lund University)
- Eriksson, U. (2011). Astronomi på distans. *Populär Astronomi*, 12(3), 38–40.
- Eriksson, U., & Lindegren, L. (2007). Limits of ultra-high-precision optical astrometry: Stellar surface structure. *Astronomy and Astrophysics*, 476(3), 1389 - 1400.
- Eriksson, U., Linder, C., & Airey, J. (2011). Watching the sky: new realizations, new meanings, and surprising aspects in university level astronomy. In *Science learning and citizenship: Proceedings of the esera 2011 conference*. Lyon, France.
- Eriksson, U., Linder, C., & Airey, J. (2014). Tell me what you see. Differences in what is discerned when professors and students view the same disciplinary semiotic resource. In *The 5th international 360 conference: Encompassing the multimodality of knowledge*. Aarhus, Denmark: Aarhus University.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2011). Watching the sky - new realizations, new meaning, and surprising aspects in university level astronomy. In *The Foundations and Frontiers of Physics Education Research (FFPER) conference*. Bar Harbor, Maine, USA.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2012). Who needs 3d when the universe is flat? In *Gordon Research Conference Astronomy's Discoveries and Physics Education*. Colby College, Waterville, ME, USA.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013a). Awareness of the three dimensional structure of the universe. In *The 21st Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*. University of the Western Cape, Bellville, South Africa.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013b). The overlooked challenge of learning to extrapolate three-dimensionality. In *The International Conference on Physics Education, ICPE*. Prague, Czech Republic.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2013c). What do teachers of astronomy need to think about? In *Nordic Physics Days*. Lund, Sweden.
- Eriksson, U., Linder, C., Airey, J., & Redfors, A. (2014). The Anatomy of Disciplinary Discernment: An argument for a spiral trajectory of learning in physics education. In *The First Conference of the International Association for Cognitive Semiotics (IACS)*. Lund, Sweden.
- Ertmer, P. A., & Newby, T. J. (1996). The expert learner: Strategic, self-regulated, and reflective. *Instructional science*, 24(1), 1-24.
- ESA. (1997, February). The Hipparcos and Tycho Catalogues (ESA 1997). *VizieR Online Data Catalog*, 1239.
- ESA. (2014). *Gaia mission*. European Space Agency. Retrieved 2014-10-20, from <http://www.cosmos.esa.int/web/gaia/science-performance>
- Etkina, E., Murthy, S., & Zou, X. (2006). Using introductory labs to engage students in experimental design. *American Journal of Physics*, 74(11), 979–986.
- Eyer, L., & Grenon, M. (1997). Photometric Variability in the HR Diagram. In *Esa sp-402: Hipparcos - venice '97* (p. 467-472).
- Favia, A., Comins, N. F., & Thorpe, G. L. (2013). The elements of item response

- theory and its framework in analyzing introductory astronomy college student misconceptions. I. Galaxies. *arXiv:1206.2303 [physics.ed-ph]*.
- Favia, A., Comins, N. F., Thorpe, G. L., & Batuski, D. J. (2014). A direct examination of college student misconceptions in astronomy: A new instrument. *J Rev Astron Educ Outreach*, 1(1), A21-A39.
- Fekel, F. C., Henry, G. W., Baliunas, S. L., & Donahue, R. A. (2004, January). Variability in a Large Sample of Sun-Like Stars. In A. K. Dupree & A. O. Benz (Eds.), *IAU Symposium* (p. 269).
- Fendler, L. (2003). Teacher reflection in a hall of mirrors: Historical influences and political reverberations. *Educational researcher*, 32(3), 16–25.
- Fischer, D. A., Howard, A. W., Laughlin, G. P., Macintosh, B., Mahadevan, S., Sahlmann, J., & Yee, J. C. (2014). Exoplanet detection techniques.
- Flückiger, M. (1974). *Albert einstein in bern, switzerland*. Verlag Paul Haupt Bern.
- Fraser, D., & Linder, C. (2009). Teaching in higher education through the use of variation: Examples from distillation, physics and process dynamics. *European Journal of Engineering Education*, 34(4), 369–381.
- Fredlund, T., Airey, J., & Linder, C. (2012). Exploring the role of physics representations: an illustrative example from students sharing knowledge about refraction. *European Journal of Physics*, 33(3), 657.
- Fredlund, T., Airey, J., & Linder, C. (2013). Att välja lämpliga semiotiska resurser. In E. Lundqvist, R. Säljö, & L. Östman (Eds.), *Scientific literacy: teori och praktik* (pp. 59–70). Gleerups.
- Freedman, R. A., Geller, R. M., & Kaufmann, W. J. (2010). *Universe* (9th ed.). New York: W. H. Freeman.
- Fricke, W., Schwan, H., Lederle, T., Bastian, U., Bien, R., Burkhardt, G., . . . Walter, H. G. (1988). Fifth fundamental catalogue (FK5). Part 1: The basic fundamental stars. *Veroeffentlichungen des Astronomischen Rechen-Instituts Heidelberg*, 32, 1-106.
- Frink, S., Quirrenbach, A., Fischer, D., Röser, S., & Schilbach, E. (2001, February). A Strategy for Identifying the Grid Stars for the Space Interferometry Mission. *PASP*, 113, 173.
- Gadamer, H. G. (2004). *Truth and method* (2nd ed.). Great Britain: Continuum Publishing Group.
- Gardner, H. (1993). *Frames of mind: The theory of multiple intelligences (tenth-anniversary ed.)*. New York: Basic Books.
- Geertz, C. (1973). *The interpretation of cultures: Selected essays* (Vol. 5019). Basic books.
- Gerjets, P., Scheiter, K., & Catrambone, R. (2004). Designing instructional examples to reduce intrinsic cognitive load: Molar versus modular presentation of solution procedures. *Instructional science*, 32(1), 33-58.
- Gibson, J. J. (1950). *The perception of the visual world*.
- Gibson, J. J. (1977). *The theory of affordances*. Hillsdale, NJ: Erlbaum.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA:

