Exploring the Chemical Evolution of Globular Clusters and their Stars

Observational Constraints on Atomic Diffusion and Cluster Pollution in NGC 6752 and M4

PIETER GRUYTERS
Abstract


Through the cosmic matter cycle, the chemical evolution of the Milky Way is imprinted in the elemental abundance patterns of late-type stars (spectral types F to K). Due to their long lifetimes (1 Hubble time), these stars are of particular importance when it comes to studying the build-up of elements during the early times of our Galaxy. The chemical composition of the atmospheric layers of such stars is believed to resemble the gas from which they were formed. However, recent observations in globular clusters seem to contradict this assumption. The observations indicate that processes are at work that alter the surface compositions in these stars. The combined effect of processes responsible for an exchange of material between the stellar interior and atmosphere during the main sequence lifetime of the star, is referred to as atomic diffusion. Yet, the extent to which these processes alter surface abundances is still debated.

By comparing abundances in unevolved and evolved stars all drawn from the same stellar population, any surface abundance anomalies can be traced. The anomalies, if found, can be compared to theoretical predictions from stellar structure models including atomic diffusion. Globular clusters provide stellar populations suitable to conduct such a comparison. In this thesis, the results of three independent analyses of two globular clusters, NGC 6752 and M4, at different metallicities are presented. The comparison between observations and models yields constraints on the models and finally a better understanding of the physical processes at work inside stars.

Keywords: stars: abundances – stars: atmospheres – stars: fundamental parameters – globular clusters: individual: NGC 6752 and M4 – techniques: spectroscopic

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"To confine our attention to terrestrial matters would be to limit the human spirit."
— Stephen Hawking
The globular cluster M4 through the eye of the WFCAM, a near-IR wide field camera at the UK Infra Red Telescope. Overlaid is the reddening map based on the $V - I$ colour. The reddening map was made to deredden the photometric data of M4 used in Paper III of this thesis. The red colour corresponds to regions that suffer more extinction by interstellar dust clouds than the blue regions.

A three part zoom-in on the globular cluster NGC 6752. The top image was made by © Daimon Peach using a 20 inch (0.51 m) f/6.8 Corrected Dall-Kirkham (CDK) Astrograph telescope together with an FLI-PL6303E camera. The image consists of 7 LRGB (Luminance, Red, Green and Blue) exposures (L: 6x3mins. RGB: 1x3mins). The middle and bottom image were both taken with the Hubble Space Telescope by the NASA Space Telescope Science Institute.
List of papers

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

"Atomic diffusion and mixing in old stars IV: Weak abundance trends in the globular cluster NGC 6752"  
*Astronomy & Astrophysics*, **555**, A31

II  **Gruyters, P.**, Nordlander, T., Korn, A. J.  
"Atomic diffusion and mixing in old stars V: A Deeper look into the globular cluster NGC 6752"  
*Astronomy & Astrophysics*, **567**, A72

III  **Gruyters, P.**, Nordlander, T., Richard O., Korn, A. J.  
"Atomic diffusion and mixing in old stars VI: Chemical abundance variations in M4"  
Submitted to *Astronomy & Astrophysics*

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List of papers not included in the thesis

The following are publications to which I have contributed but that are not included in this thesis.

1. **A VLT VIMOS IFU study of the ionisation nebula surrounding the supersoft X-ray source CAL 83**
   Pieter Gruyters, Katrina Exter, Timothy P. Roberts, and Saul Rappaport

   *Astronomy & Astrophysics, 565*, A89, 2014

3. **The lyman-alpha reference sample: I. Survey outline and first results for Markarian259**
   Göran Östlin, Matthew Hayes, Florent Duval, Andreas Sandberg, and 19 coauthors
   Resubmitted to *The Astrophysical Journal*

4. **Lyman alpha escape and physical properties of the interstellar medium of the nearby edge-on starburst galaxy Mrk1486**
   Florent Duval, Lucia Guaita, Matthew Hayes, Göran Östlin, Thøger Rivera-Thorsen, Pieter Gruyters, and 14 coauthors
   to be submitted to *Astronomy & Astrophysics*

Conference contributions

- **Weak atomic diffusion trends in NGC 6752**
  Pieter Gruyters, Andreas J. Korn, and Paul S. Barklem

- **On atomic diffusion and the cosmological lithium abundance**
  Pieter Gruyters, Andreas J. Korn, and Paul S. Barklem
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"With every passing hour our solar system comes forty-three thousand miles closer to globular cluster M13 in the constellation Hercules, and still there are some misfits who continue to insist that there is no such thing as progress."
— Ransom K. Ferm
1. Globular clusters

Before describing the more concrete work done during this Ph.D., it is useful to present some background about the theory of atomic diffusion and how it affects the chemical composition of a stellar atmosphere. So let me start by giving some background information about stars, more precisely, Population II stars and Globular Clusters.

1.1 Stellar populations

The Universe was born about 13.8 Gyr ago as a hot dense photon-baryon plasma sea. This happening is usually referred to as the Big Bang. Three to ten minutes after the Big Bang, the Universe was already cool enough so that protons and neutrons could come together to form the light chemical elements: hydrogen ($\sim 0.75$ by mass fraction) which is the most abundant element in our Universe, helium ($\sim 0.25$), and a tiny amount of lithium ($\sim 5 \times 10^{10}$ atoms per hydrogen atom). This process is called Big Bang nucleosynthesis (BBN). The first stars in the Universe came into being a few hundred million years after the Big Bang. These stars are believed to have been very massive (see e.g. review articles by Bromm & Larson 2004 and Bromm & Yoshida 2011). This is the result of the fact the primordial gas the stars formed from lacked effective cooling agents as they basically existed out of pure hydrogen. The first gas clouds were also much warmer than present-day molecular gas clouds in which stars nowadays form. This is because present-day clouds are full of dust grains and metal-based molecules instead of pure hydrogen. The dust grains and metal-based molecules provide efficient cooling mechanisms so that the present-day clouds can cool down to temperatures of the order of 10 K, which is much cooler than the 200 to 300 K reached in the metal-free primordial gas clouds by molecular hydrogen cooling. As the Jeans mass, the minimum mass that a clump of gas must have to collapse under its own gravity, is proportional to the square root of the gas temperature (and inversely proportional to the square root of the gas pressure), the primordial gas clouds would have been almost 1 000 times more massive than present star-forming clouds. The possibly massive stars formed from the primordial gas are referred to as Population III (Pop III) stars. Their high masses are in stark contrast to the dominant low-mass stars we find in our Galaxy nowadays. After a few million years these Pop III stars exploded as supernovae and subsequently started to pollute the pristine, metal-free gas with the first heavy chemical elements.
Once these metals started to get mixed into the primordial gas, low-mass stars could be formed because the metals act as coolants. During this second period of star formation, some stars having masses less than that of the Sun may even have formed. These stars are formed from slightly metal-enriched material, and constitute Population II. Owing to their low masses they live longer than the Sun and thus may still be observable today. The Sun and other metal-rich stars are labelled as Population I stars. Pop I stars are formed more recently from gas much richer in metals than the gas used to spawn Pop II stars.

1.2 Basic properties of globular clusters

All known stars in our Galaxy are either Pop II or Pop I stars and reside in either of the three main components of our Galaxy: in the central compact region or bulge, in the surrounding disc and spiral arms, or in the extended spheroidal-shaped halo. The Sun, just like most of the Pop I stars, resides in the disc, while the metal-poor or Pop II stars, which are comparatively rare, are more commonly found in the halo. Also part of the halo are most of the globular clusters (GCs). These are dense stellar conglomerates (typically a couple of hundred thousand stars) that are considered to be the oldest ($\geq 10$ Gyr) stellar aggregates in our Galaxy. Fig. 1.1 shows the layout of the Galactic halo with its globular clusters, and other stellar conglomerates belonging to the Milky Way system, such as dwarf spheroidal galaxies (dSphs) and ultra faint dwarf galaxies (UFDs).

Until the beginning of the 21st century, astronomers believed that GCs were rather simple objects and that their stars were formed simultaneously from one giant molecular cloud. Hence it was believed that their stars constituted a homogenous stellar population in terms of distance, age and elemental composition (a single stellar population, SSP). This idealistic view has now been overturned by significant observational evidence for multiple stellar populations (see Sect. 1.4), the discovery of peculiar objects such as blue stragglers (main sequence stars that are more luminous and bluer than stars at the main sequence turn-off point for the cluster) and millisecond pulsars, and the realisation that their evolution may have been affected by mass segregation, stellar mergers, core collapse or even a central intermediate-mass black hole. While we can be relatively sure of the same distance for all stars within a GC, the idea that they have been formed at the same time and hence assuming the same age and chemical composition for all stars within a GC, is no longer accepted.
Figure 1.1. The Galactic halo and its substructures. The globular clusters NGC 6397 and NGC 6752 are located slightly to the right of the Galactic center, just below the disc towards the constellation Pavo. M4 resides in the Scorpio constellation, slightly above the disc, just right of the center of the figure. Image Credit: © O. Frohn.

http://armchairastronautics.blogspot.se/p/milky-way-halo.html
1.3 Low-mass stellar evolution

In the previous section, we discovered that GCs are complicated systems with multiple chemically distinct populations. In this section however, we consider GCs to be simple, and consisting of stars having uniform ages and chemical compositions, which serves a first approximation. This way we can assume that the individual evolution of the single stars is a unique function of stellar mass (neglecting e.g. angular momentum). Under this assumption, the complete population of the GC can be modelled by a single isochrone in the Hertzsprung-Russell (HR) diagram, a diagram that shows the behaviour of the stellar luminosity (y-axis) as a function of effective temperature (x-axis). A more commonly used form of the HR diagram is the Colour-Magnitude Diagram (CMD), in which the colour represents the effective temperature while the stellar luminosity is represented by the magnitude of the star. All cluster stars plotted in such a diagram can then be modelled by one isochrone which reveals the mass and evolutionary status of each star.

Globular clusters are generally considered to be genuinely old (\( \geq 10 \) Gyr) and do only experience star formation during their formation. As a result they now host only low-mass, long-lived stars, i.e. stars having a lifetime of around 10 Gyr. This means that all massive stars have long been extinct and even stars with 1 solar mass are reaching the end of their stellar evolution. In order to understand chemical signatures in GC stars we thus have to focus on evolutionary properties of low-mass stars. These stars slowly climb the main sequence in the CMD as they become brighter during their long-lasting quiescent H-burning phase. These stars are referred to as dwarfs. The heavier stars in the cluster are only now reaching the end of their main sequence life as they approach the turnoff point (TOP). This point is a fairly sensitive age indicator for the cluster. Stars that are more massive than the stars at the TOP will have exhausted their hydrogen fuel in the core and have therefore undergone core contraction and shell expansion. As the envelope of the star cools and expands, the convective zone extends inwards. The star gets a more reddish colour which makes it move onto the subgiant branch (SGB) in the CMD. Stars on the SGB are thus characterised by cooler temperatures and higher luminosities than stars at the TOP as H-burning sets in in the hydrogen shell surrounding the contracting core. As shell-burning continues, the star becomes brighter and ascends the almost vertical redgiant branch (RGB). The core, consisting of helium, will grow in size since more and more H is converted into He via shell-burning. The convective zone, on the other hand, recedes to deeper layers until it reaches the H-burning shell. When this happens, the first dredge-up occurs and processed material is brought up to the surface layers of the star while in the stellar center the H-burning layer is replenished with hydrogen. At this point it becomes impossible to directly measure the initial C, N & O abundances of the star. Above a certain mass threshold, helium will ignite and the star has
reached the uppermost tip of the RGB, marking the end of the red giant phase. More massive stars will then enter a phase of He-core burning the horizontal branch (HB) phase, followed by He and H-shell burning, during the so-called asymptotic giant branch (AGB) phase, before they end up as white dwarfs after they have lost their circumstellar envelopes due to pulsations and mass loss during the post-AGB (P-AGB) phase. All these phases are shown in the CMD of the cluster M3 given in Fig. 1.2. Note that the giant phases of evolution are very short compared to the main sequence life time. The vast majority of the stars in a cluster hence are located on the main sequence even though the total light of the cluster is dominated by the much brighter giants, giving it a red colour.

Figure 1.2. The observed CMD of the cluster M3. The evolutionary phases are marked by their abbreviations, see text for details. Image credit: Renzini & Fusi Pecci (1988).

1.4 Chemically distinct populations in globular clusters
It has been known since the 1970s that GCs display large star-to-star abundance variations for the light elements such as Li, C, N, O, Na, Mg and Al. The observational patterns of these elements are well assessed, see e.g. the review by Gratton et al. (2004). Variations in the heavier elements, O, Na, Mg, and Al, are only observed in the more massive clusters and a detailed review of the origin of the variations is discussed in the review by Gratton et al. (2012).
The signature of the lighter elements (Li, C, N) is understood as a mixture of initial composition (referred to as the GC's primordial composition) together with evolutionary changes. The latter include first dredge-up after the end of the main sequence and mixing on the RGB, which are known to occur in low-mass Pop II field stars as well as in the cluster analogues (Charbonnel et al. 1998; Gratton et al. 2000; Smith & Martell 2003). As these abundance variations are found in evolved as well as in unevolved stars still on the main sequence of GCs (Gratton et al. 2001; Ramírez & Cohen 2002; Carretta et al. 2004; D'Orazi et al. 2010), the composition has to be imprinted in the gas by a previous generation of stars. This means that GCs harbour at least two stellar generations that are clearly distinguished by their chemistry.

High-precision photometry using images from the Hubble Space Telescope (HST) has revealed multiple distinct main sequences for ω Centauri (Bedin et al. 2004), NGC 2808 (Piotto et al. 2007), and NGC 6397 (Milone et al. 2012a). Recent studies have also shown a split main sequence for the massive GC 47 Tucanae (Anderson et al. 2009) and NGC 6752 (Milone et al. 2010, 2012b). From stellar evolutionary models, the multiple main sequences are attributed to stellar populations with different He fractions Y. The different Ys are a result of pollution of the interstellar gas by first-generation stars having a range of masses. The more massive stars go through H-burning at a higher temperature during the CNO cycle than the less massive stars. This results in enhanced production of He. In addition to He, such models also predict enhanced production of N and Na, and depletion of C and O. Second-generation stars that are formed out of the polluted gas will then show these signatures. Bragaglia et al. (2010) have now confirmed this pattern of enhancement/depletion among the blue and red main sequence stars in NGC 2808.

Over the last decade, the Padova group (Carretta et al. 2010, and references therein) has performed a chemical abundance analysis of a large sample of horizontal branch stars (>1200) in 19 Galactic GCs. They postulate that for a stellar cluster to be a GC, it must be old (age greater than 5 Gyr) with an absolute magnitude $M_V < -5.1$, but above all, show a Na-O anticorrelation. The Na-O anticorrelations for their complete sample are given in Fig. 1.3. Except for Na-O anticorrelations, some GCs also show evidence for Mg-Al, and partly, C-N and Li-Na anticorrelations. Those can be regarded as fingerprints of different populations. By carefully analysing the anticorrelations, the authors come to the conclusion that each GC has a first generation made up of roughly 1/3 of the stars in the GC, dubbed the primordial component (P). This P component is characterised by low Al, Na and high Mg abundances compared to the mean values found for the cluster. The more massive the GC, the stronger the Al and Mg abundances deviate from the cluster's mean values. The remaining stars are second-generation stars. These are formed from the gas pool polluted by intermediate-mass and/or high-mass first-generation
stars (Carretta et al. 2009) and can be separated into an intermediate (I) and extreme (E) population according to the degrees of change in O and Na. The bulk of the second-generation stars form the I population and is composed of stars with moderate variations in the light elements O, Na, Mg and Al. These variations are the result of proton-capture reactions in H-burning at high temperature (Carretta et al. 2009). The I population is smaller in GCs with more extended Na-O anticorrelations and larger in GCs with larger α-element ratios. The E population is only present in massive GCs and constitutes second-generation stars with signatures of extreme chemical composition characterised by extremely high Al and low Mg abundances.

