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SOLAR TWINS AND
SOLAR ANALOGUES IN
GALACTIC SURVEYS

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In memory of Frithjof Brauer. I will never forget you.

Contents

Abstract

The Sun is a crucial benchmark for how we see the universe. Especially when it comes to the visible range of the spectrum, stars are commonly compared to the Sun, as it is the most thoroughly studied star.

In this work I have focussed on two aspects of the Sun and how it is used in modern astronomy. Firstly, I try to answer the question on how similar to the Sun another star can be. Given the limits of observations, we call a solar twin a star that has the same observed parameters as the Sun within its errors. These stars can be used as stand-in suns when doing observations, as normal night-time telescopes are not built to be pointed at the Sun. There have been many searches for these twins and every one of them provided not only information on how close to the Sun another star can be, but also helped us to understand the Sun itself. In my work I have selected ~ 300 stars that are both photometrically and spectroscopically close to the Sun and found 22 solar twins, of which 17 were previously unknown and can therefore help the emerging picture on solar twins.

In my second research project I have used my full sample of 300 solar analogue stars to check the temperature and metallicity scale of stellar catalogue calibrations. My photometric sample was originally drawn from the Geneva-Copenhagen-Survey (Nordström et al. 2004; Holmberg et al. 2007, 2009) for which two alternative calibrations exist, i.e. GCS-III (Holmberg et al. 2009) and C11 (Casagrande et al. 2011). I used very high resolution spectra of solar analogues, and a new approach to test the two calibrations. I found a zero–point shift of order of +75 K and +0.10 dex in effective temperature and metallicity, respectively, in the GCS-III and therefore favour the C11 calibration, which found similar offsets. I then performed a spectroscopic analysis of the stars to derive effective temperatures and metallicities, and tested that they are well centred around the solar values.

Tiivistelmä

Aurinko on ratkaisevan tärkeä vertailukohta havainnoillemme universumista. Erityisesti visuaalisella alueella tähtiä verrataan yleisesti Aurinkoon, koska se on kaikkein parhaiten tutkittu tähti.

Tässä työssä olen keskittynyt kahteen aspektiin liittyen Aurinkoon ja sen käyttöön modernissa tähtitieteessä. Ensiksi yritän vastata kysymykseen, kuinka samanlainen Auringon kanssa toinen tähti voi olla. Johtuen havaintoihin liittyvistä rajoituksista, kutsumme Auringon kaksoseksi tähteä, jonka havaitut parametrit vastaavat Aurinkoa virheiden rajoissa. Näitä tähtiä voidaan käyttää Auringon sijaisina havaintoja tehdessä, koska normaaleja öisiin havaintoihin tarkoitettuja teleskooppeja ei ole rakennettu suunnattavaksi Aurinkoon. Useissa havainto-ohjelmissa on etsitty näitä kaksosia ja jokainen niistä on tuottanut lisää tietoa siitä miten samankaltainen Auringon kanssa toinen tähti voi olla, mutta myös auttanut ymmärtämään itse Aurinkoa. Työssäni olen valinnut ∼300 tähteä jotka ovat fotometrisesti ja spektroskooppisesti lähellä Aurinkoa ja löytänyt 22 Auringon kaksosta, joista 17 oli ennestään tuntemattomia ja jotka täten voivat auttaa kokonaiskuvaa Auringon kaksosista muodostumaan.

Toisessa tutkimusprojektissani olen käyttänyt 300 Auringon kaltaisen tähden kokonaisotostani tarkistaakseni lämpötila- ja metallisuusskaalojen kalibroinnin tähtikatalogeissa. Fotometrinen otantani on peräisin Geneva-Copenhagen-Survey -havainto-ohjelmasta (Nordström et al. 2004; Holmberg et al. 2007, 2009) jolle on olemassa kaksi vaihtoehtoista kalibrointia ts. GCS-III (Holmberg et al. 2009) ja C11 (Casagrande et al. 2011). Näiden kahden kalibroinnin testaamiseksi käytin Auringon kaltaisten tähtien hyvin korkean resoluution spektrejä sekä uutta lähestymistapaa. Löysin +75 K ja +0.10 dex siirtymän efektiivisissä lämpötiloissa ja metallisuudessa GCS-III nollapisteissä ja täten päädyn suosimaan C11 kalibrointia, joka löysi samankaltaisia poikkeamia. Tämän jälkeen suoritin spektroskooppisen analyysin otannan tähdille johtaakseni efektiiviset lämpötilat ja metallisuudet sekä testasin että ne ovat hyvin keskittyineitä Aurinkoa vastaaviin arvoihin.

List of publications

  I **New solar twins and the metallicity and temperature scales of the Geneva-Copenhagen Survey**,
Datson, J., Flynn, C., & Portinari, L. (2012), MNRAS, 426, 484 `[arXiv:1207.4610]`

  II **Solar analogues and solar twins in the HARPS archive**,
Datson, J., Flynn, C., & Portinari, L. (2014), MNRAS, 439, 1028 `[arXiv:1401.1316]`

III **Towards stellar effective temperatures and diameters at one per cent accuracy for future surveys**,
L. Casagrande, L. Portinari, I.S. Glass, D. Laney, V. Silva Aguirre, **J. Datson**, J. Andersen, B. Nordström, J. Holmberg, C. Flynn, M. Asplund (2014), MNRAS, 439, 2060 `[arXiv:1401.3754]`

IV **A spectroscopic study of solar twins and analogues**,
Datson, J., Flynn, C., & Portinari, L. (2014), submitted to A&A[1]

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[1]The final, published version of this paper might differ from the one presented in this thesis.

List of abbreviations

2MASS - Two Micron All-Sky Survey
AU - astronomical unit
BB - black body
CCD - charge-coupled device
CMD - colour-magnitude diagram
CNS - catalogue of nearby stars
CO WD - carbon oxygen white dwarf
ESO - European Southern Observatory
EW - equivalent width
FEROS - Fiber-fed Extended Range Optical Spectrograph
GALAH - GALactic Archaeology with Hermes
GCS - Geneva-Copenhagen-Survey
GUI - graphical user interface
HARPS - High Accuracy Radial velocity Planet Searcher
HRD - Hertzsprung-Russell Diagram
IFU - integral field unit
IMF - initial mass function
IRFM - infra-red flux method
ISM - interstellar medium
MOS - multi object spectrograph
MPG - Max-Planck-Gesellschaft
MS - main sequence
NIR - near infrared
RAVE - RAdial Velocity Experiment
RG - red giant
RGB - red giant branch
SDSS - Sloan Digital Sky Survey
SED - spectral energy distribution
UV - ultra violet

Chapter 1

Introduction

In the history of human life, the Sun has always played an important role. Sunrises, sunsets and eclipses shaped the beliefs of the early humans. For the primitive people the Sun was a God or an object being moved around by a God. They worshipped it, gave offerings and sacrifices. This view of a deity stayed on for thousands of years. We also know from most ancient cultures, that they had myths about the Sun God, like Amon-Ra for the Egyptians, or Phoebus-Apollo for the Greeks and Romans. The non-divine nature of the Sun was first noted by the Greek philosopher Anaxagoras in 434 B.C. He referred to it as a "hot rock", therefore removing the idea of it being a deity and turning it into something material, that can be studied. He also called the moon a "great rock", giving both a natural origin, instead of a divine one.

Since then, the nature of the Sun was much discussed and many views challenged. In 140 A.D. Ptolemy suggested, that the Sun was just another planet orbiting Earth, making it no more or less special than any other planet. This remained the dominant view until the 15$^{\text{th}}$ century, when Nicholas Copernicus proposed that the Sun was actually the centre in the Solar system. Finally in the late 16$^{\text{th}}$ century, Giordano Bruno said that the Sun is a star, like many others, being the first person in the modern age to come to that conclusion, for which he was burnt for heresy.

It took another century for inventions like the telescope to help people understand the nature of the Sun and other celestial bodies further. Sunspots, for example, had been observed already since the 4$^{\text{th}}$ century BC by Chinese astronomers, but only in the early 17$^{\text{th}}$ century Galileo Galilei could identify them as what they are. To be able to also examine the night sky in more detail, at the same time, the age of spectroscopy could begin, when Isaac Newton started his experiments on optics, showing that by us-

ing a prism, the light of the Sun could be separated into its components, showing that all the colours of the rainbow exist within its light. Before then, astronomers could only look at stellar light as a whole, being able to distinguish more blue looking stars from more red looking stars, etc., but it gave them merely one overall colour. Through the invention and application of prisms, and later gratings, astronomers managed to open science to a new field of research: stellar spectroscopy.

The spectrum of the Sun In the early 19$^{\text{th}}$ century Joseph von Fraunhofer, using self-made, very pure prisms and gratings, observed dark absorption lines in the otherwise continuous spectrum of the Sun (Fraunhofer 1817). They had already been discovered by William Wollaston, 15 years earlier, who thought them to be gaps between the colours of the Sun (Wollaston 1802). Fraunhofer gave them the letters A, B, C,... in the order in which they appeared in the spectrum, from red to blue. He did not offer any explanation for the gaps, keeping the discovery purely empirical, though noting, that some lines also appear in stellar spectra, others do not, thus making it impossible for all the lines to be of terrestrial origin. Herschel (1833) considered them to be caused through absorption in a cool gas, either in the Earth's or the Sun's atmosphere. Twenty years later, Sir David Brewster discovered that some line strengths varied with the Sun's elevation and season, therefore correctly realising their origin to be the Earth's atmosphere (Brewster 1836). Some of the original nomenclature is still in active use, as can be seen in the sodium D lines, or calcium H and K lines (see Fig. 1.1).

Only a few decades later Gustav Kirchhoff coined the term black body radiation for the spectrum emitted by a hot object over the whole wavelength range. This radiation can be described by Planck's law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}, \tag{1.1}$$

where $B_\lambda(T)$ is the spectral radiance, h is Planck's constant, k_B is the Boltzmann constant, c is the speed of light, T the temperature of the object and λ is the wavelength of the emitted light. The resulting spectra for a range of temperatures can be seen in Fig.1.2. Depending on the temperature (T) of the object the spectrum changes and its emission peak (λ_{max})
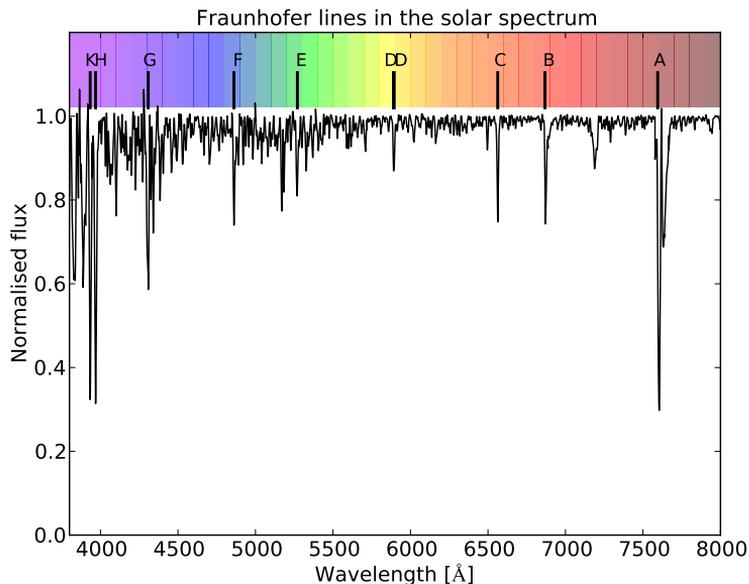
Figure 1.1: Fraunhofer lines in a spectrum of the asteroid Ceres, reflecting the solar light, taken with the Fiber-fed Extended Range Optical Spectrograph (FEROS) instrument on the Max-Planck-Gesellschaft/European Southern Observatory (MPG/ESO) 2.2 m telescope on La Silla on the 1st June 2010. The spectrum has been smoothed, using IRAF, to show the strong Fraunhofer lines more clearly.

shifts, following Wien's displacement law

$$\lambda_{max} = \frac{b}{T} \tag{1.2}$$

with Wien's displacement constant $b = 2.8977721 \cdot 10^{-3}$ m K. With a given temperature in Kelvin, λ_{max} will be in units of metre [m].

In astronomy the emission of a star is often approximated with that of a black body (BB), that emits the same overall radiative power as the star. The temperature of the black body that gives the same total flux as the star, is called its effective temperature (T_{eff} hereafter).
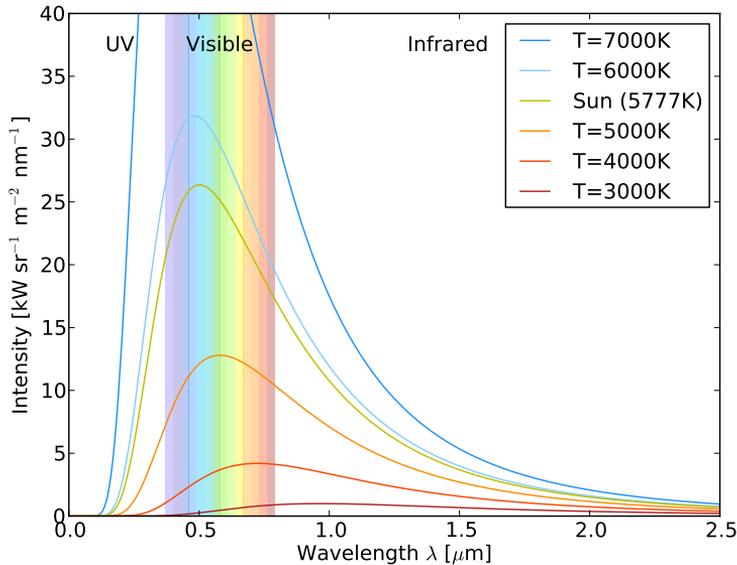
Figure 1.2: Blackbody spectra at different effective temperatures. Note how the intensity maximum shifts to the red with decreasing temperature.

This approximation fits observations quite well, although in reality the stellar flux spectrum consists of a BB spectrum formed below the lowest layers in the photosphere of the star, which in the Sun is about 300 km thick (Eddy & Ise 1979) and is superimposed with absorption lines, which form in the higher layers as more photons can leak out and interact with their environment. Also the continuum of the spectrum is influenced by these sources of absorption, and can show significant differences from a BB through line blanketing (Milne 1928), as the metals in the photosphere absorb part of the energy and reemit it at a lower energy level, thus distorting the original shape of the BB.

The effective temperature is defined as:

$$T_{\text{eff}} = \sqrt[4]{\frac{L}{4\pi R^2 \sigma}} \tag{1.3}$$

where L is the luminosity of the object, R its radius and $\sigma = 5.6704 \cdot 10^{-5}$ erg cm^{-2} s^{-1} K^{-4} is the Stefan-Boltzmann constant. In the case of the Sun, where the luminosity is $L = L_\odot = 3.844 \pm 0.004 \cdot 10^{33}$ erg s^{-1} (Bahcall et al. 1995; and references therein) and the radius is $R = \mathrm{R}_\odot = 6.9599 \pm 0.0007 \cdot 10^{10}$ cm (Schou et al. 1997), its effective temperature is commonly adopted to be 5777 ± 3 K.

Astronomical observations Generally, astronomers have two basic techniques when looking at the Sun and the objects in the night sky: those of photometry and spectroscopy. Photometry gives a quick and effective way to classify astronomical targets. Depending on the filters used, broadband or narrow-band, the resulting fluxes can be used to determine magnitudes, colour indices, or even some stellar characteristics, like effective temperature and metallicity. These magnitudes and colour indices can then be used to place objects onto the Hertzsprung-Russell diagram (see Fig. 2.2 in Chapter 2). Using photometry allows to cover a wide range of objects in one field and a visual inspection of the area in the sky. It also can go deeper than other methods, as all photons from a point–like source hit the same spots on the charge-coupled device (CCD), which is the most common type of detector in optical astronomy. Therefore the photons accumulate, instead of being distributed into many different spectral colours.

In basic spectroscopy, either long-slit (e.g. ALFOSC, Djupvik & Andersen 2010) or echelle (e.g. FEROS, Kaufer et al. 1999), the light of a single target is being spread into wavelength bins, giving a flux in each. Depending on the spectrograph's resolving power the bins cover a wider or narrower wavelength area. This resolving power is defined as

$$R = \frac{\lambda}{\Delta\lambda} \tag{1.4}$$

with $\Delta\lambda$ being the narrowest spectral range that can still be resolved at the given wavelength λ. The higher the resolving power R, the narrower the lines that can be identified. There is however a minimal width that a spectral line can have, caused by natural broadening. The uncertainty principle states that as any excitation state has a finite lifetime; the shorter its lifetime, the more uncertain its energy. Therefore the energy of each spectral line is a distribution and not a sharp single value. Additionally there are also other sources of spectral line broadening; e.g. the collisional

or pressure broadening. In dense environments like stars, atoms collide frequently, which reduces the lifetime of the excited states and therefore makes the energy more uncertain. Also, there is Doppler or thermal broadening, meaning that through the motion of the atoms, the observed wavelengths can be red- or blue-shifted. Fig. 1.3 shows how the resolution affects spectral features, where e.g. a line triplet blends into a single feature, in which the lines cannot be resolved. It is possible, that the triplet consists of even more components, which cannot be resolved, even with the higher resolving power used.
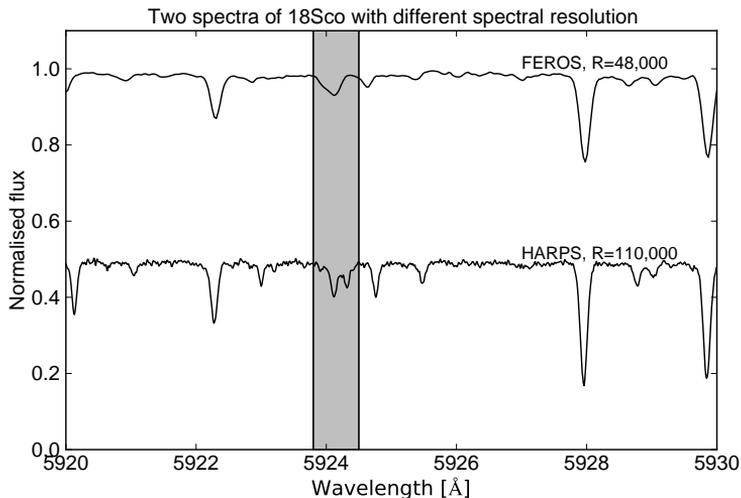
Figure 1.3: $10 \, \text{Å}$ in the spectrum of HD146233 (18Sco), taken with two different spectrographs (FEROS and HARPS) with two different resolving powers, $R = 48,000$ and $R = 110,000$, respectively. Note how the highlighted feature shows three distinct lines in the higher resolution spectrum, whereas in the lower resolution one they are blended into one. This feature is a combination of atmospheric water lines, as well as stellar iron and nickel lines and therefore shows the necessity of knowing which lines one wants to resolve when choosing the resolution power used for the study.