- Houghton Mifflin.
- Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (Vol. 3, p. 3-24). Springer Netherlands.
- Glaser, B. G., & Strauss, A. (1967). *Discovery of grounded theory. strategies for qualitative research*.
- Gooding, D. C. (2006). From phenomenology to field theory: Faraday's visual reasoning. *Perspectives on Science*, 14(1), 40–65.
- Goodwin, C. (1994). Professional vision. *American anthropologist*, 96(3), 606-633.
- Gould, A., Ford, E. B., & Fischer, D. A. (2003, July). Early-Type Stars: Most Favorable Targets for Astrometrically Detectable Planets in the Habitable Zone. *ApJ*, 591, L155-L158.
- Gray, D. F. (2005). *The Observation and Analysis of Stellar Photospheres, 3rd Edition*. ISBN 0521851866. Cambridge, UK: Cambridge University Press.
- Gray, R. O. N. (2014). The distinction between experimental and historical sciences as a framework for improving classroom inquiry. *Science Education*, 1-15.
- Gregory, R. L. (1966). *The eye and the brain*. New York: McGraw-Hill Book Company.
- Guba, E. G., & Lincoln, Y. S. (1989). *Fourth generation evaluation*. Newbury Park, CA: Sage.
- Gunn, J. E., Siegmund, W. A., Mannery, E. J., Owen, R. E., Hull, C. L., Leger, R. F., ... Wang, S.-i. (2006, April). The 2.5 m Telescope of the Sloan Digital Sky Survey. *AJ*, 131, 2332-2359.
- Halbwachs, J. L., & Pourbaix, D. (2005, January). Astrometric Binaries with a Variable Component. In C. Turon, K. S. O'Flaherty, & M. A. C. Perryman (Eds.), *Esa sp-576: The three-dimensional universe with gaia* (p. 575).
- Halbwachs, J.-L., & Pourbaix, D. (2007, August). Gaia Treatment of Astrometric Binaries with a Variable Component: VIM, VIMA, VIMO. In *Iau symposium* (Vol. 240, p. 267).
- Halliday, J., M. A. K. (1978). *Language as social semiotic: the social interpretation of language and meaning*. London: Edward Arnold.
- Hammer, D., & Berland, L. K. (2014). Confusing claims for data: A critique of common practices for presenting qualitative research on learning. *Journal of the Learning Sciences*(ahead-of-print), 1-10.
- Hansen, J. A., Barnett, M., MaKinster, J. G., & Keating, T. (2004a). The impact of three-dimensional computational modeling on student understanding of astronomical concepts: a quantitative analysis. *International Journal of Science Education*, 26(11), 1378.
- Hansen, J. A., Barnett, M., MaKinster, J. G., & Keating, T. (2004b). The impact of three-dimensional computational modeling on student understanding of astronomy concepts: a qualitative analysis. *International Journal of Science Education*, 26(13), 1575.
- Hanson, R., & Murdin, P. (2000). Parallaxes. *Encyclopedia of Astronomy and*

Astrophysics.

- Hansson, L., & Redfors, A. (2006). Swedish upper secondary students' views of the origin and development of the universe. *Research in Science Education*, 36(4), 355–379.
- Hansson, L., & Redfors, A. (2007). Upper secondary students in group discussions about physics and our presuppositions of the world. *Science & Education*, 16(9-10), 1007–1025.
- Hansson, L., & Redfors, A. (2013). Lower secondary students' views in astrobiology. *Research in Science Education*, 1–22.
- Hattie, J. (2009). *Visible learning : a synthesis of over 800 meta-analyses relating to achievement*. London: Routledge.
- Hattie, J. (2012). *Visible learning for teachers : Maximizing impact on learning*. Florence, KY, USA: Routledge.
- Hatton, N., & Smith, D. (1995). Reflection in teacher education: Towards definition and implementation. *Teaching and teacher education*, 11(1), 33–49.
- Hatzes, A. P. (2002). Starspots and exoplanets. *AN*, 323, 392-394.
- Hazelton, R. L. C., Shaffer, P. S., & Heron, P. R. L. (2013, July 17-18). Assessing the impact of a computer simulation in conjunction with tutorials in introductory physics on conceptual understanding. In P. V. Engelhardt, A. D. Churukian, & D. L. Jones (Eds.), *Perc proceedings*. Portland, OR.
- Hedberg, J., & Alexander, S. (1994). Virtual reality in education: Defining researchable issues. *Educational Media International*, 31(4), 214–220.
- Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in cognitive science*, 3(3), 446-474.
- Hegarty, M. (2014). Spatial thinking in undergraduate science education. *Spatial Cognition and Computation*.
- Hegarty, M., Keehner, M., Cohen, C., Montello, D. R., & Lippa, Y. (2007). The role of spatial cognition in medicine: Applications for selecting and training professionals. *Applied spatial cognition*, 285–315.
- Hekker, S., Reffert, S., Quirrenbach, A., Mitchell, D. S., Fischer, D. A., Marcy, G. W., & Butler, R. P. (2006, August). Precise radial velocities of giant stars. I. Stable stars. *A&A*, 454, 943.
- Henry, G. W., Donahue, R. A., & Baliunas, S. L. (2002, October). A False Planet around HD 192263. *ApJ*, 577, L111-L114.
- Heyer, I., Slater, S., & Slater, T. (2013). Establishing the empirical relationship between non-science majoring undergraduate learners' spatial thinking skills and their conceptual astronomy knowledge [Journal Article]. *Revista Latino-Americana de Educação em Astronomia - RELEA*(16), 45-61.
- Heywood, D., Parker, J., & Rowlands, M. (2013). Exploring the visuospatial challenge of learning about day and night and the sun's path. *Science Education*, 97(5), 772-796.
- Hoskin, M. (1996). *The cambridge illustrated history of astronomy*. Cambridge: Cambridge University Press.

- Hoskin, M. (1999). *The cambridge concise history of astronomy*. Cambridge: Cambridge University Press.
- Hoskinson, A.-M., Couch, B. A., Zwickl, B. M., Hinko, K. A., & Caballero, M. D. (2014). Bridging physics and biology teaching through modeling. *American Journal of Physics*, 82(5), 434-441.
- Howard, I. P. (2002). *Seeing in depth, vol. 1: Basic mechanisms*. Toronto, ON, Canada: University of Toronto Press.
- Hubona, G., Wheeler, P., Shirah, G., & Brandt, M. (1999). The relative contributions of stereo, lighting, and background scenes in promoting 3d depth visualization. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 6(3), 214-242.
- Hudgins, D. W., Prather, E. E., Grayson, D. J., & Smits, D. P. (2006). Effectiveness of collaborative ranking tasks on student understanding of key astronomy concepts. *Astronomy Education Review*, 5(1), 1-22.
- Hunt, E., Pellegrino, J. W., Frick, R. W., Farr, S. A., & Alderton, D. (1988). The ability to reason about movement in the visual field. *Intelligence*, 12(1), 77-100.
- Ingerman, Å., Linder, C., & Marshall, D. (2009). The learners' experience of variation: following students' threads of learning physics in computer simulation sessions. *Instructional science*, 37(3), 273-292.
- Ingerman, Å., Linder, C., Marshall, D., & Booth, S. (2007). Learning and the variation in focus among physics students when using a computer simulation. *NorDiNa*, 3(1), 3.
- Isik-Ercan, Z., Zeynep Inan, H., Nowak, J. A., & Kim, B. (2012). 'we put on the glasses and moon comes closer!' urban second graders exploring the earth, the sun and moon through 3d technologies in a science and literacy unit. *International Journal of Science Education*, 1-28.
- Itza-Ortiz, S. F., Rebello, N. S., Zollman, D. A., & Rodriguez-Achach, M. (2003). The vocabulary of introductory physics and its implications for learning physics. *The Physics Teacher*, 41(6), 330-336.
- Jackson, E. (1891). *The earth in space - a manual of astronomical geography*. Boston: D.C.: Heath and Co.
- Jewitt, C. (2003). Re-thinking assessment: Multimodality, literacy and computer-mediated learning. *Assessment in Education: Principles, Policy and Practice*, 10(1), 83-102.
- Jimoyiannis, A., & Komis, V. (2001, February). Computer simulations in physics teaching and learning: A case study on students' understanding of trajectory motion. *Comput. Educ.*, 36(2), 183-204.
- Jones, B. L., Lynch, P. P., & Reesink, C. (1987). Children's conceptions of the earth, sun and moon. *International Journal of Science Education*, 9(1), 43-53.
- Jorissen, A., Mowlavi, N., Sterken, C., & Manfroid, J. (1997, August). The onset of photometric variability in red giant stars. *A&A*, 324, 578.
- Joseph, N. M. (2011). *Stereoscopic visualization as a tool for learning astronomy concepts*. Unpublished doctoral dissertation.
- Kali, Y., & Orion, N. (1996). Spatial abilities of high-school students in the