Using the evidence of different generations within GCs given by their chemistry, Carretta et al. (2010) developed a formation scenario for GCs. Formation of GCs starts from a cosmological fragment with a mass in the range of the dSph’s, i.e. $10^6 - 10^9 \, M_\odot$ which is near the Milky Way ($R_{GC} \sim 10$ kpc) at a very early epoch (<2 Gyr from Big Bang). The fragment consists of a dark
matter clump that gravitationally binds the gas \((10^5 - 10^8 \, M_\odot)\) which has a negligible/small metal pre-enrichment. The interaction of the fragment with the Milky Way triggers (early) star formation (Whitmore & Schweizer 1995). Over the course of a few million years, \(10^4 - 10^5 \, M_\odot\) of gas is transformed into stars and a precursor population is formed in the unborn GC. The most massive of those will explode as SNe after \(\sim 10^7\) yr. The result is twofold: i) metal-enrichment of the remaining part of the fragment/satellite to the metallicity value currently observed in the GC; and ii) the SNe efficiently trigger star formation in the remaining part of the cloud before nucleosynthesis of the intermediate mass stars can efficiently contribute to the enrichment of the gas. This second episode of star formation forms a few \(10^5 - 10^6 \, M_\odot\) of stars in a large association (size \(\sim 100\) pc) and constitutes the first population of the GC. The remaining primordial gas gets completely dispersed throughout the GC over a timescale of \(\sim 10^7\) yr by the strong winds from primordial-generation massive stars and core collapse SNe. The gas ejected by primordial massive stars becomes mixed with the leftover primordial gas and gives rise to a gas cloud which is chemically enriched in the center. From this enriched gas the second generation (SG) of stars is born. After the onset of this star-formation phase, the remaining gas is swept away by core collapse SNe from this second generation, terminating this last episode of star formation and the structure loses all dark matter. Also almost all the precursor stars are lost and a large fraction of the first generation of stars. This occurs earlier in more massive clusters. As a result massive clusters are enriched by stars over a restricted range of mass. Only a fraction of the primordial population of stars remains trapped into the very compact central cluster which now consists predominantly of second-generation stars. This is the type of GC that may survive over a Hubble time and we may observe at present.

Interesting notes related to the formation scenario are:

- according to this scenario, GCs and dSph's are formed in the same way, the only difference being that GCs are formed from dark matter halos closer to the center of the Galaxy.

- a large fraction of the primordial population should have been lost by the proto-globular clusters. These stars consequently make up the main component of the halo field stars (see further).

- the extremely low Al abundances found for the primordial population of massive GCs can be seen as an indication of a fast pre-enrichment process during the formation of the primordial population so that no stars with intermediate metallicity have been formed.
Figure 1.4. Schematic view of the evolution of fast rotating massive stars. The colours reflect the chemical composition of the various stellar regions and of the disc (see text for details). (Top) During the main sequence, a slow outflowing equatorial disc forms and dominates matter ejection with respect to radiative winds. (Middle) At the beginning of central He-burning, the composition of the disc material spans the range in [O/Na] observed today in low-mass cluster stars. The star has already lost an important fraction of its initial mass. (Bottom) Due to heavy mass loss, the star moves away from critical velocity and does not supply its disc anymore; radiatively driven fast wind takes over before the products of He-burning reach the stellar surface. Image and caption credit: Decressin et al. (2007a).
Although this appears to be a promising scenario for the formation of GCs, it lacks some observational support. The large number of expelled low-mass precursor and primordial stars from GCs should be present in the field. However, to date only a couple of hundred stars with $[\text{Fe/H}] \leq -2$ have been analysed in high-resolution spectroscopic studies (see Christlieb 2006, for an overview of surveys), and fewer low-metallicity stars are found than expected by the scenario, raising the question why? Alternatively, one must assume a top-heavy initial mass function (IMF) at low metallicities (Skillman 2008; Komiya et al. 2010).

Another potential problem is the lack of spread in metallicity in the GCs. If the gas ejected by the precursor core-collapse SNe is retained in the initial structure then the ejecta of the primordial core-collapse SNe must also be retained and hence second-generation stars should have a higher metallicity. That is, unless a large fraction of the mass of the initial structure is lost in a short period of time.

An alternate scenario to this qualitative formation scheme to explain the globular cluster chemistry was presented by Decressin et al. (2007b,a). Their scenario explains the observed multiple populations as a result of pollution by the winds of fast rotating massive stars (FRMS). These stars rotate at the critical rotation velocity and hence form an equatorial disc around them. Due to the low mass-loss velocities of these discs ($< 50 \text{ km s}^{-1}$), the FRMS ejecta will get mixed with the pristine gas while it is easily retained by the potential wells of GCs. A second generation of stars is then formed out of this polluted gas.

The O-Na anticorrelation stems from the assumptions made in the scenario. 1) The first-generation stars are born out of proto-cluster gas, pre-enriched in heavy metals during the halo chemical evolution. These first-generation stars then present the highest $[\text{O/Na}]$ value one can observe in the GC under investigation since they have the same initial composition as their field contemporaries. 2) The first-generation stars are fast rotators and will form a slowly outflowing Keplerian equatorial disc. The ejected material forming the disc contains the products of the CNO cycle, the Ne-Na and the Mg-Al chains, brought up

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1 Stellar abundances can be presented in the bracket notation $[X/Y]$. This notation indicates how much an element $X$ is deficient or enriched with respect to the solar composition, relative to an element $Y$, which is usually iron or hydrogen (in the case that iron is the element under investigation). The metallicity of a star usually refers to the iron abundance in the star relative to hydrogen. Using the bracket notation this then becomes:

$[\text{Fe/H}] = \log(N(\text{Fe})/N(H)) - \log(N(\text{Fe})/N(H))_{\odot},$

with $N(X)$ the number density of element $X$.

2 This is the velocity at the equator at which the centrifugal acceleration balances gravity.

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from the core to the surface of the star by rotational mixing. It gives rise to the observed chemical anomalies in second-generation stars. The evolution of a FRMS of about \(60\, M_\odot\) is given in Fig. 1.4. The various stellar regions are colour coded to their chemical composition. Green corresponds to regions having the initial chemical composition while blue and red represent regions polluted by respectively H- and He-burning products. The typical [O/Na] value is also indicated for each stellar region. During most of its MS lifetime the star will rotate at the critical velocity, but eventually it will evolve away from this critical limit due to the heavy mass loss. At that time, the radiatively driven fast wind takes over and the disc will decouple from the star. This happens before the He-burning products reach the stellar surface so that the slow wind is not contaminated by He-burning products during the central He-burning phase (see bottom of Fig. 1.4). The vicinity of the massive stars are thus only enriched by H-burning products (i.e. light elements). The He-burning products are ejected with high velocities by the evolved massive stars and supernovae and escape from the GC. At this time, new star formation gets triggered in the vicinity of the massive stars and second-generation stars are born before all the ejected material is fully mixed with the pristine matter. Because at the beginning of the disc-star phase, the ejecta consist mostly of pristine material, the stars born early on will have similar composition to that of the first-generation stars (see upper panel of Fig. 1.4). With time, the slow wind will gradually become more and more polluted in H-burning products and from it stars with more and more anomalous chemical composition are formed (see middle panel of Fig. 1.4). This phase is rather short and lasts only for a few million years, e.g., 4.5 Myr for a \(60\, M_\odot\) star (Decressin et al. 2007a). This is why we observe a seemingly zero age difference between first- and second-generation stars. The end result is then the large star-to-star spread in light elements which we observe today in GC stars.

The FRMS scenario provides a plausible explanation for the chemical anomalies observed in GC stars. But just as the scenario proposed by Carretta et al. (2010), it suffers from what is called the mass budget problem: we observe too few first-generation stars in GCs to explain the observed amount of second-generation stars. Given the currently observed first-to-second generation ratios in GCs and that the second-generation stars are formed out of the ejecta of FRMS, the scenario can only account for about 10% of the total number of low-mass stars. The degree of pollution is thus insufficient to reproduce the observations (D’Ercole et al. 2011). Part of the solution seems again to be given by the use of a non-canonical IMF. One also has to assume that the GC was initially 10 to a 100 times more massive than observed today and that almost all first-generation stars have been lost while second-generation stars are kept by the GC. This selective loss of first-generation stars may occur as a response to early mass loss triggered by gas expulsion by supernovae (Gratton et al. 2012). The mass loss induces a change in the potential well which
will unbind stars in the outer parts of the GC. As second-generation stars form centrally in the cluster, mostly first-generation stars are lost to the cluster and the correct ratio of stars is, at least qualitatively, generated.

1.5 Lithium

Besides the multiple population studies in GCs, which gives us information on the chemical history of the Galaxy, GCs are also very useful to study the origin of the Universe. The detection of lithium in the atmospheres of old metal-poor Pop II stars has given us the opportunity to study one of the primordial isotopes synthesised by nuclear reactions directly after the Big Bang. By observing the cosmic microwave background radiation (CMB), theorists are able to deduce the baryon density ($\Omega_b h^2$) of our Universe at the moment of recombination about 380,000 years after the Big Bang. This is before the first stars were born and altered the chemical composition of the Universe. Calculation of standard BBN based on the derived baryon density will then yield the abundances of the primordial isotopes. The recent results from the PLANCK space satellite pinpoint the baryon density at ($\Omega_b h^2$) = 0.02207 ± 0.00033 and with this value the initial abundance$^3$ of $N(^7\text{Li})/N(\text{H}) = 4.89^{+0.41}_{-0.39} \times 10^{-10}$ or $A(\text{Li}) = 2.69 \pm 0.04$ (Coc et al. 2013). This abundance is however significantly higher than what is observed for the Spite plateau (Spite & Spite 1982) in the Galactic halo: 2.22 ± 0.06 (Spite et al. 2012). The Spite plateau emerges observationally when deriving Li abundances of warm ($5800 \text{ K} < T_{\text{eff}} < 6500 \text{ K}$, where $T_{\text{eff}}$ is the effective temperature of the star) unevolved metal-poor (Pop II) stars in the halo of our galaxy with a metallicity in the range ($-3.5 < [\text{Fe/H}] < -1.5$). On discovery, the plateau was interpreted as directly displaying the primordial lithium abundance formed during BBN. As the lithium plateau value lies about a factor of 2-3 below the CMB+BBN predicted primordial lithium abundance, we now know that the measured lithium abundance in stars is not the primordial lithium abundance. The stars must have undergone surface depletion in Li. Michaud et al. (1984) predicted the depletion occurred via gravitational settling and weak mixing in the radiative zones of Pop II stars. This was shown to be a successful explanation when Richard et al. (2005) published stellar evolution models which treat atomic diffusion and radiative acceleration together with some additional mixing that increases the efficiency of the lithium destruction by bringing it down to the hotter regions inside the star. The models could reproduce the Spite plateau by assuming rather strict limits to the efficiency and extent of the additional mixing transport. The lack of understanding of the underlying physical mechanism responsible for this additional mixing transport is a point that has attracted crit-

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Stellar abundances can also be presented in the following format: $A(X) = \log \epsilon(X) = \log(N(X)/N(H)) + 12$, where the 12 is arbitrarily added for convenience.
icism. A theoretical outline of atomic diffusion and additional mixing will be given in Chapter 2.

1.6 Observational applications: atomic diffusion

The preceding sections demonstrated the usefulness of chemical abundance analyses on GC stars. Not only did they reveal some interesting abundance patterns for the light elements in giants, recent studies have also shown that heavier elements, such as calcium, titanium, and iron, can show trends with evolutionary phase of GC stars. An example of this is given by Korn et al. (2007) for the metal-poor ([Fe/H] ~ −2.1) GC NGC 6397. These authors traced the existence of systematic differences in the surface abundances between stars of different evolutionary phases. As a spectroscopic analysis of a star only reveals the chemical composition of the outermost layers (a few 100 km in dwarf stars on the MS), we have to turn to indirect methods to get any information about the deeper layers. By comparing stars of different masses and evolutionary phase, having presumably the same initial chemical composition in terms of these heavy species, we can indirectly trace processes in the stellar interiors and obtain a glimpse of what happens below the outer convection zone that is continuously mixed and thus chemically homogeneous.

The key assumption here is *same initial chemical composition*. As GCs are now considered to have multiple populations, one has to make sure that the initial stellar abundances that are compared do have the same initial chemical composition. This is done, on the one hand, by analysing elements which do not show large star-to-star abundance variations, such as Ca, Ti, Sc and Fe. In addition, one can make sure to compare only stars within the same population by first deducing the population they belong to by analysing elements such as Mg, Al and Na.

In what follows, the theoretical framework behind atomic diffusion is outlined.
2. Atomic diffusion and competing transport processes

Figure 2.1. Hertzsprung-Russell diagram. The regions where atomic diffusion is expected to produce observable effects are marked by the ovals. The shaded regions are ruled out to see effects of atomic diffusion (see text for more details). Image credit: Pearson Education 2008 but modified by the author.

2.1 Atomic diffusion

Atomic diffusion (AD) is a slow but continuous process that modifies the chemical composition in the radiative zones of stars during their lifetimes and
leads to chemical stratification inside them. It is a complex interplay between a number of processes such as gravitational settling, radiative acceleration, and convection, which transport atoms around in the stellar atmosphere. The net result of AD are relative average velocities of elements. However, since these velocities are generally small, they are effectively counteracted by (fast) rotation and large-scale motions such as convection. Looking at the HR diagram (see Fig. 2.1) one can immediately rule out the hot side of the HR diagram as short-lived massive stars are characterised by fast rotations and other macroscopic velocities. The cool side of the HR diagram can be excluded since there the stars have thick convection zones which effectively inhibit the effect of AD on surface abundance. This leaves us with the central region of the HR Diagram and stars with roughly one to a few solar masses. AD is only expected to show significant and directly observable effects in stars with stable surface layers, such as the chemically peculiar stars, or in stars with thin outer convection zones. As metallicity correlates with the thickness of the outer convection zone for these solar-mass stars, it is expected that AD effects should be observable in relatively warm metal-poor stars (spectral types A, F and G) and that they should gradually become weaker with increasing metallicity. The focus of this Ph.D. thesis lies with the AD effects on these metal-poor stars (see Sect. 2.2).

Even though AD is not expected to produce sizeable effects in all stars, diffusion of elements in stellar structure in general seems inevitable. This is the case since:

- Stars are round and self-gravitating systems. They thus develop pressure, density, and temperature gradients in their interiors.

- Stars consist of gases with different atomic masses and structures. Due to the structural gradients and the different physical properties, these gaseous components will behave differently, leading to a chemical stratification.

Stellar structure models are obtained from the solution of the stellar structure equations. These form a set of differential equations and are e.g. given in Prialnik (2010, equations 5.1 - 5.4). The set basically consists of:

- the hydrostatic equilibrium equation which balances pressure and gravity and implies that the pressure decreases outwards,

- the continuity equation which requires mass conservation and describes the distribution of mass,
• the radiative-transfer equation which describes the propagation of radiation through a partially opaque medium, and

• the thermal equilibrium equation which implies that energy produced within the star is transferred outwards.

