Chemical Abundance Analysis of Population II Stars

The Summary Includes a Background in General Astronomy

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Abstract

We are made of stardust in the sense that most atomic nuclei around us have been formed by stars. Stars synthesise new elements and expel them to the interstellar medium, from which later new generations of stars are born. We can map this chemical evolution by analysing the atmospheric contents of old Galactic halo stars. I have done two such investigations. A vigourous debate is going on whether the oxygen-to-iron ratio varies strongly with the general metal-content of halo stars. In my first study, I made an abundance analysis of 43 halo stars, and found no support for such a variation. I have also found that there probably is a cosmic spread in the abundances of oxygen, magnesium, silicon, and calcium relative to iron for halo stars. This may be an indication that the halo was built up by subsystems with differences in the star formation rate. In my second study, I performed a thorough abundance analysis of the star HE0338-3945, which is strangely overabundant in both r- and s-elements. Several other stars have been found with abundance patterns curiously similar to this star, and I define new criteria for the class r+s stars. The abundance similarities among the r+s stars suggest a common formation scenario. However, as the s-elements usually are considered to be produced in binary systems of low mass, and r-elements in supernovae of Type II, this scenario is not obvious. In the article I discuss seven hypotheses, and several of them are dismissed.

Keywords: Astronomy, Galactic evolution, Halo, Milky Way, Oxygen, r-element, s-element, Stellar abundances

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Don’t panic
List of Papers

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


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1. Introduction

Who am I? How was the Earth created, and the stars, and the flowers and - us? Man has always been curious, and when knowledge has not been sufficient, our fantasy has produced an explanation. Modern astronomy is, however, so fascinating that it lets our knowledge and imagination go hand in hand.

The universe is marvellous. The extremely hot and brilliant worlds that are out there, the cool ones, the dark ones, the twisted, the violent and the colourful ones, the incredibly dense, the lonely space. They are so exciting and let your imagination run free. Apart from that, just the fact that we are here and can appreciate it is fantastic.

I study stars. Old ones, from the creation of our Galaxy the Milky Way. I have investigated the chemical composition of the surfaces of some of these stars, and the big aim is to try to understand the history of the elements and how the Milky Way was formed.

Everyday life sitting by the computer fiddling with the data is not exciting, but ever so often real insights pop up and I actually feel I touch eternal questions.

This is not a textbook on astronomy, or even on stellar spectroscopy. It is an introduction to certain parts of astronomy written to give the general audience a background to understand my scientific work.
Figure 1.1: This image symbolises the curiosity of mankind. It is, however, not from the middle ages, but from a book by Camille Flammarion published in 1888. [125]
Part I:
Introduction to some parts of astronomy
2. A shorter brief on time

In 1929 Edwin Hubble discovered that galaxies all over the sky move away from us, and that galaxies further away have greater velocities than nearby ones [99] [132]. He reached the conclusion that the universe is expanding. Does this also imply that we live in the absolute centre of it? No, now we know that it is space itself that expands, and that actually all galaxies – everywhere – move away from each other. The distances between the galaxies increase, but the galaxies themselves do not expand because their gravity binds them together [53].

It is not enough that the universe expands. Recent observations of supernovae in very distant galaxies made in the Supernova Cosmology Project [113] and High-Z Supernova Search [119], have shown that we live in a forever expanding universe, and that the expansion rate is actually accelerating. The cause for this is a strange dark energy filling space and which is represented in the equations of general relativity through Einstein's newly restored cosmological constant. In fact, about three quarters of all energy in the universe seems to be in the form of this dark energy. A little less than one quarter is proposed to be in the form of an exotic type of matter we don’t know what it is called dark matter. Only some percent of all energy is in the form of the ordinary matter which we can see and are made of [129]. The universe surprises again and is more amazing than we thought.

In the universe space, time and gravity are described by the theory of general relativity. But there are other forces than gravity: electromagnetism, the strong and the weak forces. The strong force holds protons and neutrons together inside the nuclei of atoms, and the weak force is responsible for certain kinds of radioactive decay. It is believed that the forces we see today are separate aspects of an ancient superforce from the dawn of time, and that the reason for the different behaviour of the forces now is that the energy content in the universe has been diluted by the expanding space.

Theories which describe the unification of all four forces of nature, so called theories of everything, are still just a dream, but theories for the unification of the strong, the weak and the electromagnetic forces, so called grand unified theories, are rather well established [102]. The theory for joining weak and electromagnetic forces was very successful in predicting the existence of the particles W and Z bosons [102]. The early history of the universe is in many
respects the history of this superforce, and what effects its splitting had.

If we start from the beginning the universe was created in the Big Bang, 13.7 billion years ago [88], see Fig 2.1. The age of the universe has been a major controversy for a long time, but the Wilkinson Microwave Anisotropy Probe (WMAP) team has now pinned down the accuracy to close to one percent [129]. 13.7 billion years is indeed very old. To put it in perspective, the solar system is thought to be 4.56 billion years old, and humans have existed for only a few million years [53] [129].

Thus, 13.7 billion years ago time, space, forces and matter originated out of a singularity. Space and time were indistinguishable and had an infinite density. Much more we cannot say about the actual Big Bang event, because the equations of physics we have available are not valid in the singularity. A more complete description of space-time is required [88]. All we can say is that we do know amazingly much of what happened just after the Big Bang.

Although the theories are highly speculative, our understanding goes as far back as $10^{-43}$ s after the Big Bang [53] [88]. Before this so-called Planck time the unknown quantum effects of gravity were bound to be important, and according to the theories of everything, all four forces were joined into a single superforce. At the Planck time the energy density in the universe had decreased so much that the force of gravity separated [132].

The universe continued with two forces until $10^{-35}$ s after Big Bang. Then the strong force separated from the still joined electromagnetic and weak forces [102]. At that point something spectacular happened: An immense energy released forced the universe to expand enormously. In the short time between $10^{-35}$ s and $10^{-32}$ s after Big Bang the universe expanded roughly $10^{50}$ times [29] [53] [88] [104] [129] [132]. There are some speculations that the cause of this so-called inflation was the release of potential energy as a fundamental scalar field moved to its minimum energy state [88].

The inflation era is also the origin of all light and matter in the universe. When the scalar field had almost reached its minimum, it is believed that it started to oscillate near the minimum value. As a rapidly oscillating field, it lost energy by creating pairs of elementary particles, and thus created matter [88]. The particles then annihilated with newly created antiparticles and produced copious amounts of highly energetic photons [53].

The theories of the history of the universe are rather shaky until around $10^{-11}$ s after the Big Bang. Then we hit fairly firm ground as the electromagnetic and weak forces separated from each other [102] [132]. The temperature was still very high in the universe and particles collided so violently that the quarks, the building blocks of for example protons and neutrons, were free. The time of confinement came at $10^{-5}$ s after Big Bang, when the quarks finally were able to stick together and form ordinary particles [132].

The photons in the universe were still energetic enough to create pairs of
Figure 2.1: This illustration summarises the history and growth of the universe. The time-intervals given are drawn on a logarithmic scale after the Planck time, but the indicated expansion of space is not drawn to scale. Of course this is just the general picture given by the main stream theories. The drawing is based on data from these references: [15] [18] [53] [88] [102] [104] [129]
particles and antiparticles in pair-production at this time. But as the universe expanded their wavelength increased due to redshift, and thus the energy of the photons decreased. Soon the photons didn’t have enough energy to produce particles anymore, and as particles met antiparticles and annihilated to create photons, a flow of photons came about. At $10^{-4}$ s after Big Bang a shower of photons came from the annihilation of protons and neutrons, and at 1 s after Big Bang a similar shower came from annihilation of electrons. This flow of light created shortly after the Big Bang is called the primordial fireball [53].

So why are we here – matter and antimatter got destroyed in the annihilations? It seems that the universe had another symmetry break when matter formed during the inflation era. For every billion of antiparticles or so, it seems that a billion and one particles were created. Thus, these extra particles remained after annihilation, and there were not only photons inhabiting the universe [53].

The temperature sank in the universe, and soon the protons and neutrons could form atomic nuclei. A hydrogen nucleus is simply a proton, but now also deuterium and different forms of helium nuclei formed. Even tiny amounts of lithium nuclei were produced. In the end of this era, at approximately 15 minutes after Big Bang, there were about 25 % helium and 75 % hydrogen by mass. This was the primordial nucleosynthesis. Essentially all heavier elements were formed much later by stars [53] [132], see Chapter 4.

At a time of 379,000 years after the Big Bang the universe had cooled so much that atoms could form for the first time, and is therefore called the time of recombination [129] [132]. This was a major event in the history of the universe because the light, which before had been trapped by the hot ionised gas, was now free to roam the space. Space had until that time been an opaque haze, but now became transparent [132].

We can still observe these photons which were created during the inflation era and set free at the time of recombination. They have cooled very much since then, but are still detectable. The radiation is called the microwave background, and has an energy content equal to the temperature $2.728 \pm 0.002$ K [129] [132].

The microwave background is amazingly uniform, as can be seen in the sky maps taken by the Cosmic Background Explorer (COBE) [50] and Wilkinson Microwave Anisotropy Probe (WMAP) [129] satellites. Tiny variations around the average tell us, however, that the matter and radiation in the universe were not absolutely uniform at the time of recombination. This was fortunate, because these were the concentrations of matter that about a billion years later [129] had grown to become clusters of galaxies, one of which now about 14 billion years after the Big Bang, contains us.
3. Galaxies and galaxy formation

3.1 Galaxies

Galaxies are majestically beautiful objects consisting of enormous assemblages of stars, gas, dust and some tantalising unknown stuff, held together by gravity. How were they formed? We can get important clues simply by looking deep into space\(^1\). Another way of studying galaxy formation is to distinguish the background story of the inhabiting stars. That is what I have done with a small sample of stars in our Galaxy, see Chapters 7 and 8. This chapter is devoted to give you some background on the formation of galaxies, before moving on to stars and what they can tell us\(^2\).

It has not always been accepted that galaxies are distant objects. It was a shock to many astronomers, and others, when Edwin Hubble established the extra-galactic nature of some strange looking nebulae in 1924. He later developed a classification system that is still the basis for all discussions of galaxies. The system divides galaxies into ellipticals, lenticulars, spirals, barred spirals and irregulars, see Fig. 3.1.

*Morphologies of Hubble sequence galaxy types*

- Elliptical galaxies are, as the name hints, spherical or ellipsoidal in shape with no obvious internal structure, except that they are denser in the centres. They are dominated by red old stars, and generally have a very small amount of interstellar gas and dust.
- The most prominent features of spiral galaxies are the spiral armed disks. Some have also a central concentration of stars called a bulge. The bulges consists of closely packed and mostly old stars, moving in every direction and with a large range in speed – just like small ellipticals. The disks are flattened discus-like structures with overall rotational motions. They are rich in gas and dust and have more or less prominent spiral arms. Bright blue new-born stars embedded in thick clouds of interstellar matter lit up the arms like Christmas lights.
- Barred spirals have the spiral arms emanating from the ends of a

\(^1\)It takes time for light to travel, so the further away we look the further back in time we see, and the younger are the galaxies seen.
\(^2\)In this chapter I outline the theories as if they were 'the truth', just to give a general background. A more problematic view is given in Chapter 5, and in my scientific work.
Figure 3.1: The Hubble classification scheme for galaxies. Elliptical galaxies are denoted E0 to E7 to indicate their degree of flattening. Spirals are denoted Sa, Sb and Sc depending on the size of the central bulge and how tight the arms are wrapped. Barred spirals, SB-galaxies, are denoted along similar lines as normal spirals. Lenticular galaxies are divided into S0 or SB0 depending on the eventual appearance of a bar. Irregular galaxies are divided into Irr I and Irr II. Irr I galaxies display evidence of ongoing star formation, and Irr II:s have a disturbed appearance perhaps caused by violent mergers. [15] [24] [29] [38] [53] [103] [105] [117]

bright elongated bar extending across the bulge. Both normal and barred spirals exist in a wide range of forms, see Fig. 3.1.

- Lenticular, or lens shaped, galaxies have large bulges and small disks, but no spiral arms. They appear like an intermediate form between ellipticals and spirals. Their stars are predominantly old, and they contain only small amounts of gas and dust.
- Irregular galaxies display no obvious symmetry or structure. They vary enormously in appearance, but are all rather small and contain large amounts of gas and dust.

Both the smallest and the largest and most massive galaxies are ellipticals, as their linear sizes range from a few 1,000 ly$^3$ to a few 100,000 ly. Ellipticals are also the most common form of galaxy in the universe, but among the largest and brightest galaxies, spirals dominate. There are also other types of galaxies not included in the Hubble fork diagram. A few per cent of all galaxies contain intensely bright compact nuclei which send out immense amounts

[3]$^3$Light-year, ly, is the distance light can travel in one year, and equal to 9.5 · 10$^{12}$ km.
of radiation at all wavelengths. These belong to a special class called active galaxies. Others are blue compact galaxies, H II (i.e. ionized hydrogen) galaxies, and dwarf forms of spheroidals and irregulars. The galaxies are not evenly distributed in space, but are grouped in larger clusters and superclusters which form a very large scale structure in the universe. How did all these varieties and structures form?

### 3.2 The dark matter mystery

To be able to answer the question of the origin of galaxies one has to go back to the time of recombination. Sky maps of the microwave background originating from that epoch show tiny fluctuations around the average density of matter [129]. What was these lumps? This question has a close connection to the 'missing mass' problem of galaxies. Observations made of a large number of galaxies and galaxy clusters show rotation curves, and a spread in radial velocities, that do not fit the mass seen in stars and clouds of gas and dust [116]. There is mass missing; dark matter that we cannot detect in other ways than by its gravitational influence. This elusive new form of matter seems to constitute about 90% of the mass in the universe.

Some of the dark matter is probably baryonic, i.e. ordinary matter such as planets, brown dwarfs4, and hot thin intergalactic gas. But measurements indicate that this hidden ordinary matter can only account for a small fraction of the missing matter [116] [129]. During the last decade or so after the discovery of the non-baryonic dark matter, many more or less wild theories have been proposed of what it is [129] [132]. Probably there are supermassive black holes in the centre of many galaxies, but a new form of matter seems anyhow needed. The most popular theory is that this matter is some form of cold dark matter, e.g. massive unknown particles travelling at relatively slow speed [86] [130]. However, other explanations have been suggested such as cosmic strings, i.e. a remnant from the symmetry-breaking at the inflation era.

### 3.3 Galaxy formation

The question of the egg or the chicken is vital also in discussions on galaxies, i.e. to what extent are the different types of galaxies determined by the conditions at birth and what is caused by evolution? In the first half of the last century the Hubble sequence was considered as an evolutionary scheme, but in the 1960's Eggen, Lynden-Bell & Sandage [46] put forward a theory of galaxy formation as a collapse of a single gigantic primordial gas cloud. In this

4Brown dwarfs are small failed stars, shining due to contraction.
scenario stars were formed during the collapse, marking out the formation development by their age differences. The total mass, angular momentum\(^5\), and rate of star formation in a cloud then determined whether it became a spiral or an elliptical galaxy [53]. A variation of this scenario is the top-down theory, in which even greater primordial gas clouds broke apart and the subclouds formed separate galaxies in galaxy clusters.

