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Exoplanets: Gaia and the importance of
spectroscopic follow-up

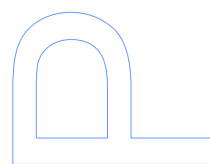
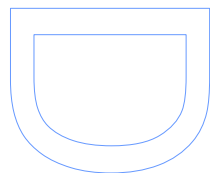
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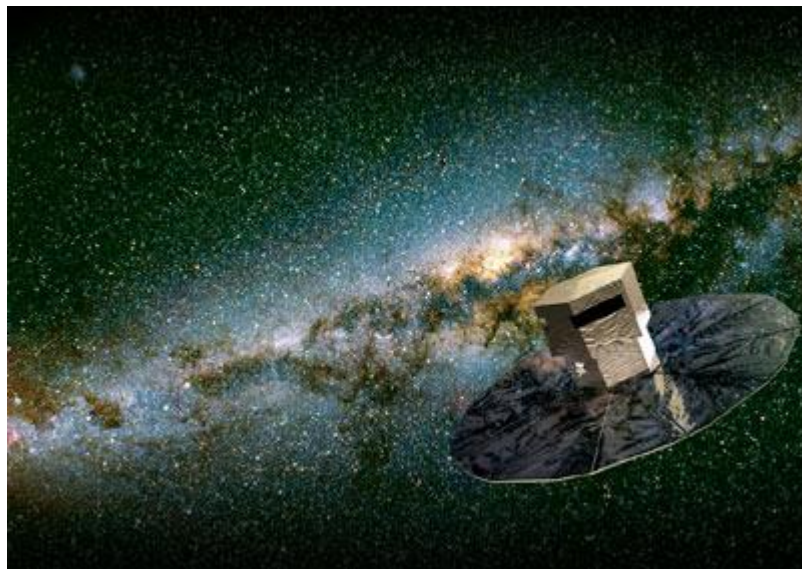
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Exoplanets: Gaia and the importance of spectroscopic follow-up

Lisa Benamati

Tese de Doutoramento apresentada à
Faculdade de Ciências da Universidade do Porto, Departamento de
Física e Astronomia,
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2015





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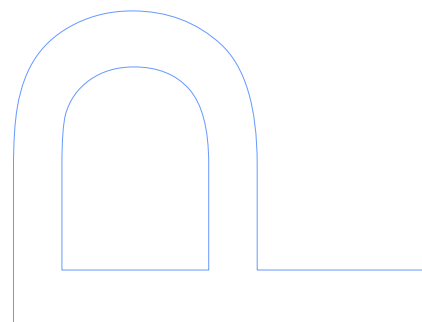
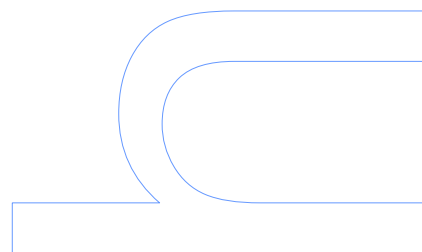
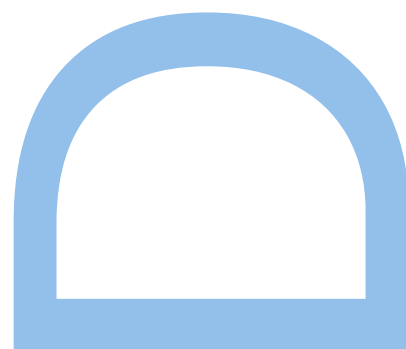
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Tese de Doutoramento

Orientadores: N. C. Santos, A. Sozzetti

2015

Ai miei genitori

"Grazie per esserci e sostenermi sempre."

In this thesis I present the story of my PhD project. Starting with a short introduction and then presenting the work done using astrometry and spectroscopy and finishing with a description of the work done related to evolved stars.

With the launch of Gaia on December 2013, a new era for astrometry and also for the astrophysics started. In the context of exoplanet research, Gaia will allow us to *a)* significantly refine our understanding of the statistical properties of extrasolar planets (and binary systems, too), *b)* achieve crucial tests of theoretical models of gas giant planet formation and migration, *c)* provide important contributions to the understanding of direct detections of giant extrasolar planets, and much more.

These measurements in combination with spectroscopy and the present day and future extrasolar planet search programs will give a crucial contribution to several aspects of planetary systems astrophysics (formation theories, dynamical evolution, etc.). In my PhD, I explored the importance of spectroscopic follow-up as complement to Gaia data.

In Chapter 2 I describe our software code to analyze synthetic one-dimensional data of Gaia and combine it with RV data. We used Hipparcos data to test the programs. Having no new solution using the Hipparcos data for the exoplanet-hosts (HD134113 and HD219828) we tried to use it for binary systems. In Chapter 3 I present the work done with the binary systems (CD-436810, G135-46, G27-44, G63-5, G237-84, HD16784, HD7424 and HD192718) using statistical methods to find a range of solutions for the mass of the companion and its orbital period because of lack of accuracy of the astrometric data. We did not obtain well constrained results, but two systems showed that the candidate companions at 1σ of confidence level are brown dwarfs. For one system, then, we found two different solutions based on analysis of two different reductions of the Hipparcos data. We concluded that the old Hipparcos reduction seems to be more compatible with our results. The results of this work have been published in Benamati et al. (2013). The last chapter of this thesis describes the derivation of stellar parameters and abundances of 12 elements for a sample of giant stars which have been searched for planets. These parameters and abundances allow us to study the statistical properties and chemical evolution of evolved stars and in the future, also, the connection with the giant planets. The results of these works will be published in Alves et al. (2015) and Adibekyan et al. (2015).