The wavelength window observed also depends on the resolving power, as one can fit only a certain length of data onto the CCD. The higher the resolving power, the smaller the wavelength window that can be observed.

Therefore it is helpful to use echelle spectrographs, in which the spectrum is cut into parts and then stacked next to one another onto the CCD, giving far more coverage than just by having one single sweep of the spectrum over the detector. Today there are also many Multi-Object-Spectrographs (MOS), like GMOS (Hook et al. 2004) and FMOS (Kimura et al. 2010) and Integral-Field-Units (IFU) like SAURON (Bacon et al. 2001) available, allowing to measure many spectra at once from the same field via fibre feeds. However, time remains the main disadvantage in spectroscopy, compared to photometry. Because the photons are being spread over a wavelength window, it is necessary to integrate longer to get the strength of signal that is required. This means it costs more telescope time and sets a lower limit as to how faint one can go when choosing targets for a given telescope aperture.

The big advantage in spectroscopy is the amount of information that can be found in the resulting spectra. Where photometry allows you to determine some magnitudes, colours and through these some basic stellar parameters, through spectroscopy one can determine almost anything: e.g. effective temperature, surface gravity, chemical composition, as the shape and strengths of the spectral lines in the spectrum are directly linked to these parameters. Lines usually get stronger (deeper) with decreasing gravity, but also increasing metallicity and decreasing temperature can have a similar effect. This depends on many properties and effects that are strongly linked to each other, therefore two stars can have similar lines, even if for one star the metallicity is higher and the temperature is lower, as these two effects can compensate. This kind of degeneracy is one of the main problems in determining exactly the physical parameters of a star.

Of course there are also a number of other techniques in astronomy, like polarimetry, which divides the observed light into polarised components and has been used since the 1920s (Barabascheff 1926). The amount of these different polarisation states can give vital information about where the light comes from. Furthermore, there are many other wavelength ranges than the visual. There are many telescopes and satellites that carry out observations, taking images and spectra, in the infrared (from near to far), like the SOFI instrument on the NTT (Moorwood et al. 1998) or the HERSCHEL satellite (Pilbratt et al. 2010), radio (e.g. Effelsberg, Wielebinski 1971), sub-mm (e.g. ALMA, Kurz & Shaver 1999), UV (e.g. GALEX, Bianchi & GALEX Team 1999) and X-rays (e.g. ROSAT and CHANDRA, Aschenbach et al. 1981; Weisskopf et al. 1995). The very high energy radiation is detected

by telescopes on Earth, using the particles these rays produce when hitting the Earth's atmosphere, e.g. MAGIC (Fonseca 1999), HESS (Kohnle 1999) and the upcoming CTA (Emmanoulopoulos et al. 2010).

This study Using optical very high resolution spectroscopy to better understand the properties of stars is one of the main points in this work, as well as using it to compare stars to the Sun. I focus on targets that are similar to our Sun, searching for those that are as close to solar as possible and therefore may deserve to be called solar twins, as well as using them as test benches for stellar catalogues.

In Chapter 2, I will give an overview on solar twins and analogues, what they are and why they are interesting objects. In Chapter 3, I will then discuss the connection to stellar catalogues and how to use solar twins and analogues to test the catalogue calibrations. In Chapter 4, I will describe which information we need for the analysis from the stellar spectra and briefly introduce the software used to extract it. In Chapter 5, I summarise the articles presented in this work and finally in Chapter 6 present the ongoing and future work.

Chapter 2

Solar twins and analogues

Stars come in a range of masses, from over 100 M$_\odot$ to $\approx$ 0.08 M$_\odot$, the lowest mass deemed to still be a star. As discussed more quantitatively later, the distribution of stellar masses favours low mass stars over more massive stars, so that the most numerous stars in the Milky Way have a mass significantly below solar, while Sun-like stars (G-type dwarfs) amount to only about 1% of all stars in the Milky Way. In my work, I aim to find stars, that are the most similar to the Sun, or so called "Solar twins" within the solar neighbourhood.

2.1   The Sun as a Main Sequence star

In the late 1890s astronomers endeavoured to derive a classification scheme for stars. One of the pioneers of that era was Edward C. Pickering, who, together with his assistant Williamina Fleming, divided the stars into groups depending on the number and depth of hydrogen lines one could see in their spectra. They defined 22 groups, which they labelled as type A, B, C, etc. (not to be confused with the Fraunhofer line names) going from Hydrogen rich to Hydrogen poor (Pickering 1890). This Pickering–Fleming system was a purely descriptive classification of the observed spectral lines and it was not clear what the physical significance of this scheme was. Only a few years later, in the early 1900s, Pickering's assistant Annie Jump Cannon revisited the classification. She found that she could order the spectra in a sequence, according to specific spectral lines getting stronger or weaker. It was a smooth transition without sudden steps. She kept some of the initial classes, reduced the number of groups to seven (Cannon & Pickering 1901): O, B, A, F, G, K and M. Today we know that this order follows the tem-

perature of the star with an O star being the hottest and an M star being the coolest. They are called stellar spectral types. Cannon also introduced a sub-classification for the stars, using numerals from 0-9 to further divide these spectral types, instead of reintroducing more letters, with 0 being the hottest and the 9 the coolest star within the type. This scheme is known as the Harvard spectral classification, and remains by far the most commonly used to this day.

Apart from these spectral classes, another important parameter for a star is its apparent luminosity or "magnitude". A system for this was implemented roughly 2000 years ago by the Greek astronomer Hipparchus by comparing the brightness of stars to one another. As the human eye was the only detector in those days, it is not surprising that the magnitude system therefore is based on a logarithmic scale, just like (approximately) the eye. Nowadays we define magnitude, following the formalisation by Pogson (1856), who set a magnitude 1 star to be 100 times as bright as a magnitude 6 star. It gave the following formula, when determining the magnitude of a star in comparison to another:

$$m - m_{\mathrm{ref}} = -2.5 \log_{10} \left(\frac{I}{I_{\mathrm{ref}}} \right), \qquad (2.1)$$

with m being the apparent magnitude of the star in question, m_{ref} is the magnitude of the comparison/reference star and I and I_{ref} are the corresponding intensities/brightnesses. Pogson (1856) set his scale in comparison to the star Polaris with a magnitude of 2. After discovering later that Polaris is a variable star, the comparison star was switched to Vega, which has a magnitude of 0.

This is only the apparent magnitude of a star, or how bright they appear to us on the night sky, which is a combination of their intrinsic luminosity and their distance. To be able to really compare stars, to know which ones are physically more luminous than others, there is absolute magnitude. This was first defined by Kapteyn (1902) in the early 1900s and then twenty years later standardised by the International Astronomical Union (Fowler 1922), as the star's apparent magnitude, if it were at a distance of 10 parsec (pc). The relation between apparent magnitude and absolute magnitude is therefore given by:

$$m = M - 5(1 - \log_{10} d), \tag{2.2}$$

where m is the apparent and M is the absolute magnitude of the star and d is its distance in pc. As an example, the Sun has an apparent magnitude of -27, as it is so close, whereas its absolute magnitude is only $+4.83$.

About ten years after the Harvard spectral classification scheme had been introduced, based on work by Ejnar Hertzsprung on the luminosity of stars (Hertzsprung 1907), Henry Norris Russell derived a specialised diagram by plotting stars by their absolute magnitude versus their spectral type (Russell 1914). Today this is known as the Hertzsprung-Russell-Diagram (HRD, see Fig. 2.1 and Fig. 2.2) and is a very important tool in modern astronomy. There are different versions of the HRD, some using spectral classes, some using effective temperatures, or colours as a proxy for effective temperature. They are all based on the same principle, that stars of a certain type and colour have a specific effective temperature.

The diagram itself is quite simple in its structure. The stars fall into two major groups, the main one, which in a volume limited sample would hold about 90% of the stars, being a long strip from the top left to the bottom right of the diagram and the second group is smaller and located more towards the top right. The first group is called the Main Sequence (MS), the second group is the Red Giant Branch (RGB). From this diagram it is easily understood that giving the spectral class of a star is not enough to fully classify it, at least for the cooler types G-M, as it could belong to the MS or the RGB, making it very different in absolute magnitude. Therefore in the 1940s, the Harvard classification was again revised to include a so-called luminosity class. By assigning to each star a Roman numeral of 0-VI, they were identified as being hypergiants (0), supergiants (I), bright giants (II), giants (III), sub-giants (IV), dwarfs (V) or sub-dwarfs (VI). Dwarfs and sub-dwarfs are considered MS stars, with sub-dwarfs lying slightly below the main MS. Later it was found that they are stars that show significantly weaker absorption lines from metals in their spectra (Chamberlain & Aller 1951; Kaler 1989). This is the Yerkes or MKK (Morgan Keenan Kellman) spectral classification system (Morgan et al. 1943), later reduced to the MK system, after some revisions. In this way the Sun was classified as a G2V star, making it a fairly cool MS star in the larger scheme, but a hotter one within the G-class.
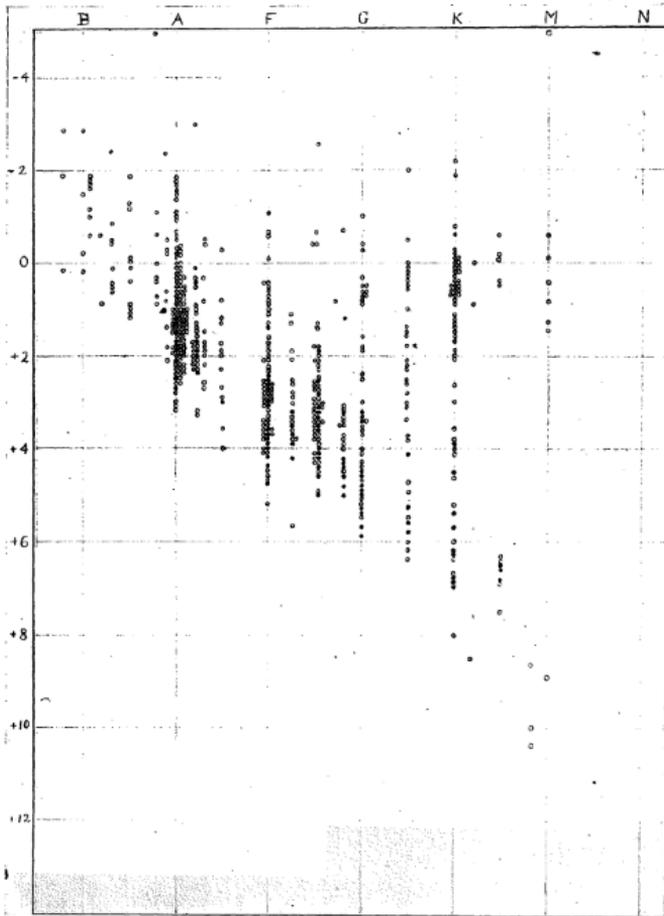
Figure 2.1: One of the first Hertzsprung-Russell diagrams, taken from Russell (1914), using data from more then 550 binary stars. The abscissa shows the spectral types B, A, F, G, K, M and N, the ordinate shows the absolute magnitude, ranging from +14 to −5. The Main Sequence can be seen spanning from the top left to the bottom right, as well as the Red Giant Branch, branching off from the MS towards the upper right corner.

Stellar evolution models show that a star spends around 90% of its lifetime burning hydrogen into helium in its core, because the efficiency of energy production through helium burning and any subsequent stages
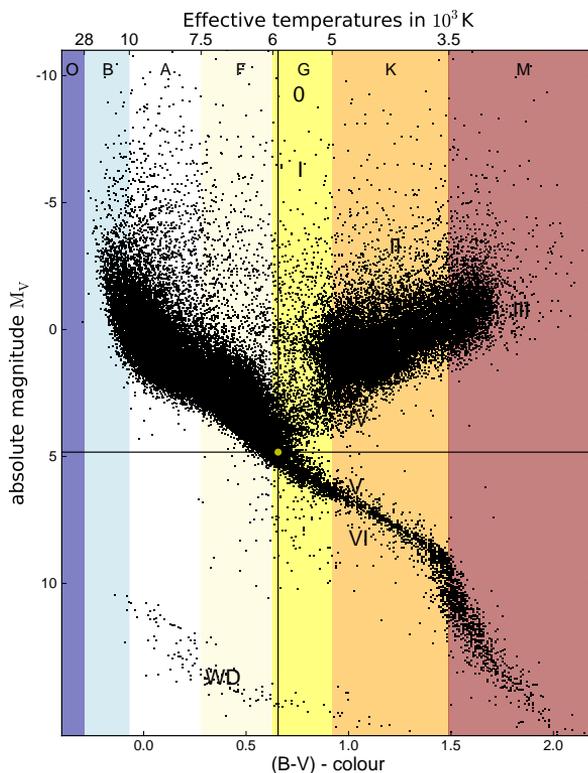
Figure 2.2: Hertzsprung-Russell-Diagram of nearby stars in the Milky Way, with the position of the Sun clearly marked. Data points for ∼51000 stars are taken from the HIPPARCOS (Perryman et al. 1997) catalogue. Additional data for ∼3000 stars are taken from the Catalogue of Nearby Stars (Gliese & Jahreiss 1991). Note that this is not a volume limited sample and that the relative numbers of stars is not representative. There are many more stars at the low mass end, relative to the higher masses, than can be seen here. Absolute magnitude is plotted versus $(B - V)$ colour, spectral type and effective temperature. Roman numerals indicate the luminosity types.

is only $\approx 10\%$ of that of hydrogen burning. During this main part of its lifetime the star does not change much on the surface, it is a MS star. As it evolves, after the MS phase, it starts to expand and grows more luminous. Its position in the HRD will then change, as it moves from the MS to the RGB region.

Assuming the star is spherically symmetric and made of a hot plasma, it can be described by the four equations of stellar structure:

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \rho(r), \tag{2.3}$$

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -G\frac{m(r)\rho(r)}{r^2}, \tag{2.4}$$

$$\frac{\mathrm{d}L}{\mathrm{d}r} = 4\pi r^2 \epsilon(r), \tag{2.5}$$

$$\begin{cases} \frac{\mathrm{d}T}{\mathrm{d}r} = -\frac{3}{4ac}\frac{\kappa(r)\rho(r)}{T^3(r)}\frac{L(r)}{4\pi r^2}, & \text{radiative transport} \\ \frac{\mathrm{d}T}{\mathrm{d}r} = \frac{\gamma-1}{\gamma}\frac{T}{P}\frac{\mathrm{d}P}{\mathrm{d}r}, & \text{convective transport} \end{cases} \tag{2.6}$$

where m is the mass, ρ is the density, P is the pressure, G is the gravitational constant, L is the luminosity, ϵ is the energy generation rate per unit mass, T is the temperature, a is the radiation constant, c is the speed of light, κ is the opacity and γ is the adiabatic index. All parameters are given at the distance r from the centre of the star.

The first equation describes the mass distribution within the star. It is called the mass conservation law. The second one is the hydrostatic equilibrium, meaning it shows how the self gravitation of the star caused by its mass and the internal pressure caused by the hot plasma of particles and radiation keep one another in balance. The third equation describes how the energy the star radiates into space is being kept in balance with the energy it produces on the inside, it is the energy conservation law. The last two equations describe how the energy is being transported from the inside outward. This equation is different, depending on the transportation

process, whether it is through radiation or convection, which depends on the star and the location within the star, as the process can change between the core and the envelope.

We know from these equations that the mass of a star is the main property that determines its structure on the MS, as well as its future evolution. It determines other properties like temperature, pressure, gravity, etc. and it thus makes sense to divide stars into mass classes. Temperature and mass are closely linked, therefore the historic temperature classes can be seen as mass classes, as along the MS the hot stars are more massive and the cold stars are less massive.

A star like the Sun spends about 10 Gyr on the MS, with a radiative core and a convective envelope. It then becomes a Red Giant (RG) and finally ends as a carbon–oxygen white dwarf (CO–WD), after burning helium.

2.2 The Sun – in numbers

As we will discuss, the Sun is an unexceptional star in mass[1] and average in chemical composition and age. As it is also the nearest star, it is by far the best known. It is the only one we can study by sending probes and getting close-up observations. It also means we can or even must use other methods to derive its parameters than those used for other stars.