Most of the standard stellar structure models disregard particle transport outside convection zones and only take into account chemical composition variations due to nuclear reactions. Surface abundance variations during the main-sequence lifetime of the stars are thus neglected and the stellar gas is treated as being homogeneous outside the stellar core. The mean molecular weight $\mu$ is introduced in the fundamental hydrostatic equilibrium equation. Similarly, in the radiative transfer one assumes stars to consist of a gas with an average behaviour with respect to the photons. The corresponding equation is modelled by the Rosseland mean opacity, which is introduced as an average absorption coefficient into the radiative transfer equation.

As it is, real stars consist of a mixture of chemical elements, all feeling the same global pressure and temperature gradients. Still, the chemical elements will have a different behaviour with respect to each other depending on their own molecular weights and electric charges. On the detailed level, the individual ions/atoms of which stellar gas is composed, will have different velocities with respect to each other as they all absorb photons according to their own atomic state. The net result from the radiation field is an upwards movement of the atoms as they absorb the photons. This is called radiative acceleration or radiative levitation. The size of the movement depends on the characteristics of the affected species but is in any case small. The time scales of the small movements before the acquired momentum is distributed to the surroundings due to collisions, are very short. Nonetheless, they are of great importance because AD corresponds to what happens during these movements. This is what is generally ignored in the standard stellar structure models and the models only take into account what happens after the collisions occur. Such a simplified treatment is justified in the presence of strong mixing (e.g. in convection zones). There, the relative motions of the various components of the stellar gas (and thus the effect of AD) can be inhibited. In the radiative layers this is not the case and the net effect of AD on the elements will depend mostly on the relative strength of gravity compared to the radiative acceleration. Element accumulation will occur where gravity and radiative acceleration balance each other, while depletion occurs as long as gravity dominates.
2.2 Atomic diffusion in Pop II stars

The competition between gravity and radiative acceleration is element-specific, but in general AD will cause heavy elements to diffuse from the surface layers downwards to greater depth (in solar-mass stars\(^1\)). As a result, surface layers (i.e. from the bottom of the surface convection zone (SCZ) to the stellar surface) will appear somewhat depleted in metals. As large-scale motions such as convection effectively counteract AD, the effects of AD will only be observable in stars with thin SCZs. This gives us a range of stellar masses between roughly 0.5 and 1.5 \(M_{\odot}\). We know that AD is at work in the Sun (Proffitt & Michaud 1991) but larger effects are expected in warm metal-poor stars (Pop II), as they are generally older and their convective envelopes are thinner. In contrast, giant stars are predicted not to show this effect, as their deep outer convection zones restore the original composition in their atmosphere. Stellar evolution models including AD suggest then a general settling of elements at the TOP, which gradually resurface as the stars evolve toward the RGB (Richard et al. 2002).

Besides abundance trends between TOP and RGB stars, AD also has an effect on the overall evolution of the star through its effect on helium. AD is responsible for helium settling into the core. This in turn causes an offset in the core hydrogen abundance which results in a shorter main-sequence lifetime as the core's hydrogen is more rapidly exhausted. All this translates into that models on an isochrone will have a lower mass at a given evolutionary stage. Hence, including AD in stellar models leads to models with cooler effective temperatures at a specific evolutionary stage compared to standard models without AD (Richard et al. 2002). Aside from the effective temperature, the downward diffusion of helium is accompanied by a corresponding change in mean molecular weight which can be mapped as a shift in surface gravity (Stromgren et al. 1982). This means that a line spectrum of a helium-normal atmosphere can be mimicked by a line spectrum of a helium-poor atmosphere at a somewhat higher \(\log g\) (Korn et al. 2007).

The abundance variation predicted by stellar structure models including AD can be tested observationally by comparing abundances in unevolved and evolved stars all drawn from the same stellar population. In this sense, GCs offer adequate laboratories to test and put observational constraints on the theoretical expectations. However, since the effects of AD are believed to be small in the given metallicity and age range of the observable GCs, it becomes hard to trace them observationally. Nonetheless, using the Very Large Telescope (VLT) Korn et al. (2007) were able to show AD at work in the GC NGC 6397

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\(^1\)This is because the radiation field in these stars is not strong enough to overcome the gravitational force on most of the elements.
at a metallicity \([\text{Fe/H}] = -2.1\). 

The predictions of AD are, however, not supported by these observations straight off. To achieve agreement between theory and observation, AD needs to be counteracted by competing transport processes which we refer to as additional mixing (AddMix), i.e. non-canonical mixing not provided by convection. This AddMix is present just below the SCZ and hinders the downward diffusion of heavy elements. As AddMix does not affect the helium settling in the core, the overall evolution will be similar regardless of this parameter. The efficiency of AddMix sets the depth of the settling of elements in the way that a higher efficiency corresponds to a deeper mixing. This is especially important for lithium. Li is readily destroyed at temperatures of roughly \(2.5 \times 10^6\) K which is easily reached in the deeper stellar layers. AddMix that is too efficient will thus allow Li to diffuse down to layers where it can be burned. As the star evolves to the RGB, the SCZ expands inwards, reaching layers depleted in lithium. The surface layers will get diluted with Li-depleted material leading to a smooth drop in the surface Li abundance. Conversely, an up-turn is expected to occur when the inwards expansion of the SCZ reaches layers with higher Li abundance in case AddMix does not completely erase the stratification due to atomic diffusion. For all other elements, an up-turn is always expected as the deepening SCZ causes resurfacing of deposited material, irrespective of to the efficiency of AddMix.

AddMix can be prescribed in stellar-structure models by an extra term in the diffusion equation, adding a simple analytical function that accomplishes mixing down to layers of a specific temperature. The free parameter involved in this modelling, the efficiency relative to AD, must, at present, be determined empirically from the observations, i.e. from the amplitude of the elemental abundance trends as is investigated in this thesis.

2.3 Stellar structure models including AD and AddMix

To include AD in the standard stellar-structure models, an extra equation is added to the set of stellar structure equations. This extra equation models how microscopic movements result in a net transport of elements through the star. We here give the theoretical framework for atomic diffusion and additional mixing.
2.3.1 Modelling AD

AD can be modelled as a basic physical transport process. The diffusion equation for AD can be written as

$$\rho \frac{\partial X_i}{\partial t} = -\nabla \cdot [\rho D_{li} \nabla \ln X_i + \rho v_g X_i]. \quad (2.1)$$

Here, $X_i$ is the mass fraction of species $i$, $D_{li}$ is the atomic diffusion coefficient for species $i$ and depends on the collisional rates, and $v_g$ is the diffusion velocity given by

$$v_g = -D_{li} \left\{ \left( A_i - \frac{Z_i}{2} - \frac{1}{2} \right) g - A_i g_{\text{rad}, i} \right\} \frac{m_p}{kT} - kT \frac{\partial \ln T}{\partial r} \right\} \quad (2.2)$$

where, $A_i$ and $Z_i$ are respectively the mass number, giving the number of nucleons, and the atomic number, giving the number of protons, for a given species $i$. The $g$ and $g_{\text{rad}, i}$ represent the gravity and the radiative acceleration of the species $i$, and $kT$ is the thermal diffusion coefficient. From this equation one sees that competition between $g$ and $g_{\text{rad}}$ emerges.

The competition between gravity and selective radiative accelerations will result in the chemical stratification of the stellar atmosphere. This is mainly due to the fact that the average values of the velocities of the atomic species deviate from the Maxwellian mean value. Models including diffusion incorporate the Boltzmann equation for a diluted collision-dominated plasma which at equilibrium has the Maxwellian distribution function as its solution. By introducing small deviations from the Maxwellian distribution, transport properties can be computed.

An approximate solution to the Boltzmann equations can be obtained by following the Chapman-Enskog theory (Chapman & Cowling 1970). It assumes that the total distribution function of a given species can be written as a convergent series, each term of the series representing successive approximations to the distribution function. The computations of a trace ion diffusing in a stellar plasma lead to the statistical diffusion velocity $v_g$ of the trace ion given in Eq. 2.2. Next, we will take a closer look at $g_{\text{rad}}$.

2.3.2 Radiative acceleration

Michaud (1970) was the first to suggest that radiative accelerations could explain observed overabundances of some elements in chemically peculiar A stars, which could not be explained by the standard stellar structure models taking only convection into account. Since then, AD including radiative accelerations, modelled from first principles, has been used to explain chemical peculiarities in pre-main sequence, main sequence and horizontal branch stars (Vauclair & Vauclair 1982; Michaud et al. 1983; Richer et al. 2000; Richard et al.
Radiative accelerations are the result of the change in momentum due to bound-bound or bound-free interactions between photons and particles. The radiative accelerations can be calculated to a first approximation by using the fraction of the momentum flux that each element absorbs,

\[ g_{\text{rad}}(A) = \frac{L_{\text{rad}}}{4\pi r^2 c} \kappa R \int_0^{\inf} \frac{\kappa_u(A)}{\kappa_u(\text{total})} P(u) \, du. \]  

(2.3)

The first factor \( L_{\text{rad}}/4\pi r^2 c \) is the total radiative momentum flux at radius \( r \), \( u \) is the dimensionless frequency variable

\[ u \equiv h\nu/kT, \]  

(2.4)

and \( P(u) \) is the normalised blackbody flux, given by

\[ P(u) \equiv \frac{15}{4\pi^4} \frac{u^4 e^u}{(e^u - 1)^2}. \]  

(2.5)

To compute the radiative acceleration of elements, the complete knowledge of the monochromatic opacities is required. Such element-specific knowledge has been obtained over the last twenty years by the OPAL community (Rogers, Swenson, & Iglesias 1996; Iglesias & Rogers 1996) and an international collaboration operating under the name Opacity Project (Seaton 2005). Large datasets of atomic and radiative data for astrophysically abundant ions have been made available to the stellar community. In this thesis we will use models computed with the Montréal-Montpellier stellar evolution code (Richer et al. 2000; Turcotte et al. 2000; Richard et al. 2001). It is the only code that treats radiative accelerations in a complete, accurate, and consistent way. The models use monochromatic OPAL data to compute Rosseland opacities and radiative accelerations for each mesh point and at each evolution time step. During each iteration over the star's structure the abundances are updated. The Burgers' flow equations for ionised gases (Burgers 1969) are solved for all diffusing elements to determine diffusion coefficients and velocities. A complete description of AD including radiative accelerations can be found in Richer et al. (1998).

In what follows, we will try to shed some light on how to incorporate Add-Mix into the diffusion equation. To do so we follow the formulations by Richer et al. (2000) and Richard et al. (2001).

2The total radiative momentum flux varies as \( 1/r^2 \) from the surface down to the region where energy is generated. This variation follows that of local gravity except near the core as energy generation is more concentrated to the core than the mass.
2.3.3 AddMix and additional transport mechanisms

Macroscopic transport processes such as convection and AddMix can easily be included by simply adding to the diffusion equation of each species a pure diffusion term given by

\[- (D_T + D_{\text{mix}}) \frac{\partial \ln X_i}{\partial r}. \tag{2.6}\]

Here $D_T$ and $D_{\text{mix}}$ are diffusion coefficients with $D_{\text{mix}}$ representing the effects of convective motions and $D_T$ parametrising AddMix. The values of $D_T$ and $D_{\text{mix}}$ are the same for all species, but $D_{\text{mix}} = 0$ in radiative layers. In convective layers $D_{\text{mix}}$ is computed using the mixing-length theory that uses the mixing-length approximation given by $D_{\text{mix}} \approx \langle vl \rangle$. This choice results in large values of $D_{\text{mix}}$ and very homogeneous convection zone abundances. Below the SCZ, $D_T$ will be important and is assumed to be a function of density and temperature given by

\[D_T = 400D_{\text{He}}(T_0) \left( \frac{\rho(T_0)}{\rho(T)} \right)^3. \tag{2.7}\]

where, $D_{\text{He}}$ is the atomic diffusion coefficient for helium at density $\rho(T_0)$ and is approximated by the analytical expression (Richer et al. 2000)

\[D_{\text{He}} = 3.3 \times 10^{-15} \frac{T^{2.5}}{4\rho \ln(1 + 1.125 \times 10^{-16}\frac{T}{\rho})}. \tag{2.8}\]

$D_T$ can be anchored at a given temperature, $T_0$, so that $D_T(T_0) = 400D_{\text{He}}(T_0)$. In this way AddMix can be parametrised and fixed at a reference temperature $T_0$. One has

\[\rho_0 = \rho(T_0) \text{ and } D_T = 400D_{\text{He}}(T_0) \left( \frac{\rho_0}{\rho} \right)^3. \tag{2.9}\]

In order for AddMix to have any effect, it should occur below the SCZ. The mixed mass, i.e. the mass affected by AddMix, encompasses the mass from the surface down to where $D_T = 2D_{\text{He}}$ for a given value of $T_0$. The models are referred to by specifying the AddMix parameter, i.e. T6.0 refers to a model in which $D_T$ is 400 times larger than the He atomic diffusion coefficient at $\log T = 6.0$ and varies with $\rho^{-3}$. The density dependence ($\rho^{-3}$) is suggested by the Be abundance on the Sun (Proffitt & Michaud 1991). Fig. 2.2 gives an example of this. The figure displays five AD models with different efficiencies of AddMix as a function of the depth in a 0.77 \(M_\odot\) star with a metallicity of $[\text{Fe/H}] = -2.31$. For comparison $D_{\text{He}}$ is included. The advantage of this formalism is that it is simple and hence easily implemented in other stellar evolution model codes.
Candidates for AddMix include rotational instabilities of various kinds (see e.g. Charbonnel & Vauclair 1992; Vauclair 2003; Talon et al. 2006), internal gravity waves (Talon & Charbonnel 2003, 2004, 2005), fingering convection (Vauclair 2004; Théado et al. 2009; Théado & Vauclair 2012). Also mass loss could affect the abundance variation in the stars (Vauclair & Charbonnel 1995; Vick et al. 2010). All of these candidates show promising frameworks but need further investigation.

Vick et al. (2013) investigated mass loss and showed that it can produce effects very similar to AddMix in MS Pop II stars. However, the mass-loss rates needed to create these effects are much higher than observed for example in the Sun. As mass-loss rates have never been measured in MS Pop II stars, mass loss can not completely be ruled out as the explanation for AddMix but it seems unlikely that mass-loss rates of the order of $10^{12} M_\odot \text{yr}^{-1}$ will ever be observed for MS Pop II stars. If anything, mass loss is expected to be weaker in Pop II stars than in the Sun.

Thermohaline mixing or fingering convection as it is dubbed in stars, on the other hand, is a very promising framework as it is a direct result of AD. The mechanism works as follows. Due to radiative accelerations, individual heavy
elements can be pushed upwards before they collide with their surroundings and share the acquired momentum. This has only a small effect on the global gas but can cause an accumulation of heavy elements. At the same time, helium settles downwards and induces a stabilizing contribution to the global molecular weight $\mu$-gradient. This in turn leads to an increased mean molecular weight and an unstable chemical stratification. In the end the layers get chemically mixed through fingering convection where the heavy elements sink back down by creating characteristic finger shapes. The problem here is that in Pop II stars there might not be enough metals to create layers with different $\mu$ to get the $\mu$ inversion needed to start the fingering convection. For more information see the recent work by Zemskova et al. (2014).

This leaves rotationally induced mixing and internal gravity waves as possible explanations. Whatever the physical origin, it is clear that in order to get a better understanding of AddMix, more observational and theoretical work will be needed. It is, however, highly improbable that only one process will emerge as being the physical origin of AddMix. As long as AddMix cannot be modelled from physical principles, one has to rely on the parametrisation presented above. The hope is that, irrespective of the mixing agent, the amount of mixing can be empirically constrained, e.g. by the amplitude of the abundance trends observed in GCs and presented in this thesis.
3. Spectral line formation

As far as stars are concerned, chemical abundances are predominantly derived from spectral absorption lines. The lines are mostly formed in the upper part of the stellar atmosphere or photosphere. The shape and strength of these lines are a direct result of the physical conditions in the star’s atmosphere, which are set by the stellar parameters and the elemental abundances. The most fundamental point to bear in mind is that the strength of the line absorption is set by the number of absorbers producing the absorption. This means that the atomic level populations will be our primary concern. But also keep in mind that we are most interested in the ratio of the line absorption to the continuous absorption. More continuous absorption corresponds to a thinner photosphere, and thus fewer atoms to contribute to the spectral line. This is how the hydrogen abundance indirectly, via the H\(^+\) ion, comes into play as it is the main contributor to the stellar continuous opacity in the optical wavelength range. More information about continuous absorption can be found in chapter 8 of Gray (1992).