Although the singe-collapse scenario is still considered as an important part of galaxy formation, the top-down theory was completely replaced by its opposite: the bottom-up scenario [41]. This paradigm at the moment was proposed both from observation and theory in 1978 by Searle & Zinn [124] and White & Rees [140]. It is consistent with the cold dark matter theories, and suggests that galaxies formed by the merging of smaller primordial gas clouds, so called protogalaxies, or even developed dwarf galaxies. The idea is quite successful, as it is compatible with both the anisotropy of the cosmic microwave background [129] and the many small galaxies seen in the Hubble Space Telescope observations of the distant ancient universe\(^6\) [36] [53] [86] [97] [130].

Small perturbations among the collision-less dark matter were seeded already at the inflation era, according to the bottom-up theory. The fluctuations grew due to gravity, and the small clumps of dark matter merged into larger ones. The theory proposes that the masses of the protogalaxies were comparable to dwarf galaxies already at the epoch of recombination [41]. Heated ordinary matter, i.e. primordial gas consisting of hydrogen, helium and small amounts of lithium, were mixed in with the dark matter. It participated in the merging, cooled subsequently, congregated at the centres, and eventually formed the galaxies we see today [13].

The protogalaxies were very close together in the early universe, and tidal interactions imposed rotation on them [84]. The angular momentum of a protogalaxy probably played a vital part in the determination of its final morphology, but one assumes that the local merging rate was the most important aspect [36] [41] [58]. It is likely that there were many different formation scenarios for different types of galaxy, but some more frequent than others [41].

The principal way of creating an elliptical galaxy was, according to the bottom-up theory, by merging protogalaxies in such a way that the larger structure had a low overall rotation. This often happened in environments with high merging rates. Then the larger protogalaxy continued to collapse until the dispersion of the random velocities of the components halted it. This caused vigourous star formation and virtually all gas was used up at once. The pro-

\(^5\)Angular momentum is overall rotation.

toggalaxy developed into an elliptical with early formed stars and little gas left [58].

If, on the other hand, the merging rate of the protogalaxies was relatively low and the angular momentum high, the gas settled gradually. The stellar formation rate became rather low, and the gas then had time to radiate away its kinetic energy. In such situations a rotating disk was formed, and the protogalaxy became a spiral [36] [41] [53] [58].

Other types of galaxies certainly formed by protogalaxies with intermediate angular momenta and merging rates, but the whole era of galaxy formation is still obscure [89]. However, the mentioned extreme scenarios may explain many observed features of galaxies, such as why ellipticals are more common than spirals. The assumption is that this depends on the high merging rate in the early universe. Any attempt to form stable disks early on was probably prevented by plunging and ripping mergers [41]. This also explains why ellipticals are more abundant in dense galaxy clusters, spirals more frequent in sparse, why spirals have a lot of gas left, and elliptical galaxies have non, and why spirals were more common in the past [41] [53] [58].

The merging seems to have peaked about 1–3 billion years after Big Bang [41] [58]. After that, the merging rate declined as the distances between the galaxies grew with the expansion of the universe, and the supply of collisional candidates diminished – galaxy formation became galaxy evolution.

The process of merging continues to this day, and is the most dramatic example of galaxy evolution. In the giant collisions stars very rarely hit each other, but any interstellar media left collide violently [53]. This starts massive star formation in so-called star bursts. Stars can be thrown out of the galaxies in such events, and the galaxies may be stripped of their gas and dust. Spirals were a lot more common in the early universe, and late collision events are probably responsible for the depletion. It is debated, however, whether injured spirals transform into ellipticals or not [13] [41] [48] [86].

The lives of ellipticals are rather quiet after the formation era, apart from the ageing of the inhabiting stars, and an occasional supernovae going off now and then. They have no, or very little, interstellar gas left after the formation, and thus cannot form later generations of stars. Spiral galaxies have, on the other hand, plenty of gas left. They have an ongoing star formation in their disks ignited, among other things, by the sweeping waves of the spiral arms.

### 3.4 The Milky Way

Our home Galaxy is one of billions of such systems in the observable universe. It is called the Milky Way after the old Greek saga about the god Zeus letting his illegitimate son Heracles suck on his wife Hera's brest, her awaking, get-
Figure 3.2: A drawing of the probable appearance of our Galaxy, the Milky Way. [29] [43] [53] [71] [101] [106] [108] [114] [117]
ting furious, and snatching the breast out of the baby’s mouth, thus spreading her milk over the velvet night sky.

The Milky Way, or just the Galaxy with capital G, is seen as a misty band stretching across the sky in clear dark nights. It is the combined light of about a 100 billion stars, which is concentrated to this band [101]. Our Galaxy is a barred spiral galaxy of type SBB or SBC, and our star the Sun resides in the disk, thus the misty band in the sky [101]. There are different stellar components in the Galaxy, often referred to as Populations, see Chapter 5.3. The stars in each population all have a certain set of spatial, kinematical, age, and chemical abundance distributions, and the main components of the visible Galaxy are the bulge, the disk with its spiral arms, and the halo, see Fig. 3.2.

The bulge is the nucleus of the Galaxy, and has a weak bar discovered in 1991 by Binney et al. [19]. The bar is roughly 6,000 ly in diameter, and seen at an angle of 25–30 degrees from our direction [71]. The stars of the bulge are numerous and very old, but the Galactic centre probably also contains a black hole named Sagittarius A* [106]. Estimates of the mass of this black hole arrive at dazzling $10^6 M_\odot$ of matter inside a radius of the same size as the distance between the Sun and the Earth [118].

The bulge is surrounded by a gaseous disk about 100,000 ly in diameter. The disk is in fact two disks: one thin disk and a thicker one, found by Gilmore & Reid in 1983 [59] [114]. The two disks have different kinematical, abundance and age properties – the thicker one being quite old and the thinner one younger [17]. The thin disk contains large amounts of gas and dust, and has a spiral structure with the arms probably emerging from the tips of the central bar. The arms are formed by density waves which sweep through the disk at lesser speed than the general rotation, initiating star formation by compressing the interstellar medium. The Sun is situated near the equatorial plane of the thin disk, some 25,000 ly from the Galactic centre, and near the inner edge of the Orion arm [43] [106].

The bulge and the disks are surrounded by a sparsely populated spheroidal distribution of stars, called the halo. Like the bulge it is very old, and has roughly the same diameter as the disks. Two different stellar populations have been discovered also in the halo, distinguished mainly by their kinematical properties [62] [63] [112]. Globular clusters also belong to the halo. They are dynamically bound spheroidal groups of $10^4$–$10^6$ stars born at the same time. These clusters are among the most ancient entities in the universe$^8$, and halo field stars are also considered very old. Both the clusters and field star

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$^7$It is customary in astronomy to denote masses in the units of the solar mass, $1 M_\odot = 1.99 \times 10^{30}$ kg.

$^8$Some astronomers think that the smallest structures surviving recombination are similar in mass to globular clusters and dwarf galaxies, and that they may be the basic building blocks of galaxies [41] [53] [144].
population circle the galactic centre in eccentric orbits tilted at random angles to the galactic plane.

The formation scenario proposed for the Milky Way has changed in the same way as the general galaxy formation theories. Thus, the single cloud collapse, suggested by Eggen et al., has been seriously questioned by the bottom-up scenario. The bottom-up theory seems far more plausible in the light of extra-galactic galaxy studies [48] [100] [123], and discoveries of the fluctuations in the microwave background [129]. Much compelling evidence has also been found in the Milky Way, e.g. the age differences among globular clusters [27] [116] [124], the severe difference in angular momentum between the halo and the disk [27] [116], the existence of high-latitude and high-velocity interstellar clouds falling into the Galaxy, the lack of a radial abundance gradient in the outer halo [116] and in the thick disk [60], the distinct and smooth abundance trends with metallicity for the thin and thick disks [16], the signatures of supernova of Type Ia enrichment (see Chapter 4) in the thick disk which implies a very long thick disk phase [108], the relatively small proportion of metal-poor solar-type stars in the solar neighbourhood [116] [121] (see Chapter 5.3), etc. The Sagittarius dwarf galaxy is currently in a catastrophic collision with the Milky Way [27] [77] [96] [114]. This small galaxy is merging with our disk at the far side of the bulge, but this is not as clear evidence for the bottom-up scenario as one may think. It has been shown that dwarf systems like this one have another abundance pattern than Galactic halo stars of the same metallicity, and this is an argument against dwarf systems building the Galaxy [136]. However, other astronomers have pointed out that these independent systems probably have had a slower star forming rate than the ones which far back in time built up our Galaxy [51]. Thus, the objection falls.

In one of our investigations we found another result supporting the merging scenario, see Chapter 7. The collapse-theory suggests a gradient star formation rate valid for the halo, but the bottom-up scenario predicts different ones for different sub-groups of the halo. Our study supports the last statement.

I can outline a theory of the formation of the Galaxy, but mark my word, this is only a hypothesis. The Milky Way may have formed in several steps. First a protogalaxy formed in a fast merging of several smaller protogalaxies very early on in the history of the universe. The new protogalaxy, with its ongoing massive star formation, had apparently a rather small angular momentum, and collapsed under its own gravity until the velocity dispersion of the newly formed stars prevented further contraction. Now the bulge had been formed [41] [58]. The universe expanded and the number of protogalaxies in the vicinity of our Galaxy-embryo were reduced [41] [58], but some time here the Galaxy acquired some rotation from a near encounter [84]. The merging rate dropped and the accreting protogalaxy-gas had time to radiate away most of its kinetic energy [41] [58]. The angular momentum was, however,
not affected by this, and a rotating disk settled around the bulge [36] [41] [53] [58]. Now, i.e. some 10 to 12 billion years ago [114], something disastrous happened; a small, but not ridiculous small, satellite galaxy collided with the disk, thus causing it to thicken9 [16] [17] [58] [86] [96] [114]. It appears that there was a slight decline in the star formation rate between the formation of the two disks [54] [64] [65] [108]. This is also supported by the theory of an impact of yet another medium sized merger, which induced the creation of the bar and the spiral arms in the new thin disk [96]. The accretion of gas continued, however, after the thickening of the original disk, eventually a new thin disk of gas had gathered, and star formation started again. The halo had been built up by the capture of protogalaxies before the creation of the thick disk [114]. According to estimates, the Milky Way may have accreted on the order of a few hundred small satellites to build the halo in this manner [96] [114]. The original tiny protogalaxies shredded as they plunged through the disk, and became halo field stars [43].

The Galaxy still has about 150 globular clusters, and is a member of the Local Group – a smaller group of 3 large and over 30 small galaxies [43] [127]. It is the second largest after the Andromeda Galaxy, and as mentioned above, the Sagittarius dwarf galaxy is colliding with the Milky Way right now. The consequence of this is unclear, but the Galaxy was lucky during historical merging events – major mergers could have disrupted it severely, and maybe even destroyed it.

A reflection to make is that to some extent we are back to the view of the Hubble sequence as an evolutionary scheme. The halos and bulges forms first, then dust may settle so the galaxies transform into spirals, and later they may become irregular galaxies if they are hit by large late mergers. However, we now know that there are many ways to form different types of galaxies, and that most of the galaxy evolution happens during the relatively short period of galaxy formation.

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9 This is the most probable scenario as e.g. a hiatus is noted in the star formation between the thick and thin disks [108].
4. Stars and the formation of the elements

4.1 Diamonds in the sky

You are made of stardust. It is an astonishing and intriguing thought, but also true. The only matter created in the Big Bang were different forms of hydrogen and helium, and tiny amounts of lithium, see Chapter 2. All other elements in the universe have been formed later in the hot interior of stars, or by dying stars\(^1\). Thus, to understand the origin of the elements and, finally, our own origin, we need to understand the structure and evolution of stars\(^2\).

Stars appear as glittering diamonds against the velvet dark night sky, but really they are giant boiling gas spheres at enormous distances. The gas is held in static or quasi-static equilibrium by a balance between gravity and pressure. The pressure is generated by one or more of hot ionised gas pressure, radiation pressure, or a degenerate gas pressure\(^3\).

Stars come in all sorts of masses, sizes, and temperatures. The different types can best be differentiated in a Hertzsprung-Russell diagram (HR-diagram), as illustrated by Fig. 4.1. In a HR-diagram the stellar effective temperature\(^4\) is plotted against the luminosity\(^5\) of the star, or with equivalent measurables.

Among the main groups of stars are the main sequence stars, along a narrow band across the HR-diagram. There are giants and even larger supergiants with radii of up to about \(1000 \, R_\odot\)\(^6\), but with rather cool surfaces. Much smaller are the hot white dwarfs with radii around \(0.01 \, R_\odot\). The heaviest stars are believed to weigh around \(100 \, M_\odot\). They are rare and reside in the upper part of the HR-diagram, but the numerous less massive stars have a lower mass limit of \(0.08 \, M_\odot\), and often low luminosities.

\(^1\)A few elements have actually been produced by spallation of heavier nuclei by cosmic rays in the interstellar medium [87].

\(^2\)Sparse references are given in this chapter, as most facts are not controversial. The references are: [31] [32] [42] [49] [53] [72] [74] [81] [87] [94] [98] [107] [116] [138] [135] [139].

\(^3\)A fully degenerate gas has particles packed together as tightly as physically possible with maintained identities. The degenerate pressure is depending solely on the density.

\(^4\)The effective temperature, \(T_{\text{eff}}\), is the temperature of a black body radiating the same total energy per unit area as the star, and often a good approximation to the stellar surface temperature.

\(^5\)The luminosity, \(L\), is the energy radiated per unit time from a body.

\(^6\)\(R_\odot\), with notation \(\odot\) meaning the solar value, is the solar radius of 700,000 km.
Figure 4.1: The Hertzsprung-Russell diagram displayed as effective temperature in Kelvin plotted against the luminosity of the star in units of the solar luminosity. For historical reasons the temperature scale goes from high to low. The HR-diagram is very useful for distinguishing between different kind of stars, and here the main types are shown. Stars can also be distinguished by their spectral class, and the letters denoting different classes are shown. There are also different luminosity classes, although not displayed here. The sun has spectral class G with subclass 2 and luminosity class V, i.e. G2V. Lines for similar stellar radii, in units of the solar radius, are also shown in the diagram. [53].
Thus, most stars are less massive and less luminous than the Sun, but giants and white dwarfs need not be much more massive than our star. The different appearances are a result of the differing evolutionary stages of these stars. Stars evolve because of their continuous leakage of energy, and as a stellar fuel runs out, the star is forced to shrink to release gravitational energy. The core temperature then rises, and another phase of the stellar life sets in. This cause a dramatic change in the stellar structure and this is reflected by the luminosity, the effective temperature, and the radius. The star draws a track in the HR-diagram as it evolves, but the route and speed along this path depend on the stellar mass and chemical composition.

4.2 The birth of a star

Stars form out of giant molecular clouds made of gas and dust. The clouds contain vast amounts of matter, often more than \(10^5 \, M_\odot\), and are very dense and cold. The formation of stars is a rather complicated process, and the triggering still quite unclear. It probably starts as something disturbs a cloud – it can be a nearby supernova, a passing density wave in the galaxy, or even nearby starbirths. If the compression is large enough for gravity to overcome pressure, the disturbed part of the cloud continues to contract under its own weight in a runaway process.

During the initial collapse the cloud is fairly thin and all released gravitational energy is radiated away. The cloud stays at roughly the same temperature and even though the pressure increases, the diminishing volume allows gravity to continue the contraction. The minimum mass a cloud must have to collapse under its own gravity is reduced as energy abandons the cloud. The cloud therefore becomes unstable and splits up in several smaller clouds, which continue to collapse independently. The original cloud usually undergo fragmentation in several steps, but this cannot go on forever. As the density increases, only half of the liberated energy escapes. The other half starts to heat the contracting gas, and the increased temperature leads to a halted fragmentation.