The mass of the Sun has been known since the 18th century. As the Earth moves around the Sun in an elliptical orbit, it is possible to determine the Sun's mass through Kepler's 3rd law of planetary motion (Kepler et al. 1619):

$$\text{M}_\odot = \frac{4\pi^2}{G} \frac{(1\text{AU})^3}{(1\text{yr})^2} \tag{2.7}$$

The length of a year was well known at the time, and the Earth-Sun distance had only recently been measured during the Venus transits of 1761 and 1769. Hornsby (1771) had found it to be on average $93,726,900$ miles ($150.839 \cdot 10^9$ m), which differs by only 0.8% to today's measure of $149,597,870,700$ m (which is the definition of 1AU = 1 as-

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[1]It can be considered a relatively high mass star, compared to the typical average stellar mass in the mass distribution function, but within the range of stellar masses it is neither specifically high or low mass.

tronomical unit). In 1798 Henry Cavendish determined the Gravitational constant G to be $G = 6.74 \cdot 10^{-11}$ m^3 kg^{-1} s^{-2}, which is accurate to within 1% of today's accepted value of $G = 6.67 \cdot 10^{-11}$ m^3 kg^{-1} s^{-2}. All these values have been determined with increasing accuracy and the current estimate of the Solar mass is $1.9891 \pm 0.0002 \cdot 10^{33}$kg (Lang 1999), which we call a solar mass 1 M$_\odot$ and is the unit of measure for stellar masses.

Stars have typical masses between $0.08 - 100$ M$_\odot$. Objects below the lower limit are brown dwarfs and planets, and objects above ≈ 100 M$_\odot$ have uncertain masses, so the upper limit is hard to establish, unlike the lower limit. In theory no MS star can have a mass below 0.08 M$_\odot$,[2] as the temperature in the core would not reach high enough to ignite the Hydrogen fusion; equally no MS star can have a mass above ≈ 100 M$_\odot$, as the radiation pressure would then exceed the gravitational force and drive a massive outflow. This limit is called the Eddington limit, or Eddington luminosity and is given by

$$L_{Edd} \cong 1.26 \cdot 10^{31} \left(\frac{M}{\text{M}_\odot} \right) W = 3.2 \cdot 10^4 \left(\frac{M}{\text{M}_\odot} \right) L_\odot \qquad (2.8)$$

in solar values. Higher mass stars are known, however, they are rare and probably unstable (Martins 2014); here we focus on solar-type MS stars.

Another astrophysical unit of measure is the solar radius, given by Lang (1999) to be $R = \text{R}_\odot = 6.9598 \pm 0.0007 \cdot 10^{10}$ cm. This has been measured through helioseismology (Schou et al. 1997) and measurements of meridian transits (Brown & Christensen-Dalsgaard 1998). Recent Mercury and Venus transits have also been used to determine the solar radius further (Emilio et al. 2012; Hauchecorne et al. 2014) and found it to be slightly larger, around $\text{R}_\odot = 6.963 \cdot 10^{10}$ cm.

Knowing the solar radius means one still needs the Solar luminosity to determine its effective temperature from its definition (see Eq.1.3). The luminosity is very closely linked to the so-called Solar constant, which is a measure for the amount of radiation per unit area at 1 AU,

$$L_\odot = 4\pi k I_\odot A^2, \qquad (2.9)$$

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[2]Note that this value is for solar composition only, as the limit is metallicity dependent.

where $L_\odot$ is the Solar luminosity, k is a constant reflecting the fact that the mean Sun-Earth distance is not exactly 1AU, A is the unit distance (1AU) and $I_\odot$ is the solar constant at 1AU. It was measured by Pouillet (1838), who found it to be 1.2 kW/m^2. This is only $10\,\%$ lower than today's value. Many subsequent measurements yielded values that were too high (as much as 2.9 kW/m^2 due to erroneously applied corrections), until Abbot (1958) found it to be between $1.3 - 1.5$ kW/m^2, depending on the time of year. The modern value is on average 1.361 kW/m^2 (Kopp & Lean 2011), which is determined through space-based observations. As shown in the previous chapter (see Eq.1.3), using the solar constant and the measured solar radius, we can determine the value for the solar effective temperature of 5777 ± 3 K.

Another important Solar value is the Sun's surface gravity, given by the Gravitational constant G, the Sun's mass and radius:

$$g = \frac{GM}{R^2}. \tag{2.10}$$

Surface gravity g is typically given in cgs units ($g_\odot = 27423 \pm 8 \frac{\text{cm}}{\text{s}^2}$) and more usually as a log g value, which for the Sun is log $g = 4.44$ dex,[3] given the above mentioned values for $G, \text{M}_\odot$ and $\text{R}_\odot$ (in cgs units).

To determine the age of the Sun, there are different options. The first detailed measurements of other solar system bodies, like meteorites and asteroids through radioactive chronology, assuming that everything formed at the same time resulted in an age estimate of $(4.55 \pm 0.07) \cdot 10^9$ yrs (Patterson 1956). Later an age estimate for the Sun itself was given by Guenther (1989) to be $(4.49 \pm 0.04) \cdot 10^9$ yrs. Another fifteen years later, helioseismic measurements yielded a value of $(4.57 \pm 0.11) \cdot 10^9$ yrs (Bonanno et al. 2002), which is the currently accepted value.

The surface composition of the Sun very likely reflects to a good approximation (of order 0.05 dex) the composition of the molecular cloud from which it formed $4.6 \cdot 10^9$ yrs ago. In the Big Bang model, in the first few minutes mostly hydrogen was formed and also helium and traces of light elements like lithium. The primordial mass fractions resulted in $X \simeq 0.75$ (hydrogen fraction), $Y \simeq 0.25$ (helium fraction) and $Z = 10^{-8}$ (all other

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[3]Note that it is a convention to use the nomenclature "dex" to show that it is a logarithmic (base 10) value.

elements, called "metals"). By definition $X + Y + Z = 1$. Since then the interstellar medium (ISM) has been polluted by a small fraction ($\approx 2\%$) of metals. Stars produce them in their core (Burbidge et al. 1957) and when they run out of fuel, these metals are partly blown into the ISM through supernovae, planetary nebulae or mass loss outflows. So by the time the Sun formed, the composition of the ISM had changed significantly from the Big Bang values.

Since the 1920s the question of the solar composition has been studied (Russell 1929; Suess & Urey 1956; Goldberg et al. 1960) and in the last fifteen years there have been many reviews on the topic (Grevesse & Sauval 1998; Asplund et al. 2009) using more precise atomic data and 3D modelling, so that today we estimate that the Sun was born with $X = 0.715, Y = 0.270$ and $Z = 0.014$.[4] Recently Asplund et al. (2009) determined the current solar composition, after $4.6 \cdot 10^9$ years to be $X = 0.738, Y = 0.249$ and $Z = 0.013$.[4] These values correspond to the photosphere composition, as that is all that can be examined directly through spectroscopy.[5] Note that the values for Y and Z are expected to be lower than for the solar parent cloud by about $6-8\%$, as through thermal diffusion, gravitational settling and radiative acceleration the more heavy elements slowly move to the Sun's central regions. Also note that the solar metallicity estimate of 1.4% is lower than the classical value of 2% (Anders & Grevesse 1989), which is mainly due to the revised lower abundances of carbon, nitrogen and oxygen.

For stars other than the Sun it is impossible to determine these values so accurately, therefore the term metallicity often refers to the amount of iron, as this is the element best determined spectroscopically for Sun–like stars. It is defined as

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_* - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_\odot \tag{2.11}$$

with N_{X} (X = Fe, H) the number of atoms of element X in the star per unit volume. Metallicity per se does not have a unit, as it is a logarithm of a ratio of numbers. It is however a convention when referring to logarithmic (base

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[4]These values have typical errors of 0.5%.

[5]Asteroseismology and stellar evolution models are used to determine the interior composition.

ten) values to give a unit called dex (cf. log g). The solar metallicity is 0, by definition. The logarithmic scale relative to the Sun implies that stars with higher than solar metallicities have [Fe/H] > 0, those with lower metallicity have [Fe/H] < 0. [Fe/H] = 1 would mean that the star has $10^1 = 10$ times the metallicity of the Sun (note that to date there has been no star observed that is this metal-rich), [Fe/H] = -1 means it is merely $10^{-1} = \frac{1}{10}$ of the Sun. Fig. 2.3 shows the distribution of stellar metallicities for F, G and K main sequence stars in the solar neighbourhood. The values were taken from the Casagrande et al. (2011) reanalysis of the Geneva-Copenhagen Survey (Nordström et al. 2004), which shows the peak metallicity to be close to solar. Note, that the original calibration of the same dataset gave a peak at lower metallicity (-0.15 dex), making the Sun more metal–rich than the local average.
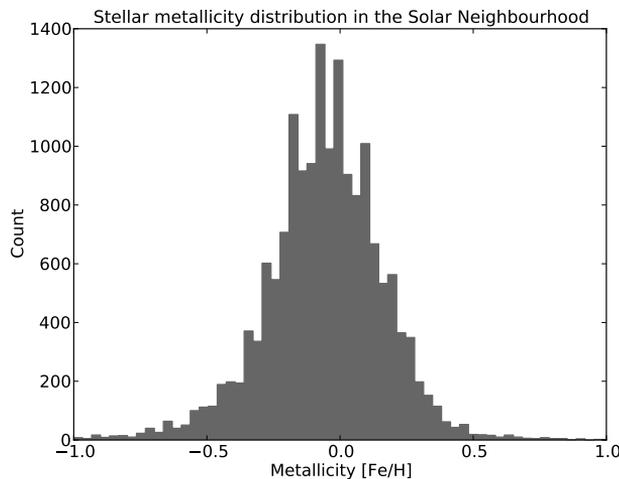

Figure 2.3: Distribution of stellar metallicities in the solar neighbourhood for F, G and K stars, taken from Casagrande et al. (2011). Note how the maximum lies just slightly below the solar value of 0.00 dex, therefore making the Sun a star with quite average (or slightly above average) metallicity in the solar neighbourhood.

We have known for over a century that the Sun also shows magnetic activity (Maunder 1894) and has since been extensively studied (e.g. Greaves & Newton 1928; Evans 1959). In the late 1970s Wilson (1978) made a study on magnetic activity in MS stars. Later White & Livingston (1981) examined the correlation between the flux in the Calcium H and K lines of the Sun and its chromospheric activity cycle, as these lines are some of the few formed in the solar chromosphere (Hall 2008), which can be studied from the ground (most other chromospheric lines lie in the UV or beyond). As Willson & Hudson (1991) have shown, the Sun has an 11 year activity cycle, with an amplitude in the luminosity variation of $\sim 0.1\%$. In my work, I tried to avoid very young and active stars, as they show broadened spectral lines, due to their rotation speeds, which make our differential analysis more unreliable (see also Chapter 4).

2.3   What is a solar twin?

Since the 1980s, when people started looking for stars that are close to the Sun in all its characteristics or "solar twins", the question of how exactly to define a solar twin has been debated. In an initial paper on the subject, Cayrel de Strobel et al. (1981) defined a solar twin to be a star having "*at the same time the same effective temperature, gravity, bolometric magnitude, metal content and microturbulance of the Sun within observational accuracy*". This defined for them a solar twin. At that time no star was found that fell into that category.

Nearly a decade later, Cayrel de Strobel & Bentolila (1989) made a new attempt to define solar analogues and solar twins as follows: "*Solar analogues are unevolved or slightly evolved Pop I stars having the same effective temperature and the same photometric properties as the Sun.* [...] *Real solar twins are hypothetical stars having all their physical parameters, i.e. mass, chemical composition, age and luminosity, rotation, velocity fields, magnetic fields and chromospheric activity, etc.* [...]*, equal to those of the Sun.*" This of course implies that a real solar twin does not exist; it is a hypothetical construct. The question would then be, how close to a solar twin can a star actually get?

True to their definition, Cayrel de Strobel et al. never published a paper claiming to have found a true solar twin, but always stars that are close twins, like HD 186427 and HD 44594 by Cayrel de Strobel (1990). A few

years later they re-defined them to be "*ideal stars possessing fundamental physical parameters [...] very similar, if not identical to those of the Sun*" (Cayrel de Strobel et al. 1996), i.e. they relaxed the criteria slightly.

Others searching for solar twins used these definitions with more or less detail. Friel et al. (1993) defined that for a real solar twin "*every observable and derivable physical quantity must be identical within observational errors to that of the Sun*". However in addition the stars would have to be in a similar evolutionary state as the Sun. Their closest twins were 16 Cyg A and 16 Cyg B, however they were no solar twins as such.

Porto de Mello & da Silva (1997) used the Cayrel de Strobel & Bentolila (1989) definition of a solar twin, being very careful in saying that it remains an open question whether a "true" solar twin exists or not. They found 18 Sco (HD 146233, HR 6060) to be the star that "*best approaches the solar twin concept*".

In the past 15 years most people have referred to their possible solar twins to be "*extremely close*" (Porto de Mello et al. 2000), "*closest ever*" (King et al. 2005) or "*quasi solar*" (Meléndez & Ramírez 2007). However the concept of a twin being a star that is solar in all its parameters within the observational errors is also a common definition in recent work (Porto de Mello et al. 2000; Meléndez & Ramírez 2007; Takeda & Tajitsu 2009). In some cases the definition of a solar twin can be found to have been stretched to include all stars within pre-defined spectroscopic parameter limits (Ramírez et al. 2009) or even solar-type stars, like the G3V star HD 187123 (Butler et al. 1998), but these are exceptions.

In my work I have used the following definitions of solar twins and analogues, which are non-physical and thus difficult to implement: Stars, that are very solar, but show some distinctive differences to the Sun, meaning those photometrically close to the Sun within some limits are called solar analogues. They could include solar twins, but are mostly not. Those stars, which on closer inspection with high resolution spectroscopy have the observed and derived parameters[6] that are indistinguishable from solar within our error bars, are called solar twins. The size of the errors depends highly on the quality of the data and the way the parameters have been determined. In my work I have used two different definitions for quantify-

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[6]Note, that in this work these are the equivalent widths of spectral lines and not final stellar parameters like effective temperature or metallicity. Therefore our twins are determined directly from their spectral features and not from any derived values, which can differ from those of the Sun by more than their errors.

ing these errors, as I have used different types of spectra for my analysis. Therefore in Paper I and IV (FEROS data), I define a solar twin to have the derived values within 2σ of the solar values (σ being the scatter) and in Paper II (HARPS data) the values have to be within 1% of solar (for details see Paper I, II and IV).

As mentioned above, looking for solar twins means looking at one or many of the stars' observables to compare them to the Sun. Fortunately many of these parameters are linked. For example, when considering a G-type dwarf star, one immediately confines the mass and temperature of the star to solar-like values (see Fig. 2.2), as the mass determines the size, the luminosity and also the temperature of the star. In this way it is easy to search for a solar twin by narrowing the criteria to a few basic ones, like colour (temperature), luminosity (size) and metallicity, as the resulting stars will consequently also have solar-like masses, radii and gravity. Age, however, is a different story.

The age of an isolated main sequence star is difficult to measure. As mentioned before, stars evolve very slowly on the HR diagram during their time on the main sequence and therefore, until now, there has not been any really accurate method to determine stellar ages. Typically they have errors of several tens of percent, whereas for a solar twin one would want errors of only a few percent at the most.

One way to determine ages is to measure the change in luminosity in time. It is of course impossible to observe a star that long to see these changes. Therefore it is common to use stellar isochrones and determine ages based on the position of a star in the CMD. They are theoretical lines in the HRD, that predict where a star of a certain age should be, meaning how its luminosity has evolved thus far. They can be calculated for all kinds of ages, every point of the line representing a star of a different mass. Therefore when deciding on which isochrone fits the star best, one determines not only its age, but its mass and metallicity at the same time. In practice the resulting age is rather uncertain because of the evolution in this phase is very slow, causing the different isochrones to lie very close together and making it difficult to determine the best one. Therefore age is often ignored when looking for solar twins. We know the age of the Sun mainly because we have the whole solar system to probe through analysis of asteroids and meteorites, which formed at the same time as the Sun. For other stars we do not have that possibility, with some exceptions.

In the mid-1980s Ulrich (1986) found that through asteroseismology

one can probe the interior of a star to the extent that it would allow astronomers to determine ages. However it took another twenty years until tentative measurements were made by Vauclair (2009) on the two stars μ Ara, a G3IV-V star and ι Hor, a F8V star. The determined ages were 7 ± 1 Gyr for μ Ara and 625 ± 5 Myr for ι Hor. Only four years ago Metcalfe et al. (2010) published a more extensive and accurate determination of age for the KEPLER star, KIC 11026764, a G0IV star and found an age of 5.94 ± 0.05 Gyr. Since then a few more stars have followed. Ramírez et al. (2011) showed that using isochrones can be as good as asteroseismology, if the stellar parameters of the star are very precise, as can be obtained differentially for solar twins with very high resolution spectra. They determined ages for the 16 Cyg A+B system of $7.15^{+0.05}_{-1.03}$ Gyr and $7.26^{+0.69}_{-0.33}$ Gyr, which are in good agreement with the asteroseismological age of 6.8 ± 0.4 Gyr by Metcalfe et al. (2012). Hopefully in the near future, with large photometric surveys like KEPLER (Borucki et al. 2008), it will be possible to also constrain age better when looking for solar twin stars, thus making it possible to find a star that is a solar twin in age as well as the parameters discussed so far.

Another more complicated and unconnected parameter is the stars' chromospheric activity. Not many solar twins or close solar twins have been studied in connection with activity, apart from 18 Sco (Hall & Lockwood 2000; Hall et al. 2007), which was found to have a ~ 7 yr activity cycle showing the same amplitude in luminosity variation of $\sim 0.1\%$ as the Sun. Recently Porto de Mello et al. (2014) also included activity in their selection of possible solar twins, therefore moving this parameter more into the focus of current work. In my work I specifically tried to avoid young, active stars in my sample, by removing those with high rotational values, as they cannot be solar twins by age anyway. Chromospheric activity is also often studied in connection with exoplanets (Dumusque et al. 2011).