3.1 Line formation

3.1.1 Local thermodynamic equilibrium

The stellar interiors are characterised by high densities and temperatures. Under such conditions the energy partitioning of matter is fully controlled by the very high rate of collisions between particles. As all processes of excitation and ionisation happen in complete equilibrium, excitation and ionisation fractions, and the velocity distributions are independent of the radiation field. They thus can be described by the Boltzmann, Saha and Maxwell equations at the local kinetic temperature. These are the conditions for local thermodynamic equilibrium (LTE).

Under LTE the relative number populations of different excitation levels is given by the Boltzmann distribution:

\[
\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\Delta \chi / kT}.
\]

Here, \(\Delta \chi = \chi_j - \chi_i\) is the excitation energy difference between level \(i\) and \(j\), \(g_{i,j}\) is the statistical weight of level \(i/j\) and \(k\) is the Boltzmann constant.
Note that the equation is dependent on the temperature as the only atmospheric parameter. Turning to the ionisation fractions, one finds that they follow the Saha equation:

\[ \frac{N_{i+1}}{N_n} N_e = \frac{1}{\Lambda^3} \frac{2 u_{i+1}}{u_i} e^{-\frac{I}{kT}} \]  \hspace{1cm} (3.2)

where \( N_i \) is the total number density of a given atom in the \( i \)-th state of ionisation, \( N_e \) the electron density, \( u_i = \sum g_i e^{-E_i/kT} \) the partition function of species \( i \), and \( \Lambda \) the thermal de Broglie wavelength of an electron given by:

\[ \Lambda = \sqrt{\frac{\hbar^2}{2\pi m_e kT}} \]  \hspace{1cm} (3.3)

with \( m_e \) being the mass of an electron and \( \hbar \) the Planck constant. Here, one sees that the ionisation fractions given by the Saha equation \( 3.2 \) are dependent on both the surface gravity and the chemical composition through \( N_e \), as well as on the temperature just like the Boltzmann equation.

To derive the level populations for all elements, one needs the physical conditions at each layer of the stellar photosphere. These conditions can be obtained from a model atmosphere, which consists of a table containing a reference depth scale (optical depth or column mass), and the physical parameters, e.g. temperature, and gas and electron pressure or density. With the physical conditions known, the level populations can be retrieved for any given depth by solving the Saha and Boltzmann equations. Once the level populations of all elements are specified, the opacity for each layer of the atmosphere can be computed so that the radiative transfer equation\(^1\) can be solved at any given wavelength. The result is the synthetic spectrum, which can then be compared to observations.

Generally speaking, the density of absorption lines increases with decreasing wavelength. As neutral species have low excitation and ionisation potentials compared to their ionised counterparts, the lines of neutral species (atomic lines) dominate over lines of singly-ionised species (ionic lines). This however, does not mean that it reflects the relative amount of neutral and ionised species in the stellar atmospheres. For example, in stars with solar-like temperatures \( \text{Fe I} \) is a minority species (only a few percent of \( \text{Fe} \) can be found in this state), and most iron is in the singly-ionised form. In fact, this is true for all elements having a low ionisation potential (\(<6-8 \text{ eV}\)).

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\(^1\)The radiative transfer equation is given by \( \frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \) and couples the change in specific intensity per optical depth to the source function.
3.1.2 Strength of a spectral line

From equations 3.1 and 3.2 one sees that the strength of different lines will vary from the TOP to the RGB. The strength of a line can be measured by integrating the depression of the emergent flux profile of a spectral line normalised with respect to the continuum:

\[ W_\lambda = \int \frac{F_\lambda^{\text{cont}} - F_\lambda}{F_\lambda^{\text{cont}}} \, d\lambda \]  

(3.4)

This is the so-called equivalent width (EW) of a line. From the equation one sees that the EW is measured in units of wavelength, usually in mÅ.

For weak lines the EW varies in proportion to the ratio of the line opacity to the continuous opacity, \( l_\nu / \kappa_\nu \). In stars with solar-like temperatures bound-free transitions of \( \text{H}^- \) form the dominant source of continuous opacity in the optical and \( \kappa_\nu \) will thus vary with the number density of \( \text{H}^- \). In the cooler atmospheres of RGB stars, \( \text{H}^- \) gets less ionised but as the atmospheres are more diluted, the electron pressure is lower and hence less \( \text{H}^- \) is formed. For a given temperature, the electron pressure will set the amount of \( \text{H}^- \) through the Saha equation and thus the RGB stars will generally have a lower continuous opacity than the TOP stars. For neutral iron, the situation is inverted, the importance of the electron pressure is subject to the temperature difference and the amount of Fe i is doubled from approximately 2\% to 4\% of the total iron content from the TOP to the RGB. Due to the lowered continuous opacity and the raised line opacity, the lines from neutral metals will be significantly stronger in the RGB stars than in the TOP stars. Since the EW of an ionised species such as Fe ii is dictated only by the inverse dependence of \( \kappa_\nu \), the line strength should also be stronger in RGB stars than in TOP stars. The EW of lines from singly-ionised species are generally larger for the more evolved stars. The difference is, however, smaller than for neutral species since iron is mostly ionised\(^2\), and the majority species are less sensitive to changes in the ionisation balance.

The Saha equation 3.2 tells us that a change in temperature will shift the ionisation fraction. A large relative population variation is expected for the minority species while the majority species are mostly unaffected. From this we conclude that, just like the continuous opacity, the minority species, such as Fe i, are temperature sensitive. Besides temperature, the ionisation fractions are also sensitive to a change in gravity as this will alter the electron pressure which enters the Saha equation 3.2 through \( N_e \). This affects mainly the majority species, such as Fe ii, as the change in continuous opacity (mainly H\(^-\)) is canceled by the effect on line opacity for minority species only.

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\(^2\)The degree of ionisation is high for elements with low ionisation potentials. See the Saha equation 3.2
Using these mechanisms, the atmospheric conditions in a star can be evaluated. By comparing the abundances derived from lines with different excitation energy, the effective temperature can be assessed: a difference in abundance between low- and high-excitation lines signals a mismatch in excitation populations and thus an incorrect effective temperature. Similarly, a mismatch in abundances derived from lines of different ionisation stages indicates that an incorrect surface gravity is used in the model. These conditions are commonly referred to as the excitation and ionisation equilibrium, respectively.

3.2 Improving the modelling: 3D and Non-LTE

Over the last decades, much effort has been made to improve the realism of the modelling of stellar spectra. The 1D and LTE assumptions have been relaxed and the effects of 3D temperature distributions and departures from LTE are being investigated thoroughly. Corrections for abundances derived under 1D and LTE assumptions are now available for a number of elements such as iron, calcium and lithium. Here we will give an overview of why these corrections are generally needed.

3.2.1 3D modelling

Standard 1D stellar models are calculated under the assumption of hydrostatic equilibrium and are time-independent. A first look at the Sun immediately tell us that this may not be a good approximation. The surface of the Sun is dominated by granulation, the observable manifestation of broad, warm upflows (granules) surrounded by narrow, cool downdrafts (intergranules). Each of these flows has its own specific temperature structure and will thus produce its own line profile. Stronger line profiles will be produced in the granules as they have a steeper temperature gradient than the downdrafts or intergranules (see discussion in Asplund 2005). Line profiles from granules will also be slightly blue-shifted relative to the rest-frame wavelengths while lines from intergranules will be red-shifted as they move away from the observer. The lines in an observed stellar spectrum are thus an average profile over all the different contributions and in general will be characterised by asymmetries and wavelength shifts. This is depicted in Fig. 3.1. In metal-poor stars, the adiabatic cooling of the convective flows plays a stronger role since the radiative heating through absorption by lines is reduced. This leads to lower temperatures in the outer stellar layers and a steeper temperature gradient than the one that would arise from a 1D atmospheric model (see Fig. 3.2). This results in larger populations for neutral minority species than in 1D stellar atmospheres and thus in stronger lines for these species.
Figure 3.1. Spatially resolved line profiles of the Fe I line at 608.27 nm across the predicted granulation in a 3D hydrodynamical simulation of the solar atmosphere. The thick line corresponds to the spatially averaged profile. The blue-shifted granules give rise to stronger lines with higher continuum intensities compared to the red-shifted intergranular lanes. The steeper temperature structure in the granules tends to make the lines stronger, while the largest vertical velocities in the photosphere are encountered in the intergranules. Image credit: Asplund et al. (2000).

One advantage of 3D models is the lack of free parameters such as macro- and microturbulence that need to be varied ad-hoc to reproduce the spectrum in 1D. However, since the $T$ and $\tau$ are inhomogeneous at a single geometrical depth, solving the radiative transfer equation becomes much more complex. Calculating 3D models is thus a very computationally heavy process. This is why the treatment of the line opacity is usually simplified and line formation is treated in LTE to the dismissal of realism. One way around this is to replace the temperature distribution in a 1D stellar atmosphere with the averaged result of a 3D simulation. This is usually referred to as a 1.5D model and allows for a full non-LTE treatment.

3.2.2 Non-LTE
The assumption of LTE fails when conditions are no longer set locally, meaning radiative processes dominates over collisional processes. As the photons carry non-local information, one must consider non-local effects. The radiative
Figure 3.2. Temperature distribution in a 3D hydrodynamical model atmosphere of a metal-poor star ([Fe/H] = -3). The colour coding represents the amount of gas at a particular temperature where red colours represent more gas of a given temperature at a given depth. The zero-point for the depth-scale corresponds roughly to the continuum optical depth unity. The dashed line represents the corresponding theoretical 1D MARCS model atmosphere (Gustafsson et al. 2008). Note how the 3D temperatures are much cooler and fall below the radiative equilibrium expectations in the optically thin layers. This is due to the dominance of expansion cooling in the upflows over the radiative heating owing to the spectral lines. It is this difference that will impact the line profiles formed in those atmospheric layers such as molecular and low-excitation lines of in particular minority species. Image credit: Asplund (2004).

The radiative-transfer equation will then be solved by assuming non-local thermodynamical equilibrium or non-LTE (NLTE) and the level populations are no longer given by the Saha and Boltzmann equations (i.e. 3.2 and 3.1). Instead one assumes statistical equilibrium (SE), which implies that the radiation field and level populations do not vary with time. SE is given by

\[
\frac{dN_i}{dt} = \sum_{j \neq i} N_j P_{ji} - N_i \sum_{j \neq i} P_{ij} = 0. \tag{3.5}
\]

Here, \( N_i \) is the population of level \( i \) and \( P_{ij} \) are the transition rates for radiative and collisional processes given by \( P_{ij} = A_{ij} + B_{ij} J_\nu + C_{ij} \) with \( A_{ij} \), \( B_{ij} \), and \( C_{ij} \) being the Einstein coefficients for radiative emission, radiative absorption/stimulated emission, and collisional excitation/deexcitation. \( J_\nu \) is the mean intensity averaged over the transition profile.

NLTE complicates the radiative-transfer problem enormously as radiation couples physically separate regions and the rate equations must be solved simultaneously with the radiative transfer equation for all relevant equations. The main effect of interest of NLTE is a difference in the line strength comp-
pared to LTE predictions. This happens either because the line source function departs from the Planck function, or because the line opacity has changed. In case of the former, a departure coefficient \( \beta_i \equiv n_i / n_i^{LTE} \) is introduced (for convenience). Here, \( n_i \) is the actual population density of a level \( i \) and \( n_i^{LTE} \) the corresponding Saha-Boltzmann value (Wijbenga & Zwaan 1972). If \( \beta_i > 1 \) the line will be stronger in NLTE as there are more absorbing atoms in the lower level of the transition present than in LTE.

The departure coefficients can be put into the line source function \( S^l_{\nu} \) which is the ratio of emissivity to extinction and given in NLTE by

\[
S^l_{\nu} = \frac{2 \hbar \nu^3}{c^2} \frac{1}{\beta^l_{\nu} \exp \hbar \nu / kT - 1}
\]

This becomes \( S^l_{\nu} = \beta_u / \beta_l B_\nu \) in the absence of stimulated emission (or negative absorption), where \( B_\nu \) is the Planck function. In NLTE, the intensity depends on the populations, which depend on the intensity, meaning everything depend on everything else.

There are two ways to apply NLTE corrections. Either the corrections are given as a set of population departure coefficients \( \beta_i \) or the resulting difference between LTE and NLTE values for line strength and elemental abundance are tabulated for a grid of stellar-parameter combinations. In the former solution, the \( \beta_i \) are applied to the line formation code to correct the LTE populations and so the correct line shape will be synthesised in the synthetic spectrum. In the latter, interpolations will give the NLTE correction to the abundances derived from an LTE analysis. In any case, the abundance corrections will always be given by

\[
\Delta \log \epsilon = \log \epsilon_{NLTE} - \log \epsilon_{LTE}.
\]

### 3.2.3 Measuring techniques for spectral lines

Absorption lines can be be analysed with a variety of techniques. The choice for one technique or the other will depend on the number of lines used for the derivation of the abundance, the number of stars, the spectral region, the spectral resolution, or the desired accuracy of the analysis. Most spectroscopists use either the equivalent widths (EW) to determine the abundances or a synthetic spectrum which is fit to the observed spectrum. The advantage of the EW analysis is that it is essentially insensitive to broadening effects on the line by e.g. stellar rotation, large-scale convective motions in the atmosphere, or broadening introduced by the instrument. When the atomic lines are blended (as is generally the case), it is more desirable to deduce the abundances by fitting a synthetic spectrum to the observations as the EW measures the total...
depression in the selected line region regardless of blends.

The number of lines to analyse can help decide whether the analysis should be carried out automatically (in case of using a large amount of lines to deduce the abundances) or by eye-judgement (when using only a few lines). An automated analysis will derive abundances by fitting synthetic spectra to the observations. The lines are selected by placing a so-called line mask over the spectral region to be fitted. This procedure was used in Paper II and III. For Paper I, we opted for a line-by-line analysis where the observations are fitted by on-the-fly calculated synthetic spectra and the difference is minimised by eye. A more detailed overview of this line-by-line analysis is given in Chapter 6 while the automated analysis which we apply in Paper II and III is summarised in Chapter 7.
Part II: Scientific Work

"The purpose of life is the investigation of the Sun, the Moon, and the heavens."
— Anaxagoras
4. Medium- and high-resolution spectroscopy with FLAMES-GIRAFFE and -UVES

The observations for this project were carried out at the Very Large Telescope (VLT), the world's most productive ground-based facility for astronomy. The VLT, shown in Fig. 4.3, is an observatory operated by the European Southern Observatory (ESO) on Cerro Paranal in the Atacama Desert of northern Chile and consists of four individual telescopes, each with a primary mirror with a diameter of 8.2 m.

For the research we intended to perform we collected stellar spectra. These were obtained by using the Fibre Large Array Multi-Element Spectrograph (FLAMES) coupled to the Ultraviolet-Visual Echelle Spectrograph (UVES) and to the Grating Instrument for Radiation Analysis with a Fibre-Fed Echelle (GIRAFFE). Both spectrographs are located at the ESO VLT-UT2 Kueyen (Pasquini et al. 2002) with the main differences between the two spectrographs being the spectral resolution and wavelength coverage achieved during a single exposure.