- perception of geologic structures. *Journal of Research in Science Teaching*, 33, 369-391.
- Kalleberg, R., Balto, A., Cappelen, A., Nagel, A.-H., Nymoen, H. S., Rønning, H., ... Vandvik, B. (2010, September). *Research ethics guidelines for internet research* (Tech. Rep.). Norway: National Committee for Research Ethics in the Social sciences and the Humanities (NESH). Retrieved 26 aug. 2014, from <https://www.etikkom.no/no/In-English/Publications/Internet-research-/>
- Karlsson, A., d'Arcio, L., den Hartog, R., & Fridlund, M. (2006, July). Darwin: a mission overview. In *Space telescopes and instrumentation i: Optical, infrared, and millimeter*. ed. mather, john c.; macewen, howard a.; de graauw, mattheus w. m.. *proc. spie*, vol. 6265, 62651o (2006). (Vol. 6265).
- Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. (1993, January). Habitable Zones around Main Sequence Stars. *Icarus*, 101, 108-128.
- Keating, T., Barnett, M., Barab, S. A., & Hay, K. E. (2002). The virtual solar system project: Developing conceptual understanding of astronomical concepts through building three-dimensional computational models. *Journal of Science Education and Technology*, 11(3), 261-275.
- Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation spatial ability's unique role. *Psychological Science*, 24(9), 1831-1836.
- Kerski, J. J. (2008, January). Developing spatial thinking skills in education and society. *ArcWatch: Your e-Magazine for GIS News, Views, and Insights*.
- Khatri, R., Henderson, C. R., Cole, R., & Froyd, J. (2013, July 17-18). Over one hundred million simulations delivered: A case study of the phet interactive simulations. In P. V. Engelhardt, A. D. Churukian, & D. L. Jones (Eds.), *Perc proceedings*. Portland, OR,.
- Kikas, E. (1998). Pupils' explanations of seasonal changes: age differences and the influence of teaching. *British Journal of Educational Psychology*, 68(4), 505-516.
- Koch, D. G., Borucki, W., Dunham, E., Geary, J., Gilliland, R., Jenkins, J., ... Weiss, M. (2004, October). Overview and status of the Kepler Mission. In J. C. Mather (Ed.), *Optical, infrared, and millimeter space telescopes. proc. spie*, (2004) (Vol. 5487, p. 1491).
- Koch, D. G., Borucki, W. J., Basri, G., Batalha, N. M., Brown, T. M., Caldwell, D., ... others (2010). Kepler mission design, realized photometric performance, and early science. *The Astrophysical Journal Letters*, 713(2), L79.
- Koedinger, K., & Anderson, J. (1990). Abstract planning and perceptual chunks: Elements of expertise in geometry. *Cognitive Science*, 14, 511-550.
- Kohl, P. B., & Finkelstein, N. D. (2008). Patterns of multiple representation use by experts and novices during physics problem solving. *Physical Review Special Topics-Physics Education Research*, 4(1), 010111.
- Kohl, P. B., Rosengrant, D., & Finkelstein, N. (2007a). Comparing explicit and implicit teaching of multiple representation use in physics problem solving. In *2006 physics education research conference* (Vol. 883, pp. 145-148).

- Kohl, P. B., Rosengrant, D., & Finkelstein, N. D. (2007b). Strongly and weakly directed approaches to teaching multiple representation use in physics. *Physical Review Special Topics-Physics Education Research*, 3(1), 010108.
- Kohnle, A., Baily, C., Hooley, C., & Torrance, B. (2013, July 17-18). Optimization of simulations and activities for a new introductory quantum mechanics curriculum. In P. V. Engelhardt, A. D. Churukian, & D. L. Jones (Eds.), *Perc proceedings*. Portland, OR.
- Kontogeorgiou, A. M., Bellou, J., & Mikropoulos, T. (2008). Being inside the quantum atom. *PsychNology Journal*, 6(1), 83-98.
- Kopeikin, S., & Gwinn, C. (2000). Sub-Microarcsecond Astrometry and New Horizons in Relativistic Gravitational Physics. In K. J. Johnston, D. D. McCarthy, B. J. Luzum, & G. H. Kaplan (Eds.), *Iau colloq. 180: Towards models and constants for sub-microarcsecond astrometry* (p. 303).
- Koponen, I. T., & Mäntylä, T. (2006). Generative role of experiments in physics and in teaching physics: A suggestion for epistemological reconstruction. *Science & Education*, 15(1), 31–54.
- Kovalevsky, J., Mueller, I. I., & Kolaczek, B. (1989). Reference frames in astronomy and geophysics. In *Reference frames* (Vol. 154).
- Kovalevsky, J., & Seidelmann, P. (2004). *Fundamentals of Astrometry*. ISBN 0521828724. Cambridge, UK: Cambridge University Press, 2004.
- Kozhevnikov, M., Hegarty, M., & Mayer, R. (2002). Spatial abilities in problem solving in kinematics. In M. Anderson, B. Meyer, & P. Olivier (Eds.), *Diagrammatic representation and reasoning* (pp. 155–171). Berlin: Springer-Verlag Inc.
- Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & cognition*, 33(4), 710-726.
- Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. *Journal of Science Education and Technology*, 15(1), 111–132.
- Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *The Journal of the Learning Sciences*, 9(2), 105–143.
- Kress, G. (2009). *Multimodality: A social semiotic approach to contemporary communication*. Routledge.
- Kress, G. (2010). *Multimodality - a social semiotic approach to contemporary communication*.
- Kress, G., Jewitt, C., Ogborn, J., & Tsatsarelis, C. (2001). *Multimodal teaching and learning: The rhetorics of the science classroom*. London: Continuum.
- Kress, G., & van Leeuwen, T. (2001). *Multimodal discourse: The modes and media of contemporary communication*. London: Edward Arnold.
- Kuhn, T. S. (1970). *The structure of the scientific revolutions*. University of Chicago Press.