2.4   Why look for solar twins?

Different instruments   The Sun is best studied star and our most fundamental calibrator to link observable to physical parameters, which is why we want to compare other stars to it. We even express stellar parameters in solar units: solar mass, solar radius, solar metallicity, etc. The Sun is also a resolved star, meaning we can see a disk when observing it and not a

point source, and of course it is very bright. However, most telescopes are typically designed never to be pointed at the Sun, but only at dim, night time objects. Therefore one possibility, when trying to compare stars to the Sun would be to use different telescopes for each. There are those that are designed to be pointed at the Sun (solar telescopes, like the Swedish Solar Telescope (SST) on La Palma) and those used to study the other targets. However, when using different telescopes one introduces different sources of systematic errors and calibrations into the measurements. The telescopes might be in very different places, the observations taken in very different times of the day/night, the detectors react differently, the filters are different, etc. There are dozens of characteristics which affect the measurements. It is important to use the same telescope and instrument for the targets and the Sun, so that these effects are cancelled out. Therefore, by using solar twins, instead of the Sun, to compare stars to, it is possible to use the same telescope and instrument and thereby limit the systematic error to a minimum. For this one needs solar twins all around the sky and so it is important to go on searching for these twins, even if some have already been found. Therefore using big surveys to search for them, like I have done in my work, is a good way to start.

Different methods When trying to observe the stars and the Sun in a comparative way, not only does one face different instruments, but also different methods. The main example is stellar temperatures. As mentioned, the Sun is so close that its disk can be resolved, whereas stars are typically point sources. So, when looking at the effective temperature of a given star (see Eq.1.3), which is defined through the luminosity and the radius, one would need to know the stellar radius first to be able to determine the Solar and stellar temperature using the same methods. Until recently, few MS stars had measured radii. Early methods included eclipsing binaries (e.g. Harris et al. 1963; Andersen 1991) and lunar occultations (e.g. MacMahon 1908; Jennings & McGruder 1999), but nowadays the main progress is in the increasing accuracy and reach of interferometry.

Already in the 1920s Michelson & Pease (1921) started using interferometry to determine stellar radii, as this technique allows to resolve the disk of the star. They used it on α Ori, which has a luminosity class of Ia, meaning it is a supergiant and therefore very large and easiest to measure. They found it to have a radius of $193 \cdot 10^6$ km, which is about 278 $R_\odot$ and not much smaller than the orbit of Mars in the Solar system. However, it

took until the 1990s for astronomers to begin measuring stellar radii for a few tens of giant and MS stars. Danchi et al. (1995) and later van Belle & PTI Collaboration (1997) managed to measure radii for samples of giants using the ISI (Infrared Spatial Interferometer) and the PTI (Palomar Testbed Interferometer), respectively. Fifteen years later, this technique is widely used in different wavelengths for different stellar targets, including MS stars (e.g. Boyajian et al. 2012); however, it remains limited to very nearby stars, as they show the largest discs on the sky. Nevertheless, with the growing accuracy and by using larger telescopes and baselines in the near future it will soon be possible to also measure stars that are smaller and further away, giving astronomers wider access to another fundamental parameter of stars, their radii. In the meantime, to be able to compare stars to the Sun, by using the same methods on both, it is necessary to have "stand-in-suns", or solar twins.

For most stars, we use indirect, calibrated photometric or spectroscopic means to determine their effective temperatures. These show systematic offsets of $50 - 100$ K, much larger than the typical internal uncertainties of each method (few tens of K). Therefore we need to check through independent ways that the stellar effective temperatures are "on the same scale" as the Sun. Solar twins can provide information on how the temperature scale within a catalogue or a survey relates to the Sun. If we find the solar twins to have effective temperatures systematically different from the Sun, it means the calibration of that catalogue or survey should be revisited. This possibility to check catalogue calibrations is especially timely, as we are acquiring increasing amounts of data from many different large surveys, which will provide us with a deep, comprehensive census of the stellar populations in the Milky Way. Therefore, as discussed in Chapter 3 and 4, it is important to be sure that the stellar parameters we derive are both precise and accurate (Solar twins as calibrators add accuracy).

Solar twins and exoplanets Another popular reason to look for solar twins is the search for other solar systems. In the past twenty years increasing numbers of planets have been found around other stars: starting from the first planet around the solar-type star 51 Peg by Mayor & Queloz (1995), which was also considered to be a good solar twin at the time (Cayrel de Strobel et al. 1996) to the thousands of planets confirmed by the KEPLER satellite only a few months ago (Rowe et al. 2014). When looking for these exoplanets, the question remains to what extent our solar

system is typical. Focussing these kinds of searches around solar twins will increase the chances of answering that specific question.

In addition, considering subtle differences in the abundance pattern of the Sun and its twins, recently there have been indications that the existence of terrestrial planets could be inferred by the abundance patterns of the refractory versus volatile elements in the host star, as well as its lithium content (e.g. Meléndez et al. 2010; Ramírez et al. 2010). The debate is open and more known twins will aid the discussion (see Section 2.6).

All these points have been addressed in my work. I have searched and found solar twins, new and old for a more homogeneous coverage of the sky.

2.5 Solar twins among the solar siblings

A solar twin should be a star, that has the same mass, the same size, temperature and gravity, and ideally also the same metallicity, chemical abundances, age, etc. as the Sun. Therefore the obvious source for such a star would be the same molecular cloud which also formed the Sun, ensuring the same chemical composition and age. However, just how many stars have actually formed from that cloud? Measurements of the isotopes in asteroids tell us that there has been a supernova in the solar neighbourhood, that enriched the interstellar medium with certain elements (Looney et al. 2006). However, to have a star massive enough to end its life as a supernova, the minimum cluster size from which this star and the Sun were born can be estimated to have been 10^3 M$_\odot$ (Portegies Zwart 2009). Bland-Hawthorn et al. (2010) say that the cluster could not have been too small, as there is evidence of a supernova in the solar neighbourhood. In addition the cluster could not have been too large either, as otherwise the cluster members would not have dispersed yet. However, as there are many uncertainties in these assumptions, they conclude, that the solar parent cluster must have had a mass of $10^3 - 10^5$ M$_\odot$. M67, one of the most massive open clusters known today is considered to have been born with $\sim 2 \cdot 10^4$ M$_\odot$ (Hurley et al. 2005), but today carries only a tenth of that mass due to mass loss and stellar escapes. Assuming the lower limit of 10^3 M$_\odot$, what are the chances that more than one of the stars formed from it would be of one solar mass, thus making them solar siblings and at the same time solar twins?

In the mid 1950s, Salpeter (1955) described the distribution of stellar masses (for masses above 0.1 M$_\odot$) in the solar neighbourhood by the

following power law (see also Fig. 2.4):

$$\xi(M) = \xi_0 \left(\frac{M}{M_\odot} \right)^{-2.35}, \qquad (2.12)$$

with $\xi(M)$ being the so-called initial mass function (IMF) and ξ_0 a normalisation constant; in a cluster, the IMF is normalised over the total mass. As the name suggests, this function describes the mass distribution initially, meaning when the stars were born, but not necessarily later, as the stars evolve. When observing a cluster of stars today, depending on its age, most of the high-mass stars will have evolved and become white dwarfs, neutron stars or even black holes and are thus no longer easily observable. The IMF however includes those stars and therefore gives a view of the distribution as it was. By integrating this IMF over a given mass range, e.g. M_1 to M_2, one can determine the number of stars in that mass range, born at the same time and from the same cloud (Eq. 2.13). Additionally, by integrating $M\xi(M)$ over a given mass range then gives the mass in the formed stars (Eq. 2.14):

$$\int_{M_1}^{M_2} \xi(M)\mathrm{d}M = \frac{\xi_0}{1.35} \left[\left(\frac{M_1}{M_\odot} \right)^{-1.35} - \left(\frac{M_2}{M_\odot} \right)^{-1.35} \right], \qquad (2.13)$$

$$\int_{M_1}^{M_2} M\xi(M)\mathrm{d}M = \frac{\xi_0}{0.35} \left[\left(\frac{M_1}{M_\odot} \right)^{-0.35} - \left(\frac{M_2}{M_\odot} \right)^{-0.35} \right]. \qquad (2.14)$$

We can determine the normalisation constant ξ_0 by assuming that the total mass in the cloud was at the lower limit of $10^3 M_\odot$ (Portegies Zwart 2009), which gives a normalisation of $\xi_0 = 172$ $M_\odot$ for the parent cluster of the Sun.

If we further assume the distribution of stars born from the cloud follows this Salpeter IMF (Salpeter 1955), about 3000 stars were formed from the solar parental cluster. For this approximation we consider a star to have solar mass, if it is within 2% of a solar mass. This is reasonable, as e.g. 18 Sco, a well known very close solar twin was found to have a mass of $M = 1.02 \pm 0.03$ $M_\odot$ (Bazot et al. 2011). Only about 7 of the sibling stars

would satisfy this criterion to be between $0.98 M_\odot$ and $1.02 M_\odot$.[7] These would be solar twins, as the molecular cloud would have made them of the same age and chemical composition as the Sun.
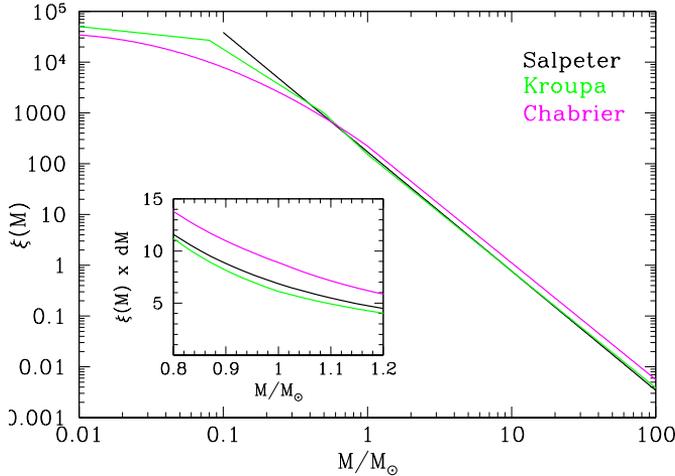

Figure 2.4: The IMF as described by Salpeter (1955), Kroupa (2001) and Chabrier (2003), normalised to a cluster of 10^3 $M_\odot$. Note that while the Salpeter IMF is traditionally truncated at the low mass stellar limit of 0.1 $M_\odot$, modern IMFs extend into the substellar or brown dwarf regime, but due to the turn over the amount of mass stored there, and therefore the overall mass normalisation, is not very sensitive to the low mass limit. The insert shows the number of stars formed as a function of mass, within a $\pm 2\%$ range; (e.g. 7 stars are formed from the Salpeter IMF with a mass of 1 ± 0.02 $M_\odot$. (Courtesy of L. Portinari)

Since Salpeter (1955), a great deal more work has been done on measuring the shape and normalisation of the IMF. In the late 1970s, Miller & Scalo (1979) found that observations of the stellar mass distribution at the low mass end did not keep following Salpeter's power law, but there was a clear turn-over, stating that there were less low mass stars and brown dwarfs formed than initially thought. These observations were repeatedly con-

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[7]Note that these numbers are for the minimum mass of the solar parent cluster. Using the upper limit would increase the amount of twins by a factor of 100

firmed, most recently by Kroupa (2001) and Chabrier (2003) (see Fig. 2.4).

The existence of this turn-over immediately implies that relatively more stars of higher masses are formed, as the "lost mass" at the low end has to be redistributed. Indeed, it somewhat increases the number of solar mass stars (by about 30%) from ~ 7 to ~ 9 (see the insert of Fig.2.4). Including the possibility, that the total cluster mass was merely a lower limit and can be up to a factor of 100 larger, there are of the order of 10 to 1000 stars in the Milky Way that are simultaneously solar twins and solar siblings. Irrespective of whether the cluster was of the lower or upper limits, less than 1% of the solar siblings are expected to be solar twins.

Looking for these solar siblings is a challenge of its own, as they have had $\sim$5 Gyr (which is the age of the Sun) to move away from their birthplace and disperse between the other stars. Portegies Zwart (2009) concluded in their work, through simulations of the cluster dissolution, that about $10 - 40\%$ of the solar siblings should be found within a radius of 1 kpc around the present-day location of the Sun. Searching for a handful of stars within 1 kpc is like looking for a needle in a haystack, also given the fact that until recently the most detailed volume complete census of the Solar Neighbourhood barely went out to 50 pc, like the Geneva-Copenhagen-Survey (Nordström et al. 2004). In the past few years there have been larger surveys like RAVE (Steinmetz 2003), that have observed and taken spectra of tens of thousands solar type dwarf stars out to ~ 0.5 kpc and the Gaia-ESO Survey that reaches them out to ~ 1 kpc, so there is a slight chance of finding 'solar twin siblings' in their datasets. Also the HERMES/GALAH survey on the AAT (Freeman 2010) will provide detailed information on about 10^6 stars, reaching out to about 1 kpc for dwarf stars. Bland-Hawthorn et al. (2010) simulate, depending on how the solar siblings mixed into their surroundings, that HERMES/GALAH could find of the order of 10 to 30 solar siblings. If out of 3000 siblings, only 7 are twins, we would be extremely lucky to find a single solar sibling twin in the HERMES/GALAH estimate.

A different approach to the problem would be to start off from a search for all solar siblings. Recently Batista et al. (2014) used the extensive HARPS archive (High Accuracy Radial velocity Planet Searcher, Mayor et al. 2003) at the ESO 3.6m telescope at La Silla – to look for solar siblings in the FGK dwarf sample by Adibekyan et al. (2012). By selecting the stars which show the closest match in chemical abundances, ages and stellar kinematics, they found one candidate HD186302 for a solar sibling. Whereas its metallicity is solar within the errors [Fe/H] $= -0.03 \pm 0.05$,

its effective temperature of $T_{\mathrm{eff}} = 5662 \pm 62\mathrm{K}$ is too low to be a solar twin, yet quite close.[8] They started with a sample of 1111 FGK stars and found one possible sibling candidate, therefore when looking at surveys like HERMES/GALAH with 10^6 stars, there may be as many as 10^3 siblings in such samples. Also Ramírez et al. (2014) recently studied 30 stars with promising dynamical and chemical characteristics in search for solar siblings. Through very precise elemental abundance analysis they found one star in the sample that proved to be a promising sibling in all their requirements for dynamics and chemistry. However it is a late F–type star and thus cannot be a solar twin.

2.6   The quest for solar twins - to this day

The methods on how to look for solar twins are very diverse. Spectroscopic observations date back as far as the 1960s, when Wallerstein (1962) used photographic plate detectors to measure the equivalent widths of spectral lines to apply the curve of growth analysis to determine abundances in stars compared to the Sun, or Spite (1969) used line depths, as a function of equivalent width and line depth ratios to determine effective temperatures. From the early 1980s, when CCDs became available Branch et al. (1980) measured the Hα line wing profiles to determine effective temperatures and weak iron lines for the iron abundances. Cayrel de Strobel et al. (1981) also used the equivalent widths and curve of growth analysis for their twin searches, the CCDs allowing a better accuracy than the photographic plates. Photometric and spectrophotometric techniques followed and complemented the spectra in the late 1970s and 1980s, when Golay et al. (1977) compared seven colours of possible solar twins to those of the Sun, Neckel (1986b) determined the position of their targets in colour-colour-diagrams, Hardorp (1978) divided the target spectra by the solar spectrum and searched for the flattest residuals and Neckel (1986a) compared the stars' whole spectral energy distribution (SED) to that of the Sun. Especially when using these photometric methods, soon the question of the true solar colours arose. Already in the 1950s to 1970s e.g. Stebbins & Kron (1957), Kron (1963) and Croft et al. (1972) did studies on the colours of the Sun in different photometric systems, a question that is

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[8]This star never made it into my solar twin search samples (see Papers I, II and IV), as its absolute magnitude of 5.11 was outside of my selection range ($4.63 < M_{\mathrm{V}} < 5.03$).

still being addressed today (e.g. Holmberg et al. 2006; Ramírez et al. 2012; Casagrande et al. 2012).

Effort focussed on studying many different solar type stars to determine their parameters, to see how close to solar they are. α Cen A (e.g. Furenlid & Meylan 1984; Soderblom & Dravins 1984; Engvold 1987; Pottasch et al. 1993) was a frequent target, as it is merely 1.339 ± 0.002 pc (Söderhjelm 1999) away and the Sun's nearest neighbour. But it turned out to be significantly more metal rich ([Fe/H]=0.24 ± 0.03 dex) and hotter ($T_{\text{eff}} = 5847 \pm 27$ K, Porto de Mello et al. 2008) than the Sun. Other stars like HD 44594 became new favourites (Cayrel de Strobel & Bentolila 1989), though that also proved to be too metal rich ([Fe/H]=0.15 ± 0.01 dex) and too hot ($T_{\text{eff}} = 5840 \pm 14$ K, Sousa et al. 2008). Also during the 1990s and after 2000, only a few more stars were studied more closely as likely solar twins, like 16 Cyg A and B (Friel et al. 1993; King et al. 1997) and 18 Sco (HD146233) (Porto de Mello & da Silva 1997; Soubiran & Triaud 2004). The latter is still one of the closest solar twins claimed, as its radius $R = (1.010\pm0.009)$ R$_\odot$ and mass $M = (1.02\pm0.03)$ M$_\odot$ were confirmed, by combining interferometry and asteroseismology, to be within a few percent of the solar values (Bazot et al. 2011).
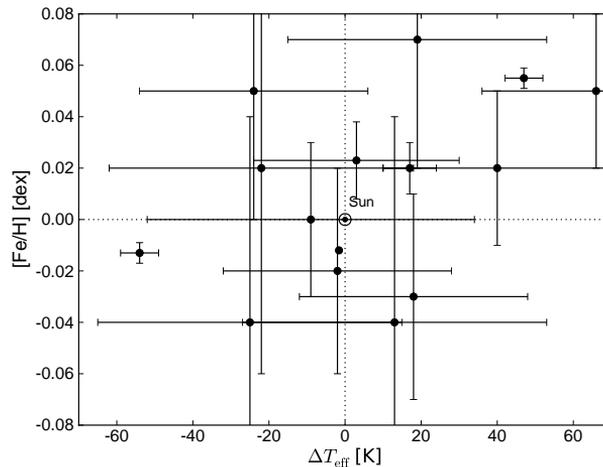

Figure 2.5: Twins from Table 2.1 showing the differences to the solar values, including errors. The position of the Sun is marked.