As a cloud fragment shrinks it rotates faster, which will cause the gas to form a disk around the so-called protostar. The gas in the disk collide and the resulting lumps may be the embryo to a planetary system or, for higher masses, another star or two. However, most of the gas spirals in towards the protostar and accretes onto it. Until now, the protostar’s major source of energy has been gravitational energy due to accretion and shrinkage, but as the core reaches high enough temperature, the small amount of deuterium in the gas starts to fuse with ordinary hydrogen. At the same time carbon starts to transform into nitrogen, and lithium is also participating in fusion processes. This produces
a lot of energy, and while the outer envelopes continue to fall inward, the core reaches a balance for a while.

The protostar resides inside a cocoon of gas and dust, composed by the remains of the original cloud. Such stellar nurseries can be observed as red blobs at infrared wavelengths, but more spectacular is to witness the actual birth. Hubble Space Telescope has taken amazing pictures of this, e.g. the Herbig-Haro objects HH-1/HH-2, the Horsehead nebula, and the Eagle nebula\(^7\). The hatching is probably linked to the deuterium burning\(^8\). The large energy release during this phase may produce a strong wind and a convection zone\(^9\), thus creating a powerful magnetic activity via a generator effect. The wind is collimated into jets in the polar directions by the magnetic field lines and the disk. Herbig-Haro objects are then formed when these bipolar outflows hit the interstellar medium and glow beautifully. The protostellar wind halts and eventually turns around the infalling gas, and in the end the cocoon around the protostar is blown off.

Star formation is an inefficient process, and only a few percent of the gas in the initial cloud is generally converted into stars. Nor does all protostars become stars; if the new-born protostar weights less than 0.08 \(M_\odot\) it can never ignite hydrogen fusion. Such objects end up as brown dwarfs – failed stars shining due to contraction, and with a steadily increasing part of its gas degenerate\(^10\). Protostars of higher mass than about 100 \(M_\odot\) can probably not exist, because the radiation pressure make such stars disrupt during the birth.

The protostar has been 'born', but to become a full-fledge star it has to essentially stop contracting. This is achieved only when the star has adjusted to hydrogen burning. Hydrogen burning starts a bit later when the deuterium burning has run out of fuel. Then the core has to shrink again to maintain energy production. The contraction rises the central temperature and finally, at a core temperature of 6 million degrees, hydrogen starts to fuse into helium. This marks a new era and the protostar has now become a real star.

The main sequence is the locus for stable hydrogen burning stars in the HR-diagram, and the previous evolution of shrinking and warming corresponds to a shifting from far right to the main sequence band in the diagram. Stars of different masses follow separate tracks, with tracks of higher mass stars being nearly horizontal and ending up at the high luminosity end. Low mass stars

\(^7\)Hubble Space Telescope pictures of stellar births:
http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/24/image/c
http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/12/

\(^8\)By burning astronomers don’t mean ordinary burning of material, but nuclear fusion processes.

\(^9\)Convection is energy transport by currents of the media itself; either it is streams of hot gas as in a star, or hot liquid streams as in heated water.

\(^10\)Actually brown dwarfs fuse their small amount of deuterium, but they never achieve hydrogen burning. Thus, they are failed stars.
move somewhat down-left to lower luminosities at the main sequence. The time it takes to create a star is fairly short – at least from an astronomical perspective. The settling on the main sequence depends strongly on the mass of the final star, e.g. a $15M_\odot$ mass star takes only 20,000 years to become a main sequence star, while for a solar mass star it takes around 50 million years.

4.3 The middle ages

In the middle of the last century the pioneering work of Margaret Burbidge, Geoffrey Burbidge, William Fowler, Fred Hoyle [23] [76], Alastair Cameron [25], Paul Merrill [95], and many others, laid the ground for modern nuclear synthesis theories. These theories, together with major advances of stellar evolution models and observational spectroscopy, have made it possible to imagine plausible scenarios for the production of essentially all chemical elements in the periodic system$^{11}$.

During the time on the main sequence the star takes its first step through the chart of nuclei, as the simplest element hydrogen is fused into helium in the stellar cores. The transformation occurs either via the pp-chain, where protons fuse together into helium via deuterium, or via the CNO cycle, where different isotopes$^{12}$ of carbon, nitrogen and oxygen act together as a catalyst.

The pp-chain ignites at comparably low central temperatures. The energy in low mass main sequence stars is therefore produced in this way, although some reactions of the CNO cycle may be active and change the element ratios. Stars with masses greater than about $1.1M_\odot$ reach higher core temperatures, which means that the CNO cycle is dominating, at least for higher metallicities$^{13}$. The nuclear reactions of the CNO cycle have a very large energy output, and radiation is not efficient enough to transport it all to the surface. The high mass stars have therefore a convective inner core, while low mass stars are content with radiative energy transport in the cores. However, because of their cooler surfaces the latter have convective outer envelopes, and stars less massive than $0.3M_\odot$ are so cool that they are fully convective.

The stars on the main sequence have masses of about $0.08–100M_\odot$, but their corresponding luminosities range roughly $10^{-3}–10^6$ times the luminosity of the Sun, see Fig. 4.1. Thus, the brightest stars, with masses about $10^3$ times

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$^{11}$The periodic system is a well-known table in which all existing chemical elements are placed in order according to atomic number, i.e. how many protons they have in their nuclei.

$^{12}$Atoms of an element have always the same number of protons in their nuclei, but may have different numbers of neutrons. Then the atoms are different isotopes of the same element.

$^{13}$Astronomers use the term metals to refer to all elements other than hydrogen and helium. It is a bit odd, as the term is used quite differently by other scientists. The metallicity is the amount of metals in the star compared to the amount of metals in the Sun. See also footnote 2 of Chapter 6.
the faintest, are squandering their fuel at a rate of $10^9$ times faster. This has, of course, a profound impact on the how long the fuel content in the core last. In fact, for stars of masses less than $0.5 \, M_\odot$ the main sequence lifetime exceeds the current age of the universe, while stars of $100 \, M_\odot$ end their evolution in less than some 100,000 years. This has been visualised in Fig. 5.1 in Chapter 5. The lifetimes are also dependent on the chemical composition of the stars, but to a much lesser degree; stars with a lower content of metals have somewhat shorter lifetimes. The main sequence era constitute the main part of a stellar life, as the nearly three fourths of a star’s mass consists of hydrogen. Our star, the main sequence star called the Sun, is currently in the middle of its middle age – it was born 4.56 billion years ago, and is going to look roughly the same for approximately the same amount of time.

4.4 Stellar deaths

When hydrogen is exhausted in the core, the star has an energy crisis. The solution is, as always, to shrink to release gravitational energy. The temperature rises and eventually the star starts to fuse hydrogen into helium in a shell outside the helium core. This causes the outer envelope to expand, and the surface temperature drops. The star leaves the main sequence fairly rapidly and a new phase of the stellar life starts. The evolution up until now has been relatively similar for all stars, but their deaths are drastically dependent on their masses.

4.4.1 Death as something beautiful

About 95% of all stars in the universe have masses between 0.5 and $8 \, M_\odot$, and the deaths of these low and intermediate mass stars resemble each other very much. Most of them end their lives by shredding their envelopes, and blowing them away in a spectacular sight called a planetary nebula. The late evolution of some low- and intermediate-mass stars has been visualised in a HR-diagram, see Fig. 4.2.

After the main sequence a low or intermediate mass star develops into a red giant with high luminosity, low surface temperature and episodic mass loss [5]. This transformation occurs as the hydrogen shell burning adds material to the core and causes it to contract. The stellar luminosity then rises, the surface temperature drops as the envelope expands, and a deep convective zone develops. The material in the outer regions of the star thus get mixed, and gas with altered element ratios will be brought to the surface in this first dredge-up phase\footnote{The abundances of hydrogen (\(^{4}\text{He}\)), nitrogen (\(^{14}\text{N}\)) and carbon (\(^{13}\text{C}\)) rises in the stellar atmosphere.}. This is important because as the elemental abundances in
Figure 4.2: A star changes its surface temperature and brightness as it ages, so the life of a star draws a track in the HR-diagram. The changing appearances of a $1 \, M_\odot$ and a $5 \, M_\odot$ star are visualised here, although the transition from far right to the main sequence during birth is omitted for clarity. The stars spend most of their lives on the main sequence, but as hydrogen runs out in the stellar cores and shell hydrogen burning starts, they move up and right in the diagram (1). At the basis of the giant branch they experience the first dredge-up. At the tip of the giant branch (2) they ignite core helium burning, the $1 \, M_\odot$ star through a helium core flash and the more massive one smoothly. The transition down to the horizontal branch (3) is fast, and for the low-mass star very fast. The horizontal branch is positioned further to the left for stars with a smaller content of heavier elements. As core helium is exhausted the stars experience a second dredge-up and move up the asymptotic giant branch. There they become unstable and go through a series of strong thermal pulses at the tip (4). The $5 \, M_\odot$ star also experience third dredge-up phases. The envelopes of the stars are blown away due to strong stellar winds, and the stars move swiftly towards higher effective temperatures as the stellar cores are exposed. The stars have now become planetary nebulae around small hot stars which develop into white dwarfs (5). As time goes by the planetary nebulae are dissolved and the white dwarfs cool steadily (6), until they become extinct black dwarfs. [21] [31] [53] [139] [143]
the stellar atmosphere change, it is no longer a record of the abundances of
the original the cloud from which the star formed\textsuperscript{15}. The first dredge-up is
followed by a rather long period on the red giant branch, where the helium
core gradually grows by the combustion of hydrogen in its surrounding shell.

The helium burning starts when the core of the star has reached about a
half solar mass and a temperature of $10^8$ K. These values depend on chemical
composition, but are quite insensitive to the total stellar mass – although very
low-massive stars never reach this stage, see Fig. 5.1. The way of ignition is,
however, heavily dependent on the total mass. For stars of intermediate mass,
i.e. about $2.2-8 M_\odot$, the transition to helium burning in the core goes quite
smoothly, but for lower mass stars it is a trauma inside a star with a stiff upper
lip. These stars develop electron degenerate cores while burning hydrogen in
a shell, and as the degenerate material cannot adjust to the released energy
by expansion, there is a thermal runaway known as the helium core flash.
During a few hours the rate of energy generation in the core reaches values of
order $10^{10} L_\odot$, i.e. comparable with the total luminosity of our Galaxy. This
is all happening in the stellar core, and the star shows nothing of this on the
outside. When the temperature has raised far enough helium fusion starts, and
the degeneracy is finally removed. The core is suddenly able to expand, and
this results in a shrinkage of the stellar envelope. The luminosity then drops,
and the star settles itself on the horizontal branch, see Fig. 4.2.

During the horizontal branch epoch helium fuses into carbon and oxygen
via the triple $\alpha$-process in the stellar core, while hydrogen continues to fuse
into helium in a shell outside. However, the core content of helium is not infin-
ite, and when it is exhausted the star may experience a second dredge-up\textsuperscript{16}. It ends up with a quiescent core of carbon and oxygen surrounded by a helium
burning shell and, further out, a hydrogen burning shell. This rearrangement
of the energy production makes the star once more move towards higher lu-
minosities and lower effective temperatures in the HR-diagram, and it climbs
the asymptotic giant branch (AGB). As the star evolves, its outer envelop ex-
perience a series of thermal pulses caused by runaway fusion processes in the
thin helium burning layer. The expansion and contraction of the burning lay-
ers during the thermal pulses make the stellar envelope to actually detach from
the core. It may also create short lived deep convection zones and thus a third

\textsuperscript{15}Strictly speaking, the stellar atmosphere is not a hundred percent true record of the abundances
in the pre-stellar cloud on the main sequence either, as e.g. the deuterium burning and some
CNO cycle fusion alter the ratios in the pre-main sequence stage. Some elements may also
settle below the observable surface due to the pull of gravity. Others may be driven upward by
radiation due to large cross sections, which causes higher abnormally high concentrations in the
surface layers \cite{87}.

\textsuperscript{16}The abundances of hydrogen ($^4\text{He}$), nitrogen ($^{14}\text{N}$) and carbon ($^{13}\text{C}$) rises even more in the
stellar atmosphere.
dredge-up phase for stars above about $2 M_\odot$\textsuperscript{17}.

An amazingly rich chemistry is found in the outer regions of AGB stars. Oxygen is very important in the atmosphere before the eventual third dredge-up phase, but afterwards huge amounts of carbon has been transferred to the surface, and it dominates the chemistry. Another interesting fact is that large amounts of free neutrons are released\textsuperscript{18} in the fusion processes going on in the region between the burning shells. These free neutrons hit nuclei of atoms\textsuperscript{19} thus creating other isotopes of the seed element or, after beta-decays\textsuperscript{20}, other elements. This is the important slow $s$-process of neutron capture, one of three existing ways\textsuperscript{21} of creating elements heavier than iron. About half of the stable nuclei heavier than iron are believed to be synthesised during the late stages of evolution of low and intermediate mass stars [135].

The final death of a low mass star is a beautiful sight\textsuperscript{22}. The thermal pulsations come faster and faster, and the outer layers are blown away. In just a few 10,000 years the whole envelope of the star is shredded, and it glows as the extremely hot bare stellar core radiates onto the surrounding gas. The AGB star has turned into a planetary nebula (PN) surrounding a white dwarf. The white dwarf shrinks until the matter reaches degeneracy. Afterwards, it shines just out of heat and slowly it fades away, the gas and newly created dust in the planetary nebula then dispersed since long. This is the end of the majority of all stars in the universe, and also the faith of our Sun.

Actually, not all stars reaching the white dwarf stage end their lives as cold dwarfs. If the star is a member of a binary system, it may explode as a supernova of Type Ia (SN Ia). The scenario is that both stars are of low mass, but one slightly more massive than the other. The more massive one develops faster than the other and reaches the planetary nebula stage first, thus contaminating its twin with blown off gases and dust. Later, when the least massive star reaches the AGB- or PN-phase, it is its turn to dump material on its companion. The companion has turned into a white dwarf at this stage, and if the mass of it exceeds $1.4 M_\odot$ after the mass transfer, the electron degenerate pressure cannot hold against the weight. The white dwarf transform into a neutron

\textsuperscript{17}The abundances of carbon and some other elements, especially $s$-elements rises in the stellar atmosphere.

\textsuperscript{18}Free neutrons may be produced either by the main source carbon via $^{13}\text{C}(\alpha,n)^{16}\text{O}$ or by neon via $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$.

\textsuperscript{19}Starting seed nuclei in this process is mainly iron ($^{56}\text{Fe}$).

\textsuperscript{20}A beta decay is when a neutron in an atomic nucleus emits an electron and is transformed into a proton. The atom nucleus is therefore transformed to an element with higher atomic number.

\textsuperscript{21}The three ways of creating elements heavier than iron are the rapid $r$-process, the slow $s$-process and the rare proton $p$-process.

\textsuperscript{22}Hubble Space Telescope pictures of planetary nebulae:
http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/32/
star and the outer envelope disrupts in a gigantic explosion. Huge amounts of iron is produced by these kinds of supernovae.

Intermediate mass stars may also explode as supernovae, but they achieve it single-handed. Low mass stars end their lives after helium burning, but intermediate stars of masses roughly 6–8 $M_\odot$ may start carbon burning after compressing their cores all the way to electron degeneracy. At the asymptotic giant branch they may suddenly ignite carbon in their cores and due to the degeneracy explode as supernovae, leaving only shredded gases left [31].