- Lachaume, R. (2003). On marginally resolved objects in optical interferometry. *A&A*, 400, 795-803.
- Lanza, A. F., Rodonò, M., & Pagano, I. (2004). Multiband modelling of the Sun as a variable star from VIRGO/SoHO data. *A&A*, 425, 707.
- Latour, B. (1986). Visualization and cognition. *Knowledge and society*, 6, 1–40.
- Latour, B., & Woolgar, S. (1979). *Laboratory life: The social construction of scientific facts*. Princeton University Press.
- Law, D. J., Pellegrino, J. W., Mitchell, S. R., Fischer, S. C., McDonald, T. P., & Hunt, E. B. (1993). Perceptual and cognitive factors governing performance in comparative arrival-time judgments. *Journal of Experimental Psychology: Human Perception and Performance*, 19(6), 1183-1199.
- Lee, B. (2013, April). Three-dimensional displays, past and present. *Physics Today*, 36(66), 4.
- Lelliott, A., & Rollnick, M. (2010). Big ideas: A review of astronomy education research 1974–2008. *International Journal of Science Education*, 32(13), 1771–1799.
- Lemke, J. (1990). *Talking science: Language, learning and values*. Norwood, NJ: Ablex.
- Lemke, J. (1995). Intertextuality and text semantics. In P. Fries & M. G. (Eds.) (Eds.), *Discourse in society: Systemic functional perspectives. meaning and choice in language* (pp. 85–114). NJ: Ablex.
- Lemke, J. (1998). *Teaching all the languages of science: Words, symbols, images, and actions* (Vol. 13; Tech. Rep.). Brooklyn College, City University of New York: School of Education, Brooklyn College.
- Lemke, J. (2001). Articulating communities: Sociocultural perspectives on science education. *Journal of research in science teaching*, 38(3), 296–316.
- Lemke, J. (2005). Multiplying meaning. *Reading science: Critical and functional perspectives on discourses of science*, 87–114.
- Lemke, J. (2007). Video epistemology in-and outside the box: Traversing attentional spaces. *Video research in the learning sciences*, 427–460.
- Lemke, J. (2009). Multimodality, identity, and time. *The Routledge handbook of multimodal analysis*, 140–150.
- Lena, P., Lebrun, F., & Mignard, F. (1998). *Observational astrophysics. 2nd rev. and enl. ed.* Heidelberg, Germany: Springer-Verlag Inc.
- Lesgold, A., Robinson, H., Feltovich, P., Glaser, R., Klopfer, D., & Wang, Y. (1988). Expertise in a complex skill: Diagnosing x-ray pictures [Book Section]. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (p. 311-342). Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.
- Leverington, D. (2013). *Encyclopedia of the history of astronomy and astrophysics*. New York: Cambridge University Press.
- Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry* (Vol. 75). Sage Publications, Incorporated.
- Lindegren, L. (1978). Photoelectric astrometry - A comparison of methods for

- precise image location. In F. V. Prochazka & R. H. Tucker (Eds.), *Iau colloq. 48: Modern astrometry* (p. 197-217).
- Lindegren, L. (1980, September). Atmospheric limitations of narrow-field optical astrometry. *A&A*, 89, 41-47.
- Lindegren, L. (2005, January). The Astrometric Instrument of Gaia: Principles. In C. Turon, K. S. O'Flaherty, & M. A. C. Perryman (Eds.), *Esa sp-576: The three-dimensional universe with gaia* (p. 29).
- Linder, C. (1992a). Is teacher-reflected epistemology a source of conceptual difficulty in physics? *International Journal of Science Education*, 14(1), 111-121.
- Linder, C. (1992b). Understanding sound: so what is the problem? *Physics Education*, 27(5), 258.
- Linder, C. (2013). Disciplinary discourse, representation, and appresentation in the teaching and learning of science [Journal Article]. *European Journal of Science and Mathematics Education*, 1(2), 43-49.
- Linder, C., Airey, J., Mayaba, N., & Webb, P. (2014). Fostering disciplinary literacy? south african physics lecturers' educational responses to their students' lack of representational competence. *African Journal of Research in Mathematics, Science and Technology Education*.
- Linder, C., & Marshall, D. (2003). Reflection and phenomenography: towards theoretical and educational development possibilities. *Learning and Instruction*, 13(3), 271 - 284.
- Lindgren, R., & Schwartz, D. L. (2009). Spatial learning and computer simulations in science. *International Journal of Science Education*, 31(3), 419-438.
- Lindgren, R., Tscholl, M., & Moshell, J. M. (2013, July 17-18). Meteor: Developing physics concepts through body-based interaction with a mixed reality simulation. In P. V. Engelhardt, A. D. Churukian, & D. L. Jones (Eds.), *Perc proceedings*. Portland, OR.
- Lindstrøm, C., & Sharma, M. D. (2009). Link maps and map meetings: Scaffolding student learning. *Physical Review Special Topics-Physics Education Research*, 5(1), 010102.
- Ling, L. M. (2011). *Variation theory and the improvement of teaching and learning*. Göteborg: Acta Universitatis Gothoburgensis.
- Ling, L. M., & Marton, F. (2011). Towards a science of the art of teaching: using variation theory as a guiding principle of pedagogical design. *International Journal for Lesson and Learning Studies*, 1(1), 7-22.
- Linn, M., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta- analysis [Journal Article]. *Child Development*, 56, 1479-1498.
- Lipşa, D. R., Laramée, R. S., Cox, S. J., Roberts, J. C., Walker, R., Borkin, M. A., & Pfister, H. (2012). Visualization for the physical sciences. *Computer Graphics Forum*, 31(8), 2317-2347.
- Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction*, 13, 157-176.

- Ludwig, H.-G. (2006). Hydrodynamical simulations of convection-related stellar micro-variability i. statistical relations for photometric and photocentric variability. *A&A*, 445, 661-671.
- Ludwig, H.-G., & Beckers, J. (2008). Towards the interferometric imaging of red supergiants. In A. Richichi, F. Delplancke, F. Paresce, & A. Chelli (Eds.), *The power of optical/IR interferometry: Recent scientific results and 2nd generation VLTI instrumentation* (p. 602). Springer.
- Lutz, T. E., & Kelker, D. H. (1973, October). On the Use of Trigonometric Parallaxes for the Calibration of Luminosity Systems: Theory. *PASP*, 85, 573.
- Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., ... Charlot, P. (1998, July). The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry. *AJ*, 116, 516-546.
- Magntorn, O. (2007). *Reading nature - developing literacy through teaching*. Unpublished doctoral dissertation.
- Makarov, V. V., Beichman, C. A., Catanzarite, J. H., Fischer, D. A., Lebreton, J., Malbet, F., & Shao, M. (2009). Starspot Jitter in Photometry, Astrometry, and Radial Velocity Measurements. *ApJ*, 707, L73-L76.
- Mant, J. (1995). A survey of british primary school teachers' understanding of the earth's place in the universe. *Educational Research*, 37(1), 3-19.
- Mant, J., & Summers, M. (1993). Some primary,Äschool teachers' understanding of the earth's place in the universe. *Research Papers in Education*, 8(1), 101-129.
- Maries, A. (2013). *Role of multiple representations in physics problem solving*. Phd dissertation, University of Pittsburg.
- Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, 200(1140), pp. 269-294.
- Martin, B., & Brouwer, W. (1992). The subjective side of science.
- Marton, F. (2014). *Necessary conditions of learning*. Routledge.
- Marton, F., & Booth, S. (1997). *Learning and awareness*. Lawrence Erlbaum Associates.
- Marton, F., & Pang, M. F. (2013). Meanings are acquired from experiencing differences against a background of sameness, rather than from experiencing sameness against a background of difference: Putting a conjecture to the test by embedding it in a pedagogical tool. *Frontline Learning Research*, 1.
- Marton, F., & Trigwell, K. (2000). Variatio est mater studiorum. *Higher Education Research & Development*, 19(3), 381-395.
- Marton, F., & Tsui, A. (2004). *Classroom discourse and the space of learning*. Mahwah: Lawrence Erlbaum.
- Mason, J. (2002). *Researching your own practice : the discipline of noticing* [Book]. London: Routledge Farmer.
- Mayer, R. E. (2003). The promise of multimedia learning: using the same instructional design methods across different media. *Learning and Instruction*, 13(2), 125 - 139.

- Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). New York: Cambridge University Press.
- Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, 38(1), 43-52.
- McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today*, 37(7), 24-32.
- McDermott, L. C., & Redish, E. F. (1999). Resource letter: Per-1: Physics education research. *American Journal of Physics*, 67(9), 755-767.
- McKagan, S., Perkins, K., Dubson, M., Malley, C., Reid, S., LeMaster, R., & Wieman, C. (2008, April). Developing and researching phet simulations for teaching quantum mechanics. *Am. J. Phys.*, 76(4), 406-417.
- Merali, Z. (2013). Did a hyper-black hole spawn the universe? *Nature News*.
- Merkt, M., Weigand, S., Heier, A., & Schwan, S. (2011). Learning with videos vs. learning with print: The role of interactive features. *Learning and Instruction*, 21(6), 687 - 704.
- Merriam, S. (2009). *Qualitative research: A guide to design and implementation*. San Francisco, CA: Jossey Bass.
- Merriam, S., & Associates. (2002). *Qualitative research in practice: Examples for discussion and analysis*. San Francisco, CA: Jossey-Bass.
- Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). *Computers & Education*, 56(3), 769-780.
- Miller, A. I. (1984). *Imagery in scientific thought: Creating 20th century physics*. Boston: Birkhauser.
- Miller, B. W., & Brewer, W. F. (2010). Misconceptions of astronomical distances. *International Journal of Science Education*, 32(12), 1549-1560.
- Mintz, R., Litvak, S., & Yair, Y. (2001). 3d-virtual reality in science education: An implication for astronomy teaching. *Journal of Computers in Mathematics and Science Teaching*, 20(3), 293-305.
- MODE. (2012). *Glossary of multimodal terms* (Vol. 2013) (Web Page No. Dec. 4). Retrieved from <http://multimodalityglossary.wordpress.com>
- Monnier, J. D. (2003a). Astrophysics with Closure Phases. In G. Perrin & F. Malbet (Eds.), *Eas publications series* (Vol. 6, p. 213).
- Monnier, J. D. (2003b, May). Optical interferometry in astronomy. *Rep. Prog. Phys.*, 66, 789-857.
- Montello, D. R. (1997). The perception and cognition of environmental distance: Direct sources of information. In *Spatial information theory a theoretical basis for gis* (pp. 297–311). Springer.
- Mulholland, J., & Ginns, I. (2008). College moon project australia: Preservice teachers learning about the moon's phases. *Research in Science Education*, 38(3), 385-399.
- Murray, C. A. (1983). *Vectorial astrometry*. Bristol: Adam Hilger.
- National Research Council. (2006). *Learning to think spatially: Gis as a support*

- system in the k-12 curriculum. The National Academies Press.
- National Research Council. (2012). *Discipline-based education research: Understanding and improving learning in undergraduate science and engineering*. Washington, DC: The National Academies Press.
- Nawrot, M., & Joyce, L. (2006). The pursuit theory of motion parallax. *Vision Research*, 46(28), 4709-4725.
- Newcombe, N. S., & Stieff, M. (2012). Six myths about spatial thinking. *International Journal of Science Education*, 34(6), 971.
- Nilsen, T. (2014). *Trends in physics competence – using timss for in-depth studies to characterize norwegian studetns’ physics competence and factors influencing and explaining changes in this competence*. Unpublished doctoral dissertation, Faculty of Educational Sciences, University of Oslo.
- Noce, G., Torosantucci, G., & Vicentini, M. (1988). The floating of objects on the moon: Prediction from a theory or experimental facts? *International Journal of Science Education*, 10(1), 61-70.
- Norman, D. A. (1988). *The psychology of everyday things*. Basic books.
- Northedge, A. (2002). Learning for life in the 21st century. sociocultural perspectives on the future of education. In G. Wells & G. Claxton (Eds.), . Oxford: Blackwell Publishers.
- NSB. (2014). *Science and engineering indicators 2014*. National Science Board. Retrieved from <http://www.nsf.gov/statistics/seind14/>
- Nussbaum, J. (1979). Children’s conceptions of the earth as a cosmic body: A cross age study. *Science Education*, 63(1), 83-93.
- Nussbaum, J., & Novak, J. D. (1976). An assessment of children’s concepts of the earth utilizing structured interviews. *Science Education*, 60(4), 535-550.
- Offerdahl, E. G., Prather, E. E., & Slater, T. F. (2002). Students’ pre-instructional beliefs and reasoning strategies about astrobiology concepts. *Astronomy Education Review*, 1, 5.
- Ojala, J. (1992). The third planet. *International Journal of Science Education*, 14(2), 191-200.
- Ojala, J. (1997). Lost in space? the concepts of planetary phenomena held by trainee primary school teachers. *International Research in Geographical and Environmental Education*, 6(3), 183-203.
- Orion, N., Ben-Chaim, D., & Kali, Y. (1997). Relationship between earth-science education and spatial visualization. *Journal of Geoscience Education*, 45, 129–132.
- Ornek, F. (2008). An overview of a theoretical framework of phenomenography in qualitative education research: An example from physics education research. In *Asia-pacific forum on science learning & teaching* (Vol. 9).
- Pallrand, G. J., & Seeber, F. (1984). Spatial ability and achievement in introductory physics. *Journal of Research in Science Teaching*, 21(5), 507–516.
- Panagiotaki, G., Nobes, G., & Potton, A. (2009). Mental models and other misconceptions in children’s understanding of the earth. *Journal of Experimental*

- Child Psychology*, 104(1), 52-67.
- Parker, J., & Heywood, D. (1998). The earth and beyond: developing primary teachers' understanding of basic astronomical events. *International Journal of Science Education*, 20(5), 503-520.
- Pasachoff, J. M. (2002). Pasachoff's points. *The Physics Teacher*, 40(4), 196-198.
- Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles concepts and evidence. *Psychological science in the public interest*, 9(3), 105-119.
- Patton, M. Q. (2002). Two decades of developments in qualitative inquiry a personal, experiential perspective. *Qualitative Social Work*, 1(3), 261-283.
- Paulson, D. B., Saar, S. H., Cochran, W. D., & Henry, G. W. (2004, March). Searching for Planets in the Hyades. III. The Quest for Short-Period Planets. *AJ*, 127, 1644-1652.
- Pena, B. M., & Gil Quilez, M. J. (2001). The importance of images in astronomy education. *International Journal of Science Education*, 23(11), 1125-1135.
- Perrin, G., & Malbet, F. (Eds.). (2003). *Observing with the VLT interferometer* (Vol. 6).
- Perryman, M. (2014). Resource letter exo-1: Exoplanets. *American Journal of Physics*, 82(6), 552-563.
- Perryman, M., de Boer, K. S., Gilmore, G., Høg, E., Lattanzi, M., Lindegren, L., . . . de Zeeuw, P. (2001). Gaia: Composition, formation and evolution of the galaxy. *arXiv preprint astro-ph/0101235*.
- Perryman, M. A. C. (2000). Extra-solar planets. *Reports of Progress in Physics*, 63, 1209-1272.
- Piaget, J. (1929). *The child's conception of the world*. London: Routledge/Kegan Paul.
- Piaget, J. (1930). *The child's conception of physical causality*. London: Routledge/Kegan Paul.
- Plummer, J. D. (2014). Spatial thinking as the dimension of progress in an astronomy learning progression. *Studies in Science Education*, 1-45.
- Plummer, J. D., & Maynard, L. (2014). Building a learning progression for celestial motion: An exploration of students' reasoning about the seasons. *Journal of Research in Science Teaching*, n/a-n/a.
- Podolefsky, N. S. (2013, July 17-18). Intentional design for empowerment. In P. V. Engelhardt, A. D. Churukian, & D. L. Jones (Eds.), *Perc proceedings*. Portland, OR.
- Podolefsky, N. S., Adams, W., Lancaster, K., & Perkins, K. (2010, July 21-22). Characterizing complexity of computer simulations and implications for student learning. In *Physics education research conference 2010* (Vol. 1289, p. 257-260). Portland, Oregon.
- Podolefsky, N. S., & Finkelstein, N. D. (2006). Use of analogy in learning physics: The role of representations. *Physical Review Special Topics-Physics Education Research*, 2(2), 020101.
- Podolefsky, N. S., & Finkelstein, N. D. (2008). How abstract is abstract? layering