After the year 2000, surveys started to specifically look for solar twin stars (Porto de Mello et al. 2000; Hamilton et al. 2003). More detailed analysis of the previously suspected solar twins became more popular, as the analysis methods became more accurate. Recent additions to the group of close twins were HD 98618 (Meléndez et al. 2006), HIP 100963 (HD195034) (Takeda et al. 2007) and HIP 56948 (HD101364) (Meléndez & Ramírez 2007). However the first two proved to have elevated lithium abundances (0.47 ± 0.09 dex and 0.60 ± 0.07 dex, respectively, with the solar value being 0 by definition), whereas HIP 56948 is closer to the Sun also in that respect, having a lithium abundance of 0.23 ± 0.05 dex (Meléndez et al. 2012).

With the number of solar twins increasing it then became possible to make comparisons between the Sun and solar twins to look for distinct differences. Earlier, Lambert & Reddy (2004) found that the Sun seemed to have less lithium (factor of 10) than other solar–type disk stars, giving rise to the conclusion that the Sun was peculiar in its lithium content. This discussion was again addressed when it became possible to compare the Sun to solar twins, not only solar–type stars and still remains under debate, especially as there are indications that when comparing solar–like stars with and without planets, a low Li abundance might be related to planet formation (Meléndez & Ramírez 2007; Meléndez et al. 2010; Baumann et al. 2010). Additionally it is discussed that the Li content might also be merely decreasing with age and any other interpretation is a bias in the data. Studies have been made, determining ages of solar twins and analogues by means of isochrone fitting or stellar evolutionary tracks (Takeda et al. 2007; Monroe et al. 2013) and looking at their Li abundances, which show these trends.

Linked to this, at the same time, Meléndez et al. (2009) and Ramírez et al. (2009, 2010) found a way to possibly determine the existence of terrestrial planets from elemental abundances in the host stars. They found very specific abundance patterns in the refractory versus volatile elements in the Sun and planet host stars, with respect to stars with no known planets. In solar twin stars there seems to be an overabundance of refractory elements, compared to the Sun and planet host stars; a difference that, for the Sun, can be removed when adding all refractory elements from the terrestrial planets in the solar system. However, whether this is a genuine signature of terrestrial planet formation remains under debate, as e.g. studies of solar twins stars in the open cluster M67 suggest that these specific abundance patterns can be explained by the stars' birth environment instead

Önehag et al. (2014). Ultimately this requires more data to be better determined. Our sample of 15 solar twins, for which we have UVES data available, will contribute to this line of research (see Chapter 6).

Table 2.1: A compilation of Solar twins from the past ten years. Values are taken from Porto de Mello et al. (2014) (Po14), Monroe et al. (2013) (Mo13), Meléndez et al. (2012) (Me12), Schuler et al. (2011) (Sc11), Önehag et al. (2011) (On11), Takeda et al. (2007) (Ta07), Meléndez et al. (2006) (Me06) and King et al. (2005) (Ki05). Authors marked with (*) give differences to the solar values, not absolute values. Note that Ta07 give no errors.

Name	T_{eff} [K]	$\log g$ [dex]	[Fe/H] [dex]	Source
16 Cyg A	5796 ± 34	4.38 ± 0.12	0.07 ± 0.05	Sc11
16 Cyg B	5753 ± 30	4.40 ± 0.12	0.05 ± 0.05	Sc11
HD98618	66 ± 30	0.01 ± 0.03	0.05 ± 0.03	Me06*
HD98649	5775 ± 30	4.44 ± 0.08	-0.02 ± 0.04	Po14
HD101364	17 ± 7	0.02 ± 0.02	0.02 ± 0.01	Me12*
HD118595	5755 ± 40	4.44 ± 0.08	0.02 ± 0.08	Po14
HD143436	5768 ± 43	4.28 ± 0.12	-0.00 ± 0.03	Ki05
HD146233	5795 ± 30	4.42 ± 0.05	-0.03 ± 0.04	Po14
	5824 ± 5	4.45 ± 0.02	0.055 ± 0.004	Mo13
	40 ± 30	0.01 ± 0.02	0.02 ± 0.03	Me06*
HD150248	5750 ± 40	4.39 ± 0.06	-0.04 ± 0.08	Po14
HD164595	5790 ± 40	4.44 ± 0.05	-0.04 ± 0.08	Po14
HD195034	-1.6	-0.026	-0.012	Ta07*
HD197027	5723 ± 5	4.35 ± 0.02	-0.013 ± 0.004	Mo13
M67–1194	5780 ± 27	4.44 ± 0.04	0.023 ± 0.015	On11

Table 2.1 summarises the Solar twins claimed in the last decade by various authors, using various definitions thereof (see Section 2.3). Fig. 2.5

shows these twins and how close to solar they are. Differences to the solar values are plotted and the position of the Sun clearly marked. It can be seen that there are a few targets that are solar within the errors, whereas some clearly have the wrong effective temperatures and metallicities. However, for a final decision on whether or not these twins are solar or only close to solar, one needs better data and closer inspection.

Chapter 3

Galactic Surveys and stellar parameters

3.1 The era of Galactic Surveys

We are living in an epoch when large Galactic Surveys are becoming increasingly more important, as means of understanding the evolutionary history of the Milky Way, also as a key to galaxy evolution and cosmology at large. These large surveys and catalogues of stellar parameters include the HIPPARCOS mission in the 1990s (Perryman et al. 1997; van Leeuwen 2007), Two Micron All-Sky Survey (2MASS, Skrutskie et al. 1995), Sloan Digital Sky Survey (SDSS, York et al. 2000) and the Sloan Extension for Galactic Understanding and Exploration (SEGUE, Yanny et al. 2009), the Geneva-Copenhagen-Survey (GCS, Nordström et al. 2004; Holmberg, Nordström & Andersen 2007, 2009) and RAdial Velocity Experiment (RAVE Steinmetz 2003). Currently we are eagerly awaiting data from HERMES/GALAH (Freeman 2010), the Gaia-ESO survey (GES, Gilmore et al. 2012), the LAMOST Experiment for Galactic Understanding and Explorations survey of the Milky Way structure (LEAGUE, Deng et al. 2012) and Gaia (GAIA, Munari 2003), which will provide us with a deep, comprehensive census of the stellar populations in the Milky Way. All these surveys produce huge amounts of data, accessible to all. They however do not merely provide images or spectra that have been taken, but some of them also derive parameters for their target objects. Therefore calibrating the survey data is one of the most important tasks of the astronomers involved.

Depending on the survey, the data consists of images taken with specific narrow-band or broad-band filters, or spectra taken over different wave-

length ranges. HIPPARCOS and TYCHO gave positions, parallaxes and magnitudes in 3 different colours H_P, B_T and V_T, the latter two are close to the Johnson-Cousins B and V filters, 2MASS took images in the near-infrared (NIR) and delivered NIR magnitudes in J, H and K and SDSS gave optical colours in its own photometric system (SDSS filters). The GCS used the Strömgren filter system (see Fig. 3.1 for a comparison of these systems).

Surveys like RAVE, HERMES/GALAH, Gaia-ESO and LEAGUE are spectroscopic and therefore take spectra in the visible wavelength range.

The next large upcoming survey of stars Gaia, has the main purpose of astrometry (positions, distances and proper motions); it will provide magnitudes in its own system, called G-magnitudes, which is a very broad range (3300 Å to 10000 Å), cut into two parts: the blue part $G_{BP} = 3300-6800$ Å and the red part $G_{RP} = 6400-10000$ Å. The integrated flux over those ranges will give the G-magnitudes, which will provide stellar parameters through colour relations. Secondly, it will provide low resolution spectra for BP and RP spectrophotometry ($R < 100$) and finally medium resolution (R=11,500) spectra around 8470-8740 Å aimed at radial velocity determination around the CaII triplet and another colour G_{RVS} (Jordi et al. 2010).

Note that for all surveys many standard stars have to be observed to make sure that the internal scales are consistent and that e.g. the magnitudes that are being provided are correctly extracted (e.g Omongain 1986; Nikolaev et al. 2000; Pancino 2012b; Francis 2013).

To translate these images and spectra into stellar parameters that can be used for further analysis, there is a need to find fundamental relations between the observables and the quantities one aims to derive. Ideally this would mean including stars with well known parameters in the survey. Then one could easily see what they look like in the survey colours or spectral range and then translate that into the known values. One target like that would be the Sun. However, as remarked before, the Sun is too bright to be used for these purposes. Therefore other means are necessary.

3.2 Methods to calibrate stellar temperatures

The calibration of stellar parameters has been extensively studied in the past. In the mid to late 20th century, the studies focussed on calibrations of one specific parameter, like effective temperature (e.g. Mel'Nikov 1958; Kienle & Labs 1973; Magain 1987) or rotation (e.g. Labonte 1982), or mak-
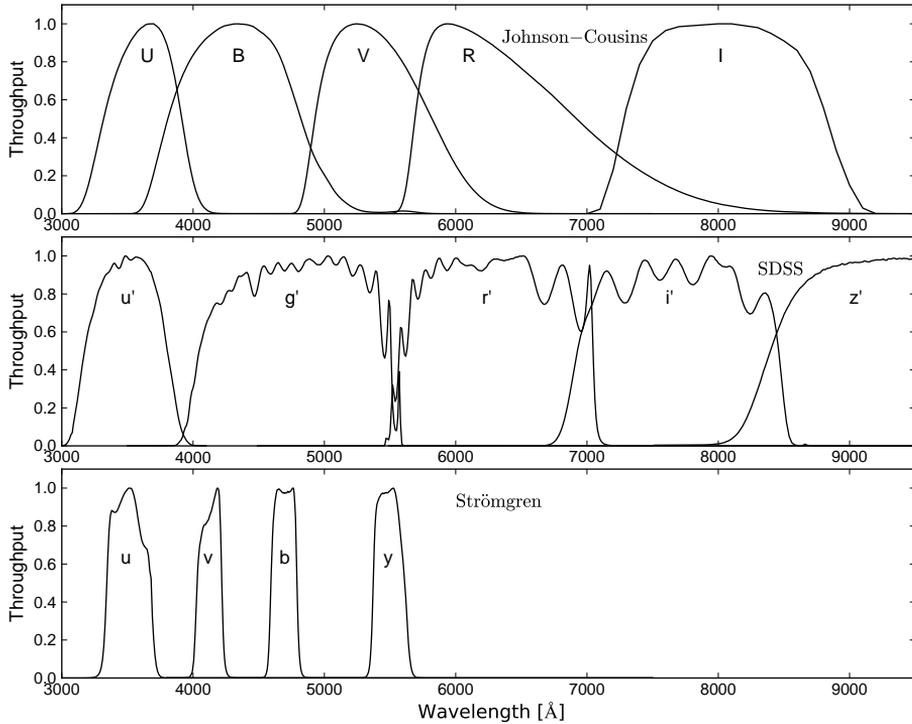
Figure 3.1: Filter transmission curves for different filter systems. Note how the throughput for every filter system is different. Values are taken from the Nordic-Optical-Telescope (NOT) filter webpage and Bessell (2005). All curves are normalised to have maximum throughput of value 1.

ing comparisons of the stellar spectrum to the solar spectrum (e.g. Lind & Dravins 1980). Also today astronomers look for the most accurate calibrations of effective temperatures, metallicity, etc. (e.g. Sousa et al. 2010; Worthey & Lee 2011; Wallerstein et al. 2012) with most of them using scales set relative to well measured benchmark stars.

There are different methods to achieve these calibrations, some being more fundamental and direct than others. As discussed in Chapter 1 and Section 2.4 the most fundamental method to determine stellar effective temperatures is interferometry, through measuring stellar angular diame-

ters and thus their radii. Then, through the use of Eq. 1.3 one can calculate effective temperatures. To date this is only possible for very nearby main sequence and/or physically large stars (i.e. giants). In the following I present other methods used to calibrate past and ongoing large surveys.

3.2.1 The Infra-Red-Flux-Method

As early as the 1970s Blackwell & Shallis (1977) (see also Blackwell et al. 1979) found a way to determine the angular diameter and effective temperature of a star by means of flux ratios. They named it the Infra-Red Flux Method (IRFM) and it is based on the fundamental equation for photometric stellar effective temperatures (Eq. 1.3), which can be rewritten as:

$$F_{\text{bol}}(S) = \sigma T_{\text{eff}}^4, \tag{3.1}$$

with $F_{\text{bol}}(S)$ being the star's bolometric surface flux. As we measure the flux arriving at the Earth's atmosphere, the equation becomes:

$$F_{\text{bol}}(E) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\text{eff}}^4, \tag{3.2}$$

with θ being the star's angular diameter. This relation can be generalised to be used on monochromatic stellar fluxes:

$$F_\lambda(E) = \left(\frac{\theta}{2}\right)^2 \phi(T_{\text{eff}}, g, \lambda, [\text{Fe/H}]), \tag{3.3}$$

where ϕ is the surface flux of the star in the given wavelength and depends on the star's effective temperature, gravity, the observed wavelength and metallicity. As the name implies, the IRFM is based on infrared wavelengths, as the stellar spectra show hardly any dependance on metallicity and gravity in that region, which corresponds to the Rayleigh-Jeans tail of the spectrum (for stellar effective temperatures above 4500 K; see Fig. 3.2).

The fluxes are almost purely dependant on effective temperature, thus eliminating the other dependancies (see also Fig. 3.2):
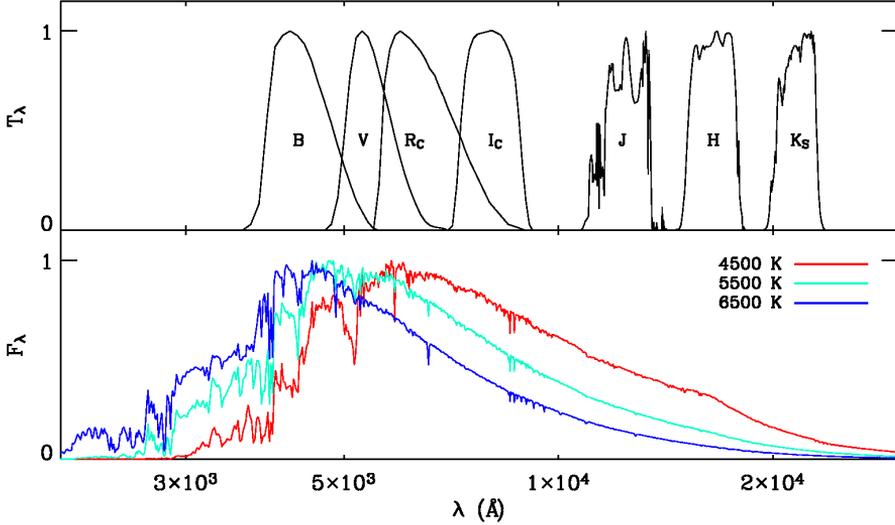
Figure 3.2: Shown are the Johnson-Cousins and 2MASS filters and spectra for three stars at different temperatures. It is clear that in the infrared (J, H and K bands) for stars hotter than 4500 K, the spectra show hardly any spectral lines and are very smooth, thus being almost purely dependant on effective temperature. Taken from Casagrande et al. (2010) (their figure 2).

$$F_{\mathrm{NIR}}(E) \simeq \left(\frac{\theta}{2}\right)^2 \phi(T_{\mathrm{eff}}). \tag{3.4}$$

The main equation of the method is given by

$$\frac{F_{\mathrm{bol}}(E)}{F_{\mathrm{NIR}}(E)} = \frac{\left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4}{\left(\frac{\theta}{2}\right)^2 \phi(T_{\mathrm{eff}})} = \frac{F_{\mathrm{bol}}(S)}{F_{\mathrm{NIR}}(S)}, \tag{3.5}$$

which states, that the flux ratio of the star's total flux and the infrared flux, as measured on Earth is equal to the ratio of the surface fluxes and the dependance on the angular diameter is eliminated. The right-hand side

requires stellar models and cannot be directly observed. However, as the flux ratio above is almost only dependant on effective temperature, contrary to other model-dependant methods that are sensitive to gravities, metallicities, etc. the IRFM can easily iterate towards reliable effective temperatures and therefore is considered one of the more fundamental methods for stellar temperature determination. As a purely photometric method, it is sensitive to reddening and the absolute flux calibrations of the input photometry (Casagrande et al. 2006, 2010; see also Paper III).