Although the 'S' in FLAMES stands for spectrograph, FLAMES by itself is merely a fibre positioning system consisting of several components including an optical corrector providing excellent image quality and tele-centricity over the full field of view, and a Fibre Positioner (OzPoz) hosting two circular plates, which each can hold up to 132 fibres. By using two plates the dead time between observations can be limited to less than 15 minutes as the non-observing plate is positioning the fibres for the subsequent observations.
FLAMES can access targets over a field of view 25 arcmin in diameter. The light from the observed targets is collected through fibres with a diameter of 1 arcsec, which are equipped with microlenses and fed to either UVES or GIRAFFE, the actual spectrographs.

UVES is a cross-dispersed echelle spectrograph located at Nasmyth platform B of the ESO VLT-UT2 Kueyen and designed to operate with high efficiency. By splitting the light beam coming from the telescope into two arms (UV-Blue and Visual-Red) within the instrument, UVES can cover a spectral range from the atmospheric cut-off at 3 000 Å to the long-wavelength limit of the CCD detectors (~ 11 000 Å). The resolving power is 40 000 when a 1 arcsec slit is used. Since the commissioning of FLAMES in 2003, UVES can be used in fibre mode which allows for multi-object spectroscopy (MOS). In fibre mode, UVES is fed the light of eight targets simultaneously by the fibres coming from FLAMES. As the 1 arcsec apertures of the fibres project onto five UVES pixels, the resolving power is limited to $\lambda/\Delta\lambda = 47 000$. There are also only three standard UVES Red setups offered, these have central wavelengths of 520, 580 and 860 nm respectively and cover 2 000 Å each (see the FLAMES manual for details).

Unlike UVES, GIRAFFE cannot be used without FLAMES. Operated in the MEDUSA-mode, GIRAFFE allows to collect spectra of up to 132 targets simultaneously. Equipped with two gratings, GIRAFFE can produce spectra over the entire visible range 3 700–9 000 Å with low- to medium-resolution ($R = 7 500–30 000$), with a typical wavelength coverage of 200 Å.

4.1 Targets

During the course of the project we have investigated two GCs similar in age but different in metallicity. Below, a short overview of each cluster is given along with their main parameters and a short review of some of the studies presented in the literature.

4.1.1 NGC 6752

NGC 6752 is one of the most massive GCs in our Galaxy. It lies at a distance of about 4 kpc from the Sun, below the Galactic plane. The metallicity of the cluster is [Fe/H] = −1.6 and the age estimate is about 12 Gyr.

Throughout the last decennia, NGC 6752 has been studied in detail by quite a number of authors. In 2001, Gratton et al. (2001) published a study in which they derived chemical abundances for 9 TOP and 9 base-RGB stars in NGC 6752 to study O-Na and Mg-Al anticorrelations. They also deduced Fe abundances for the stars and found no indication of variations between TOP
James et al. (2004) rederived Fe abundances for the 9 TOP and 9 base-RGB (hereafter bRGB) stars in the Gratton sample while performing an abundance analysis for heavy elements in the stars. They again found no Fe abundance difference between the two groups. Over recent years, the Padova group has published a series of papers (e.g. Carretta et al. 2006, 2007a,b,c; Gratton et al. 2006, 2007) in which they analyse anticorrelations in a sample of 19 GCs including NGC 6752 and NGC 6397. A recent paper by Carretta et al. (2012) presented evidence for three distinct stellar populations in NGC 6752. Being only interested in anticorrelations, none of their papers addresses possible variations in Fe abundance with evolutionary phase. In this paper we revisit NGC 6752 from a diffusion point of view. Preliminary results were already presented in Korn (2010) indicating a small but systematic abundance difference in iron between TOP and RGB stars:

$$\Delta \log \varepsilon(Fe) = -0.10 \pm 0.03 \quad (4.1)$$

between TOP and RGB stars. AD and AddMix in NGC 6752 is the topic of Papers I and II.

4.1.2 Messier 4

Messier 4 or in short M4, is one of the nearest GCs to the Sun and hence a fairly well-studied object. M4 has an age of roughly 12 Gyr and a metallicity of $[Fe/H]=-1.1$. The cluster is less massive than NGC 6752 which means that possible chemical populations will be less distinct and that there is no evidence for an extreme population in this cluster. Although M4 is located at merely 1.8 kpc (Hendricks et al. 2012) from the Sun, it is not the easiest target to observe as it resides just above the plane of our Galaxy behind the outer...
portion of the Scorpius-Ophiucus dust cloud complex. As a result, the line-of-sight towards M4 is heavily obscured by dust and the light coming from the stars in M4 is subjected to extinction and reddening. This, however, only presents a problem for photometric studies. Pure spectroscopic studies are unaffected. We will come back to how to deal with the reddening in Sect. 5.1.1 in Chapter 5.

During the end of the last century, M4 was the subject of some abundance studies based on the bright giant stars. Norris (1981) was the first to discover a CN bimodality in M4. But it was unclear if the bimodality resulted from deep mixing in giants or if it reflected some built-in primordial difference among the cluster stars. Follow-up abundance studies in which the behaviour of the light elements was investigated revealed a rather complex picture. An overview of these studies is given in the paper by Ivans et al. (1999). With the arrival of high-resolution spectrographs at the 8–10 m class telescopes and the discovery of chemically distinct populations in GCs, M4 was subjected to a new series of abundance studies but this time the main aim was to find and characterise the populations. Such work was presented by e.g. Marino et al. (2008, 2011) and Villanova & Geisler (2011). In their search for the primordial lithium content of M4, Mucciarelli et al. (2011) are the only ones who addressed the possibility of AD to be at work in M4. Their null-finding inspired us to reanalyse their data in the hope to discover an AD signature. M4 is under investigation in Paper III.

Figure 4.3. Left: Messier 4 as seen by the Wide Field Imager on the MPG/ESO 2.2-meter telescope in La Silla, Chile. Right: Finding chart of M4 in the constellation Scorpius. Image credits: ESO, IAU and Sky & Telescope.
5. Analysis of stellar spectra

In order to be able to infer elemental abundances from a stellar spectrum, it is necessary to determine the fundamental stellar parameters. These are i) the effective temperature $T_{\text{eff}}$, and ii) the surface gravity $\log g$, which we can obtain from photometric observations of the GC, and iii) the (approximate) metallicity of the stars, given by the global metallicity of the GC. We then use a spectral synthesis code to determine the remaining parameters such as individual abundances, and micro- and macroturbulence by comparing a synthetic spectrum with our observations and minimising the difference.

5.1 Effective temperature

To first approximation one can assume that a star emits a continuous flux spectrum which behaves with frequency as that of a black-body. Colour indices\(^1\), i.e. differences between the flux sampled in different wavelength regions, can be used as temperature indicators. From Wien's displacement law for black-body radiation ($\lambda_{\text{max}} \propto T^{-1}$), it follows that the flux peak is located at shorter wavelengths, the higher the $T_{\text{eff}}$ of the star. Using calibrated scaling relations obtained by empirical or theoretical means, one can then translate between colour and $T_{\text{eff}}$. In our case, these relations are calibrated on the so called infra-red flux method (IRFM, Blackwell et al. 1986). The IRFM is based on obtaining the apparent bolometric flux for a large calibration sample of stars and then using the ratio between the bolometric flux ($\propto T_{\text{eff}}^4$) and the flux measured at a specific reference wavelength in the near infra-red ($\propto T_{\text{eff}}$). The obtained ratio is independent of the distance to the star but highly sensitive to $T_{\text{eff}}$. Widely-used IRFM-calibrated scaling relations are those derived by e.g. Alonso et al. (1996, 1999); Ramírez & Meléndez (2005) and Casagrande et al. (2010).

The effective temperatures of stars analysed in Papers I and II are based on mediumband $uvby$ Strömgren photometry. The photometric observations were carried out by F. Grundahl and obtained with the DFOSC instrument on

\(^1\)The colour index of a star is defined as the difference between the magnitude of a star measured in two different passband filters. The colour indices are usually given in a photometric system that consists of a set of standard filters. Examples are the Johnson $UBVI$ broadband system by Johnson et al. (1966) and the $uvby$ mediumband system by Strömgren (1966). See the review by Bessell (2005) for more information on photometric systems.
the Danish 1.54 m telescope on La Silla in Chile. The data reduction and photometric calibration procedures are discussed in the papers on globular cluster $uvby$ photometry by Grundahl et al. (1998, 1999). The $T_{\text{eff}}$ values are estimated using the empirical color calibration by Alonso et al. (1996, 1999) or Ramírez & Meléndez (2005).

For Paper I, the effective temperatures were derived by F. Grundahl using the $(b - y)$ colour index as temperature discriminator. For Paper II, we constructed a photometric effective-temperature scale from the $(v - y)$ and $(b - y)$ colour indices using relations for MS stars (Alonso et al. 1996; Korn et al. 2007) and giant stars (Alonso et al. 1999, 2001; Korn et al. 2007), assuming $[\text{Fe/H}] = -1.6$ for all stars. The uncertainties in photometric colours were reduced by constructing colour-magnitude fiducial sequences for the cluster (see Fig. 5.1), as described in Korn et al. (2007) and Lind et al. (2008). The observed colour is projected onto the fiducial sequence at constant $V$ magnitude. This leads to a more precisely determined $T_{\text{eff}}$. Detailed information on the actual values and uncertainties can be found in the respective Papers.

![Figure 5.1. Observed colour-magnitude diagrams (CMD) for NGC 6752. The grey symbols correspond to the complete photometric catalogue while the black symbols represent the targets selected for Paper II. The solid red lines represent the constructed fiducial sequences for the $(v - y)$ (left) and $(b - y)$ (right) colour index. To the right of each CMD the corresponding distances in colour to the fiducial sequences are given for the spectroscopic targets.](image)

For Paper III, we took a slightly different approach as no mediumband $ubvy$ Strömgren photometry was available for M4. Instead we used broadband $UBVI$ photometry, provided by Y. Momany, to derive the effective temperatures using the $(V - I)$ colour index. A detailed description of the photometry can be found in Momany et al. (2003) while the derivation of the effective temperatures is outlined in Sect. 5.1.1 below.
5.1.1 Reddening

As stellar light travels through the Galaxy towards Earth, it passes through dust clouds in the interstellar medium and the light suffers extinction. Additionally, the colours of the stars appear redder than their intrinsic colour as light with shorter wavelengths is preferentially scattered. This is what is called *redden-ing*.

![Figure 5.2. The Scorpius-Rho Ophiuchi Cloud Complex. The brown-black bands are thick dust clouds blocking the light coming from the stars behind. The cloud complex is located at an estimated distance of about 460 light-years. Just behind the cloud complex lies Antares, the bright yellowish star in the middle of the image. At a distance of approximately 550 light-years, Antares is almost 900 times bigger and about 10 000 times more luminous than the Sun. Both Antares and the Scorpius-Rho Ophiuchi Cloud Complex lie in front of M4, which is the bright white dot situated slightly to the right just above Antares in the image but has an actual distance of 7 200 light-years. Image credit: © Tóth Gábor.](image)

Correcting for reddening is in principle straightforward. Given the colour excess\(^2\) in a certain colour index, one only needs to subtract the excess from the observed colour index. Most GCs are located well above or below the Galactic plane and consequently only marginally affected, e.g. the colour excess in

\[^2\text{The colour excess of a star is defined as the difference between the star's observed colour index and its intrinsic colour index, which is the theoretical colour index in absences of extinction. Extinction affects shorter wavelengths stronger than longer wavelengths. By determining the colour excess in a given set of filters, the properties of the matter responsible for the extinction can be derived (see e.g. Howarth 1983). In the }UBVI\text{ photometric system the colour excess is usually expressed in the }B\text{ and }V\text{ filters and written as}\\E(B-V) = (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}}.\]
(B − V) for NGC 6752 is $E(B − V) = 0.04$ (Harris 1996). The line of sight towards M4 is, however, heavily affected by interstellar dust due to its low Galactic latitude and its location behind the Sco-Oph cloud complex, meaning: i) a large amount of global reddening $E(B − V) = 0.37$ (Hendricks et al. 2012), ii) a strong extinction in the V-band $A_V = 1.39$ (Hendricks et al. 2012) and iii) a significant amount of spatially differential reddening (Ivans et al. 1999). The peak-to-peak differences within a distance of at least 10 arcsec of the cluster centre ranges from $δE(B − V) \geq 0.05$ (Cudworth & Rees 1990) to $δE(B − V) = 0.25$ (Mucciarelli et al. 2011). All this makes it a cumbersome job to transform the colours and magnitudes into luminosities to derive effective temperatures.

Correcting the differential reddening poses a serious problem as the reddening varies across the face of the cluster. Differential reddening causes stars to scatter more around the actual sequence than would be expected from their photometric uncertainties. This leads to an apparently broader evolutionary sequence in the colour-magnitude diagram (CMD) of the cluster. Moreover, the scatter will depend on the angle between the sequence and the reddening
vector, which gives the direction along which the reddening takes place. The reddening vector corresponds to the ratio between total and selective extinction, e.g., $A_V/E(B - V)$. The larger the angle between vector and sequence, the larger the scatter will appear to be. The scatter will appear small in the regions of the CMD where the vector is parallel to the sequence. This is illustrated in Fig. 5.3, which shows the reddening vector for the $(V - I)$ and $(B - V)$ CMDs assuming $E(V - I) = 0.63$ and $E(B - V) = 0.37$, and using a reddening law with $R_V = A_V/E(B - V) = 3.76$. As the reddening vector for $(B - V) - V$ is almost parallel to the MS the dereddening of the MS is very sensitive to uncertainties in $V$. We therefore chose to use $(V - I)$ to determine the reddening.

To correct for the spatially differential reddening across the face of the cluster, a fiducial sequence was determined by eye for the $(V - I) - V$ CMD. The selective extinction in $(V - I)$ is then determined by matching the fiducial to a 12 Gyr isochrone computed with the chemical composition $Y = 0.25$, $[\text{Fe/H}]=-1.1$ and $[\alpha/\text{Fe}] = +0.4$ using the stellar evolution code of Richard et al. (2002) which includes atomic diffusion. Before the matching could be done, the fiducial colours needed to be transformed into $T_{\text{eff}}$ values. The transformation was carried out by applying the $(V - I)$ calibration of Ramírez & Meléndez (2005). The difference in $(V - I)$ between the fiducial and the isochrone then gives the selective extinction $E(V - I) = 0.63$. The matching is shown in the right panel of Fig. 5.3.

![Figure 5.4](image_url)

*Figure 5.4.* Direct comparison of the $(V - I) - V$ and $(B - I) - V$ CMDs before and after applying the derived differential reddening correction. The bar indicate the direction of the reddening vector. Symbols and lines as in the left panel of Fig. 5.3.

Once the selective extinction is known, an average differential reddening value along the reddening vector can be obtained for each star. This was done
by generating a reference sample of stars based on all stars located near the main-sequence turnoff point, $16.7 \leq V \leq 18.3$ and computing their distance along the reddening vector to the fiducial sequence. For each star, the average reddening was then determined by median filtering amongst the nearest $\leq 35$ neighbouring reference stars within a distance of 60 arcsec on the sky. As an extra check, the corresponding dereddening in $(B - I)$ colour index was also derived. As Ramírez & Meléndez (2005) do not provide a $(B - I) - T_{\text{eff}}$ transformation, the Hendricks et al. (2012) transformation factors (see their Table 3) were used to obtain $E(B-I) = 1.06$ from the derived value of $E(V-I)$. The result of the dereddening procedure is shown in Fig. 5.4. The figure shows the $(V-I) - V$ and $(B-I) - V$ CMDs before and after correcting for reddening. Note the drastic improvement of the scatter at the TOP and along the RGB.