- meaning in physics. In *Aip conference proceedings* (Vol. 1064, p. 167).
- Polanyi, M. (1965). The structure of consciousness. *Brain*, 88(4), 799-810.
- Pourbaix, D., Ivezić, Ž., Knapp, G. R., Gunn, J. E., & Lupton, R. H. (2004). Color-Induced Displacement double stars in SDSS. *A&A*, 423, 755-760.
- Pourbaix, D., Platais, I., Detournay, S., Jorissen, A., Knapp, G., & Makarov, V. V. (2003). How many Hipparcos Variability-Induced Movers are genuine binaries? *A&A*, 399, 1167-1175.
- Prain, V., Tytler, R., & Peterson, S. (2009). Multiple representation in learning about evaporation. *International Journal of Science Education*, 31(6), 787-808.
- Prather, E. (2005). Students' beliefs about the role of atoms in radioactive decay and half-life. *Journal of Geoscience Education*, 53(4), 345.
- Prather, E. E., Rudolph, A. L., & Brissenden, G. (2009). Teaching and learning astronomy in the 21st century. *Physics Today*, 62(10), 41-47.
- Prather, E. E., Slater, T. F., & Offerdahl, E. G. (2003). Hints of a fundamental misconception in cosmology. *Astronomy Education Review*, 1, 28.
- Price, A., & Lee, H.-S. (2010). The effect of two-dimensional and stereoscopic presentation on middle school students' performance of spatial cognition tasks. *Journal of Science Education and Technology*, 19(1), 90-103.
- Ptolemy, C. (1984). *Almagest* (G. J. Toomer, Ed.). Duckworth.
- Ptolemy, C. (2nd century C.E.) *Almagest*.
- Radick, R. R., Lockwood, G. W., Skiff, B. A., & Thompson, D. T. (1995). A 12 Year Photometric Study of Lower Main-Sequence Hyades Stars. *ApJ*, 452, 332.
- Ramadas, J. (2009). Visual and spatial modes in science learning. *International Journal of Science Education*, 31(3), 301-318.
- Rapp, D. N. (2005). Mental models: Theoretical issues for visualizations in science education. In *Visualization in science education* (p. 43-60). Springer.
- Rawlins, D. (1993). Tycho's 1004-star catalog. *DIO, the International Journal of Scientific History*, 3(1).
- Redish, E. F. (2003). *Teaching physics with the physics suite*. John Wiley & Sons Hoboken, NJ. (On line at <http://www2.physics.umd.edu/redish/Book/>)
- Richardson, A. (1977). Verbalizer-visualizer: A cognitive style dimension. *Journal of Mental Imagery*.
- Riegel, K. W. (1973). Light pollution outdoor lighting is a growing threat to astronomy. *Science*, 179(4080), 1285-1291.
- Roald, I., & Mikalsen, O. (2001). Configuration and dynamics of the earth-sun-moon system: an investigation into conceptions of deaf and hearing pupils. *International Journal of Science Education*, 23(4), 423-440.
- Roberts, D. A. (2007). Promoting scientific literacy: Science education research in transaction. In C. Linder, L. Östman, & P.-O. Wickman (Eds.), *Linnaeus tercentenary symposium*.
- Robson, C. (2011). *Real world research: a resource for users of social research methods in applied settings*. Wiley.
- Rockenfeller, B., Bailer-Jones, C. A. L., & Mundt, R. (2006). Variability and

- periodicity of field M dwarfs revealed by multichannel monitoring. *A&A*, 448, 1111.
- Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception*, 8(2), 125-134.
- Rosengrant, D., Etkina, E., & Van Heuvelen, A. (2007). An overview of recent research on multiple representations. In *2006 physics education research conference* (Vol. 883, pp. 149–152).
- Rosengrant, D., Van Heuvelen, A., & Etkina, E. (2006). Case study: Students' use of multiple representations in problem solving. In *2005 physics education research conference* (Vol. 818, pp. 49–52).
- Rundgren, C.-J., & Tibell, L. A. (2009). Critical features of visualizations of transport through the cell membrane-an empirical study of upper secondary and tertiary students' meaning-making of a still image and an animation. *International Journal of Science and Mathematics Education*, 8, 223-246.
- Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education*, 58(1), 136 - 153.
- Saar, S. H., Butler, R. P., & Marcy, G. W. (1998). Magnetic Activity-related Radial Velocity Variations in Cool Stars: First Results from the Lick Extrasolar Planet Survey. *ApJ*, 498, L153.
- Saar, S. H., & Donahue, R. A. (1997). Activity-related Radial Velocity Variation in Cool Stars. *ApJ*, 485, 319.
- Sadler, P. M. (1996). Astronomy's conceptual heirarchy [Conference Proceedings]. In J. R. Percy (Ed.), *Astronomical society of the pacific conference series* (Vol. 89, p. 46). Astronomical Society of the Pacific.
- Sadler, P. M. (1998). Psychometric models of student conceptions in science: Reconciling qualitative studies and distractor-driven assessment instruments. *Journal of Research in Science Teaching*, 35(3), 265-296.
- Sazhin, M. V., Zharov, V. E., & Kalinina, T. A. (2001). Parallax distortion by the weak microlensing effect. *MNRAS*, 323, 952-964.
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. detection, search, and attention. *Psychological review*, 84(1), 1.
- Schneps, M. (1989). *A private universe* [Film or Broadcast]. Astronomical Society of the Pacific.
- Schön, D. A. (1979). Generative metaphor: A perspective on problem-setting in social policy. *Metaphor and thought*, 254, 283.
- Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.
- Schön, D. A. (1991). *The reflective turn: Case studies in and on educational practice*. New Work: Teachers College Press.
- Schön, D. A., & Argyris, C. (1978). *Organizational learning: A theory of action perspective*. Reading, MA: Addison-Wesley.