### 4.4.2 Better to burn out than fade away

Massive stars live their lives fast and furiously. They reach the temperature for hydrogen ignition very quickly, and consume the fuel in their cores very fast. As a consequence they stay at the main sequence for just a short while, before the next stage sets in. After helium exhaustion, a star of mass higher than approximately 8 $M_\odot$ moves smoothly on to carbon burning creating mainly neon, but also oxygen, sodium and magnesium. Then new rounds of core thermonuclear reactions follow in several steps: Neon is transferred into oxygen, silicon and magnesium, then oxygen is fused into silicon, phosphorus, sulphur and magnesium, and as a last step silicon burns into a variety of nuclei from sulphur to nickel, but mostly into iron. With every step, the star continues to burn the previous fuels in shells around the core. Finally the star resembles an onion, with a huge hydrogen envelope surrounding concentric shells of subsequent hydrogen-, helium-, carbon-, neon-, oxygen-, and silicon-burning matter outside a quiescent iron core.

Massive stars move swiftly back and forth in the HR-diagram along almost horizontal evolutionary tracks in the supergiant region after leaving the main sequence. In doing so, they pass the cepheid instability strip, i.e. a certain region in the HR-diagram in which a star has a combination of luminosity and effective temperature making it unstable and pulsating. The pulsations trigger strong stellar winds and heavy mass loss, and the amount of mass loss is a wild card in the stellar evolutionary calculations. Stars of masses more than about 25 $M_\odot$ suffer extreme mass loss. They often lose their whole stellar envelopes because their strong radiation fields push the gas away. These stars are called Wolf-Rayet stars, and the cool gas emanating from them is very important for interstellar chemistry, as it may be rich in carbon, nitrogen and oxygen.

The time scales for the different burning stages diminish with each step, from several million years for hydrogen burning, to days for the silicon fusion phase in a massive star. But the fierce nuclear fusion gets an abrupt ending when the silicon fuel is exhausted in the core. The core now consists mainly of the iron isotope $^{56}$Fe, and further fusion would require rather than liber-
ate energy, since nuclei with this number have the maximal nuclear binding energy.

The way of generating energy by fusion is now closed, and the star has to shrink to maintain the energy production. This causes further heating of the core and the photon energies become so high that they begin to split up atom nuclei into protons and neutron. The dissociation requires energy, and a catastrophic runaway contraction of the core starts. The immense particle density rises, as many more particles have to share a diminishing volume, and this forces electrons and protons to combine into neutrons which simultaneously produce neutrinos. The collapse only halts when the core reaches nuclear densities, and the core matter becomes degenerate. The envelopes around the stellar core have followed the core’s collapse, and at the sudden stop they bounce back and collide with the still infalling gas above it. This, together with a vast amount of released neutrinos, transfer huge energies to the gas and within seconds it explodes in a gigantic supernova of Type II, Ib or Ic, (SN II, SN Ib, or SN Ic) depending on how much gas is left of the envelope [139].

The collapsed core forms a very compact object, either a neutron star or a black hole. A neutron star may be regarded as gravitational bound atomic nucleus with a diameter of about 30 km. This may be compared to the ordinary size of a normal atomic nucleus of some $10^{-15}$ m. A black hole, cherished by so many science fiction writers, is an immensely compact object with such strong gravitational force, that not even photons can escape beyond its boundaries. Black holes are made by massive stars with cores heavier than those forming neutron stars. It is suggested, however, that the most massive stars, with masses above $30–40 M_\odot$, may collapse into black holes without an associated supernova explosion. The envelopes of such stars are simply swallowed by the black hole along with the core contents [31], [139].

It is believed that vast amounts of free neutrons are released during a supernova collapse, and that they penetrate the atomic nuclei in the stellar gas. But in contrast to the slow s-process in action during the AGB phase of low mass stars, the nuclei do not have time to decay into stable forms of elements before another neutron hits them. The process is rapid, why it is called the r-process, due to the extreme environment in a supernova. Many heavy elements and isotopes in the periodic table are probably formed in this way.

(Mn), iron (Fe), cobalt (Co) and nickel (Ni), all with mass number 56.
5. Galactic chemical evolution

Galactic chemical evolution is the study of the origins of the elements\(^1\). It combines Big Bang nucleosynthesis (Chapter 2), galaxy formation and evolution (Chapter 3), interstellar medium chemistry and dynamics, atomic, nuclear and particle physics, and – most importantly – stellar physics (Chapter 4). Stellar nucleosynthesis have produced almost all the different elements in the universe, and ever since the first stars ignited about 200 million years after the Big Bang \([129]\), they have enriched the interstellar medium. Thus, stellar abundance analysis gives insight not only to stars – it allows us to use stars as tracers of the history of the elements, of our Galaxy, and in the end, the history of the universe.

5.1 Concepts of galactic chemical evolution

The return of the gas – cosmic recycling

Eggen, Lynden-Bell & Sandage \([46]\) showed in the 1960s that it is possible to study the formation history of the Galaxy using stellar abundances. Stars have proven to be very useful, as by analysing their atmospheric composition we can get information on both past and present nucleosynthesis.

Ongoing nucleosynthesis can be observed in stars in their later evolutionary stages. They have altered their atmospheric composition through deep envelope convection, and/or by strong stellar winds revealing deeper layers with newly synthesised elements.

Most of the stars on the main sequence or turn-off point, on the other hand, have not undergone deep mixing since they began to burn hydrogen. Although vigourous nucleosynthesis is going on in their stellar interiors, this has not yet affected the composition of the outer atmospheres of such stars. The stellar atmospheres have preserved the composition of the initial cloud\(^2\), and by analysing their abundances of different elements, we are digging into an ancient past like archaeologists. We witness the interstellar gas from the time and place where the stars were born. We see the cosmic recycling of matter,

\(^1\)The word chemical is misleading, as Galactic chemical evolution concerns the origin and evolution of the nuclear species of the elements, irrespective of which eventual molecule they are part of.

\(^2\)As noted in footnote 15 of Chapter 4, this is not entirely true.
as the elements produced and expelled to the interstellar medium by previous
generations of stars are present in stars formed later. The cosmic recycling of
matter is illustrated in Fig. 5.1.

**Star formation rates**

How rapidly a stellar system forms stars - its star formation rate (SFR) - has
a crucial impact on its history. Unfortunately, the physics of star formation is
still not sufficiently well understood [93]. The rate depends on several param-
eters like the available amount of gas in the system, the state of the gas\(^3\), if
the system has a lot of infalling gas from intergalactic space, the rate of super-
novae explosions creating shock waves which might trigger star formation, if
the system has density waves such as spiral arms which make the gas contract,
if it has interfering neighbouring stellar systems, etc.

Small and elliptical galaxies have often had a vigourous star formation early
on in their history, but as the gas was soon exhausted, the rate of star formation
then drastically decreased. The majority of stars in these systems are therefore
very old, and contain gas which has passed through very few generations of
stars. The gas has been affected by e.g. supernovae of Type II from the short
lived massive stars of past generations, but probably not by Type Ia. Super-
novae of Type Ia may be the spectacular end of less massive binary stars, and
thus it may take on the order of one billion years before they start to contribute
their particular mixture of synthesised products to the gas, see Chapter 4.

Star formation is a very inefficient process - only a few per cent of the avail-
able gas is generally converted into stars. Systems like spirals and irregular
galaxies contain a lot of gas and dust, and although their star formation rates
were rather high in the beginning and later subsided, they never stopped form-
ing stars. There are stars of different ages in these systems, and stars formed
later contain gas enriched by the long lived low-mass stars.

By analysing the chemical composition of stars we may trace the mech-
nisms of nucleosynthesis, but we may also be able to map the star forming
history of the system, as different star formation rates determine the abun-
dance patterns in galaxies.

**Initial mass functions**

How the mass is distributed among the stars at birth in a generation is a vital
question in chemical evolutionary modelling. This distribution is referred to
as the initial mass function (IMF).

As touched upon in Chapter 4.1, most stars are less massive than the Sun,
and there is often a very limited number of massive stars formed in each stellar
generation. A classical assumption is the Salpeter distribution from 1955. It
states that for every star being produced, there are about 5 times as many stars

\(^3\)If the gas is too hot and/or dilute, it is impossible to form stars out of it.
Figure 5.1: This illustration is made to visualise stellar lives and the cosmic recycling of matter in the universe. It is pictured as a differentiated merry-go-round, with the different sections going with the same speed, but have different path lengths to cover – here equivalent to the stellar life spans. Some of the matter returns to the sea of gas and dust enriched with heavy elements, but some is lost at every circulation.

In the Big Bang hydrogen, helium and a little bit of lithium were created. The first generation of stars and failed stars, such as planets and brown dwarfs, were formed out of giant clouds containing only these elements. Big planets glow due to contraction, differentiation and radioactivity, and brown dwarfs also from some nuclear reactions. As time goes by they will just cool off and never return any matter to the interstellar medium. Stars on the other hand, shine due to fusion reactions in their cores. They expel huge amounts of gas and dust enriched by newly formed elements during their lives and deaths, see Chapter 4. Subsequent generations will therefore be formed out of gas and dust clouds containing mostly hydrogen and helium, but with a twist of heavier elements. Some material will, however, for ever be trapped in the stellar white dwarf-, neutron-star- and black-hole-remnants. Stars with masses below $0.5 \, M_\odot$ will also never contribute any recycled gases to the cloud reservoir, as they never achieve helium burning. They just fade as helium white dwarfs. Their expected lifetime on the main sequence is anyway comparable to the age of the universe, whereas the life span of massive stars is estimated to some 10 million years, at most.

The life spans are not drawn to scale in the illustration, and nor are the positions of the different stages in the stellar lives. Binary-star life cycles are not covered either. This picture is based on facts in the article on Hertzsprung-Russell Diagram in Encyclopedia of Astronomy and Astrophysics [31].
with half that mass being produced as well [93]. Recently one has started to use more complicated IMFs, which better describe observational data.

The initial mass function is generally assumed to be constant in space and time. Investigations support this [93], but fluctuations depending on e.g. the metallicity of the initial cloud have been much debated, see Elmegreen (2004) [47].

**Yields**

Yields are fundamental ingredients in galactic chemical evolution. The yield is the amount of an element created and set free to the interstellar matter per stellar generation.

Uncertainties in the data come with the field. The yields are based on rather shaky estimates of nuclear reaction rates, treatment of convection, mass cuts, explosion energies, neutron fluxes and possible fall-back of matter on protoneutron stars. They are also dependent on the correct modelling of the initial mass function, stellar rotation and mass loss, amount of binaries, mixing, identification of progenitors, and the ejection and explosion mechanisms. An example of the difficulties in the field is that we do not have any successful models of supernova explosions yet. This in spite of that massive supernovae probably are crucial sites for the nucleosynthesis of many elements, e.g. oxygen and the $r$-process elements. Iron and $s$-process elements are, however, mostly synthesised by low- and intermediate mass binary stars, which are somewhat better understood.

One also has to take into account that the yields of nuclei depend not only upon the nuclei being produced, but also upon their survival.

### 5.2 Theories of galactic chemical evolution

Theoretical modelling of galactic chemical evolution is a difficult and problematic topic, as there are a wealth of free parameters to adjust. If one concentrates to study of the atmospheres of main sequence or turn-off stars, one may map the composition of the interstellar medium from which the stars were born. The composition of this was, however, set by a complicated interplay between e.g. the stellar nucleosynthesis up to the time of star formation, the ejection mechanisms in previous generations of stars, the time aspects for these processes to occur, the mixing in the clouds of gas and dust, and the amount of infalling primordial gas diluting the enriched gas.

Thus, a model for the chemical evolution of galaxies needs to have the initial conditions determined, the star formation rate, the initial mass function, the yields, the flows of material into and out of the system, and the mixing rate specified as functions of time. The model is able to predict the total mass of
the system, the relative amount of mass in the form of gas and stars, the lock-up fraction for matter\textsuperscript{4}, and – most interestingly – the evolution of the abundances of the elements [93] [116].

The classical 'Simple model' of galactic chemical evolution assumes (1) that the system is a one-zone and closed (no inflows or outflows), (2) that the initial gas is primordial (Big Bang composition), (3) that the instantaneous recycling approximation holds (all stars formed will instantaneously eject their newly synthesised elements into the interstellar medium), (4) that the initial mass function is constant in space and time, and (5) that the instantaneous mixing approximation holds (the gas is well mixed at all times) [93].

The Simple model is relatively easy to handle, but was no success. It cannot reproduce the metallicity distribution of dwarfs of spectral class G in the solar neighbourhood. This is not surprising, as the lifetimes of intermediate mass stars, which produce the bulk of iron in the Galaxy, amount to roughly one billion years, and that the model does not include extragalactic infall. Modern evolutionary models consider these complications. They now account for e.g. a time delay between the bulk synthesis of oxygen and iron [93].

### 5.3 The chemical evolution of the Milky Way

Chemical enrichment models of the Milky Way have a wealth of free parameters, but there are also many observational facts to constrain the models with.

In the middle of the last century one realised that there are two distinct stellar components of the Milky Way: Population I, which is dominated by young, blue and metal-rich stars, and the old, red and metal-poor Population II stars. Population I has been identified as stars belonging to the thin disk of the Galaxy, and Population II as being halo stars. The light of the Galactic bulge is, however, dominated by old metal-rich red giants\textsuperscript{5}. Later, other categories have been introduced, such as the intermediate Population II\textsuperscript{6}, and Population III stars\textsuperscript{7}.

A comparison between abundance patterns of the different stellar populations and the predictions of galactic formation models leads to some insight into the formation and evolution of the Milky Way. For example, the metal-

\textsuperscript{4}The lock-up fraction is the fraction of matter locked into objects which do not contribute to the interstellar medium anymore, i.e. the matter thrown off the wheels of Fig. 5.1.

\textsuperscript{5}The star formation was so vigorous when the bulge formed, that the metal-content is very high in spite of its old age.

\textsuperscript{6}The intermediate Population II stars have been identified as thick-disk stars and the metal-poor part of the thin disk stars [108].

\textsuperscript{7}Population III stars are members of the first generation of stars in the universe. Such a star has never been observed, although two extremely metal-poor stars have recently been found: HE 1327−2326 [4] [52] and HE 0107−5240 [34] [35], with metallicities below −5.0 dex.
poor halo is identified as very old, and the disk as relatively young, as the age of a star may be very roughly estimated by its metallicity. A low metallicity implies formation early in the Galactic history, when few generations of stars had enriched the interstellar medium. However, the stellar metallicity is not a very reliable measure of the age, as it is not only dependent on the age, but on the whole set of parameters in a chemical evolution model.

The most likely way of formation for the Milky Way is the bottom-up scenario, with many separate protogalaxies forming a larger system. However, the abundances of $\alpha$-elements\footnote{Neon (Ne), magnesium (Mg), silicon (Si), sulphur (S), argon (Ar), calcium (Ca) and titanium (Ti) are usually denoted $\alpha$-elements, as their dominating isotopes are even multiples of the $\alpha$-particle (i.e. the helium (He) nucleus). Sometimes oxygen (O) is included as well.} suggest that there was a distinct separation in time between the formation of the halo and thick disk on one hand, and the thin disk on the other [93] [108]. The scenario is described in detail in Chapter 3.2.