The spatial differential extinction in $V$ ($\Delta A_V$) across the cluster as derived empirically from the comparison to $(V-I) - V$ and $(B-I) - V$ fiducial sequences is visualised in the top panels in Fig. 5.5. The surface is binned in square cells of 10 by 10 arcsec. Each cell represents the median $\Delta A_V$ for all stars that fall in the coordinate range and for which a reddening value has been assigned by the method described above. In these reddening maps, the red colour indicates regions with a reddening value above the overall mean reddening of the cluster, while the blue colour marks the regions having a reddening value below the mean. Cells with no assigned reddening value are left blank and are predominately found in the outskirts of the cluster near the edges of the map where the reference star density falls below two stars per 60 arcsec.

Both maps are qualitatively consistent with the $(B-V)$ reddening map published in Hendricks et al. (2012). The $(V-I)$ reddening map is also qualitatively similar to the $(B-I)$ map, as can be seen from the bottom panels of Fig. 5.5. These panels show the difference between the $(V-I) - V$ and $(B-I) - V$ reddening maps for the whole map and for a zoomed in region where the spectroscopic targets are located. The differences between the reddening maps are small (median difference is 0.032 mag in $A_V$ for the spectroscopic targets) for the core region of the cluster where the targets are located, while it tends to be larger ($\sim 0.1$ mag) in the outskirts. The grey points in the difference map represent the individual stars in the reference sample. The good correspondence between the two reddening maps, and the significantly decreased scatter along the RGB in Fig. 5.4, validate the accuracy of the dereddening procedure.
Figure 5.5. **Top:** Observed \( \Delta A_V \) as derived empirically from comparison to \((V - I) - V\) and \((B - I) - V\) fiducial sequences. **Bottom:** The difference between the \((V - I) - V\) and \((B - I) - V\) maps of \( \Delta A_V \), where the grey dots represent the individual stars of the reference sample. The spectroscopic targets are marked by black crosses while the X sign marks the center of the cluster. The right panel zooms in onto the region where the spectroscopic targets are located. The blue colour indicates the areas with a lower reddening than the red coloured areas. The coordinate system is normalised to the cluster center at RA = 16\(^{h}\)26\(^{m}\)45.12\(^{s}\), Dec = 26\(^{\circ}\)18'35.4''.

Note that our spectroscopic targets are located in regions with minimal difference in \((V - I) - (B - I)\).

The correction for the differential reddening allows then for the determination of \( T_{\text{eff}} \) values by using the empirical relations by Ramírez & Meléndez (2005). The differences between the \((V - I) - V\) and \((B - I) - V\) reddening maps found for the targets give rise to small differences in the \( T_{\text{eff}} \) scales of 4 ± 40 K and 13 ± 76 K for giants and dwarfs, respectively. The corresponding scatter about the \((V - I)\) fiducial sequence is 45 K and 135 K, for giants and dwarfs. The median absolute deviation when executing the nearest neighbours filtering is just 0.032 mag in \( V \) or 0.015 mag in \((V - I)\). The latter corresponds to a change in \( T_{\text{eff}} \) of just 40 K and 68 K for giants and dwarfs, respectively, which is consistent with the scatter in difference between the reddening maps.
5.2 Surface gravity

The surface gravities of the stars are derived by using the relation between $T_{\text{eff}}$, luminosity, stellar mass and surface gravity:

The stellar luminosity $L$, is related to $T_{\text{eff}}$ and stellar radius $R$ via

$$L = \sigma T_{\text{eff}}^4 4\pi R^2 \quad (5.1)$$

where $\sigma$ is the Stefan-Boltzmann constant.

The surface gravity $g$ of a star is given by

$$g = \frac{GM}{R^2} \quad (5.2)$$

where $G$ is the gravitational constant, $M$ is the stellar mass and $R$ is again the radius of the star.

As accurate stellar radii are very difficult to derive for individual stars, we combine the two equations (5.1, 5.2) to get an expression for $g$ independent of stellar radius:

$$g = \frac{\sigma T_{\text{eff}}^4}{L} 4\pi GM \quad (5.3)$$

The luminosity is derived from the absolute bolometric magnitude $M_{\text{Bol}}$, which depends on the bolometric correction BC, apparent visual magnitude $V$, and the distance modulus $(m - M)_V$:

$$M_{\text{Bol}} = (V - (m - M)_V) + BC(T_{\text{eff}}, [\text{Fe/H}]) \quad (5.4)$$

where the apparent visual magnitude $V$ is derived using the Alonso et al. (1999) calibration for the BC. The luminosity is then computed as

$$L = L_{\odot} \times 10^{\frac{2}{5}(M_{\text{Bol,\odot}}-M_{\text{Bol}})} \quad (5.5)$$

The stellar masses can be inferred from theoretical isochrones of the clusters. However, as can be seen from Eq. 5.3, it is the $T_{\text{eff}}^4$ dependence that dominates the behaviour of $\log g$, and so exact masses are not crucial for inferring surface gravities. A rise in $T_{\text{eff}}$ of 100 K corresponds to an increase of about 0.03 dex in logarithmic surface gravity which is quite small, and for our purposes, negligible.

5.3 Chemical abundances

AD is expected to affect all chemical elements albeit to a different degree. However, not all elements are suited to study the effect by comparing groups of GC stars in different evolutionary phases. Helium is not observable in solar-type stars. Lithium is heavily affected by internal cluster pollution in some
GCs (e.g. NGC 6752 see Pasquini et al. 2005; Shen et al. 2010). Beryllium and boron require near-UV spectroscopy and are significantly processed in RGB stars making them unusable in a comparative study like ours. Carbon and nitrogen are dredge-up elements and thus the surface abundances may reflect contamination of the atmosphere by the processed material from the core rather than the original compositions. Other elements such as oxygen, sodium, magnesium and aluminium suffer from anticorrelations (Kraft et al. 1997) as a result of external pollution (Gratton et al. 2001). These restrictions limit us to elements such as silicon, calcium, scandium, titanium and other iron-group elements for differential analyses between groups of stars.

5.3.1 Choosing elements

By deriving the \( T_{\text{eff}} \) from photometry, we ensured that the uncertainty is not larger than \( \pm 100 \) K. However, when determining chemical abundances from lines of neutral species, this \( T_{\text{eff}} \) uncertainty will translate into a 0.07 dex abundance uncertainty, a fairly large error given the small abundance differences (\( \sim 0.1 \) dex) we are looking for (Korn 2010). For this reason it is desirable to derive abundances from ionised species. These are predominately gravity sensitive, hence, we can circumvent the aforementioned problem since a shift of \( \pm 100 \) K in \( T_{\text{eff}} \) leads to only a small shift in \( \log g \) (\( \sim 0.03 \) dex) and thus little to no influence on the abundances either (\( \sim 0.01 \) dex). This strategy limits us to the elements iron, titanium and scandium.

Stellar evolution models by Richard, Michaud, & Richer (2005) including AD with AddMix parametrised by T6.0, predict the strongest variation for silicon and magnesium:

\[
\Delta \log \epsilon(X) = \log \epsilon(X)_{\text{RGB}} - \log \epsilon(X)_{\text{TOP}} = 0.2.
\]  

In what follows, I will give a summary of the methodology used to derive the abundances in the different papers and briefly summarise the main results.
6. Weak atomic diffusion trends in NGC 6752 (Paper I)

In Paper I, we investigate high-resolution FLAMES-UVES spectra of stars in the GC NGC 6752 at [Fe/H] = −1.6. At this metallicity, the number of measurable lines is rather low in the optical. Given the high resolution of UVES (\(R = 47\,000\)) and the low number of lines from ionic species, we opted to perform a line-by-line differential analysis with respect to the Sun. This we do by comparing the line-abundances derived from stellar spectra to the corresponding line-abundances in the Sun and correcting for offset. In that way we minimise most potential biases introduced by choosing specific atomic data.

6.1 A line-by-line differential analysis

Abundances are derived using SIU (Reetz 1991), a visualisation tool to compare observed and theoretical spectra. SIU is equipped with a built-in line-synthesis module. The module uses one-dimensional hydrostatic model atmospheres in LTE with an ODF representation of line opacity (MAFAGS, Fuhrmann et al. 1997; Grupp 2004). In our differential analysis, we use the high-S/N Kitt-Peak Solar Atlas (Kurucz et al. 1984) as the reference solar spectrum to compare our line abundances with.

6.1.1 Microturbulence

The microturbulence \(v_{\text{mic}}\) is a free parameter that is required in 1D model atmospheres to synthesise saturated lines. The turbulence in this case refers only to small-scale motion, i.e. smaller that the mean free path of the electron, which makes it impossible to model the motions. One therefore adds the microturbulence to the doppler shift and assumes a Gaussian profile. The result for weak lines is a broadened profile and the equivalent width is hardly affected. Saturated or near saturated lines on the other hand, experience a strengthening as part of the line is shifted into the wings by avoiding the saturated wavelength region. The \(v_{\text{mic}}\) can be determined by requiring that line abundances are independent of line strength. Hence, one needs to determine the line abundances of lines of different strengths in order to determine \(v_{\text{mic}}\). Given the abundant of Fe lines in an optical spectrum, Fe lines are usually used to determine \(v_{\text{mic}}\).
Table 6.1. Parameters of adopted Fe\textsc{ii} lines by assuming $v_{\text{mic}} = 1.0$ km s$^{-1}$.

<table>
<thead>
<tr>
<th>Mult. (#)</th>
<th>$\lambda$ (Å)</th>
<th>$E_{\text{low}}$ (eV)</th>
<th>log $g_f$</th>
<th>log $\varepsilon(\text{Fe})_{\odot}$ (dex)</th>
<th>$\Xi_{RT}$ (km s$^{-1}$)</th>
<th>EW (mÅ)</th>
<th>TOP$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>5284.1</td>
<td>2.88</td>
<td>-3.30</td>
<td>7.69</td>
<td>3.5</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>4923.9</td>
<td>2.88</td>
<td>-1.53</td>
<td>7.55</td>
<td>3.7</td>
<td>186</td>
<td>X</td>
</tr>
<tr>
<td>48</td>
<td>5362.8</td>
<td>3.19</td>
<td>-2.57</td>
<td>7.50</td>
<td>3.4</td>
<td>76</td>
<td>X</td>
</tr>
<tr>
<td>48</td>
<td>5264.8</td>
<td>3.22</td>
<td>-3.08</td>
<td>7.50</td>
<td>3.6</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>5425.2</td>
<td>3.19</td>
<td>-3.33</td>
<td>7.53</td>
<td>3.4</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>5325.5</td>
<td>3.21</td>
<td>-3.32</td>
<td>7.51</td>
<td>3.5</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>5316.6</td>
<td>3.14</td>
<td>-1.89</td>
<td>7.53</td>
<td>3.5</td>
<td>119</td>
<td>X</td>
</tr>
<tr>
<td>49</td>
<td>5234.6</td>
<td>3.21</td>
<td>-2.22</td>
<td>7.51</td>
<td>3.5</td>
<td>101</td>
<td>X</td>
</tr>
<tr>
<td>49</td>
<td>5197.5</td>
<td>3.22</td>
<td>-2.27</td>
<td>7.50</td>
<td>3.2</td>
<td>90</td>
<td>X</td>
</tr>
</tbody>
</table>

(a) Iron lines used in the microturbulence determination of the TOP stars.

Figure 6.1. Individual line abundances of solar Fe\textsc{ii} lines as a function of line strength (top) and excitation energy of the lower level $E_{\text{low}}$ (bottom). One point seems to deviate from the others. However, since we perform a differential analysis, an error in the line data will not affect the final result.

As the Fe abundances were deduced from Fe\textsc{ii} lines of different strength, $v_{\text{mic}}$ can be determined by requiring that the Fe\textsc{ii} line abundances show no trend with equivalent width. The number of Fe\textsc{ii} lines we were able to fit varies with evolutionary state, for the RGB and bRGB stars nine lines were fitted while for the SGB star we could fit eight lines. The line wavelengths can be found in Tab. 6.1. Only five lines could be measured in the TOP stars, these are marked by an X in the last column of the table. Tab. 6.1 gives the line data for the nine solar Fe\textsc{ii} lines that are used for the differential analysis. The line data includes the lower excitation energies ($E_{\text{low}}$) and the oscillator strength (log $g_f$). Beside the line data for each line, the table contains the measured line-abundances in dex, the full width half max of the rotational profile ($\Xi_{RT}$) in km s$^{-1}$ and the equivalent width (EW) of the lines in mÅ. The
line-abundances for the Sun were derived by assuming $v_\text{mic} = 1 \text{ km s}^{-1}$ as this removed any trend with line strength for the nine lines. Fig. 6.1 shows that we do not have a trend with line strength for the solar Fe\textsc{ii} lines. We thus are confident that any trend with line strength in our stellar spectra is a result of an erroneous microturbulence and hence needs to be corrected for. The fits to the solar lines are displayed in Fig. 6.2.

To derive $v_\text{mic}$ for the stellar spectra we use the same approach as for the Sun but use the differential line abundances to remove any trend with line strength. Once the microturbulence is set, the mean Fe abundance is calculated using only the lines that were measured in all groups of stars, i.e. we derive the Fe abundance using five Fe\textsc{ii} lines.

6.2 Results

LTE abundances were derived for eight elements such as the light elements lithium, sodium, magnesium and aluminium, the $\alpha$-elements calcium and titanium, and other elements such as scandium, iron and barium. Afterwards, NLTE corrections were applied to Li, Na, Mg, Ca and Ba using the grid of

Figure 6.2. Fits to the nine iron lines in the solar spectrum that are used to determine the Fe abundance differentially. The black points are the observations while the red solid line is the fit to the line.
NLTE predictions by Lind et al. (2009a, 2011), and Osorio et al. (in prep.) for Li, Na and Mg, respectively. NLTE corrections for Ca and Ba were applied following Mashonkina et al. (2007) and Mashonkina et al. (1999). The abundances for Sc, Ti and Fe were derived from lines of ionised species that are believed to be formed under near-LTE conditions as they constitute the dominant ionisation stages of the respective element. We thus assume NLTE corrections to be negligible.

6.2.1 Abundance trends

The line-by-line differential abundance analysis revealed weak element-specific abundance trends for Mg, Ca, Sc, Ti, and Fe between groups of stars from the TOP to the RGB in the globular cluster NGC 6752. Although the significance of the trends is weak, they seem to indicate that AD is operational along the evolutionary sequence of NGC 6752 as they can be explained by stellar-structure models including AD and AddMix. However, the efficiency of AddMix (the T6.2 model is favoured) needed to explain the trends is higher than needed to explain the trends in NGC 6397, which has a lower metallicity. It is not clear why this is and poses an intriguing constraint for theorists in looking for a physical explanation of AddMix.

The elements are affected differently by AD and AddMix due to the element-specific interplay of gravitational settling and radiative acceleration. Hence finding trends in all elements strengthens the evidence for AD and AddMix. The results are also robust against NLTE and 3D effects.