- Schoon, K. (1992). Students' alternative conceptions of earth and space. *Journal of Geological Education*, 40, 209–214.
- Schoultz, J., Säljö, R., & Wyndham, J. (2001). Heavenly talk: Discourse, artifacts, and children's understanding of elementary astronomy. *Human Development*, 44(2-3), 103-118.
- Schwan, S., & Riempp, R. (2004). The cognitive benefits of interactive videos: learning to tie nautical knots. *Learning and Instruction*, 14(3), 293 - 305.
- Seeböhm, T. M. (2004). *Hermeneutics: method and methodology* (Vol. 50). Kluwer Academic Pub.
- Setiawan, J., Pasquini, L., da Silva, L., Hatzes, A. P., von der Lühe, O., Girardi, L., ... Guenther, E. (2004). Precise radial velocity measurements of G and K giants. Multiple systems and variability trend along the Red Giant Branch. *A&A*, 421, 241.
- Shao, M., & Colavita, M. M. (1992, August). Potential of long-baseline infrared interferometry for narrow-angle astrometry. *A&A*, 262, 353-358.
- Shapere, D. (1982). The concept of observation in science and philosophy. *Philosophy of Science*, 485–525.
- Sharp, J. G. (1996). Children's astronomical beliefs: a preliminary study of year 6 children in south-west england. *International Journal of Science Education*, 18(6), 685–712.
- Sharp, J. G., Bowker, R., & Merrick, J. (1997). Primary astronomy: conceptual change and learning in three 10-11 year olds [Journal Article]. *RESEARCH IN EDUCATION*, 67-83.
- Sharp, J. G., & Kuerbis, P. (2006). Children's ideas about the solar system and the chaos in learning science. *Science Education*, 90(1), 124–147.
- Sharp, J. G., & Sharp, J. C. (2007). Beyond shape and gravity: children's ideas about the earth in space reconsidered. *Research Papers in Education*, 22(3), 363-401.
- Shea, D., Lubinski, D., & Benbow, C. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, 93, 604-614.
- Simonelli, G., & Pilachowski, C. A. (2003). First-year college students' ideas about astronomy: A pilot study. *Astronomy Education Review*, 2(2), 166-171.
- Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments. *Presence: Teleoperators and virtual environments*, 6(6), 603–616.
- Sneider, C., Bar, V., & Kavanagh, C. (2011). Learning about seasons: A guide for teachers and curriculum developers. *Astronomy Education Review*, 10(1), 010103-22.
- Sneider, C., & Pulos, S. (1983). Children's cosmographies: Understanding the earth's shape and gravity. *Science Education*, 67(2), 205-221.
- Sorby, S. A. (2009). Educational research in developing 3-d spatial skills for engineering students. *International Journal of Science Education*, 31(3), 459-480.
- Sozzetti, A. (2005, October). Astrometric Methods and Instrumentation to Identify

- and Characterize Extrasolar Planets: A Review. *PASP*, 117, 1021-1048. doi: 10.1086/444487
- Spaenhauer, A. M. (1978, May). A systematic comparison of four methods to derive stellar space densities. *A&A*, 65, 313-321.
- Spiro, R., & Jehng, J. (1990). Cognitive flexibility, random access instruction and hypertext: Theory and technology for the nonlinear and multi-dimensional traversal of complex subject matter. In D. Nix & R. J. Spiro (Eds.), *Cognition, education, and multimedia: Exploring ideas in high technology* (p. 163-205). Hillsdale, NJ: LEA.
- Stahly, L. L., Krockover, G. H., & Shepardson, D. P. (1999). Third grade students' ideas about the lunar phases. *Journal of Research in Science Teaching*, 36(2), 159-177.
- Stake, R. E., & Trumbull, D. J. (1982). Naturalistic generalizations.
- Stansfield, R. G. (1976). *The new theology? the case of the dripping tap* (Vol. 103). JIA.
- Sterman, J. D. (1994). Learning in and about complex systems. *System Dynamics Review*, 10(2-3), 291-330.
- Stieff, M. (2004). *A localized model of spatial cognition in chemistry*.
- Stieff, M. (2011). When is a molecule three dimensional? a task-specific role for imagistic reasoning in advanced chemistry. *Science Education*, 95(2), 310-336.
- Stiles, W. B. (1993). Quality control in qualitative research. *Clinical Psychology Review*, 13(6), 593-618.
- Strauss, A. L., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. (2nd ed. ed.). London: Sage.
- Svensson, F., & Ludwig, H.-G. (2005). Hydrodynamical simulations of convection-related stellar micro-variability. In F. Favata & et al. (Eds.), *Proceedings of the 13th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun. ESA SP-560* (Vol. 13, p. 979).
- Sweller, J., & Chandler, P. (1994). Why some material is difficult to learn. *Cognition and Instruction*, 12(3), 185-233.
- Taber, K. S. (2000). Case studies and generalizability: Grounded theory and research in science education. *International Journal of Science Education*, 22(5), 469-487.
- Takeuchi, T., Velusamy, T., & Lin, D. N. C. (2005). Apparent Stellar Wobble by a Planet in a Circumstellar Disk: Limitations on Planet Detection by Astrometry. *ApJ*, 618, 987-1000.
- Tang, K., Delgado, C., & Moje, E. B. (2014). An Integrative Framework for the Analysis of Multiple and Multimodal Representations for Meaning-Making in Science Education [Journal Article]. *Science Education*.
- Tang, K., & Moje, E. (2010). Relating multimodal representations to the literacies of science. *Research in Science Education*, 40, 81-85.
- Tang, K., Tan, S., & Yeo, J. (2011). Students' multimodal construction of work-energy concept. *International journal of Science Education*, 33, 1775-1804.
- Tasker, R. F., & Dalton, R. M. (2006). Research into practice: Visualisation of the

- molecular world using animations. *Chemistry Education Research and Practice*, 7, 141-159.
- Tasker, R. F., & Dalton, R. M. (2008). Visualizing the molecular world—design, evaluation, and use of animations. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (p. 103-131). Dordrecht: Springer.
- Taylor, R. S., & Grundstrom, E. D. (2011). Diagrammatic representational constraints of spatial scale in earth–moon system astronomy instruction. *Astronomy Education Review*, 10(1), 010104-8.
- Thacker, B. A. (2003). Recent advances in classroom physics. *Reports on Progress in Physics*, 66(10), 1833.
- The Exoplanet TEAM. (2014). *The extrasolar planets encyclopaedia*. CNRS - Paris Observatory. Retrieved October 18, 2014, from <http://exoplanet.eu> (<http://exoplanet.eu>)
- The Ministry of Education and Cultural Affairs. (2003, june). *The act concerning the ethical review of research involving humans* (2003:460).
- Thomas, J. J., & Cook, K. A. (2005). *Illuminating the path: The research and development agenda for visual analytics*. IEEE Computer Society Press.
- Tobias, S. (1986). Peer perspectives – on the teaching of science. *Change*, 18, 36-41.
- Touger, J. S. (1991). When words fail us. *The Physics Teacher*, 29, 90–95.
- Treagust, D. F., & Smith, C. L. (1989). Secondary students' understanding of gravity and the motion of planets. *School Science and Mathematics*, 89(5), 380-391.
- Trumper, R. (2000). University students' conceptions of basic astronomy concepts. *Phys. Educ.*, 35(1), 15.
- Trumper, R. (2001a). A cross-age study of junior high school students' conceptions of basic astronomy concepts. *International Journal of Science Education*, 23(11), 1111-1123.
- Trumper, R. (2001b). A cross-age study of senior high school students' conceptions of basic astronomy concepts. *Research in Science & Technological Education*, 19(1), 97-109.
- Trundle, K., Troland, T., & Pritchard, T. (2008). Representations of the moon in children's literature: An analysis of written and visual text. *Journal of Elementary Science Education*, 20(1), 17-28.
- Trundle, K. C., Atwood, R. K., & Christopher, J. E. (2007). Fourth-grade Elementary Students' Conceptions of Standards-based Lunar Concepts. *International Journal of Science Education*, 29(5), 595-616.
- Tsai, C.-C., & Chang, C.-Y. (2005). Lasting effects of instruction guided by the conflict map: Experimental study of learning about the causes of the seasons. *Journal of Research in Science Teaching*, 42(10), 1089-1111.
- Tully, B. (2012). *Flight to the virgo cluster*. Retrieved 2014-07-22, from <http://www.ifa.hawaii.edu/~tully/outreach/movie.html>
- Tversky, B., Morrison, J. B., & Betrancourt, M. (2002). Animation: can it facilitate? *International Journal of Human-Computer Studies*, 57(4), 247 - 262. Retrieved