Paper I, which is described in Chapter 7 of Section II, is an account of an abundance analysis of 43 halo stars, supporting the bottom-up scenario. However, the last word is not said on this. Nor do we have a satisfactory understanding of the formation of the peculiar stars described in Paper II of Chapter 8. These stars are metal-poor, and thus probably very old, but they have an extremely high content of both $r$-elements and $s$-elements. How did they form? How did they acquire their strange abundance patterns? There are a bewildering richness of evolutionary scenarios out there, which we are only in the beginning to understand.
6. To study stars

This is a short introduction to the theory, structure and terminology of stellar abundance analysis. The practice will have to wait to Part II.

6.1 What can be measured?

The founder of the philosophical movement of positivism, Auguste Comte, once made a famous remark about stars:

"While we can conceive of the possibility of determining their shapes, their sizes and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure...
Auguste Comte [37]"

Never say never again, because not even a quarter of a century later did Gustav Kirchhoff and Robert Bunsen discover that hot gases emit light in a set of very precise wavelengths, and that each element has its own unique fingerprint. Kirchhoff and Bunsen had invented spectroscopy, the remarkable technique which enables us to determine what distant objects consist of – even stars [53].

A stellar spectrum is a continuous distribution of radiation, speckled with narrow black lines. These lines are absorbed light at wavelengths intrinsic to the elements in the atmosphere of the star, see Fig. 6.1. They are called Fraunhofer lines after the German lens maker Joseph von Fraunhofer, who noted them in the solar spectrum already in 1814 [53]. Sometimes also bright emission lines appear. Although one can see many Fraunhofer lines in most stars, the same lines look different for different kinds of stars, see Fig. 6.2, and this is the basis for all stellar spectral classification.

The light emitted by a star can actually tell us nearly everything we want to know about it. By measuring the apparent magnitude\(^1\), the peak wavelength of the light, the intensities in certain parts of the spectrum, the distribution of light in general, the ionisation discontinuities and the positions, strengths and shapes of the lines, we can estimate the stellar luminosity, effective temperature, radius, mass, gravity, atmospheric pressure, atmospheric motions,

\(^1\)Apparent magnitude is the relative brightness of an object, as measured by an observer.
This is a schematic illustration of stellar light spread out as a spectrum with exaggerated hydrogen lines. The light has a maximum intensity at a specific wavelength, and therefore the star has a specific colour (in this case blue-green). In the spectrum one notes that certain wavelengths have less intensity than the rest. These so-called absorption lines show up because atoms in the atmosphere of the star absorb these wavelengths, and each element has a characteristic set of such wavelengths. The lines look dark on a photographic plate, see Fig. 6.2 [53].

magnetic fields, rotation, mass loss in stellar winds, possible twin stars or planets, radial velocity in space, spots on the surface, for spotted stars inclination as well, and last but not least – chemical composition\(^2\). Determining the distance is a bit tricky, but if the star is nearby, one can get a precise estimate by measuring its parallax\(^3\). Otherwise one has to rely on secondary methods. Of course, we cannot determine all of these features for all stars. In practise it can be very difficult even to pin down the temperature to an accurate degree – one of the most important stellar parameters.

\(^2\)The chemical composition of a star, or its abundances, is the amount of elements in the atmosphere of the star. It is usually measured as ratios: \([X/Y] \equiv \log_{10}\left(\frac{N_X}{N_Y}\right)_* - \log_{10}\left(\frac{N_X}{N_Y}\right)_\odot\), and \(\log \epsilon(X) \equiv \log_{10}\left(\frac{N_X}{N_H}\right) + 12.0\). \(X\) and \(Y\) denotes the elements, e.g. iron (Fe) and hydrogen (H), \(N_X\) denotes the number density of the element \(X\), and \(\odot\) denotes the Sun. \([X/Y]\) therefore means the relative abundance of the element \(X\) compared with the element \(Y\) in the star, as measured against the solar ratio of \(X\) to \(Y\). Metallicity, i.e. the amount of elements other than hydrogen and helium, \([\text{Me/H}]\), is usually set equal to the stellar iron abundance, \([\text{Fe/H}]\), in observational astronomy.

\(^3\)The parallax is the change in apparent position of an object, when viewed against distant objects from different angles.
Figure 6.2: This figure shows different stellar spectral classes, from O to M2. The Fraunhofer lines of elements and molecules are clearly depending on the stellar classification, even though the stars might have the same abundances. See also Fig. 4.1. The synthetic spectra are created by prof. M. Briley, Department of Physics and Astronomy, University of Wisconsin at Oshkosh, USA.
6.2 Short introduction to stellar atmospheres

Light is electromagnetic radiation and may be viewed as waves with wavelengths. The longest waves are the much used radio waves and the shortest are the dangerous gamma rays. Our eyes see the intermediate waves called optical light. It contains all the colours of the rainbow, which together form white light. But light is not only waves. According to quantum mechanics, light may also be viewed as particles called photons, each with a distinct energy.

Stellar photons originate from the star’s atmosphere - the outermost envelope of thin gas which for most stars is a fraction of a percent of the stellar radius. For reasonably hot stable stars without strong mass-loss, the atmosphere consists of three parts: the extremely hot outer corona, the medium hot chromosphere and the innermost photosphere. The photosphere includes the temperature minimum, and this is what is considered the stellar ‘surface’. Below the surface the temperature, pressure, and density rise inwards. The surface is not homogeneous for solar type stars and cooler, but bubbling like a boiling thick soup. This granulation has been beautifully pictured by the Swedish Solar Telescope on La Palma.

6.2.1 Some theory of stellar spectra

There are some basic equations for describing the physics of a stellar atmosphere. The energy equation states that the energy produced in the star must be equal to the energy flowing away as photons and stellar wind etc. No energy is generated in the atmosphere, it is merely transported out in different ways. The hydrodynamic equation is dealing with the overall motions in the atmosphere. Is there an accelerating wind in the atmosphere? Is there a steady wind, or even no major gas motions at all? The equation of radiative transfer is one of the most important in stellar physics. It describes how the intensity of light changes along a ray due to emission, absorption and scattering.

Opacity and optical depth are important concepts in stellar analysis. The opacity measures the absorption and subtraction of light via scattering from a ray per unit mass density. One can regard it as a cross section per unit mass for the medium – the larger the cross section or the higher density of the matter, the lesser distance can a ray of light move before totally absorbed or scattered away. The opacities of stellar atmospheres vary very much between stars, and it is therefore facilitating to talk about the optical depth. The optical depth measures the total opacity from a level in the star to the observer. It is a better

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4Picture of the granulation on the Sun taken by the Swedish Solar Telescope can be found at: http://www.solarphysics.kva.se/.
measure of the depth in an atmosphere than the depth measured in meters [67] [120].

The opacity is either continuous, i.e. does not change very much with wave-
length, or wavelength specific. The continuous absorption and scattering is
dominated by the photoionisation of hydrogen and helium atoms and electron
scattering in hot stars, but for cool stars the neutralisation of the negative ion
of hydrogen dominates. Wavelength specific opacities, or spectral lines, are
also very important – especially for cool stars. The numerous metal lines actu-
ally affect the shape of those stellar spectra, as they veil the wavelengths in
the UV and shifts the wavelength of maximum light to longer wavelengths.

Spectral lines are formed by absorbing and emitting atoms, ions or
molecules in the stellar atmosphere. If e.g. an atom is absorbing a photon, an
electron 'moves' (in a semi-classic view) from one electronic level to another
level with a higher energy state, i.e. an excited state further away from
the atomic nucleus. A basic principle in nature is that everything wants to be
in the lowest possible energy state. Applied to atoms, this means that an
atom left alone with an electron in an excited state will eventually move the
electron to a level with lower energy, and send away a photon. The excited
state has thus a finite lifetime, and according to Heisenberg’s uncertainty
principle the energy of the excited state has a small uncertainty. This means
that two atoms with the same excited state can emit photons with slightly
different energies, and thus wavelengths. This is called natural broadening of
a line and may affect the stellar spectra by creating a smooth profile around a
mean wavelength, see left part of Fig. 6.3.

Spectral lines are broadened by other mechanisms as well; the atoms have
heat motion, and this causes small Doppler shifts which change the wave-
lengths of the emitted photons. Also small scale motions in the atmosphere,
so-called microturbulence, causes Doppler shifts, and collisions with other
particles, denoted Van der Waals broadening, affect the energy levels as well.
Electric fields from other ions and atoms close by distort the energy levels in
Starck broadening, and magnetic fields are responsible for Zeeman splitting
and thus further broadening. Atoms belonging to the same element, but with
different amount of neutrons in the nucleus, i.e. isotopes, have slightly dif-
f erent energy levels and contribute to a broadened line profile. This is most
important and are especially affecting the line strengths of strong lines. This
applies as well to hyperfine splitting (hfs) – the coupling between the electron-
movements and the spins of the electron and atomic nucleus respectively.
Lines can also be reshaped without effects on their intrinsic strength by micro-
turbulence (for weak lines), by large scale motions called macroturbulence, by
stellar mass loss, and rotation.

The combination of all these physical processes results in a total line pro-
file, where the core of the line is dominated by the thermal motions high up
in the stellar atmosphere and the line wings are formed mostly by natural and collisional broadening deeper down. The continuum, i.e. where no absorption or emission lines are present in the spectrum, is also formed deep in the atmosphere, see Fig. 6.3.

Astronomers are interested in knowing the amount of an element in the stellar atmosphere. As spectral lines mean more opacity compared to the normal continuum level, one can deduce the abundance by measuring the strength of the line. But to calculate the abundance from the strength can be rather tricky. Weak lines are very nice as their strengths are proportional to the abundance of the element. Strong lines have become saturated, which means that more absorbers may not succeed in reducing the light much more. The strengths may therefore be rather independent of the abundance for such lines. For very strong lines, however, the lines have become over-saturated, and the wings contribute a lot to the equivalent width. The strengths are then approximately proportional to the square root of the abundances, but are then also depending on the processes broadening the line wings. It is very important to choose well...
behaved lines in an investigation, but sometimes you have to put up with bad lines, as there is nothing else to choose.

6.2.2 Model atmospheres

"Life is fritted away by details. Simplify, simplify.  
H.D. Thoreau [131]"

One needs a model atmosphere to understand the environment in which the stellar photons were created, and thus connect the line strength with an abundance of an element. Since the first model atmosphere was created in the early 20th century there has been a remarkable progress, especially during the last decades. During the last thirty years the volume and quality of atomic and molecular data has been enlarged by a factor of $10^{-2}$, computers have improved by at least a factor of $10^{6}$ in speed, and algorithms by a factor of $10^{2}$ or more [68]. This is very impressive indeed, and modern models are to a larger degree detailed and more self-consistent. Observational equipment has also improved during this time: the size of the biggest telescopes has increased by more than a factor of 3, and spectrometers are at least a factor of 50 times better. Strangely enough, this has not increased the accuracy of the abundance determinations nearly as much. There still exist severe systematic errors in abundance determinations, and this is due to the physical assumptions made in an ordinary stellar atmospheric model [68].

In the investigations presented in Part II we have used atmospheric models calculated with the MARCS code. MARCS stands for Model Atmospheres with Radiative and Convective Scheme. The first versions of the code were created in the 1970s by a group led by Bengt Gustafsson at Uppsala Astronomical Observatory [69]. The code has been much improved over the years [9] [44], and a grid of models will soon be released on the web for common use [70].

The MARCS code is a state-of-the-art classical code, and the reason for the classical epithet is the underlying assumptions made for facilitating the calculations. Firstly, the code assumes a one dimensional stratification of the atmosphere. This means that all thermodynamical variables are functions of one space coordinate, although you can choose to use a plane-parallel or a spherical geometry. Secondly, the code is based on the assumption of hydrostatic equilibrium, i.e. no large scale motions affect it. This is in fact a fairly good assumption for most stars. One also assumes a constant outpour of photons, i.e. radiative equilibrium, and that convection is dealt with through the mixing-length approximation. The latter is a widely used approximation,
however of uncertain quality\textsuperscript{5}. The code calculates a time-independent stellar atmosphere, thus the atmosphere is assumed to be stable. Fine structure in the atmosphere, such as granulation, star spots etc. is ignored, as well as magnetic fields, pressure waves, mass loss, conduction and chemical inhomogeneities. On the other hand has the sources of opacity in the atmosphere have been thoroughly explored.

Another important assumption in the MARCS model atmosphere code, is that of Local Thermodynamic Equilibrium (LTE). In LTE one assumes that there is a strong coupling between the radiation field and local conditions of the gas, and that one temperature measure is sufficient. This approximation is generally valid when collisions dominate in an atmosphere. This means that the pressure, and thus the density and gravity, is fairly high and that the radiation field is relatively weak or at least local. In the LTE approximation one approximate the local emitted radiation with the Planck in the equation of radiative transfer, and make use of the Saha and Boltzmann equations for the population numbers of different atoms and ions \cite{67} \cite{120}. This simplifies the calculations immensely, but still there is a system of coupled non-linear equations to solve simultaneously in the whole atmosphere. The equations have therefore been discretised, i.e. remade to a large number of summations instead of integrals, and linearised. A starting model is assumed and then the equations are solved numerically by a multi-dimensional Newton-Raphson method. The calculations are iterated until consistency is achieved for all depth points and all wavelength points chosen for the stratification \cite{70}.

New generation models are coming, but maybe not as fast as one could wish. The reason is obvious – it is costly, both in manpower and computers, to develop these codes. The new type of models treat the stellar atmospheric convection and radiative transfer in two or three dimensions, they relax the LTE approximation (so-called non-LTE or NLTE), and include time-dependence, winds and magnetic fields. Physically consistent models with three dimensional magnetohydrodynamic and NLTE radiative transfer are not here yet, but fortunately a few codes exist which include some of these improvements \cite{68}.

6.3 Measurement errors

Even though astronomy is not as ‘hands on’ as other parts of physics, we are doing measurements of physical data, and the data therefore suffer from errors and uncertainties. Errors can be spurious or systematic. Spurious ones

\textsuperscript{5}The mixing length approximation assumes that the convective energy is carried by ‘bubbles’ of a single size which dissolve after a mixing length. The problem is that this approximation holds only in the deep layers of a stellar atmosphere.
we cannot do so much about, more than be careful while taking data.

Major systematic error sources are abundant in stellar abundance analysis. They may arise from errors in the reduction and measurement procedure of the spectra, such as stray light, continuum placements, line-fits etc. They may also arise from erroneous atomic data, such as erroneous opacities, transition probabilities, or the handling of line broadening, etc. More systematic shifts of the results come from simplifying assumptions in the model atmospheres, such as one-dimensional atmospheres, LTE, convection treatment by the mixing-length approximation etc. One of the most important sources of systematic errors is, however, the miscalculation of stellar parameters.6 This is especially true for effective temperature and surface gravities.

Uncertainties in the measured data are a scourge, but they also act as a diving force for the scientific progress.

6.4 The structure of analysis

The structure of an observational project in astronomy, especially in stellar abundance analysis, may be viewed in Fig. 6.4 and 6.5.