3.2.2 The surface brightness method

Using the basic definitions of apparent magnitude m (Eq. 2.1), absolute magnitude M (Eq. 2.2) and luminosity L (Eq. 1.3) the key relationship for this method can be derived as:

$$m - s + 5 \log_{10} \theta = 0, \qquad (3.6)$$

where s is the surface brightness (on the magnitude scale) and θ is the angular diameter (in arcsec). Using the surface brightness as a means to determine stellar diameters was first mentioned by Pickering (1880). Later Russell (1920) assumed that s would show a linear relationship with the colour index and Hertzsprung (1922) tried to calculate the diameters through Planck's radiation law (Eq. 1.1).

In the late 1960s and 1970s Wesselink et al. (1969, 1972) realised that the method could be applied to any given photometric band (e.g. V):

$$s_V = m_V + 5 \log_{10} \theta, \qquad (3.7)$$

with m_V being the absorption corrected magnitude in the V-band. Using magnitudes and angular diameters of a few known stars, Wesselink et al. (1969) found a strong correlation between s_V and different colour indices, like $(B-V)$, therefore providing a way to infer surface brightnesses for stars with unknown angular diameters from colours. Then through Eq. 3.7 it is possible to calculate their angular diameters and effective temperatures.

Note that the IRFM is completely independent of interferometry or any other method to predetermine some stellar parameters to anchor the calibration to, while the surface-brightness method needs interferometric

data for the initial calibration.

3.2.3   Other photometric and spectroscopic methods

Buser & Kurucz (1978) favoured an approach to derive stellar parameters via stellar models. They computed synthetic colours and colour indices for a grid of stellar parameters to be able to determine the most probable parameters of a star when given its observed colours.

In the case of hot A- and B-type stars the slope of the Paschen continuum, which covers the spectral range of 3647 Å to 8207 Å can be used to determine stellar temperatures (e.g. Wolff et al. 1968; Tur et al. 1995). For higher temperatures ($T_{eff} > 10,000$ K) this method loses sensitivity, as the peak of the SED lies too far in the UV, making the UV Balmer continuum (912 Å to 3647 Å) a more appropriate region for measurement. On the other hand, for stars cooler than B stars, the extensive absorption in the spectrum becomes a problem, therefore this method only has a small working temperature region.

Another method, that uses distinctive spectral features, is to determine temperatures from the Balmer jump in the spectrum. At a wavelength of $\lambda = 3647$ Å, which is where the Balmer continuum starts, stellar spectra show a jump in the flux level. The strength of this jump is temperature sensitive (e.g. Chalonge & Divan 1952; Gray 1968). This method is also mostly useful for hot stars, as in cooler ones the Balmer jump is masked by metal absorption lines.

Apart from using continuum features, there are also methods to determine stellar temperatures from spectral lines, for example the Hydrogen lines or metal lines. In case of the Hydrogen lines, the idea is that the shape of the lines is strongly temperature dependant, but negligibly gravity dependant, as can be seen from modelling. However it may be difficult to measure these lines to a high enough precision, as they are very strong and wide and therefore blended and superimposed with many other features. Additionally the flux calibration as a function of wavelength needs to be very accurate. This makes extensive profile fitting of the lines necessary or the use of stellar models (Soderblom 1986) to determine the stellar temperatures. Alternatively the use of metal lines is possible, however these methods are not very straightforward. The shape and size of the metal lines are sensitive not only to temperature, but also to metallicity and gravity. Some lines are more dependent than others, therefore it is essential to select

the best suited lines. One common method to determine stellar effective
temperatures is from line depth ratios (Gray & Johanson 1991). Carefully
chosen pairs of spectral lines show opposite behaviour with different exci-
tation temperature, and therefore can be calibrated to these. The exact
methods and challenges for this will be discussed in the next chapter.

Another essential stellar parameter is surface gravity. Most of its indi-
cators, like the Balmer jump and the shape of the strong absorption lines
are however also strongly temperature sensitive, making it difficult to sep-
arate them. Therefore most methods to derive gravities simultaneously
derive effective temperatures. There is one fundamental way to calculate
surface gravities: through binaries. In these cases stellar mass and radius
are easily determined (Olson 1975; Popper 1980) and their gravities can be
calculated from Eq. 2.10. Gravities for other stars can then be inferred by
using calibrated relations with colour indices.

Finally, metallicity is also strongly linked to the adopted temperature
scale as will be discussed in detail in the next chapter.

3.3   Application of the methods for Galactic Surveys

Many studies have been made taking the IRFM and the temperatures de-
rived with it, to calibrate other parameters, e.g. colours to it. Alonso et al.
(1996) give an extensive list of relations between effective temperatures and
different colour indices, like $(B - V)$, $(R - I)$, etc. in the Johnson photo-
metric system but also $(b - y)$ in the Strömgren photometric system. Their
equations also include metallicity, therefore fitting effective temperature
and metallicity to the observed colours. The extension of these relations to
also e.g. the Cousins system was done by Meléndez & Ramírez (2003).

Having found relations between observable colours of stars and their
fundamental parameters then allowed large surveys to give stellar param-
eters on larger scales. For example the GCS-I (Nordström et al. 2004)
used the Alonso et al. (1996) and the Schuster & Nissen (1989) relations
in Strömgren colours to measure effective temperatures and metallicities,
respectively.

Others have been using the colour calibrations from the surface bright-
ness method to anchor their values. These are based on a sample of stars
with known angular diameters and an empirical relationship to colour in-

dices. di Benedetto (1993, 1998) was one of the pioneers in establishing a large scale temperature relation based on this method. To ensure minimal scatter and therefore smallest errors for the resulting effective temperatures, he recommended using the $(V - K)$ colour.

In two later releases of the GCS catalogue (versions II and III, Holmberg et al. 2007, 2009) the temperature calibration was updated using the di Benedetto (1998) scale, by converting the $(V - K)$ or even $(B - V)$ relations to Strömgren colours $(b - y)$. Casagrande et al. (2011) (C11) revisited the GCS-III and reevaluated their effective temperatures and metallicities by using directly the IRFM on about half of the catalogue and corresponding colour calibrations on the other half. They found that their values were on average 100 K hotter and 0.1 dex more metal rich than in the GCS-III. This difference is partly due to different temperature scales used (Casagrande IRFM implementation versus di Benedetto surface-brightness relations) and partly due to additional scatter when translating to the $(b - y)$ colour relations (see Paper III). In Fig. 3.3 for a sample of solar-type stars it can be easily seen that the GCS-III and C11 values of effective temperature and metallicity show a 1:1 slope, meaning they are mutually consistent, but with the previously mentioned offsets. This is one example where systematic differences between different scales are larger than the internal errors of the method — and the one I have specifically addressed in my papers.

The recent RAVE survey determined radial velocities and proper motions from the spectra, however in addition it also provided stellar parameters, by comparison or interpolation within a library of theoretical spectra, using the Kurucz models of stellar atmospheres (Siebert et al. 2011).

Also the ongoing surveys HERMES/GALAH and Gaia-ESO are spectroscopic and provide spectra at different resolutions and stellar parameters which have been determined through different models and partially through comparisons with the Sun. The latter is however only helpful for dwarf stars of solar metallicity (Pancino & Gaia-ESO Survey consortium 2012a) and does not work e.g. for metal-poor giants.

In addition Gaia-ESO uses 34 so-called benchmark stars to secure their calibration. These have well determined effective temperatures and surface gravities, through known stellar radii, absolute fluxes and in some cases the surface-brightness method (Heiter et al. 2015, in prep.); and corresponding metallicities, through many different methods (Jofré et al. 2014).

The Gaia-ESO benchmark stars will also be the base to calibrate stellar parameters from Gaia colours.
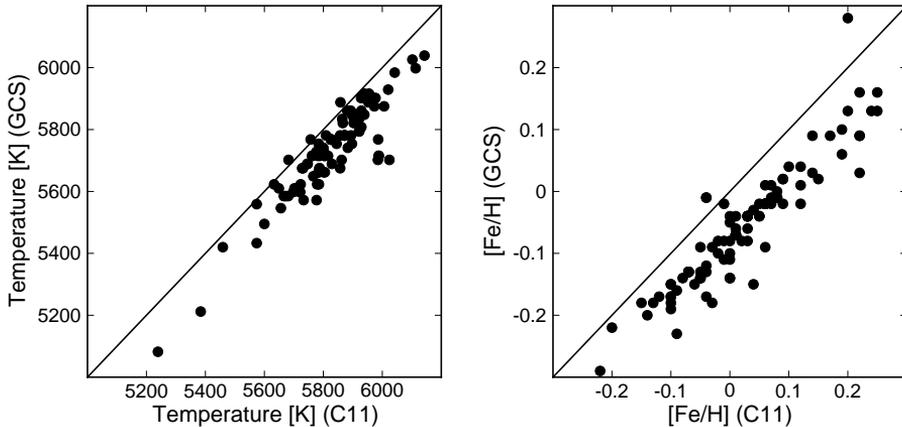
Figure 3.3: Comparison of effective temperatures and metallicities from the GCS-III and C11 for a sample of 95 solar analogue stars, which were used in Paper I. As can be seen the GCS and the C11 are mutually consistent, as there is a 1:1 slope relation between the two catalogues, however in comparison they are offset in both effective temperature and metallicity by ≈ 100 K and ≈ 0.1 dex, respectively. See also figure 2 in Casagrande et al. (2011).

Testing the calibrations   There are ways to test if a catalogue is giving well calibrated values. One possibility is to use stars for which one knows the parameters very accurately and then check what these correspond to in the catalogues which is being examined. For a thorough examination a sample of stars with well known parameters is needed, which cover the whole range of effective temperatures, metallicities, etc. This is crucial, but also difficult, as we do not have many stars with well known parameters. However, for the solar-type region of the parameter space, it is possible to use solar twins and analogues to determine the catalogue calibrations. This was one of the themes of my work. In Paper I, II and IV I have shown an independent way to test the temperature and metallicity scales around the solar values, examining the two alternative calibrations of the GCS (GCS-III and C11), favouring the latter. The methods I have developed can in principle be applied to any calibrated stellar catalogue, and extended to non–solar values using other well-known reference stars than the Sun.

Chapter 4

Spectroscopic analysis of solar analogues

There are different ways to measure the fundamental physical parameters of a star from spectra. For example, the shape of the overall spectrum depends on the stellar effective temperature, as discussed in Chapter 1 (see Fig. 1.2). However, to get more information on the composition and surface gravity in as much detail as possible, the spectrum ideally should have a high resolution and spectral coverage. It would take a large effort to achieve that and keep the shape of the continuum intact. Nowadays echelle spectrographs are widely used to record the target spectra, which are cut into short sections of wavelength at very high resolution and can be stitched together to form one long spectrum. The continuum shape information is lost and the stellar temperature is extracted from spectral lines, as well as the metallicity and surface gravity, rather than the continuum. This is a completely independent method to determine stellar parameters, without relying on the shape of the continuum.

4.1   Equivalent widths and TWOSPEC

The most widely used way to determine stellar parameters is through equivalent width (EW) measurements of selected spectral lines, especially iron lines. As mentioned in previous chapters, the appearance (depth, width, overall shape) of the spectral lines depends on the stellar parameters. The EW is defined as the width of a rectangle under the continuum level of the spectrum, which covers the same area as the spectral line (see Fig. 4.1). If the line is not blended, meaning it is single and isolated, not an overlap of

two or more lines (see Fig. 1.3) and therefore completely resolved in the spectrum (apart from the instrumental broadening), the resolving power of the used spectrograph matters less in this analysis, though the higher resolving power is always the preferred option, as it allows more lines to be used to determine the stellar parameters.
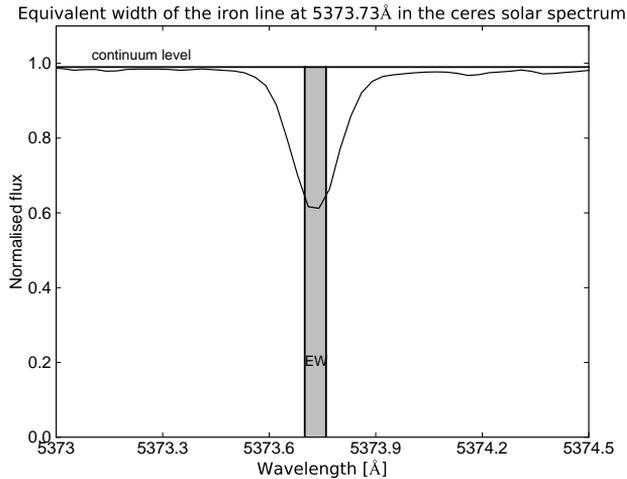

Figure 4.1: The $5373.73\,\text{Å}$ iron line in the solar reference spectrum of the asteroid Ceres, taken with the FEROS instrument on the $2.2\,\text{m}$ MPG/ESO telescope on La Silla. The resolving power is $R = 48,000$. The line's equivalent width is shown in grey and covers the same area as the amount of light absorbed in the spectral line.

There are different ways to measure the EWs. As a first step it is important to have a well determined continuum level around the line. If the level is increasing or decreasing the measured EW could be erroneous and not usable, unless carefully fitted with a sloped continuum. It is therefore not surprising, that flattening and normalising the spectrum is one of the first steps when analysing them. Only lines with a good local continuum tend to be used, if available. Secondly, the line should not be blended, meaning it should be a single line without any overlap from other lines. This means all lines should be isolated, or at least resolved well enough to be fit. Thirdly, the lines should not be saturated, because then the central part of

the line is strongly depleted of light and is no longer linearly correlated with the abundance of the given element. Once these requirements are fulfilled the actual line can be measured, for which different methods can be used. In most cases the spectral lines are fitted, using different profiles, like e.g. a Gaussian and the area (or EW) estimated from these fits. However, in my work, I have used a slightly different approach, which will be discussed in more detail shortly.

To be able to analyse a large number of spectra with a large number of spectral lines, I needed a way to do these calculations in as automated a way as possible, so I used a code to do the measurements for me, called TWOSPEC (Flynn, 2010, private communication). This program, written in FORTRAN, is optimised to differentially compare lines in two spectra with one another and to measure the equivalent widths and line depths for all lines in a given line list. The code does not fit any profiles to the spectral line, but instead computes the amount of missing light under the continuum in a $300\,\text{m\AA}$ window around the line. Tests I did by fitting Gaussian profiles to the lines using standard programs like IRAF were found to be no more accurate, i.e. the scatter in the EW measurements did not change, so this simpler method was used. For example, when analysing a list of 95 lines in the spectrum of HD147513, compared to Ceres, we achieved a scatter of only $1.4\,\text{m\AA}$ with our technique, compared to the $1.9\,\text{m\AA}$ scatter when using standard techniques. It requires a very well placed continuum in both the target and reference spectrum which is achieved by the code normalising the two spectra by the total flux in a $10\,\text{\AA}$ window around every target spectral line. This has the advantage, that when looking for solar twins, stars that are not close twins will show significant differences in the continuum fitting, as the slightly different widths of the spectral lines will also change the continuum level, set by the program, thus emphasising its difference to the Sun. Finally the line depths, which are also sometimes used, are computed by fitting a parabola to the three lowest points in the line, to find the point of least light.

In my work I have used a purely differential analysis to look for solar twins and to test the temperature and metallicity scales of the GCS-III and C11 catalogues. The exact methods are based on approaches found in the literature and new ones we developed; most of which use the following quantities, which are calculated in TWOSPEC. For some examples see Fig. 4.2:

- median difference in relative equivalent width $\langle \Delta \mathrm{EW} \rangle$ of selected spectral lines

$$\langle \Delta \mathrm{EW} \rangle = \langle (\mathrm{EW}_\star - \mathrm{EW}_\odot)/\mathrm{EW}_\odot \rangle, \qquad (4.1)$$

- median difference in relative line depth $\langle \Delta \mathrm{LD} \rangle$ of selected spectral lines

$$\langle \Delta \mathrm{LD} \rangle = \langle (\mathrm{LD}_\star - \mathrm{LD}_\odot)/\mathrm{LD}_\odot \rangle, \qquad (4.2)$$

- the scatter χ^2 in the difference in relative equivalent widths

$$\chi^2(\Delta \mathrm{EW}_{\mathrm{all}}) = \sum_{i=1..\mathrm{N}} ((\mathrm{EW}_{i,\star} - \mathrm{EW}_{i,\odot})/\mathrm{EW}_{i,\odot})^2, \qquad (4.3)$$

- the slope of a linear fit to the difference in equivalent width (or line depth) versus the excitation potential of the line.

The main idea is that the median difference in equivalent width and line depth, as well as the slope of these quantities versus the excitation potential should be zero for a solar twin. For a more detailed description of these quantities and how they were used see sections 4 and 5 in Paper I, as well as sections 3 and 4 in Paper II.

Note that all these relations are optimised for the differential analysis, immediately comparing the target's values with the solar comparison spectrum's values. Therefore this analysis can only determine which stars are solar twins, or how similar a star is to the Sun, but it does not yield directly measured stellar parameters for them. For that, one needs to do an accurate analysis of the spectral lines of the star to carefully determine the underlying effective temperature, metallicity and surface gravity. This was done in Paper IV as detailed in the next section.