- from <http://www.sciencedirect.com/science/article/pii/S1071581902910177> doi: <http://dx.doi.org/10.1006/jjhc.2002.1017>
- Udry, S., Bonfils, X., Delfosse, X., Forveille, T., Mayor, M., Perrier, C., ... Bertaux, J.-L. (2007). The HARPS search for southern extra-solar planets. XI. Super-Earths (5 and 8 M_{\oplus}) in a 3-planet system. *Astronomy and Astrophysics*, 469, L43-L47.
- Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and stem education: When, why and how. *Psychology of learning and motivation*, 57, 147-181.
- Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: a meta-analysis of training studies. *Psychological bulletin*, 139(2), 352.
- Uttal, D. H., & O'Doherty, K. (2008). Comprehending and learning from 'visualizations': A developmental perspective. In *Visualization: Theory and practice in science education* (pp. 53-72). Springer.
- van Belle, G. T. (2008). Closure phase signatures of planet transit events. *Publications of the Astronomical Society of the Pacific*, 120(868), 617-624.
- Van Heuvelen, A. (1991). Learning to think like a physicist: A review of research-based instructional strategies. *American Journal of Physics*, 59(10), 891-897.
- Vince, J., & Tiberghien, A. (2002). Modelling in teaching and learning elementary physics. *The role of communication in learning to model*, 49-68.
- von Humboldt, A. (1849). *Ansichten der natur*. J.G. Cotta, Stuttgart. Retrieved from <http://www.biodiversitylibrary.org/item/23794> (<http://www.biodiversitylibrary.org/bibliography/4722>)
- von Noorden, G. K. (1996). *Binocular vision and ocular motility: theory and management of strabismus*, (5th ed.). St Louis: Mosby.
- Vosniadou, S. (1991). Designing curricula for conceptual restructuring: Lessons from the study of knowledge acquisition in astronomy. *Journal of Curriculum Studies*, 23(3), 219-237.
- Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, 24(4), 535-585.
- Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science*, 18(1), 123-183.
- Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for stem domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817-835.
- Wall, J. V., & Jenkins, C. R. (2003). *Practical Statistics for Astronomers*. Princeton Series in Astrophysics.
- Wallace, C. S., Prather, E. E., & Duncan, D. K. (2011a). A study of general education astronomy students' understandings of cosmology. part i. development and validation of four conceptual cosmology surveys. *Astronomy Education Review*, 10(1), 010106-1.
- Wallace, C. S., Prather, E. E., & Duncan, D. K. (2011b). A study of general education astronomy students' understandings of cosmology. part ii. evaluating

- four conceptual cosmology surveys: A classical test theory approach. *Astronomy Education Review*, 10(1), 010107-010107-9.
- Wallace, C. S., Prather, E. E., & Duncan, D. K. (2012a). A study of general education astronomy students' understandings of cosmology. part iii. evaluating four conceptual cosmology surveys: An item response theory approach. *Astronomy Education Review*, 11(1), 010103-1.
- Wallace, C. S., Prather, E. E., & Duncan, D. K. (2012b). A Study of General Education Astronomy Students' Understandings of Cosmology. Part IV. Common Difficulties Students Experience with Cosmology. *Astronomy Education Review*, 11(1), 010104-11.
- Wallace, C. S., Prather, E. E., & Duncan, D. K. (2012c). A study of general education astronomy students' understandings of cosmology. part v. the effects of a new suite of cosmology lecture-tutorials on students' conceptual knowledge. *International Journal of Science Education*, 34(9), 1297-1314.
- Watson, J., & Crick, F. (1953). Molecular structure of nucleic acids. *Nature*, 171, 737-738.
- Watts, D. M. (1982). Gravity: Don't take it for granted! *Physics Education*, 17(3), 116-121.
- Watts, D. M., & Zylbersztajn, A. (1981). A survey of some children's ideas about force. *Phys. Educ.*, 16(6), 360.
- Webb, M. E. (2005). Affordances of ict in science learning: implications for an integrated pedagogy. *International Journal of Science Education*, 27(6), 705-735.
- Wellington, J., & Osborne, J. (2001). *Language and literacy in science education*. McGraw-Hill International.
- Wheatstone, C. (1852). Contributions to the physiology of vision: part the second. on some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philos Trans R Soc*, 142, 1-17.
- Whitelock, D., Brna, P., & Holland, S. (1996). What is the value of virtual reality for conceptual learning? towards a theoretical framework. In P. Brna, A. Paiva, & J. A. Self (Eds.), *Proceedings of the european conference on artificial intelligence in education (euroaie)* (pp. 136-141). Lisbon: Edições Colibri.
- Wickens, C. D., Merwin, D. H., & Lin, E. L. (1994). Implications of graphics enhancements for the visualization of scientific data: Dimensional integrality, stereopsis, motion, and mesh. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 36(1), 44-44.
- Wielen, R. (1996, October). Searching for VIMs: an astrometric method to detect the binary nature of double stars with a variable component. *A&A*, 314, 679.
- Williamson, K. E., & Willoughby, S. (2012). Student understanding of gravity in introductory college astronomy. *Astronomy Education Review*, 11(1), 010105-26.
- Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching*, 32(5), Wiley Subscription Services, Inc., A Wiley Company-534.

- Winn, W., & Jackson, R. (1999). Fourteen propositions about educational uses of virtual reality. *Educational Technology*, 39(4), 5-14.
- Wood, B. P. (1999). Visual expertise 1. *Radiology*, 211(1), 1-3.
- Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of child psychology and psychiatry*, 17(2), 89-100.
- Wright, J. T., & others. (2013). Exoplanet detection methods. In *Planets, stars and stellar systems* (pp. 489-540). Springer.
- Wylie, J. (2007). *Landscape*. Oxdon: Routledge.
- Yair, Y., Mintz, R., & Litvak, S. (2001). 3d-virtual reality in science education: An implication for astronomy teaching. *Journal of Computers in Mathematics and Science Teaching*, 20(3), 293-305.
- Yair, Y., Schur, Y., & Mintz, R. (2003). A 'thinking journey' to the planets using scientific visualization technologies. *Journal of Science Education and Technology*, 12, 43-49.
- Yore, L. D., & Treagust, D. F. (2006). Current realities and future possibilities: Language and science literacy—empowering research and informing instruction. *International Journal of Science Education*, 28(2-3), 291-314.
- Yu, K. C., & Sahami, K. (2008). Visuospatial astronomy education in immersive digital planetariums. In L. L. Christensen, M. Zoulias, & I. Robson (Eds.), *Communicating astronomy with the public* (p. 242).
- Zeltzer, D. (1992). Autonomy, interaction, and presence. *Presence: Teleoperators and Virtual Environments*, 1(1), 127-132.

Acta Universitatis Upsaliensis

*Digital Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology 1196*

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title "Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology".)

Distribution: publications.uu.se
urn:nbn:se:uu:diva-234636



ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2014