To further investigate the significance of the trends, a mean trend was computed by normalising the derived abundances of Ca, Sc, Ti, and Fe, and the models to the original abundances given by the models and afterwards averaging these normalised observations and model trends. The result can be seen in Fig. 6.3. We have also calculated the weighted mean \( \langle M \rangle \) of these points and calculated the \( \chi^2 \) with respect to this value as follows:

\[
\chi^2 = \sum_{i=1}^{4} \frac{(y_i - \langle M \rangle)^2}{\sigma_i^2} \approx 7.06 \quad \text{and} \quad \langle M \rangle = \frac{\sum y_i / \sigma_i^2}{1 / \sigma_i^2} \approx -0.027
\]

(6.1)

where \( \sigma_i \) is the error associated with each point \( y_i \). By noting that we have three degrees of freedom we can assign a probability to the null-hypothesis that all points are compatible with the weighted mean value of the points. We find that there is only a 7% probability for accepting the null-hypothesis. The combined abundance trend is thus significant at the \( \sim 2\sigma \) level and likely not the result of random scatter around a mean value due to measurement errors.
6.2.2 Chemical populations and lithium content of the cluster

We found evidence for distinct chemical populations by deriving aluminium and sodium abundances and coupling them to the magnesium abundance. Chemical tagging and the effect of chemical populations on diffusion trends is the main topic of Paper II and will be addressed in Chapter 7.

Now that we have identified AD and know which model represents the AD effects best, we turn to lithium to investigate the primordial lithium abundance of the cluster. We find that the optimal model (T6.2) indicates an initial lithium abundance of log $\varepsilon(\text{Li})_{\text{init}} = 2.58 \pm 0.10$. This is compatible with the predicted primordial abundance based on PLANCK data, log $\varepsilon(\text{Li})_{\text{CMB-BBN}} = 2.69 \pm 0.04$ (Coc et al. 2013). To come to this initial lithium abundance, we take the average of our two highest NLTE Li abundances derived for the TOP stars, which we expect to belong to the first generation and thus unaffected by intra-cluster pollution.

Pasquini et al. (2005) derived LTE Li abundances for nine TOP stars in NGC 6752 drawn from the study of Gratton et al. (2001) of which we have two stars in common (id 4383 and 4428). Using the effective temperatures of Gratton et al. (2001), which are roughly 150 K hotter than ours, they find Li abundances for the TOP stars which are, for 4383 and 4428 respectively, 0.15 and
Figure 6.4. Li\textsc{i} line at 6707 Å for the star id4428. The black line corresponds to the coadded spectrum in which we combined our data with that of Gratton et al. (2001). The red line shows the line profile Pasquini et al. (2005) adopted as their fit to the line, the blue line corresponds to our best fit.

0.32 dex higher than what we find. Using lower $T_{\text{eff}}$ values, computed according to the Alonso scale ($b - y$) colour and the reddening of $E(b - y) = 0.032$ (Gratton et al. 2003), the Li abundance for star 4383 is in excellent agreement. However, we find a 0.17 dex discrepancy for star 4428. After looking at their spectrum, we conclude the discrepancy is entirely attributed to the erroneous measurement of the EW of the Li line in their spectrum. In Fig. 6.4 shows the coadded spectrum in which our data is combined with that of Gratton et al. (2001). The red line corresponds to a fit having the same EW as stated by Pasquini et al. (2005), while the blue line is our best fit to the Li line. It is clear from the line profile that Pasquini et al. (2005) significantly overestimated the EW (42.8 mÅ compared to 35.2 mÅ) of the line and hence overestimated the Li abundance for the star. Nonetheless, our mean Li abundance computed from the five TOP stars ($\log \varepsilon(\text{Li}) = 2.26 \pm 0.13$) is in agreement with their mean Li abundance ($\log \varepsilon(\text{Li}) = 2.24 \pm 0.15$) which is derived on the hotter temperature scale of Gratton et al. (2001). Given the fairly large star-to-star scatter in lithium abundance, it is also in agreement with the mean Li abundance ($\log \varepsilon(\text{Li}) = 2.15 \pm 0.14$) derived by Gratton et al. (2001) on the cooler temperature scale of Alonso et al. (1996).
7. AD and chemical populations (Paper II)

In Paper II, we analyse spectra of 194 stars located between the cluster's TOP and the base of the RGB (bRGB). These spectra were observed with the medium-resolution spectrograph GIRAFFE operated in Medusa mode. Given the sizeable number of stars, the lower resolution and the spectral coverage, we decided to perform an automated abundance analysis instead of the manual line-by-line analysis employed for UVES spectra in Paper I.

7.1 An automated abundance analysis

The tools for the automated analysis are developed in Uppsala and are based on the spectral synthesis code Spectroscopy Made Easy (SME, Valenti & Piskunov 1996; Valenti & Fischer 2005). The code has been modified to allow non-LTE (NLTE) line formation from a grid of precomputed departure coefficients. The code uses an input spectrum, stellar parameters ($T_{\text{eff}}$, log $g$, [Fe/H] and $v_{\text{mic}}$), a line list with line parameters, line and continuum masks and a list of spectrum segments wherein the continuum is individually normalised as input. A grid of MARCS plane-parallel and spherically-symmetric model atmospheres (Gustafsson et al. 2008), all with scaled solar abundances and alpha-enhancement of 0.4 dex, is used to calculate synthetic spectra on the fly by interpolating between the models. The numerical comparison between synthetic and observed spectra is executed by a non-linear optimization algorithm (Marquardt 1963; Press et al. 1992).

7.2 Results

Taking advantage of the NLTE line formation, we derived NLTE abundances for Li, Na and Fe using the pre-computed departure coefficients by Lind et al. (2009a, 2011, 2012). Besides these elements, we also investigated the following elements in LTE: Mg, Al, Si, Ca, and Ti. As in Paper I, we applied NLTE corrections to our LTE abundances of Mg following the grid by Osorio et al. (in prep.).

The automated spectroscopic analysis of the 194 stars is one of the first "large" applications of a methodology based on automated NLTE stellar parameters. The analysis indicates weak (~ 0.1 dex) systematic abundance trends of
heavy elements with evolutionary phase along the subgiant branch, in magnesium, calcium, titanium and iron. This independent method thus confirms the results from Paper I. Furthermore, the predictions from stellar structure models including atomic diffusion with efficient additional mixing (the T6.2 model) are again in good agreement with the observed trends. As the abundances for Fe and Ti are derived from lines of ionised species, we do not expect a strong dependence of the trends on the derived photometric $T_{\text{eff}}$ scale. Nonetheless, we checked thoroughly and can conclude that the trends are not likely caused by systematic errors on, e.g., effective temperature, as flattening the abundance trend in iron would require an increase of 200 K at the turnoff point, implying an unrealistically large error in $\Delta T_{\text{eff}}(\text{TOP} - \text{bRGB})$ of 25%.

A secondary aim of the paper was to see whether the trends are affected by the distinct chemical populations NGC 6752 harbours (Carretta et al. 2012). We combined $ubvy$ Strömgren photometry and spectroscopic information from the light elements Mg, Na, Al and Si to identify the different chemical populations and try to analyse the trends for each population. We did not find evidence that the trends are affected by the chemical populations although the limited sample size and the S/N of the dwarf spectra do not allow us to make a firm statement about this.

We identify the least polluted (primordial) TOP stars in the cluster and used them to derive an estimate for the initial lithium abundance. After correcting for the effects of AD, we find $\log \varepsilon(\text{Li})_{\text{init}} = 2.53 \pm 0.10$, which is in good agreement with the result of Paper I.
8. Atomic diffusion trends in M4 (Paper III)

In Paper III, we turn to a different globular cluster, M4, at an even higher metallicity in order to further test the possible relation between AddMix and metallicity. For this research, O. Richard was asked to produce new stellar-structure models including AD and AddMix at $[\text{Fe/H}] = -1.1$. The data used for this project were previously analysed by Mucciarelli et al. (2011) (Muc2011 hereafter). However, they did not find any evidence in their iron abundances suggesting AD and AddMix to be operational on main-sequence stars in M4. As atomic diffusion affects all elements, we reanalyse the data and include several elements which Muc11 did not investigate.

Figure 8.1. Evolutionary abundance trends for iron derived from Fe I lines (left) and Fe II (right). The blue squares give the abundances derived from the coadded group-average spectra. Fe abundances for the individual stars are given as gray diamonds. Overplotted are predictions from stellar structure models including atomic diffusion with additional mixing with different efficiencies, at an age of 12 Gyr. Note the very different behaviour for the Fe I and Fe II trends, suggesting the ionisation balance is not fulfilled.

8.1 A different way of deriving $T_{\text{eff}}$

The analysis by Muc2011 is based on two different $T_{\text{eff}}$ scales. For the dwarfs they opted for spectroscopic temperatures derived from the wings of the H$\alpha$ profile, while the temperatures for the giants are based on a photometric calibration. Muc2011 argue that their results (namely the null-trend for iron) are robust to changes in $T_{\text{eff}}$ and discuss different photometric $T_{\text{eff}}$ scales. However, they did not investigate the temperature sensitivity of the iron lines used to
derive the Fe abundances. If they had derived Fe abundances from the ionised species (which are intrinsically less temperature-sensitive), they may have discovered some issues with the temperature scale as found here. In this analysis, we chose to start from one photometric $T_{\text{eff}}$ scale and argue that given the low S/N of the dwarf spectra, $T_{\text{eff}}$ values cannot be derived with sufficient precision to derive reliable abundances for all species under investigation. We therefore opted to also analyse coadded spectra, generated by grouping stars according to their stellar parameters similar to Paper I. Furthermore, we noticed that, although the iron abundances derived from neutral lines are well behaved in the cool giants, the abundance scatter becomes prohibitively large for the warm dwarfs and the group-average dwarf spectra even seem to have higher abundances than the giants. Worried by this finding, we checked the abundances derived from the ionised species for Fe and Ti and found that these temperature-insensitive lines display a completely different behaviour than that indicated by the Fe I lines. A comparison between the Fe abundances derived from lines of neutral and ionised species is given in Fig. 8.1 and visualises the problem clearly.

The finding led us to conclude that the ionisation balance was not fulfilled due to inaccuracies in the photometric temperature scale, to which neutral lines are susceptible. Experiments where the $T_{\text{eff}}$ values are directly determined from the H$_\alpha$ line, or from the Fe I excitation equilibrium, failed for dwarf spectra due to the low signal-to-noise ratio and resulted in very large differences and scatter (both often of several hundred kelvin). We therefore adopt a novel method in which we enforce the ionisation equilibrium by matching the iron abundances based on Fe I lines, to the corresponding average abundances based on Fe II lines, derived from the coadded group-average spectra. This is possible as the surface gravities are well determined and we derive Fe abundances in NLTE (Lind et al. 2012). Since the trend is very similar to what stellar structure models including atomic diffusion and additional mixing predict, we adopt the Fe predictions from the T6.2 model by O. Richard (calculated for this cluster) as the average abundances when redetermining the $T_{\text{eff}}$. On average the resulting $T_{\text{eff}}$ scale differs from the photometric by $-24 \pm 71$ K and $+45 \pm 55$ K for dwarfs and giants, respectively.
Figure 8.2. Observed abundance trends for M4 compared to the predictions from stellar evolution models including atomic diffusion and additional mixing with three different efficiencies and assuming an age of 12 Gyr. The dashed lines represent the initial abundances of the models, which have been adjusted so that predictions match the observed abundance level of the coolest stars. The diamonds represent the measurements from the individual stars while the squares represent the abundances derived from group-average spectra (see Paper III for details). Note that there are no predictions available for barium and europium.
8.2 Results

8.2.1 Abundance Trends
We simultaneously derived abundances for 14 elements in 86 stars in M4, including the light elements C, O, Mg, Al and Si, the \( \alpha \)-elements Ca and Ti, the iron-peak elements Fe and Ni and the heavy neutron capture elements Ba and Eu. Other elements we analysed include Li, N\(^1\) and K. All elements (excluding N and Eu) indicate (weak) element-specific abundance trends with evolutionary phase from the TOP to the RGB. The trends are given in Fig. 8.2 and are compared with stellar-structure models including AD and AddMix with three different efficiencies at an age of 12 Gyr. Given the large scatter in the derived abundances of the dwarfs, it is not possible to distinguish between different efficiencies of AddMix. We do however, exclude the lower efficient AddMix model T6.0, as we do not observe the strong trends predicted for Mg, Si or Fe. The trends present evidence for AD being operational along the main sequence of M4.

8.2.2 The initial Li content of M4
The average Li abundance \( A(\text{Li}) \) in the dwarfs \( (T_{\text{eff}} > 5900 \text{ K}) \) is \( 2.35 \pm 0.11 \) which is in perfect agreement with Muc2011. Basing the average Li abundance on corresponding coadded group-average spectra instead, gives the same result. The Li results for the giants are slightly different. We find \( A(\text{Li}) = 1.12 \pm 0.10 \) based on the Li abundances of the individual RGB stars \( (5250 \text{ K} < T_{\text{eff}} < 4900 \text{ K}) \) which is 0.20 dex higher than found by Muc2011. At present no obvious explanation presents itself to us.

M4 has two stellar populations which can be characterised by the nitrogen and sodium content. As no Na transitions were included in the spectra, the stars were separated based on their N abundances where possible, i.e. for the giants. N anticorrelates with O, so we investigated the possibility that the Li abundances are affected by pollution of first generation stars (N-poor, O-rich) by inspecting the \([\text{O/Fe}]-A(\text{Li})\) plane. No obvious correlation is found between the Li and O, suggesting Li is produced in the polluters (see Paper III for a discussion on the formation scenario of M4).

The evolution of Li is similar to the one presented in Muc2011 and nicely explained by T6.2 model. The initial Li abundance of the cluster can be obtained by correcting the Li abundance at TOP for the effects of AD and AddMix using the T6.2 model. This gives \( \log \varepsilon(\text{Li})_{\text{init}} = 2.57 \pm 0.10 \), very similar to the Li abundance derived for the other GC NGC 6397 and NGC 6752. We note that no correction for galacto-chemical production of lithium (by cosmic-ray

\(^1\)Reliable nitrogen abundances were only derived for the giants.
spallation) was considered when deriving the initial Li abundance content of the cluster. The empirical trends of Li abundance with metallicity (a signature of galactic production) are found to vary in the literature. Ryan et al. (1999) and Asplund et al. (2006) find trends as steep as 0.1 dex per 1 dex in [Fe/H] while Meléndez & Ramírez (2004) and Shi et al. (2007) find no trend at all. The different findings are primarily the result of differences in the adopted $T_{\text{eff}}$ scales. Accounting for cosmic-ray spallation by applying a 0.1 dex correction to the diffusion-corrected stellar Li abundances weakens the agreement with the primordial Li value. Yet, a gap of 0.1 – 0.2 dex can be explained by mixing through Pop III stars for example (see Piau et al. (2006), but note the criticism of this scenario, according to Prantzos (2006) a slight depletion of lithium would likely be accompanied by a prohibitively large production of oxygen).
9. Summary, Conclusions and Outlook

Figure 9.1. Schematic overview of how atomic diffusion and additional mixing operates in the stellar surface of Pop II stars. During the main-sequence lifetime of a star elements diffuse downwards under the influence of gravity, leaving the surface somewhat depleted in those elements. Convection hinders the downward movement within the surface layer. Below the convective surface layer, a physical process labeled additional mixing along with radiative pressure also hinders the downward movement of elements. The more efficient the additional mixing, the less depleted the surface layer will be. Image credit: © Pieter Gruyters

In this thesis we have investigated the effects of atomic diffusion (AD) and additional mixing (AddMix) on Population II stars. AD is a process that alters the surface composition of stars during the main-sequence lifetime due to prevailing forces inside the star such as gravity and radiation pressure. Given the structural characteristic of the elements, the stellar surface will be somewhat enriched or depleted in different elements. The effects of AD are effectively washed away by convection within the surface layer. For Pop II stars the outer convection zone is thin and the effects of AD need to be damped by a mechanism of unknown physical origin in order to match observations. This mechanism is referred to as AddMix and is introduced in the models below the outer convection zone. It is a tunable parameter which somewhat hinders the
settling of elements. At present, AddMix needs to be determined empirically by comparing the surface abundances of stars in different evolutionary stages all drawn from the same stellar population. This is why we studied the effects in globular clusters. Since the effects of AD are effectively removed by convection, elements settled during the MS lifetime will gradually resurface when the outer convection layer expands inwards during the subsequent evolution of the star and reaches the layers enhanced by the settled elements. By studying stars in different evolutionary stages, we compare stellar abundances supposedly affected by AD with restored abundances. Observing abundance trends then signals AD to be at work and from the size of the abundance trends we can tune the efficiency of AddMix. A schematic overview of the operational mechanism of AD and AddMix is given in Fig. 9.1.