4.2 Spectroscopic stellar parameters

For Paper IV, besides the above mentioned differential analysis, the idea was to not only test the values for the stellar parameters, that others have published, but to derive our own values. As mentioned before, the common way to determine spectroscopic stellar parameters is by measuring the
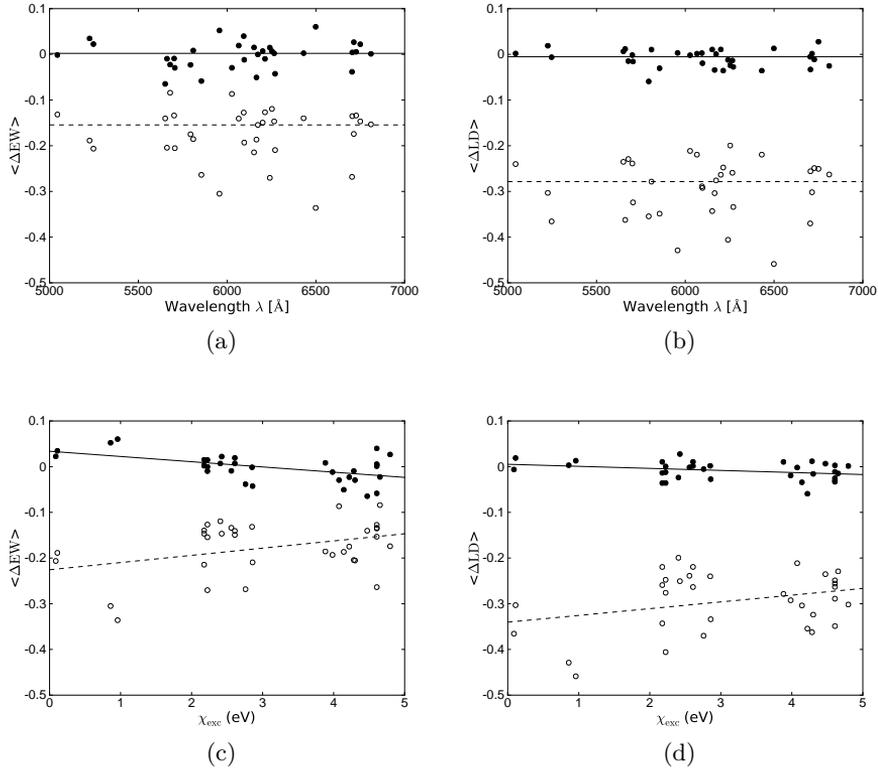
Figure 4.2: The relative difference in equivalent width or line depth versus the wavelength or excitation potential of the corresponding neutral iron lines for the two stars HD126525 (filled circles and solid lines) and HD7727 (open circles and dashed lines). In (a) and (b) the lines show the median values of the relative differences. The closer these are to zero, the more likely the star is a solar twin (see also Eq. 4.1 and Eq. 4.2). In (c) and (d) the lines show the linear fit to the relative differences versus the excitation potential for the same two stars. The closer the slope of these lines is to zero, the more likely the star is a solar twin. Looking at all four plots, it is clear that HD126525 is a solar twin and HD7727 is not.

equivalent width of as many weak, unblended and isolated iron lines as possible and to calculate the corresponding iron abundances (see Fig. 4.3).
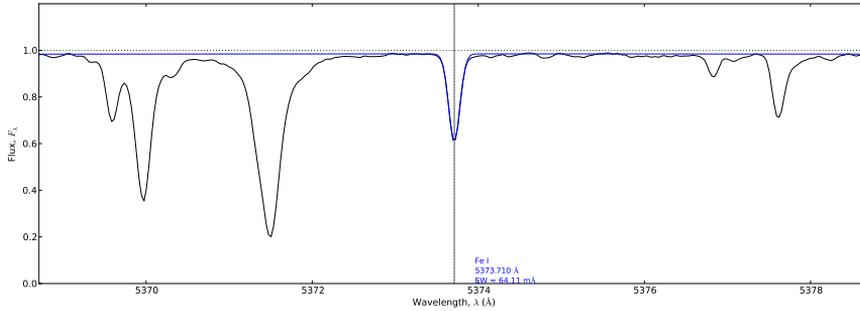
Figure 4.3: The iron line at $5373.710\,\text{Å}$ in the Ceres spectrum taken with the FEROS instrument at a resolution of $R = 48,000$, compare also to Fig. 4.1, fitted with a Gaussian (blue line) to determine its equivalent width. Shown is Flux versus wavelength. The plot is taken from the Graphical User Interface(GUI) of the SMH code used in Paper IV.

This is then compared to a grid of stellar model atmospheres with a broad coverage of physical parameters (T_{eff}, $\log g$, [Fe/H], etc.) to find the model, that fits the measured values best. The abundances derived from every neutral iron line should ideally be identical and independent of excitation potential or reduced equivalent width (EW divided by its wavelength). If the model has the wrong effective temperature and/or surface gravity, these quantities will show correlations and the model needs to be adjusted. This is an iterative process, as all dependancies are interconnected, meaning that one cannot solve for effective temperature, then for gravity, etc. but all have to be taken into account simultaneously. In addition one needs a well developed grid of stellar model atmospheres. Assuming that a set of equivalent widths for the iron lines have been measured, the usual steps are as follows:

- Step one: Using a set of initial estimates for the stellar parameters (e.g. using solar values when looking at solar-type stars), the iron abundance for every measured iron line is determined in the grid of stellar models. These usually gives a range of values that scatter around an average.

- Step two: The excitation balance. Every spectral line which formed from the neutral species of iron should give the same abundance and

show no trend with other parameters like the excitation potential. Therefore a plot of the abundance of all lines versus their excitation potentials indicates whether the model used has the correct effective temperature or not. If there is any significant slope and thus a trend in this relation, the effective temperature used in the model is wrong. It is then changed and steps one and two redone, until there is no correlation. In Fig. 4.4 the top panel shows this plot for Ceres used in Paper IV. The black line, which corresponds to the neutral iron lines shows no correlation.

- Step three: The abundances versus their reduced equivalent width are plotted, the model microturbulence changed and all steps redone until there is no correlation.[1] This is shown in the middle panel in Fig. 4.4.

- Step four: Ionisation balance. The abundances resulting from the neutral lines should be the same as the abundance from the singly ionised lines. If they differ significantly, the model most likely has the wrong surface gravity. The average abundance for neutral iron is compared to the abundance for singly ionised iron and the model surface gravity changed until both abundances are the same within the errors. The previous steps are checked and redone if necessary until all correlations are minimal.

- Step five: After checking that all correlations are as small as possible, the final average iron abundance from step four for the neutral and singly ionised lines equals the target's metallicity.

It is generally not possible to merely go through the steps one by one once, as every change of parameter will change the results of all balances, therefore one needs to adjust iteratively all the parameters combined, until all slopes are minimal within small errors and thus the balances are given.

This process can be tedious to do by hand, therefore to be more efficient and consistent I used the SPECTROSCOPY MADE HARD — SMH code by Casey (2014) to determine the stellar parameters in Paper IV. The code is written in PYTHON and has a user friendly Graphical User Interface (GUI). The code combines spectrum normalisation, which is necessary to have a

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[1]The microturbulence is a fudge factor used in 1D models to account for 3D turbulent motions, not an intrinsic stellar parameter and thus not further discussed.

straight continuum; radial velocity determination and shift to ensure that the lines are at rest wavelength; equivalent width measurements by fitting different optional fits (for Paper IV I only used Gaussian fits for these, see also Fig. 4.3); stellar parameter determinations using the MOOG spectral synthesis code by Sneden (1973) and a choice of theoretical models (in Paper IV I used the MARCS 2011 models by Gustafsson et al. 2008); elemental abundance calculations, based on the stellar parameters determined before and even spectral line synthesis, in case of heavily blended lines. Note, that contrary to the TWOSPEC analysis discussed in the previous section, our MOOG – SMH spectroscopic parameters are not the result of a differential approach, as the analysis works without a solar spectrum for comparison. However we did use a solar reflected asteroid spectrum to get formal spectroscopic solar values for an overall zero–point correction.

In Paper IV I used this process on two samples of FEROS spectra with a resolution of $R = 48,000$, covering a wavelength range of $3500 - 9200\,\text{Å}$, taken at the $2.2\,\text{m}$ MPG/ESO telescope on La Silla. The typical signal-to-noise (S/N) values were around 150. Looking at spectra for 147 stars and using a line list of 80 lines for neutral and 7 for ionised iron (taken from Biazzo et al. 2012) I determined spectroscopic effective temperatures, metallicities and surface gravities, which agree well with literature values and lie within $2\,\sigma$ (σ is the scatter) of eachother. (For full details see Paper IV, Section 3.)
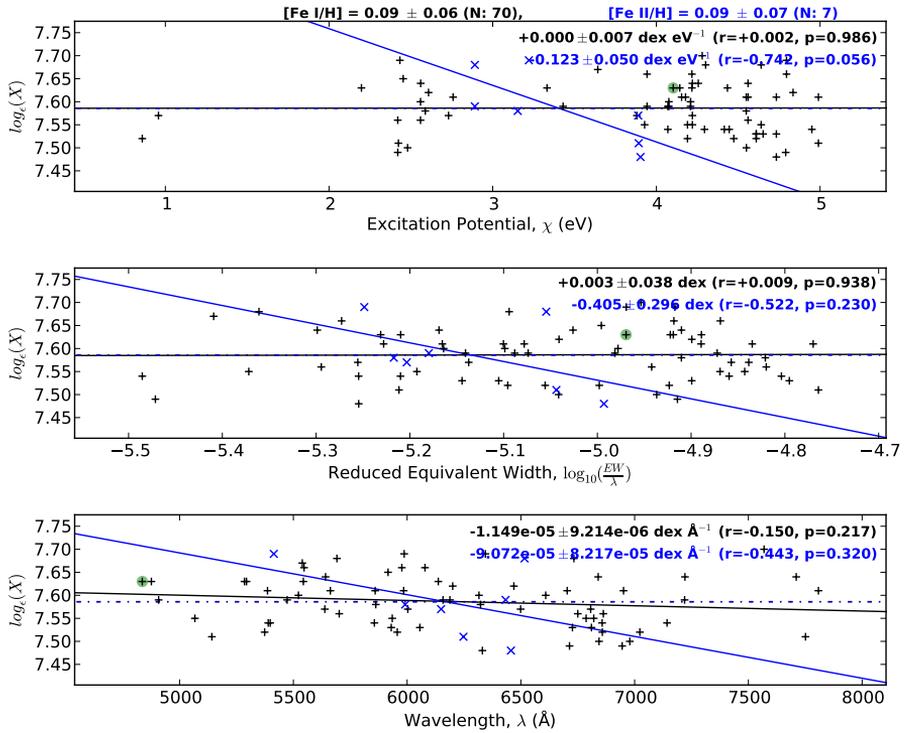
Figure 4.4: The three panels show the abundance of element X, in this case iron, versus the excitation potential at the top, the reduced equivalent width in the middle and the wavelength at the bottom and is taken from the GUI of the smh code used in Paper IV to determine stellar parameters. Black plusses and lines are used for neutral iron, blue crosses and lines for singly ionised iron. Also the calculated fits are given, as well as the error, the correlation coefficient and a probability that the slope is zero. Average abundances are given as dotted lines and quoted above the plots. The top and the middle panel show plots for steps two and three, to check that the abundances determined from all iron lines does not correlate with their excitation potential or reduced equivalent width. Ideally the slopes for lines of neutral iron (black) should be as close to zero as possible. They show if there is a necessity to change the underlying model effective temperature or microturbulance. Note the green circles are part of the GUI.

Chapter 5

Summary of articles

This chapter provides a short summary of the papers included in this thesis and my contributions. The paper summaries will be written as "we", referring to all the authors, whereas my own contributions will be referred to as "I".

5.1   Paper I

Paper I is a study of ~ 100 solar analogue stars. High-resolution FEROS spectra with $R = 48{,}000$ were analysed by means of our dedicated software TWOSPEC, that determined differences in equivalent width of selected spectral lines with respect to a solar reflective comparison spectrum of the asteroid Ceres. The aim was to find the stars which are most similar to the Sun, meaning there is on average no difference in its spectral lines compared to the Sun within errors and thus are solar twins. We investigated and compared a range of literature methods, as well as using our own, showing that they all have advantages and disadvantages. No "best method" exists, though often a twin is recovered by more than one method. We showed, that there are still many twins to be found, as of the ten we discovered in our sample, six were previously unknown.

In addition we used the whole sample of solar analogue stars to test the temperature and metallicity scale of the third release of the Geneva-Copenhagen-Survey (GCS-III) catalogue (Holmberg et al. 2009) around Sun-like stars, as there had been previous indications that their calibration might be slightly offset. We introduced a new method to disentangle the various metallicity and temperature degeneracies in the differential equivalent widths of a set of spectral lines, when comparing the Sun to other

stars. We found, that the GCS-III scales are indeed offset for Sun-like stars by (-0.12 ± 0.02) dex and (-97 ± 35) K, respectively, which is in good agreement with Meléndez et al. (2010) and Casagrande et al. (2010), who found them offset by -0.09 dex and -48 K and -0.1 dex and -100 K, respectively.

We also used this method to independently determine the solar $(b - y)$ colour and found it to be 0.414 ± 0.007, which is also in good agreement with the result of Meléndez et al. (2010), whose work is based on solar twins and quote it to be 0.411 ± 0.002. However it is slightly redder than Holmberg et al. (2006) found, which was 0.403 ± 0.013.

The initial FEROS data were already taken by the time I started the project (PI: J. Holmberg) and I was responsible for reducing the data and looking for additional data in the FEROS archive, from which I added another 50% extra to our sample of spectra. I was then the person to do the main analysis, using the TWOSPEC code, written by my supervisor Chris Flynn and also to test the results obtained with the above mentioned code. The paper was also mainly written by myself, making me the first author of the resulting publication.

5.2   Paper II

In Paper II we used a sample of 63 solar analogue stars to perform a similar analysis to Paper I. The data consisted of high-resolution HARPS spectra ($R = 115{,}000$) and were taken entirely from the ESO HARPS archive, including a high S/N spectrum of the asteroid Ceres. We used our previously introduced "degeneracy-lines-method" to test the GCS-III temperature and metallicity scales for this new set of stars, taken with a different instrument and a different telescope, as well as introducing a "neutral-ionised-method" to check the results of Paper I with much higher accuracy, due to the greatly improved quality of the data. We found the GCS-III offset to be (-55 ± 25) K in effective temperature and (-0.10 ± 0.03) dex in metallicity, thus confirming our findings from Paper I. We were also able to confirm, that the effective temperature and metallicity values determined in the Casagrande et al. (2011) reanalysis of the GCS-III are better centred around the Sun and found no significant offsets for Sun-like stars in their catalogue.

The resulting solar $(b - y)$ colour from the HARPS study was $0.409 \pm$

0.002, which is also in good agreement with the values we determined in Paper I.

We then used the data to look for more solar twins and found nine, of which five were previously unknown. There were three twin targets in common with Paper I and all three were confirmed in this paper.

My role in this work was to extract the archive data, which was reduced by the ESO pipeline and then to apply the whole analysis on the data, using again our TWOSPEC code and other short dedicated codes in PYTHON that I wrote for this purpose. I was then again the main responsible for writing the publication, making me the first author.

5.3   Paper III

Paper III was a study to compare the IRFM temperature scale with the fundamental interferometric scale, as well as the GCS-III temperature scale. The idea was to determine IRFM temperatures of stars for which interferometric angular diameters are known. The data consisted of SAAO JHK photometry for 55 stars, which was used to apply the IRFM on 16 stars with known interferometric diameters. The SAAO JHK filters being different from the 2MASS filters used by Casagrande et al. (2010) before, made it necessary to implement the whole IRFM from scratch on the new data. The known 2MASS data for some stars then allowed a comparison to be made between the two and adjust for small offsets of the order of $20 - 30$ K.

The final comparison of the IRFM temperature scale with the interferometric scale shows, that it gives excellent agreement for giants, which are easiest to measure, however for dwarf size stars current interferometric data yields temperatures that are $15 - 30$ K cooler than those determined through the IRFM. With the GCS-III temperatures being about ~ 80 K cooler than the IRFM temperatures, the interferometric scale lies between the GCS-III and the IRFM, making it impossible to favour one scale over the other.

I contributed to selecting the sample stars for the original SAAO proposal, by chosing targets that had the necessary photometry in 2MASS JHK, Johnsons-Cousins and/or Tycho2 filters to be able to tie the results to the Casagrande et al. (2010) 2MASS based scale. In addition I took an active part in the discussions.

5.4   Paper IV

For Paper IV we used a second set of high-resolution spectra of solar twins and analogues, taken with with FEROS instrument on the 2.2 m MPG/ESO telescope on La Silla, as well as the previous sample from Paper I. We determined spectroscopic effective temperatures, metallicities and surface gravities for both samples and used our methods from Paper I and II to check their resulting scales. We showed that our spectroscopic scale is well calibrated around the solar values, as the solar zero point falls at the solar values within our errors.

We also repeated our analysis with different line lists, making sure that the adopted line list for our analysis does not affect the results (which it indeed does not), as well as showing that the asteroid spectrum used for solar comparison is stable, by taking 15 spectra of Ceres and Vesta in total, over the three observing nights for the FE14 sample. We found that all asteroid spectra can as expected be considered as twins of each other, showing their median differences in equivalent widths are zero within the scatter. Also we verified, that our results do not depend on the reference spectrum (Ceres or Vesta), which agrees with recent work by Bedell et al. (2014).

In addition we also identified seven solar twins, increasing our list to 22 stars that are very close to being solar, meaning they are indistinguishable from the Sun in our methods.

As a final part of this work, we also checked if the temperature and metallicity scales in Casagrande et al. (2011) resulting from the IRFM and from the Colour Calibrations (CLBR) are the same. We showed that there might be a small difference, however it is within the errors and remains favoured over the GCS-III calibration.

I was the PI of the ESO proposal, who implemented the technical part and the observer who carried out the observations on site on La Silla, Chile. I reduced the new data and was responsible for the analysis, using MOOG and learning to use the MOOG – based package SMH by Casey (2014) to determine the stellar parameters for all my stars (see Chapter 4 for details) as well as use the previously established codes for the other parts of the analysis and I was responsible for writing the publication, making me again the first author.