Observatories are placed in scarcely populated deserts at high altitudes to get minimum contamination of stray light, and as little as possible of turbulence in the air between the telescope and space. To disperse the stellar light one usually use a reflection grating, i.e. a mirror with very fine and evenly spaced straight grooves which spreads light into a spectrum by diffraction. In high-resolution spectroscopy often echelle gratings are used, which have a stair-case profile of the grooves. The light is collected by an electronic plate called a Charged Coupled Device (CCD), which essentially is a grid of small light sensitive units, pixels, coupled in an intricate way to a computer. The pixels have individual sensitivities to light, and therefore 'pictures' called flat fields are taken to map it and remove the dependence. The readout noise of the equipment, the bias, is also measured and cared for. For spectra one has to take comparison spectra of a standard source to be able to set the wavelength scale, and one has to merge the different bits of spectra and map the stellar radial space velocity. Important for the evaluation of the quality is to estimate the resolution, the resolving power, and signal-to-noise (S/N).

The measuring of the stellar parameters temperature, gravity, metallicity and microturbulence can be done in several ways. They are needed as input to

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6 The stellar parameters considered here are the effective temperature, $T_{\text{eff}}$, surface gravity parameter, $\log g$, metallicity, $[\text{Me}/\text{Fe}]$, and microturbulence, $\xi$.

7 The resolution is a measure of the finest resolvable spectral detail that can be discerned in a spectrum.

8 The resolving power is equal to the wavelength divided by the resolution, i.e. another measure of how much details one can distinguish in the spectrum.
How to do it

Hands on doing observational astronomy is straightforward

In theory, yes...

I. Idea
   To get an idea is hard for some, others have their brains flooding.

II. Exploration
   Your brilliant idea was maybe investigated 15 years ago.

III. Time application
   Recruit people to the project to split the work, access valuable data,
   and have learned people to ask if things ... well you now.
   Restrict your sample of objects in a clever way.
   Do a lot of calculations of observing times etc.
   Make an application to a suitable telescope.
   Hopefully you succeed and get time - and as much as you asked for.

IV. Observation
   Yahoo, you will go and ride that huge thing on top of the mountain!
   It may be very wearisome to observe if you have gotten many nights,
   bad weather, a malfunctioning telescope or your preparation was lousy.

V. Reduction
   To clean the data from recording noise can be tedious, time
   consuming, and bad for your health if the computers don't work as
   they should or - worst of all - your data is corrupted in some way.

VI. Measuring
   Measuring may also be time consuming and increase your blood
   pressure, but the first glimpse of the results makes it fun anyway.

VII. Analysing
   YES - finally results. This is the hard-earned reward!
   Checking the results is boring, but necessary.

VIII. Comparing
   Very exciting stage - is your conclusions in contradiction with accepted
   theories? Then you are in luck!

IX. Article
   No computer crash which wiped away the results?
   Good, then you can start writing your opus.
   Referees reports may be a pleasure to read, but sometimes a real pain.

X. Feel proud of yourself!
   It may take years, even decades, from idea to article, but when it is
   accepted you have added another brick to the castle of knowledge.

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Figure 6.4: This list was written to amuse you a bit, but it gives a hint of the structure
of an average project in observational astronomy. A more serious analysis structure is
given in Fig. 6.5.
Figure 6.5: This figure illustrates the analysis structure for stellar abundance analysis.
the model atmosphere code, along with the abundances of hydrogen, helium and at least an approximate estimate of the metallicity, i.e. the amount of elements heavier than helium. One also needs immense amounts of atomic and molecular data for the calculations. Thus, had it not been for the careful and often tedious work made by numerous of past astronomers and atomic physicists, astronomy had been less fun today. Nowadays, much data may be found in huge data bases.

The output from the atmosphere code consists of tables of gas kinetic temperature, pressure and electron density at certain depth points in the star. Using this information, the total opacity at any wavelength can be derived, and the escaping light at the surface calculated. The theoretical spectrum is modified to mimic the effects on the stellar light by the telescope and spectrograph, and then one can compare with the observed spectrum.

The calculated lines and the observed stellar lines can be compared in two ways. The first is the equivalent width method measuring the total area of the line. This line strength is then transformed to a width, an equivalent width, of a rectangle with the same area as the original line, see Fig. 6.3. The equivalent width is compared to a calculated theoretical equivalent width based on an assumed abundance for that element, and the comparison is done iteratively until consistency is achieved. The other method is the synthetic spectrum method, and takes the line's shape as well as its equivalent width in consideration. One alters the input parameters of the analysing program to fit the line as closely as possible. Synthetic spectra is preferred for crowded spectra, i.e. when the spectral lines are blended by other lines.

The analysis has given estimates of the stellar abundances, and the usual way of presenting the result is by comparing the ratios of some elements in the star to the same ratio in the Sun, see footnote 2. In this way some systematic errors may cancel out and the astronomers can relate the abundances to our standard and best know star, the Sun. Now the speculation starts...
Part II:
Scientific work
7. The Halo Star Study of Paper I

This chapter gives some background information on Paper I. For scientific details see the article.

I have experienced that an ordinary stellar abundance analysis is no highway. It is more like a bumpy small road, full of dead ends, hopefully leading to Rome. The way of doing the analysis was not obvious. Several setups were tested before deciding on the one presented in Paper I, and often in different combinations. My contribution to this project is described in Sec. 3.1, 3.3, 4, and 5.1 to 5.6 of Paper I. I have also done a large number of comparisons with other projects, but most of them are not included in the article as they were based on other setups than the final one. I have written Sec. 2, 3.1 3.3, 5.1–5.6, and an early version of Sec. 4 of the paper. I have taken a large part in the discussion and made plots and background material to the other sections. I have done all work described in this chapter if not stated otherwise.

7.1 The early phase of the project

The aim of the halo star study has been to investigate the chemical evolution of the Galactic halo. It was initiated nearly twenty years ago by Bengt Gustafsson and Bengt Edvardsson at the Uppsala Astronomical Observatory, Sweden, together with Pierre Magarin at the Institut d’Astrophysique et de Géophysique, Université de Liège, Belgium, and Poul Erik Nissen at the Institute of Physics and Astronomy, University of Århus, Denmark.

At that time numerous disk stars had been analysed, or were about to be analysed [44], but only a limited number of the more metal-poor halo stars. Among many questions, the investigators wanted to map the trend of the α-elements\(^1\) relative to iron, as the scatter for halo stars seemed very large [66]. The questions were how much of the scatter that was real, and if there were any sub-groups in the halo-population.

Since then many other studies have been performed. However, the data was high resolution spectra which had been observed and reduced, and covered a still fairly large homogeneous sample of metal-poor stars, and half of the stars in the sample had never been analysed. When I came to the Uppsala

\(^1\)See footnote 8 of Chapter 5.
Astronomical Observatory and wanted to study stars, an opportunity showed up for continuing the analysis of the material.

7.2 The stellar sample

The sample consists of 43 metal-poor field stars of spectral classes F and G in the solar neighbourhood. The metallicities range from $-3.0$ dex to $-0.4$ dex. The sample was chosen to be fairly representative, and turned out to consist of several different types of stars: sub-giants (15), stars at the turn-off of a 14 Gyr isochrone (12), and main-sequence stars (11), but also some younger stars (4), and a single red horizontal branch star sneaked into the sample. There is also the unfortunate fact that 4 variables, 9 binaries, and 3 possible binaries are members of the sample. On the other hand, 2 interesting barium-stars are included as well.

The stars were observed by P.E. Nissen (11 stars) and P. Magain (32 stars) at the ESO 1.4 m Coudé Auxiliary Telescope, CAT, with the short camera of the Coudé Echelle Spectrometer, CES. They also made the reductions and measurements of the equivalent widths together with E. Jehin. There were some problems with the linearity of the used CCD, but we have accounted for that.

The measured lines were chosen to cover the $\alpha$-elements (O, Mg, Si, Ca, Ti), the iron peak elements (Sc, V, Cr, Fe, Ni), some odd-Z elements (Na, Al), and an s-process element (Ba). Thus, equivalent widths were measured for a maximum of 63 lines and 13 elements for each star.

7.3 The analysis

7.3.1 Fundamental parameters

The selection of the values for the stellar parameters has been a matter of major interest, as they affect the abundance results quite a lot, especially the choice of effective temperature scale. Here is a resumé of the choices of stellar parameters, and the reasoning behind them.

**Effective temperatures, $T_{\text{eff}}$**

The effective temperatures of the stars were derived from Strömgren $uvby - \beta$ photometry and an empirical temperature calibration based on the InfraRed Flux Method (IRFM).

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2One line was removed from the analysis later on due to a blend, see Paper I, Sect. 5.1.
The IRFM is a photometrical method based on the ratio of the total flux and an infrared monochromatic flux. The stellar effective temperature is estimated by comparing the theoretical ratio, based on atmospheric models, to the observed ditto. The IRFM method has an accuracy of typically 100 K and is quite reliable if the calibration is based on a large number of stars. This is why we switched from the calibration of Magain (1997b) [91], which is based on 11 stars and didn’t cover the low temperatures of our stars, to Alonso et al. (1996), which is based on 500 dwarfs and subgiants [3]. The first calculations were made by P.E. Nissen, the later ones by me.

We applied Eq. (9) in Alonso et al. (1996), and it includes the metallicity, [Me/H]$^3$, in the derivation. We iterated the derived effective temperatures until consistency was achieved with the other parameter(s).

**Metallicities, [Me/Fe]**

P.E. Nissen had in the starting years of this project derived the metallicities from Strömgren photometry via the calibration of Schuster & Nissen (1989) [122]. Then there were discussions of the reliability of this scale, as it differed from the calibration of Magain (1987a, 1989) [90] [92].

We decided to use the spectroscopically derived iron abundances as metallicities for the sample instead of photometry. The abundances were calculated from the equivalent widths of the FeI lines. This is not optimal, as the they may be affected by NLTE effects, but we had only one single line of FeII observed and a maximum of 19 of the neutral species.

Our derived spectroscopic metallicities agree nicely with the Schuster & Nissen calibration, and it occurred to us that the origin of the discrepancy between the scales of Schuster & Nissen and Magain, was the effects of the non-linear detector found by Gosset & Magain in 1993 [61].

As noted in the previous subsection, the metallicities were dependent on the other stellar parameters via the equations used, and therefore determined through iteration.

**Gravities, log g**

The surface gravities were at first estimated by isochrones using the stellar effective temperatures, their classification derived from Strömgren photometry, and an interpolation to their metallicities. The work was done by P.E. Nissen.

The photometry was later abandoned in favour of the more precise Hipparcos parallax method in combination with isochrones. Eq. (3) of Nissen et al. (1997) [110] was used, and the estimates of the stellar masses needed for it were derived by C. Yuqin. The effective temperature is also included in this

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$^3$I adopt the usual notations that [X/Y] ≡ log$_{10}$(N$_X$/N$_Y$)$_\odot$ – log$_{10}$(N$_X$/N$_Y$)$_\odot$, and log ε(X) ≡ log$_{10}$(N$_X$/N$_H$) + 12.0, X and Y denoting different elements. The abundance measures include all nuclei of an element, regardless of ionisation or molecular state.
equation, and thus the gravity parameters were iterated along with the temperatures, the metallicities and the derived iron abundances to achieve consistency.

**Microturbulences, \( \xi \)**

At first we tried to determine the microturbulence parameters individually for each star in the same way as Edvardsson et al. (1993) did [44]. The microturbulence is varying with effective temperature and surface gravity, and we aimed to derive an equation of the same type as their Eq. (9).

The starting estimation was calculated with the equation from Edvardsson et al., and the abundances of Fe and Ni were derived from many neutral lines. Then the abundances were plotted vs. the theoretical line strength, see lower panel of Fig. 5. A slope was sought and the slopes from all stars were plotted vs. the fundamental parameters of the stars, i.e. in a similar way as Fig. 6.

However, the attempts to derive an equation like Eq. (9) in Edvardsson et al. were abandoned. The starting values ranged from 0.0 to 3.5 km/s, with a mean of 1.6 km/s and a standard deviation of 0.6 km/s\(^5\), and we could not modify the stellar parameters to get a consistent result. Instead 1.5 km/s was applied as a standard value, as the mean was derived including outlier stars.

We checked how the microturbulences affected the final abundances, and as can be seen in Table 5 in Paper I, the effect is negligible in almost all cases. The only element strongly affected is barium, but these abundances are questionable anyway due to the single line measurement, a blend with iron, and no hyperfine structure applied. Thus, even if our assumed microturbulence parameters would be slightly overestimated in general, and not optimal for some stars, this has little impact on the derived mean abundances, with the exception of barium.

### 7.3.2 Line data

The line data was gathered from the Vienna Atomic Line Data Base (VALD) [85], except for the oscillator strength \( f \)\(^6\) included in the \( \log gf \) values. We instead derived astrophysical \( \log gf \) values for all lines with the Sun as the reference star modelled by the MARCS code\(^7\).

Systematic errors in oscillator strengths are notoriously a cause of error in abundance analysis, and the lack of accurate data can thwart even the most sophisticated NLTE calculations of level populations. Thus, to use astrophysical

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\( ^{4} \)When I give reference to a figure in this section, I mean a figure in Paper I.

\( ^{5} \)This was derived using original values of the effective temperatures and metallicities.

\( ^{6} \)The oscillator strength \( f \) is a factor between quantum mechanics and a semi-classical treatment of line formation. It is related to the transition probability, i.e. the likelihood that the atom will absorb or emit a photon between two particular energy states.

\( ^{7} \)See Chapter 7.3.3 for a discussion of the oscillator strengths of oxygen.
oscillator strengths was no obvious choice, as these depend on the measurement errors of the equivalent widths, the strengths of the lines in the reference star, the choice of model atmosphere etc. In this case it is also questionable due to the choice of reference star, as the Sun is much more metal-rich than the programme stars. Hidden blends in the spectrum of the Sun might not turn up in metal-poor halo stars and vice-versa, thus causing errors in the derived abundances.

Despite all objections, we did chose solar astrophysical oscillator strengths, because they simply seemed to be the best at the time. We had tested a number of different ways to get log \( g_f \) values. Accurate laboratory data would have been preferable, but were not available at the time. The log \( g_f \) values collected from VALD were of poor quality, as the abundances from different lines of the same element gave very different results. We also tried to make a differential analysis within the sample, i.e. determined the abundances of two stars with astrophysical log \( g_f \) values from the Sun, then set the derived abundances as known facts and redetermined the log \( g_f \) values from the spectra of these stars. Thereafter we determined the abundances of the rest of the stellar sample with the secondly derived oscillator strengths. This setup was tested in an attempt to at least partly avoid the issue of hidden blends in the more crowded solar spectrum. However, the internal differential analysis was found to give very similar result to the solar values, so a direct comparison with the Sun was preferred instead.

When the decision was taken to use solar astrophysical oscillator strengths, we had a debate of which solar-model atmosphere to use. The argument for the Holweger & Müller (HM) semi-empirical solar model [75] is that it represents solar limb-darkening and fluxes better than many theoretical flux-constant 1D models [20] [45] [56]. Thus, there are reasons to believe that the oscillator strengths derived from the HM model might be better in absolute terms. The argument for the MARCS model is that the stellar sample was analysed with atmospheres calculated with this code, and that running a strictly differential analysis would cancel some systematic errors. This is, of course, based on the assumption that the systematic errors behave in a similar way in the Sun as in the Population II stars.

We made the abundance analysis testing both sets of solar oscillator strengths. The HM model resulted in log \( g_f \) values 0.11 dex higher in mean than the MARCS values, and the resulting abundances showed an over-ionisation of [Fe II/Fe I] of 0.12 dex for the programme stars. For the log \( g_f \) values from the MARCS model the iron ratio was nearly zero. This supported the pure differential analysis-argument, and a MARCS solar model with the parameters \( T_{\text{eff}} = 5780 \text{ K} \), log \( g = 4.44 \text{ dex} \), [Fe/H] = 0.00 dex, and \( \xi_t = 1.15 \text{ km/s} \) was applied in the end.