9.1 Atomic Diffusion in Globular Clusters

We have derived elemental abundances for different species in two globular clusters, NGC 6752 and M4. In both clusters we observed abundance differences between evolved and unevolved stars which are best explained by stellar structure models including AD and efficient AddMix. Together with the results from Korn et al. (2007) on NGC 6397, we now have a (metallicity) sequence of three globular clusters that show the effects of AD. The clusters differ from each other primarily in metallicity with NGC 6397 being the most metal-poor one with $[\text{Fe/H}] = -2.1$ and M4 being the least metal-poor with $[\text{Fe/H}] = -1.1$. Although all three clusters show signs of AD, the element-specific abundances trends are not explained equally well by the same model. We find that the abundance trends become weaker with increasing metallicity and that the weaker trends can be explained by an increase in the efficiency of the AddMix. Some notes have to be made here, however. Although the clearest signal is found in NGC 6397, the weak abundances trends observed in NGC 6752 and M4 both suggest that AD is also operational in these clusters. Arguments that these weak trends are caused by using incorrect stellar parameters such as $T_{\text{eff}}$ can be countered by the fact that the Fe and Ti trends, for example, are derived from ionised species which are less sensitive to errors in $T_{\text{eff}}$ than their neutral counterparts. The lack of a physical explanation for AddMix is worrisome, but given the possible metallicity dependence we might start to narrow down the range of possible mechanisms. One physical mechanism that becomes more efficient with increasing metallicity, is mass loss. However, Vick et al. (2013) showed that the required mass loss rates are too high for Pop II stars in order to reproduce similar effects to AddMix. Yet, there might be more than one mechanism hiding underneath the AddMix term. It is very plausible that, in the end, multiple processes are responsible for damping AD in Pop II stars.
In addition to the three clusters presented here, earlier this year yet another study with AD implications was presented. Önehag et al. (2014) discuss the possibility of having detected a signature of AD in the open cluster M67. The open cluster has a solar-like metallicity and even though we expect AD to be at work in the Sun, it is very hard to trace the effects as they become so small due to the larger size of the outer convection in solar-like stars. Needless to say, these stars do not need a physical mechanism to damp the AD effects as the convection achieves this. In terms of AddMix, the observation in M67 does not add information to the overall picture. Yet, the finding adds more weight to the idea that AD is in fact operational in all unevolved low-mass stars and hence should generally be taken into account in stellar models if one wants to improve age determinations and our understanding of stellar structure.

9.2 The initial lithium content of globular clusters

The understanding of abundance trends is of considerable importance for cosmochronological studies. In particular, the interpretation of the Li abundance trend can help us to understand a fundamental problems in big bang nucleosynthesis (BBN): the cosmological lithium problem. Independent observations of lithium abundances in warm ($6300 \, K > T_{\text{eff}} > 5500 \, K$) metal-poor ($[\text{Fe/H}] < -1.5$) halo stars reveal a nearly constant Li abundance (the so-called Spite plateau, see e.g. Spite & Spite 1982 and Ryan et al. 1999). This led to the suggestion that these stars retain the cosmological Li abundance. The WMAP determination of the baryon-to-photon ratio from observations of the cosmic microwave background radiation (CMB) changed this view as the ratio, through big bang nucleosynthesis (BBN), implies a cosmological Li abundance that is a factor 2–3 larger than the Li abundance of the Spite plateau (Cyburt et al. 2002). AD and AddMix offers a compelling explanation to this discrepancy. Depending on the efficiency of AddMix, stellar evolution models including AD and AddMix predict a gradual settling Li leading to a depletion of surface Li abundance by 0.20–0.25 dex during the main sequence lifetime of Pop II stars. As AddMix can be constrained from element-specific abundance trends found in globular clusters, the initial Li abundance can be derived and compared to the cosmological Li abundance implied by CMB+BBN.

Fig. 9.2 shows the evolution of lithium with $T_{\text{eff}}$ for the globular clusters NGC 6397, NGC 6752 and M4. Overplotted in solid lines are the model predictions from stellar evolution models by Richard et al. (2002) including AD and AddMix with the corresponding efficiency as derived for the different clusters. The data for NGC 6397, given by the squares in the figure, were taken from Lind et al. (2009b). The abundance trends in the cluster are best explained by a stellar evolution model including AD and a low AddMix efficiency ($T_{6.0}$) at an age of 12.5 Gyr (Korn et al. 2007). Data for NGC 6752 were taken from
Gruyters et al. (2014) and are represented in the figure by the diamonds. The trends in this cluster are best explained by models with a high AddMix efficiency (T6.2) at an age of 13.5 Gyr. Finally, the Li abundances for M4 come from the yet unpublished work by Gruyters et al. (in prep.) and are displayed by the triangles. From the observed element-specific abundance trends, predictions by a model with a high AddMix efficiency (at least T6.2) was found again to fit the trends best at an age of 12 Gyr.

Figure 9.2. Observed lithium abundances of three globular clusters, NGC 6397 (squares), NGC 6752 (diamonds) and M4 (triangles) compared to model predictions (solid lines). The predictions are based on stellar evolution models including atomic diffusion and AddMix. The efficiency of AddMix was determined individually for each cluster from observed abundance trends. The average initial Li abundance log $\varepsilon$(Li)$_{\text{init}}$ = 2.55 ± 0.10 for the clusters is given by the dashed line and compares reasonably well with the CMB+BBN-predicted cosmological Li abundance log $\varepsilon$(Li)$_{\text{CMB}+\text{BBN}}$ = 2.69 ± 0.04 (Coc et al. 2013), given by the dotted line. Data are taken from Lind et al. (2009b), Gruyters et al. (2014) and Gruyters et al. (in prep.), for NGC 6397, NGC 6752 and M4, respectively.

The Li abundance in the different clusters agree rather well and show similar behaviour with $T_{\text{eff}}$, even though the metallicity of the clusters is different. The behaviour of the Li abundance is different than that of the other elements. This is because the surface abundance becomes diluted once the star evolves to become a giant and the surface convection layer extends into warmer layers depleted in lithium. The dilution seems to set in at the same temperature ($\sim 5800$ K) for the different clusters. There is a gradual change in the dilution slope with metallicity. That is, with increasing metallicity the slope seems to flatten. A possible explanation for this behaviour could be that the slope is affected by the mixing efficiency (which change the Li gradient profile in the
burning layers) and the metallicity (which could slightly change the evolution of the depth of convective zone during the SGB-RGB phase). Further investigation is necessary to get to the bottom of this. We note that the T6.0 model for NGC 6397 fails to reproduce the correct Li abundance along the observed plateaus for the TOP and RGB stars. As the models agree very well with the observations along the entire evolutionary sequence of NGC 6752 and M4, this might suggest that the T6.0 model is not the correct model for NGC 6397, even though this does not seem to be supported by the other abundance trends which seem well explained by the T6.0 model. The lack of a detailed understanding of the physics responsible for depletion in this cluster could of course also lie at the origin of the discrepancy between model and observations.

Correcting the Li abundances for the effects of AD, the initial Li abundance of the stars at their time of birth is found. The average initial Li abundance for the three clusters is found to be \( \log \varepsilon(\text{Li})_{\text{init}} = 2.55 \pm 0.10 \) and compares reasonably well with the CMB+BBN-predicted cosmological Li abundance \( \log \varepsilon(\text{Li})_{\text{CMB+BBN}} = 2.69 \pm 0.04 \) (Coc et al. 2013). The conclusion thus seems that atomic diffusion is predominantly responsible for surface Li abundances in stars on the Spite plateau being systematically lower than the primordial value.

9.3 What we have learned

The knowledge we gained during the course of the thesis is summarised in Fig. 9.3. The qualitative diagram shows the emerging metallicity-AddMix efficiency relation. The three globular clusters are placed in the diagram corresponding to their metallicity and measured AD effect on the iron abundance. On the right axis of the diagram the efficiency of AddMix is given. The position of M4 has not been exactly derived but we mark the range in which we expect the AD effects to fall. In the bottom right corner we have placed the open cluster M67. As mentioned above, this cluster does not give us information about AddMix, hence the question mark. Stellar-structure models by O. Richards suggest that the effects of AD including AddMix within the range that can reproduce the observed Li plateau (i.e. T5.9-T6.25) increase for lower metallicities. Prime targets to check this, are the low-metallicity GCs M30 and M92. Unfortunately, these are difficult targets to observe. Given that it took about 70 h on an 8 m telescope to obtain TOP spectra for NGC 6752 at a brightness which is nearly 1.5 magnitudes brighter than M30 or M90, it becomes nearly impossible to collect data on TOP stars in these clusters. As these clusters are our only way forward in order to settle this interesting problem, we hope to spark the interest of our fellow observers with less limited access to 8 m class telescopes so that we can continue the hunt for the truth behind AD, AddMix and the possible dependence on metallicity.
Figure 9.3. Qualitative diagram of the effects of atomic diffusion and additional mixing as a function of metallicity of the RGB stars in clusters studied so far. The solid line represents the possible trend between metallicity and the efficiency of additional mixing. Question marks represent uncertainties on the position of the cluster in the diagram. Data from Korn et al. (2007, NGC 6397), Gruyters et al. (2013, NGC 6752), Gruyters et al. 2014, (in prep., M4) and Önehag et al. (2014, M67).

9.4 The hunt goes on ...

Recently, a joint project was launched between Potsdam and Uppsala. Given the access of Potsdam collaborators to the Large Binocular Telescope (LBT, 2 monolithic mirrors of 8.4 m corresponding to an effective aperture of 12 m) in Arizona, we have a good possibility to obtain data on M92. The LBT is equipped with the newly build fibre-fed high-resolution Echelle spectrograph PEPSI designed at the Astrophysical Institute in Potsdam (AIP). Given the high resolution and the large optical spectral range from 3830 to 9070 Å, the instrument is perfect for the abundance analysis that would need to be performed in order to trace the AD effects. The first spectra are supposed to be obtained during the spring of 2015 and in principle first results could then be available by the end of 2015.

To be continued!
"The good thing about science is that it's true whether or not you believe in it."
—Neil deGrasse Tyson
10. My contribution to the included papers

*Paper I*
I performed the complete abundance analysis using photometric stellar parameters. I did extensive tests and came up with the methodology used in the analysis. I wrote the complete paper except for the section on 3D corrections, which was written by Remo Collet.

*Paper II*
Together with Thomas Nordlander, I carried out parts of the post-processing of the data and the determination of the stellar parameters from photometry. I was also involved in the elemental abundance determination and visually inspected the results. I performed a cluster analysis on the photometric data to determine the chemical populations in the cluster and investigated the radial distribution of the cluster. I wrote most of the paper except for the error analysis which was performed and written by Thomas Nordlander.

*Paper III*
I was involved in parts of the post-processing of the data and the determination of the methodology of the analysis. I dereddened the photometric data from which we determined initial stellar parameters and came up with the idea to use the ionisation balance to derive the final stellar parameters. I visually inspected the results and was involved in the analysis of the abundances. I was responsible for the paper and wrote large parts of it including the introduction, observation and result sections and parts of the analysis and discussion sections.
11. Swedish summary - Svensk sammanfattning

Vintergatans kemiska utveckling är inpräntad i den kemiska sammansättningen hos metallfattiga stjärnor av sen spektraltyp, så-kallade population II stjärnor. Tack vare deras långa livslängd, vilken är i storleksordningen en Hubble-tid, borde studier av dessa stjärnor ge ledtrådar om miljön de föddes i. Ett naivt antagande är att sammansättningen i stjärnornas atmosfär speglar sammansättningen av den gas de skapades av, men observationer av klotformiga stjärnhopar visar på ett mer komplicerat sammanband. Det finns indikationer på att en eller flera processer förändrar den kemiska sammansättningen i stjärnornas atmosfär under deras livstid. Den kombinerade effekten av dessa processer kallas atomärdiffusion (AD).


Genom att jämföra den kemiska sammansättningen hos utvecklade (huvudsevens-) och utvecklade (jättestjärnor) som alla förväntas ha skapats ur samma materia, kan förändringen i förekomsten av grundämnen spåras. Dessa variationer kan jämföras med teoretiska förutsägelser från stjärnstrukturmodeller. Klotformiga stjärnhopar är perfekta kandidater för en sådan jämförelse, eftersom alla stjärnor där just tros ha bildats ur samma materia. I denna avhandling presenteras resultaten från tre analyser av två klotformiga stjärnhopar med olika metallicitet. Stjärnhoparna kallas NGC 6752 och M4, och består av hundratusental stjärnor som binds samman av sin gemensamma gravitationskraft.

Informationen vi behöver för att utföra jämförelserna erhålls via ljuset från stjärnorna. Metoden kallas spektroskopi, och bygger på att man delar upp ljuset från en stjärna i dess beståndsfrågar, ett spektrum, och från detta härleder stjärnans egenskaper och ämneshalter. Ämneshalterna kan inte observeras direkt
utan måste härledas ur modeller, vars kemiska sammansättning och fysikaliska parametrar man justerar tills de återskapar det observerade spektrumet. När modellen matchar observationerna har man funnit stjärnans ämneshalter.

För att matcha observationerna i de klotformiga stjärnhoparna måste effekterna av AD skruvas ned, genom att mer effektivt blanda om materien i stjärnan nedanför konvektionszonen. Detta utförs i en mekanism vi kallar ytterligare ombländning, AddMix (additional mixing), vars fysikaliska ursprung är okänt. Mekanismen har en fri parameter, som bestämmer dess effektivitet, som bestämmer hur pass effektivt AD motverkas. Eftersom ett fysikaliskt ursprung saknas måste denna effektivitet fastställas empiriskt från observationerna.

Grundämnenas förekomster härleddes i de två klotformiga stjärnhoparna, NGC 6752 och M4. I båda stjärnhopar observeras skillnader i kemisk sammansättning mellan utvecklade och outvecklade stjärnor. Dessa skillnader, trender med utvecklingsfasen, kan förklaras med hjälp av stjärnstrukturmodeller som inkluderar AD och AddMix. Effektiviteten hos AddMix måste vara högre än vad som tidigare bestämts i en ännu mer metallfattig stjärnhop, NGC 6397 (Korn et al., 2007). Tillsammans med de tidigare resultaten kan vi nu finna en korrelation mellan effektiviteten av AddMix och stjärnornas metallicitet.

Det är oroande att vi saknar förklaring till den fysikaliska mekanism som motsvarar AddMix. Men nu när vi känner till hur dess effektivitet varierar med metallicitet kan man i framtida teoretiska studier åtminstone begränsa urvalet av möjliga mekanismar.
This thesis has been a joint effort for the better part and so it is only natural that I thank the people involved.

Looking back on the last four years, I can't but think how much I owe to the people around me. There is however, one person without whom this Ph.D. would not have been so successful as it has turned out to be. Hence, the first person on the long list of people to be thanked should be my colleague and office mate, Thomas Nordlander. You are my mentor and partner in crime, but above all, my friend. Thank you for all your patience, help and dedication. You are the best fellow Ph.D. student and collaborator one could wish for!

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Uppsala, 25 August 2014
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