Chapter 6

Future work

In my work I have shown two main things: First, that there are still many solar twins in the solar neighbourhood waiting to be discovered, and secondly that it is important to have independent ways of testing calibrations for stellar catalogues, as many further studies will make use of them. But there are still many things left to study further along these lines, which makes this kind of study very versatile. For this purpose I have already acquired data to address some of the open questions and for others I intend to apply for more data.

6.1 Solar twins and solar siblings

To date there is no perfect solar twin known with stellar parameters that are indistinguishable from the Sun. Therefore it remains an ongoing quest to find stars that are as close to the Sun as possible, making them the closest solar twins. To accomplish this one needs more and better data, meaning spectra of better S/N ratio and higher resolution, as well as probing deeper into the Milky Way, looking at fainter stars and thus increasing the inspected volume. So far mainly the solar neighbourhood has been examined and even that only partly. In my work I used the Geneva-Copenhagen-Survey catalogue as a source for targets. In my initial selection window, centred around the Sun, there were ~ 350 stars, some of which could be solar twins. During three studies (Paper I, II and IV), two with FEROS and one with HARPS, I have analysed ~ 200 of these. I have identified 22 stars from this subsample that are solar twins by my definition, meaning that they are indistinguishable from the Sun in their observed and derived parameters within the error bars. This suggests that about 10% of the

initial selection window are solar twins. Therefore, of the remaining ~ 150 targets to be examined, we would expect another 15 twins. These have so far not been part of my work, as they were either not observable or too faint, therefore needing to be observed from a different observatory and/or with a larger telescope. Fig. 6.1 shows a plot of the selection window and the observed targets to date.
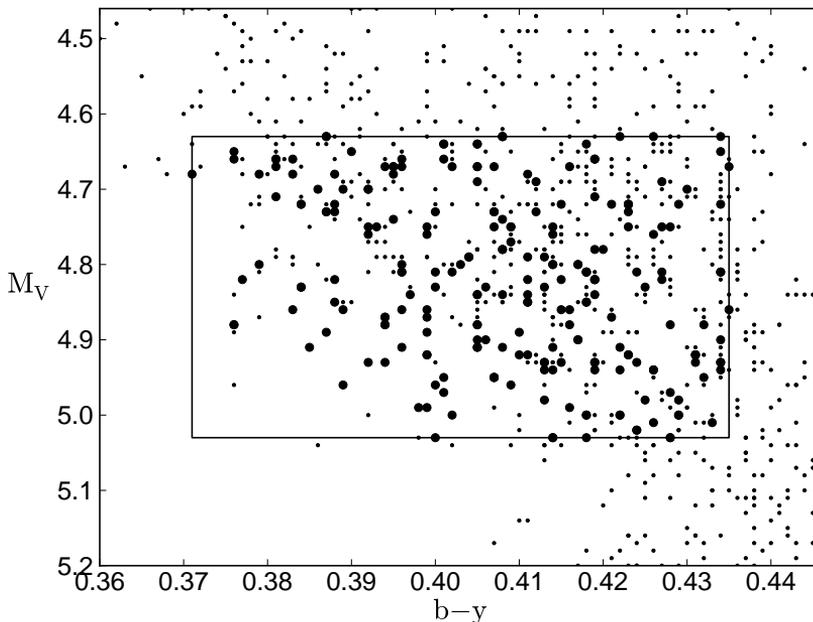

Figure 6.1: The selection window for absolute magnitude and $(b-y)$ colour in the GCS catalogue, centred around the Sun, showing in small dots all available stars, in larger dots the stars that have been studied in my work. Note that there are still small dots in the window, meaning there are still ~ 150 targets left for further studies.

Once the solar neighbourhood has been thoroughly studied it becomes essential to search further out. In the future surveys like the ongoing HER-MES/GALAH, GES and Gaia, which is now starting, and from 2019 on 4MOST (de Jong et al. 2012) will provide this increase in depth to study

the fainter and more distant stars in the Milky Way.

Apart from the question about how close to solar we can get, there are other questions the study of solar twins can possibly answer. In the past five years Meléndez et al. (2009) have suggested that through a detailed study of abundances of refractory vs. volatile elements it is possible to infer rocky planet formation, as the Sun shows anomalies with respect to solar twins (see also Fig. 6.2). This would enable an independent way to search for extrasolar planets around solar type stars. However there have been also alternative explanations to the solar abundance patterns. Önehag et al. (2011, 2014) suggested that it is due to the fact that the Sun was born in a very dense environment, whereas Adibekyan et al. (2014) put forward the idea that it is an age related feature. In favour of the planet formation interpretation, one could bring the evidence that for the 16 Cyg binary components Ramírez et al. (2011) and Tucci Maia et al. (2014) found different abundance patterns, which might be related to the fact that the primary does not seem to have any planets, but the secondary has at least one detected giant planet. Note however, that the presence of a close Jupiter does not prove (and possibly disfavours) the existence of rocky planets in the same system; and nothing is known of terrestrial planets in the 16 Cyg sytem. The question remains overall open and needs more data to be settled.

Closely linked to this question is also the specific study of the lithium abundance in the Sun and solar twins. It has been under intense debate where the different solar lithium abundance comes from, whether it really is peculiar and if so, why: it may be age-related or a result of planet formation, or not peculiar at all (e.g. Meléndez et al. 2010; Baumann et al. 2010). See also Fig. 6.3 on how different the lithium lines are for different solar twins.

Of the 22 stars I consider solar twins from my work, for 15 (from Paper I and II) I have already obtained ESO Very Large Telescope (VLT) UVES very high resolution spectra ($R = 110{,}000$) to determine exact abundances of lithium and the volatile and refractory elements to see how solar they really are, as well as use the outstanding quality of these high S/N (≈ 400) observations to examine their abundance patterns in full detail to maybe shed some light on the above mentioned open questions. Out of these 15 stars, 4 have known planets, therefore making a comparison between those with known planets and those without possible. In addition it may offer an opportunity to predict more planets, that have not been found yet. In Fig. 6.4 I show an example wavelength window for the first ten twins
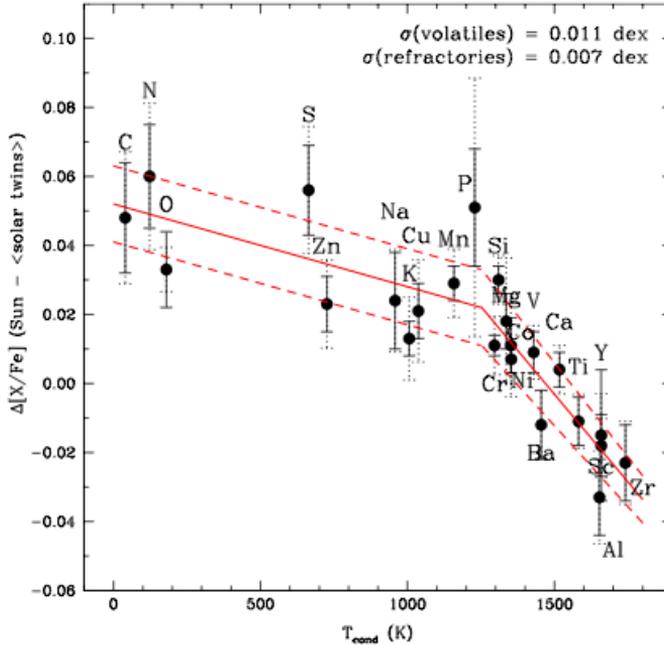
Figure 6.2: Figure 3 from Meléndez et al. (2009), showing the abundance differences between the Sun and solar twin stars for refractory and volatile elements. It shows how the volatile elements are more abundant in the Sun, whereas the refractory ones are under abundant. They propose this may be a signature for terrestrial planet formation.

for which I acquired the UVES data. It is obvious from the plot, that the spectra are very similar, as expected from solar twins and will need accurate differential line–by–line analysis to detect small differences in the refractory vs. volatile abundance pattern (Meléndez et al. 2009). I was the PI for both proposals which gave us these data.

Closely linked to the search for solar twins is the search for solar siblings. Looking for stars that were born together with the Sun will answer questions about our origin, about the solar parental cluster size, composition, etc., as well as give insights into how stars move around the Milky Way disk and how important radial mixing is (Bland-Hawthorn et al. 2010). Recently Ramírez et al. (2014) have shown how a search for solar siblings can be
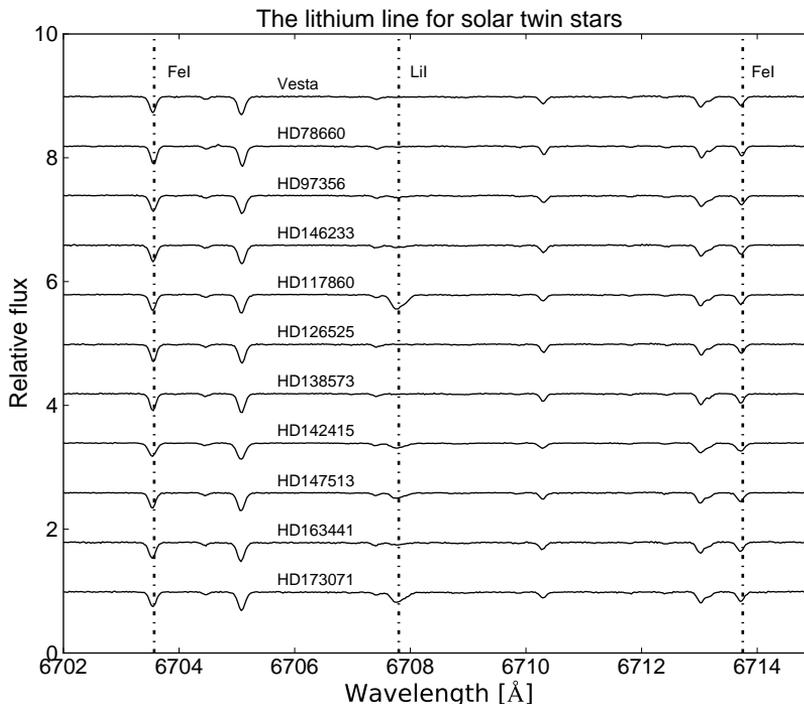
Figure 6.3: UVES spectra for the ten solar twins from Paper I and a reference solar spectrum from the asteroid Vesta, showing the difference in lithium line strength and thus abundance.

done through elemental abundance analysis. This new technique provides a promising alternative to the dynamical simulations, which were in the past the more common way to approach this problem (e.g. Bobylev et al. 2011). As the latter requires vast amounts of simulations with many parameters, it highlights the underlying uncertainties in the method. In the light of the extensive planet searches going on, another interesting question would be whether or not solar siblings are more likely to have inhabited planets than others. Valtonen et al. (2012) suggest that life spores ejected from early rocky collisions with Earth, when the solar siblings were not as dispersed as they are today, could have infected other nearby planetary systems,
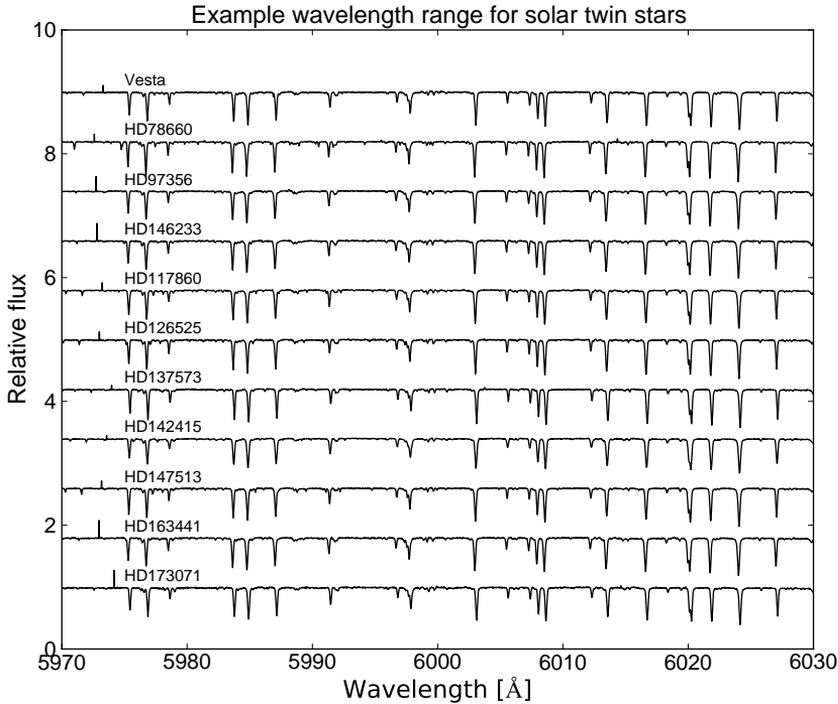
Figure 6.4: UVES spectra for the ten solar twins from Paper I and the reference solar spectrum from the asteroid Vesta. Note how similar the spectra are, thus making a more detailed study necessary to find the differences.

thus making solar siblings prime targets for the search for extraterrestrial life. My work, when looking for solar twins and the upcoming abundance analysis for these will provide possible new targets to answer some of these questions, even if the probability of finding solar siblings in my samples is very low. However, surveys like HERMES/GALAH, GES and Gaia will deliver the amount of data needed to truly look for solar siblings over the whole mass range and large volumes, which will then truly allow a search for inhabited planets around solar sibling stars.

Another natural improvement of my work lies in the use of even better data for this analysis, to make sure the errors are as small as possible and

the twins are as close to solar as possible. It would also increase the number of spectral lines that can be used for the analysis, making the results more robust. However, some of the spectra in my work already have a spectral resolution of $R \sim$100,000 (HARPS and UVES), which is one of the highest currently openly available. To achieve an even better resolution one could apply for time with the High Dispersion Spectrograph (HDS, Noguchi et al. 2002) on the Subaru telescope, which has a resolution of $R \sim 160,000$, or one would need access to the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI, Strassmeier et al. 2008) on the private Large Binocular Telescope (LBT), which has a resolving power of $R \sim 300,000$. Other than those, there are plans to have a spectrograph with $R \sim$135,000 on the E-ELT (Pasquini et al. 2008) in the future. Additionally, using these large telescopes would allow for an increase in observed volume.

The only other increase of data quality could be a higher S/N ratio, than the 150-200 we have used so far for the larger samples with HARPS and FEROS and 400 for the small sample with UVES. This would allow the use of very weak lines, that otherwise would be lost in the noise. For this purpose one would need either a long run on a small telescope (i.e. several nights at the 2.6m NOT or 3.6m ESO telescope), or a shorter run on a large telescope (i.e. a single night or two at the VLT or Keck telescopes).

6.2 Fundamental parameters in stellar catalogues

My work on stellar catalogue calibration testing can also be extended in two ways: to test different parameter regimes and to test different catalogues.

As I have shown, there seems to be an offset in the GCS calibration for solar type stars, whereas in the C11 reanalysis these offsets do not appear in my analysis. The next step would be to test the two alternative calibrations for other temperature and metallicity regimes in the catalogue. For this one needs stars with parameters that are known through fundamental ways to have a zero point to anchor this analysis to. One source of these stars are the Gaia-ESO survey benchmark stars (Jofré et al. 2014). This list consists of 34 FGK stars that span a temperature range of $3400 - 6600$ K and a metallicity range of $-2.5 - 0.5$ dex, thus providing many options to test the parameter space away from solar values.

One promising target for this would be for example β Vir (HD102870), which is significantly different from solar and therefore provides information

about another regime of stellar parameters. Literature values of its temperature, using interferometry and fundamental relations agree on 6100 ± 40 K and metallicity of 0.11 ± 0.01 dex (e.g. North et al. 2009; Boyajian et al. 2012; Jofré et al. 2014). This agrees with the GCS calibration, which gives 6109 K and 0.11 dex, whereas the C11 catalogue lists it to have 6209 K and 0.21 dex, meaning that in this case, the original GCS calibration seems better than the C11 version. This kind of controversy shows how important it is to have independent ways to determine catalogue calibrations. I could easily repeat my analysis using in the GCS a selection window for β Vir "analogues", similarly to the "solar window" used in Paper I, II and IV. My method has the advantage that it uses trends from a large sample of stars that are photometrically similar to the target star and is not based on the results of one star alone, making it more robust than other methods. β Vir has been extensively observed with FEROS and HARPS, which are the two high-resolution spectrographs I have used in my work. The next step would therefore be to extract from those archives all the GCS stars, that are photometrically similar to it. After this proposed study, the next star I could select should be cooler and more metal poor to probe this regime of parameters. However this would require very high resolution and S/N data to resolve the large number of spectral lines in stars cooler than the Sun. Alternatively I could also move on to a giant.

Another way to extend my work will be to test other catalogues. My analysis can be done for any collection of derived effective temperatures and metallicities, as it is based on the trends of those parameters. In this era of Galactic surveys a few projects immediately come to mind: RAVE, HERMES/GALAH, Gaia-ESO and Gaia. These all provide or will provide derived stellar parameters from spectra and/or photometry. Therefore it will be easy to use the methods we have developed to independently test their calibrations. This is straightforward if their targets have spectra available in an archive for a high-resolution spectrograph. Otherwise it is necessary to apply for telescope time to get these spectra. For example RAVE and Gaia-ESO spectra are already publicly accessible, therefore offering the chance to do this analysis without the need to apply for data. Of course there is the need for the reference spectra, however, in the case of Gaia-ESO there are the benchmark star spectra available and as it uses mainly FLAMES-UVES and GIRAFFE spectra, I already have asteroid spectra taken with UVES to use as solar reference for that instrument, making this a project I can address in the near future.

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