The difference between the log \( g_f \) values of the two solar models suggests
that there may exist systematic errors in our analysis of about 0.15 dex in [X/H]. The errors in [X/Fe] are probably smaller, as one then makes a differential analysis within a single star. If the absorption lines of elements X and Fe are originating in the same layers in the star, then it hopefully matters less if the temperature structure within the star is somewhat off.

7.3.3 NLTE effects in oxygen

The oxygen lines in the infrared triplet at 7774 Å are extremely sensitive to temperature due to the high excitation energy for its lower level [82]. In addition to that, they are formed deep in the atmosphere, which also make them sensitive to convection. In halo stars we see much deeper into the atmosphere due to the much less abundant absorbing metals, i.e. the optical depth scale is moved inwards. The photons of the lines come from much deeper layers where convection is important, therefore the concept of a differential analysis with the Sun as reference may be problematic in this case.

As the strength of the infrared triplet of oxygen is sensitive to its formation environment, we applied NLTE-corrections to the derived LTE abundances of oxygen. The corrections were calculated for both the programme stars and the Sun by M. Asplund with the code MULTI developed by M. Carlsson [26].

7.3.4 Model atmospheres and analysing program

We calculated stellar atmospheres from the old MARCS model atmosphere code but with improved continuum and line opacities, see Asplund et al. (1997) [9]. The modified models show a significantly steeper temperature gradient in the deeper line-forming layers compared to previous models, see also Chapter 6.2.2 for general information about the MARCS model atmospheres.

The Uppsala program EQWIDTH was used to analyse the measured stellar absorption lines. In this program LTE is assumed, but a source function is adopted which properly allows for continuum scattering. In this code, as well as in the MARCS program, the work of Barklem et al. (2000) is applied, i.e. the collisional broadening induced by neutral hydrogen and helium are accounted for by adopting the results of quantum mechanical calculations. This is an important improvement, as neutral hydrogen is the most important collisional broadener in solar type stars. Tests were made of the impact of this change.

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8Old MARCS model atmospheres, in comparison to the new ones soon to be released on the web [70].
7.4 Checking the results

Even apart from trying different set-ups for fundamental stellar- and line-
parameters, a lot of testing of the results was made9.

It is necessary to check the results thoroughly, to be able to know how much
faith to put into your results. The usual way is to limit the error estimations to
errors in fundamental parameters, and the errors are then of the order 0.1 dex
in \([X/H]\) for normal stars. Realistic errors due to systematic uncertainties are,
however, roughly 0.2 to 0.3 dex in \([X/H]\), if the errors are not coupled or cor-
related [68].

We have explored some of the systematic errors in this analysis: The ones in
the fundamental parameters, in oscillator strengths, and in collisional broad-
ening. We have investigated individual line deviations for iron and nickel as
well. The tests and error discussion is presented in detail in Paper I.

7.5 Discussion of some results

We have derived abundances of O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Fe, Ni,
and Ba for 43 halo stars. The results and an extended discussion are presented
in Sec. 4, 6, 7 and 8 in Paper I. Here I shall just comment on a few of them.

7.5.1 Oxygen

The oxygen debate

Ever since Aller & Greenstein (1960) [2] investigated the abundances of \(\alpha\)-
elements in extreme subdwarfs, and Wallerstein (1962) did a survey for disk
stars, one has been aware of the strange dependence on metallicity for these
elements. The metal-rich stars have approximately the solar content of \([\alpha/Fe]\).
This ratio then increases gradually with decreasing \([Fe/H]\) until the halo stars
start dominating around \([Fe/H] = -1.0\), where the ratio levels off [116].

Several later studies confirmed the picture of a knee in the \([O/Fe]\) vs. \([Fe/H]\)
diagram. This consensus was, however, broken in the 1990’s when an ani-
mated debate was launched, probably started by the work of Abia & Rebolo
(1989) [1]. The issue of the debate is the oxygen content of metal-poor stars
– do they show a steep continuous trend going to lower metallicities in the
\([O/Fe]\) vs. \([Fe/H]\) diagram, or is it a trend with a knee followed by a rather flat
plateau as the older papers suggest?

The ‘continuous-trend’ opinion has been argued by e.g. Boesgaard et al.
(1999) [22], and Israelian et al. (1998, 2001) [78] [79], based upon UV OH-
lines. However, the determination of the oxygen abundance from these lines

9The tests referred to in Sec. 5.1 to 5.6 in Paper I were made entirely by me. They were made
after each rerun of the analysis.

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has been seriously questioned by several works [7] [10] [111], claiming to uncertainties in modelling the UV opacities and convective inhomogeneities.

Our results on oxygen based on NLTE-corrected abundances from the IR triplet may be viewed in Figs. 3 and 10, see also Chapter 7.3.3. It clearly supports the 'knee' scenario, along with other work such as Nissen et al. (2002) [111], Gratton et al. (2003) [62], and Edvardsson et al. (1993) [44]. These investigations have been based both on the triplet lines, and the forbidden line [O I] at 6300 Å. The forbidden line is regarded as the most reliable line to use, as it is relatively insensitive to NLTE effects. Note that the trends in Eq. (4) and (5), illustrated by Fig. 10, are not forced to join. They just turn out to reach similar values at [Fe/H]~ −1.

Although the debate is not as lively as it was at the IAU General Assembly in Manchester 1998, it is not over. The results from different kinds of oxygen lines still give quite different abundances. This has been illustrated by García Pérez et al. (2005) recently, although their results for subgiants depart from other investigations for dwarfs in that their OH lines give lower [O/Fe] than the IR triplet [55].

The large discrepancies in oxygen-abundances are rather frustrating. A large part of the differences may, however, be attributed to shifting settings of the stellar parameters and oscillator strengths, differing stellar atmospheric model codes and opacities included in the models, etc. Some studies do not apply NLTE corrections to their triplet line abundances [22], which may confuse matters. The models of stellar atmospheres and spectra are still not physically consistent. The issue will hopefully be resolved when 3D-NLTE atmospheric codes can be systematically applied.

**Interpretation of the oxygen plot**

What is the cause for the behaviour of oxygen in Figs. 3a and 10? Even though the abundance of iron is a bad measure of galactic time, it gives some hint of the past galactic evolution as stars were generally less metal-rich far back in time, see Chapter 5. As noted in Chapter 4 and illustrated by Fig. 5.1 in Chapter 5, massive stars have relatively short lifetimes and may end their lives as SNe II. These supernovae produce copious amounts of oxygen but very little iron, which makes the ratio of oxygen-to-iron rather high in the gas expelled to the interstellar medium. In the plot we therefore see high values of [O/Fe] at low metallicities.

After some billion years, less massive stars in binary systems reach the end

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10The forbidden lines at 6300 and 6364 Å are difficult to measure, as they become too weak in most metal-poor stars, particularly dwarfs. One then has to rely on the stronger IR triplet around 7773 Å, which are highly sensitive to temperature and non-LTE effects, or on UV OH bands which are also sensitive to temperature, depend severely on 3D effects and has poorly determined line data [55].
of their lives, and subsequently explode as SN Ia. These supernovae have the opposite production characteristics, as they create vast amounts of iron, but very little oxygen. Thus, the ratio of [O/Fe] starts to decrease in the interstellar medium as this new type of supernova adds matter to the clouds. The 'knee' in the diagram marks when the onset of SN Ia starts to interfere on a large scale.

The trend before the knee in Fig. 3a and 10 is, however, not exactly horizontal, and one interpretation of this is that the most massive intermediate mass stars (M ∼ 6 M⊙) contribute some iron on a shorter time scale than the bulk of stars becoming SNe Ia [83].

Later on, new stars are born from these clouds, and as long as they haven’t experienced their first dredge-up of matter from their nucleosynthesis layers, their surfaces preserve the composition of the nursing clouds. It is these stars that we now observe, and despite the uncertainties in the absolute positions of the stars in the oxygen diagram, the conclusion is that there is a rather large abundance spread among the stars. The cosmic scatter supports the theory that the Galaxy was formed in the bottom-up scenario described in Chapter 3, as it seems that the these halo stars were born from clouds of different compositions.

7.5.2 The α-elements and Galactic history

Relations among the α-elements

The behaviour of the α-elements in Figs. 3a, 3c, 3e, 3f, and 3h appear to be rather similar, and we wanted to investigate if there were any systematic co-variation for the abundances of these elements. The result is displayed in Fig. 13, which shows [O, Mg, Si, Ti/Fe] vs. [Ca/Fe]. We also display disk stars from the investigation of Edvardsson et al. (1993) [44], and more metal-poor halo stars from Cayrel et al. (2004) [28] in this figure.

There are trends among the abundances of the α-elements. These co-variations are apparent for all three samples of stars, and with rather smooth transitions between them11. Fig. 13 shows trends quite close to the one-to-one relation for Mg, Si and Ti, although with a large spread – especially at high abundances. Oxygen displays a very different behaviour in Fig. 13a. The stars show a large spread around solar abundances. When going to higher [Ca/Fe], the O abundances increase more quickly than Ca, although it is soon levelled off. This is in contrast to Decauwer et al. (2005) [39], who found a similar relation for O as for the other elements. They choose as a standard Ti instead of Ca, and have also fewer stars.

To be able to further investigate the α-elements, we calculated and compared the deviations from the mean trends in the [X/Fe] vs. [Fe/H] diagrams

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11The off-set noted for the Cayrel et al. sample may most probably result from systematic errors due to differences in line selection etc.
of Figs. 3a, 3c, 3e, and 3f. The results are plotted in Fig. 15. Similar plots with the stellar samples of Gratton et al. (2003) [62] and Nissen & Schuster (1997) [112] are shown in Figs. 16–17.

Although the scatter is rather large, one sees some correlations in all plots of Figs. 15–17. The slopes turn out to be very similar among the different stellar samples, but rather different for different elements, see Table 7 in Paper I. Similar correlations are noted for both halo stars (here \([\text{Fe/H}] < -1.0\)) and disk stars (here \([\text{Fe/H}] > -1.0\)). For O the slopes of halo and disk stars are nearly identical, and this applies to calcium as well.

**Chemical enrichment in the Galaxy**

What is the cause of the trends in Fig.13 and correlations in Figs 15–17? A possible explanation is of course systematic and/or spurious errors. In the study of Paper I we conclude that errors of the order of 0.15 dex is possible for abundances \([X/H]\). Errors of this magnitude in \([\text{Fe/H}]\) would lead to slopes on the order of unity in the plots of Fig. 15–17. However, most causes\(^\text{12}\) of such errors would influence also the \([\alpha/H]\) abundances, thus reducing the total errors in \([\alpha/\text{Fe}]\). One therefore has to assume very large errors to create the correlations found in the mentioned plots. Very large random errors might also mask any possible trends in Fig. 13, and be the cause for the one-to-one trends found for \([\text{Mg},\text{Si},\text{Ti}/\text{Fe}]\) vs. \([\text{Ca}/\text{Fe}]\).

One also has to take into account that the slopes of Fig. 15–17 get progressively steeper in the order Ca, Mg, Si and O, and that the estimated errors increase in the same sequence. We investigated whether spurious errors could be the cause of the correlations and differing slopes, and concluded that errors of the order of 0.1 to 0.2 dex in \([X/\text{Fe}]\) were needed. Although this is not completely unrealistic, the results from the analysis of intrinsic errors in Section 5 of Paper I, and our comparisons with other studies in Section 6 of the same paper, suggest a general abundance error only half as great.

What about systematic deviations from the 1D LTE assumptions we have made in the analysis? In this study, as well as in Gratton et al. and Nissen & Schuster, we have only accounted for NLTE effects for the obviously affected triplet lines of O. NLTE corrections vary for different elements, and Gehren et al. (2004) [57] have shown that the NLTE corrections for Mg are metallicity dependent. Additional sources of error are 3D effects, which may amount to \(-0.5\) dex for Pop. II stars, see Table 6 in Paper II.

Although the errors due to NLTE and 3D effects seem very large\(^\text{13}\), one can probably assume that they have rather similar effects on stars of the same

\(^{12}\)Examples of such errors are errors in the stellar parameters, errors in continuum placements etc. See also Chapter 6.3 in this summary.

\(^{13}\)It seems that the NLTE and 3D effects counteract each other, at least for metal-poor stars as tabulated in Table 6 in Paper II. The resulting errors are hopefully not overwhelming.
metallicity, as the measured lines are the same\textsuperscript{14}. The expected influence of the corrections are therefore changes in the mean trends of the [X/Fe] vs. [Fe/H] plots of Fig. 3. The deviations from the mean trends are probably not affected greatly, and it is the correlations in these deviations we see in Figs. 15–17. If NLTE and 3D effects are responsible for the correlations, it must be through some other mechanism than the ordinary stellar parameters, such as rotation and/or magnetic fields.

If the trends and correlations are not caused by errors, they must be intrinsic to the stars. This would mean that the scatter around the mean trends in Fig. 3 is partly real cosmic scatter. This agrees with the bottom-up scenario described in Chapter 3 of this summary, in that the stars seem to have formed in different environments.

Different Galactic chemical enrichment scenarios may be pictured to explain Fig. 3. One is proposing an initial mass function (IMF) varying with metallicity and/or time. Supernovae of Type II model yields calculated by several groups ([142] [133] [30]) suggest that supernova progenitors of higher mass produce systematically larger amounts of light $\alpha$-elements compared to heavier ones, and also more light $\alpha$-elements compared to Fe. If the IMF varies in such a manner that very massive stars were produced in greater numbers far back in time than later, the O behaviour of Fig. 13 would be explained. We do not, however, see a similar rise in Mg, which is also a fairly light $\alpha$-element. A simple calculation also shows that the exponent of a single-parameter IMF needs to decrease by two units to be able to account for the oxygen trend.

An IMF may not only be changing with time and/or metallicity. Increasing evidence shows that a single exponent Salpeter IMF is merely a statistical mean of an IMF varying also with the environment, see Elmegreen (2004) [47]. There is also the possibility of a universal single exponent IMF, but that sufficiently low-mass regions may not form any massive stars at all, as suggested by Decauwer et al. (2005) [39]. The existence of regions with and without enrichment in the $\alpha$-elements would explain the scatter in the plots of Fig. 15–17. This would be most pronounced among the most metal-poor stars, but several investigations (Nissen et al. 1994 [109], Cayrel et al. 2004 [28], Arnone et al. 2005 [6]) show a very small scatter for these kind of stars.

Another way to explain the results are metallicity dependent yields in combination with inefficient mixing. If the $\alpha$-enriched ejecta from SNe Type II mixed with different amount of primordial gas, then the correlations of Fig. 15–17 might result. However, as noted above, the different slopes are difficult to understand in the light of the results from Fig. 13.

A possible explanation for the results are different star formation rates

\textsuperscript{14}The individual abundance deviations among the $\alpha$-elements were not that large when we tested the stellar parameters in Section 5.
(SFR). Some stars may e.g. have formed in populations with such a low SFR that SNe Type Ia may have contributed even before the enrichment of the gas by SN II had proceeded very far. The ratio $[\alpha/\text{Fe}]$ would be lower in such stars, and this would account for the scatter among the stars of Fig. 3. However, it is difficult to explain the one-to-one relations found in Fig. 13 in combination with the different slopes of Fig. 15–17.

A simple suggestion to solve the problem with the varying SFR is to assume that certain amounts of Si, Ca, Mg and Ti, are produced by some other object, in addition to the amounts produced by supernovae of Type II. This other kind of source would have a long lifetime, and Edvardsson et al. (1993) [44] suggest it to be SNe Type Ia. This would make the relative abundance ratios between the $\alpha$-elements different between halo stars and disk stars, thus distinguishable in Fig. 3, and could also produce correlations like those in Fig. 15.

The conclusion is that we don’t know. Probably the trends and correlations among the $\alpha$-elements do not result from random errors or NLTE and 3D effects influencing the stellar parameters. Maybe unknown effects from rotation and magnetic fields are important? A varying IMF seems not to be a working idea by itself, but together with a differing SFR it might work.Metallicity dependent yields are probable. The hypothesis of a varying SFR in combination with SNe Type Ia, or other types of objects, producing $\alpha$-elements at a slow rate is worth to consider.

It is possible that the interesting plots cloud just show a conspiracy between, e.g. NLTE effects, 3D effects and errors in fundamental parameters. However, if they are not, they are truly interesting.
8. The r+s star of Paper II

8.1 The HERES collaboration

The analysis of the star HE 0338−3945 was made as a part of a long term project of investigating $r$-process enhanced metal-poor stars. The collaboration is called The Hamburg/ESO $R$-process Enhanced Star survey (HERES) [33]. It aims to map the most metal-poor stars in the universe, and especially to seek stars highly enriched in $r$-process elements. The main goal is to study the nature of the poorly understood $r$-process, but also to give an independent lower limit for the age of our Galaxy, and thus also for the Universe.

The source of the HERES project stars is mostly the huge stellar data base collected in the Hamburg/ESO objective-prism survey (HES) [141], but also the earlier HK survey [14]. The HERES collaboration searches for interesting metal-poor stars through a two-step approach. First the HES and HK surveys are scanned for stars of low metallicity through moderate-resolution spectroscopy of several thousand stars. Later the candidates from such a scan are observed with VLT/UVES to get so-called snapshot spectra. These snapshot spectra have resolving power of 20,000–30,000 and a signal-to-noise of 50, which is sufficient for analysing the star. The most interesting stars are later scheduled for high-resolution, high signal-to-noise observations.

The HERES effort has been successful, as it has found 8 highly and 35 moderately $r$-process enriched stars. Thus, many unusual stars have been found, but the normal stars are just as interesting as the odd ones. The HERES collaboration has therefore made an abundance analysis of 253 stars with observed snapshot spectra [11].

8.2 The star HE 0338−3945

The HERES collaboration has in addition to the purely $r$-process enhanced stars identified some peculiar stars enriched in both $r$- and $s$-process elements. These stars deserve special attention, as they may reveal interesting clues to the production processes and sites of the neutron-capture elements. HE 0338−3945 is one of these stars, and Paper II describes a thorough abundance analysis of it.

The star HE 0338−3945 is a main-sequence turn-off star of V magnitude
15.3. It was included in the snapshot run [11], and has also been observed at high resolution with the VLT/UVES telescope at Paranal, Chile. Here I make a short description of the analysis, before giving a brief summary of the main results. For scientific details see Paper II. In Paper II, I was the main author of Sections 3.2, 4.1, 5.4, and the Appendix, and one of the authors of sections 2, 6.1, 6.2, 6.3 and 7. I also took responsibility for the coordination of the paper.

8.2.1 The analysis of HE 0338–3945

Observations and data reduction

The observational data from VLT/UVES comprised an extended wavelength coverage and a total of 42 spectra at a resolving power of 30,000-40,000. As the star is of particular interest, we wanted the best possible spectrum to analyse. I did the data reduction in the standard way by using the IDL-package Reduce. Oleg Kochukhov and Paul Barklem made the final merging into a single spectrum. Due to some problems with discontinuities and reduction artefacts in the spectrum, the usable spectral ranges were limited to 3100–5741 Å and 5847–8487 Å.

Line selection

A vital task was to search for and choose lines appropriate for measurement for as many elements as possible in the spectrum of HE 0338–3945. It is especially important to do this with care, since the spectrum is severely blended by CH lines in the blue. I did an unconditioned search in the ‘extract all’ mode of the Vienna Atomic Line Data Base (VALD) [85] for our observed wavelength regions. The resulting line list comprised roughly 126,000 lines. In addition to that, I gathered line lists of all isotopes of C2, CH and CN in the wavelength ranges covered by the UVES spectra – in total more than 933,000 lines.

Kjell Eriksson kindly calculated a MARCS model atmosphere using the most recent version [70] with the parameters from the snapshot spectrum. This model was used together with the line lists in the local program ‘Eqwi’ to derive predicted equivalent widths for all lines. Every line was checked for nearby blending lines in the lists of predicted equivalent widths. I then inspected the spectrum of HE 0338–3945 at the positions of preferably unblended lines, to check which elements were present. To the line list with selected lines from the VALD-search, I added the lines measured by Barklem et al. (2005) [11], Sneden et al. (1996) [128] and Sneden et al. (2003) [126]. Together with Paul Barklem I searched databases and literature for laboratory log \( gf \)-values, Stark broadening correction factors, isotopic and hyperfine splitting ratios, etc.

The lines were run in the synthetic spectrum program described below and confirmed as suitable or rejected, e.g. due to erroneous log \( gf \) or suspected
blends. A lot of lines were rejected in this way, and most blends were found to be due to CH. This work was done by me, but in close collaboration with Paul Barklem who made the program. The final line list comprises 621 lines for abundance measurements and 650 blending lines, i.e. the latter did not influence on the abundance estimates. The individual line data and results will be published electronically.

**Analysing program and stellar parameters**

Paul Barklem had created a working setup based on the Spectroscopy Made Easy (SME) package by Valenti & Piskunov (1996) [134], which was used for the analysis of the HERES snapshot spectrum. We chose to use the same setup with minor modifications. The program fits all lines of an element simultaneously with synthetic spectra. For details see Paper II.

The effective temperature was not derived from photometry, as in the snapshot analysis, but from careful fitting of the wings of the hydrogen Balmer Hβ- and Hδ-lines. The results were, however, all in good agreement. The other stellar parameters, metallicity, surface gravity and micro- and macro-turbulence, were derived by the analysis program, using a grid of the latest generation of the MARCS model atmospheres [70]. The metallicity was set equal to the abundance of iron derived from both FeI and FeII lines. The surface gravity was derived using the ionisation equilibria of iron and titanium lines, and the micro- and macroturbulences also from fitting the lines of Fe and Ti, requiring that the abundances from individual lines should be independent of the line equivalent widths. The resulting stellar parameters became: $T_{\text{eff}}=6160\pm100$ K, $[\text{Fe/H}]=-2.42\pm0.11$ dex, $\log g=4.13\pm0.33$ dex, and microturbulence $\xi_t=1.13\pm0.22$ km/s.

**8.3 Summary of the results**

Abundances were derived for 33 elements and we estimated upper limits for additionally 6 elements for the star HE 0338−3945. We have confirmed the high content of $s$-elements, as well as of $r$-elements. The light $s$-elements (Sr, Y, Zr) do not fit solar $s$-process abundance pattern as normalised to Ba, but are suppressed, see Fig. 2 in Paper II. Curiously enough, at least Y and Zr fit the $r$-process abundance pattern normalised to Eu. This is noted in heavily $r$-processed stars like CS 31082-001 as well [73]. The $r$-process element Eu has a notably high abundance, but we could not detect either Th or U, as these lines were weak and resided in heavily blended regions. Instead upper limits were estimated.

\[^1\text{The snapshot analysis derived 17 abundance estimates [11].}\]
We have confirmed the high abundance of C in the star, and derived an isotopic ratio of $^{12}\text{C}/^{13}\text{C} \sim 10$. We have also shown that the star has a high content of O and N, that the Na to Ni abundances seem normal for stellar matter contaminated by SNe of Type II, and that the star has a low abundance of Cu. The overabundance of Sc compared to normal Population II stars may be caused by hidden blends of C. The heavier elements produced by both the $r$- and $s$-processes (e.g. Nd, Sm and Yb) are expectedly overabundant.

The star HE 0338$-$3945 seems to be remarkably similar to HE 2148$-$1247. The identical abundance pattern, seen in Fig. 6 of Paper II, suggests a common origin for the elements under consideration\(^2\). The homogeneous comparison between HE 0338$-$3945 and HE 2148$-$1247 was made by Paul Barklem, who also compared the results with the snapshot spectrum, and the normal stars of Barklem et al. (2005).

The similarities between HE 0338$-$3945 and other $r$- and $s$-processed stars were investigated by me. As the stars seem very similar, see e.g. Fig. 8. in Paper II, we propose new criteria for the identification of stars belonging to the class of $r+s$ stars. In Section 6.3 of Paper II we discuss seven different scenarios for creating the peculiar abundance pattern seen in these stars. None of the proposed explanations is convincing at this stage. The most plausible scenario for enhancing the $s$-elements is mass transferred in a binary system. In this case, the most massive star transfers matter enriched in C and $s$-elements onto the observed star in the asymptotic giant branch phase.

How the enrichment in $r$-processed matter has occurred is not known, and many different possibilities have been proposed. The possibility that the binary system formed out of gas enriched by $r$-process elements from a SNe Type II is rejected on statistical reasons. Another proposed scenario is that the companion star may have exploded as a supernovae. A suggestion discussed by e.g. Johnson & Bolte (2004) [80], proposes that a high neutron flux in the companion AGB star created the $r$-elements as well, i.e. the $r$-elements were produced by an anomalously strong $s$-process. We have, however, not been able to verify this possibility in our $s$-process calculations\(^3\).

The $r+s$ stars form a very interesting class of stars, as they may give insight into how and where both the $r$- and $s$-elements were formed. Wishes for future studies are homogeneous high resolution NLTE analyses of all the known stars in the class. The studies will have to focus on getting reliable abundances of $r$-process elements such as Ag, Th and U, but also on the question if all $r+s$ stars are binaries. Isotopic ratios of e.g. Eu are of high priority, although difficult to reach. Last but not least on the wish list is the discovery of more members of this peculiar class of stars.

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\(^2\)The offset between the abundances could easily be due to errors in $T_{\text{eff}}$, and the scatter is consistent with the uncertainties.

\(^3\)These calculations were made by Bengt Gustafsson.
Part III:
Concluding remarks
I have made two investigations of the chemical composition of halo stars. These stars are very old, as most of them were born only some billion years after the Big Bang. Time, space and matter were created in the Big Bang, but most of the atoms around us were not made then. Only hydrogen, helium and a tiny bit of lithium were synthesised in the Big Bang. The other elements, the metals as the astronomers say, have been formed by stellar nucleosynthesis later on. New stars are born out of giant interstellar clouds of gas and dust enriched in heavy elements by stars of previous generations. This is called the chemical evolution of our Galaxy, the Milky Way.

I first participated in an investigation concerning 43 metal-poor halo stars. We investigated, among other elements, the third most common element in the universe – oxygen. We concluded that it is overabundant relative to iron in the halo stars, compared with the Sun. This is a signature of an early enrichment of the interstellar medium by supernova explosions of massive stars. However, a vigourous debate is going on whether the oxygen-to-iron ratio varies over time in the early Galaxy. We found no support for such a variation.

The halo-star study also concludes that magnesium, silicon, calcium, and titanium are generally found in rather similar amounts in stars of different age and metal-content. This suggests a common nucleosynthesis history for these elements. It is often assumed that oxygen belongs to this group, but it seems to be a bit more complicated than that.

We have also found that if a star has an unusually high or low content of one of the elements oxygen, magnesium, silicon, and calcium, compared to stars with similar metal-content, there is a high probability that the abundances of the other elements are differing in the same way. There are several possible explanations for this. Maybe the stars were born in environments with different star formation rates? Perhaps the number of massive stars producing these elements is varying between different environments and/or time? Maybe the production of these elements is depending on the metal-content of previous generations of stars, then probably in combination with an insufficient mixing in the interstellar clouds. One should bear in mind, however, that some part of these correlations may depend on the simplifying assumptions we have made in the analysis.

I have also participated in a study of the highly interesting halo star

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HE 0338−3945. It is metal-poor, but has a factor of a hundred larger barium-to-iron ratio than the Sun, and this applies to the other so-called s-elements as well. What is unusual with this star is that it is almost equally enhanced in the element europium and other so-called r-elements. Both r- and s-elements are produced through neutron capture by lighter elements.

Astronomers are rather certain of that the s-elements are formed in dying low-mass stars, while the nucleosynthesis site of the r-elements is debated. It is often thought that the latter are produced in the supernovae explosions which end the lives of massive stars. The low-mass star HE 0338−3945 is, however, not dying. It is just ending its middle-age, so it has not even reached the stage of s-element production yet. And why does it have such a relatively high r-content?

Our star is not just an odd curiosity, because several other stars of this kind have recently been found. They are unexpectedly similar to HE 0338−3945, and we define new criteria for the class called r+s stars. The similarities among the r+s stars implies that there has to be some common scenario explaining why they are so enriched in both r- and s-elements. Several theories have been proposed, and in our article we discuss seven.

None of the discussed hypotheses are entirely convincing, but we conclude that the most plausible scenario creating the s-enhancement is a mass transfer in a binary system. Gas enriched in s-elements has detached from the atmosphere of the massive star, and contaminated the observed star. How the r+s stars have been enriched in r-elements is an open question. Statistics says that they were probably not formed out of supernovae remnants of massive stars. Maybe their companion stars later exploded in another type of supernovae? But if so, why are these stars so remarkably similar? There have been speculations of a s-process in which the new elements were created by an unusually high flux of neutrons. We have made calculations of this, but not been able to produce the strange abundance pattern seen in these stars.

Speculations continue after both my investigations of halo stars. I have not found any absolute truth, but due to Natures bewildering richness, this is not often the case for scientists. I have, however, added my brick to the castle of knowledge.
10. Sammanfattning


I halostudien kom vi också fram till att mängden magnesium, kisel, kalcium och titan är ganska lika i stjärnor av olika ålder och metallinnehåll. Ämnena har därför troligen en gemensam utvecklingshistoria. Man antar ofta att syre ingår i denna grupp, men det verkar vara lite mer komplicerat än så.


Jag har också deltagit i en undersökning av den mycket intressanta halostjärnan HE 0338−3945. Den är metallfattig men har hundra gånger mer barium i förhållande till järn än vad solen har, och det gäller också de
övriga så kallade s-elementen. Det ovanliga med den här stjärnan är att den dessutom har en relativt hög halt av ämnet europium och andra så kallade r-element. Både r- och s-element bildas genom nuetronbestrålning av lättare grundämnen.

Vi är ganska övertygade om att s-elementen bildats inuti döende stjärnor med liten massa, men källan för r-elementen är omtvistad. Man antar ofta att de produceras då massiva stjärnor exploderar som supernovor. Den lågmassiva stjärnan HE 0338−3945 är dock långt ifrån att dö. Den har just avslutat sin medelålder, och har inte ens nått den s-element-producerande fasen än. Och varför har den så mycket r-element?

Vår stjärna är inte en udda kuriositet eftersom flera liknande stjärnor nyligen har upptäckts. Dessa stjärnor är oväntat lika HE 0338−3945, och vi har därför definierat nya kriterier för klassen r+s stjärnor. Likheterna antyder att det måste finnas en gemensam orsak till varför de har så höga halter av både r- och s-element. Flera hypoteser har föreslagits, och i vår artikel diskuterar vi sju.


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