Nesta tese apresento a história do meu projeto de doutoramento. Esta tese começa com uma breve introdução, seguida da apresentação do trabalho feito utilizando as técnicas de astrometria e espectroscopia. Terminando depois com uma descrição do trabalho realizado sobre estrelas evoluídas.

Com o lançamento da missão Gaia em Dezembro de 2013 iniciou-se uma nova era não só para a astrometria mas também para a astrofísica em geral. No âmbito da investigação em exoplanetas, o satélite Gaia irá-nos permitir *a)* refinar de forma significativa a nossa compreensão das propriedades estatísticas dos planetas extra-solares (e também de sistemas estelares binários), *b)* realizar testes cruciais aos modelos teóricos de formação e migração de planetas gigantes, *c)* fornecer importantes contribuições para a compreensão de detecções direta de planetas extra-solares gigantes, entre outras coisas.

Em resumo, as medições do satélite Gaia, em combinação com estudos de espectroscopia e outros projetos para a procura de exoplanetas iram dar um contributo crucial para compreensão novos aspectos sobre os sistemas planetários (e.g. teorias de formação, evolução dinâmica, etc). Ao longo do meu doutoramento explorou-se a importância da espectroscopia de alta resolução como um dado complementar aos dados do satélite Gaia.

No Capítulo 2 descreve-se o software que se desenvolveu para analisar os dados do satélite combinando-os com dados de velocidades radiais. Foram utilizados dados do satélite Hipparcos para testar os programas desenvolvidos. Dado que a precisão dos dados do Hipparcos não permitiram detectar o sinal produzido por um conjunto de sistemas planetários conhecidos, concentrei-me então no estudo de binários estelares. No Capítulo 3, apresenta-se o trabalho desenvolvido sobre vários sistemas binários (CD-436810, G135-46, G27-44, G63-5, G237-84, HD16784, HD7424 e HD192718) utilizando métodos estatísticos para a procura de uma gama de soluções para a massa do companheiro e para o seu período orbital. Embora este trabalho não tenha permitido restringir de forma precisa essa gama de soluções, os resultados mostraram que em dois casos os companheiros candidatos serão provavelmente anãs castanhas. Esta análise permitiu ainda comparar dois conjuntos de dados do Hipparcos que foram reduzidos de forma diferente. Os resultados deste trabalho foram publicado em Benamati et al. (2013).

O último capítulo desta tese descreve a derivação de parâmetros estelares e abundâncias químicas

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de 12 elementos distintos para uma amostra de estrelas gigantes que fazem parte de um programa de procura de exoplanetas. Estes parâmetros e abundâncias permitiram-nos estudar a evolução química de estrelas na nossa Galáxia, um aspecto também de grande importância no contexto do Gaia. No futuro este estudo vai permitir igualmente estudar a ligação estrela-planeta. Um destes trabalhos foi recentemente publicado (Alves et al. 2015), e um segundo foi submetido para publicação (Adibekyan et al. 2015).

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Astronomy is one of the oldest sciences in the world. Human beings have long looked up at the sky and pondered its mysteries. Even today, many people are fascinated by the question if we are alone in this Universe and, thanks to the technology development, today we are trying to answer to this question, being able to detect planets around other stars and low-mass planet, too, like the Earth. The study of exoplanets seeks also to understand how planetary systems form and evolve, and to understand the diversity of planetary system architectures. Therefore we need to understand the behaviour of all types of stars, in addition to detect and to know the orbital properties of the planets and to interpret the statistical properties of the planetary sample. Knowing well the properties of the samples of stars we can delineate conclusions about the planet population as a function of metallicities, masses, etc. and compare the results of different surveys. For a complete description of the star a number of important parameters must be defined, such as mass, luminosity, radius, age, chemical composition, angular momentum, magnetic field, mass-loss rate and circumstellar environment. The derivations of several of these parameters requires potent observational techniques such as high resolution spectroscopy. The main goals of this thesis is twofold: the first one is to understand how the use of high precision spectroscopy can be useful to better characterize planetary systems combining the radial velocities with the upcoming of the new data from Gaia; the second one is to understand how the stellar parameters and namely abundances control planet formation by studying the properties of giant stars.

Concerning the first of these goals, we exercised our combined analysis tools using existing Hipparcos data and radial velocities for a sample of low-metallicity objects observed with the HARPS spectrograph at La Silla (Pepe et al. 2002) and with the HIRES Spectrograph on the Keck 1 telescope at Mauna Kea in Hawaii (Vogt et al. 1994), in preparation for Gaia. For the second goal, we study giant stars screened for planets in RV surveys in the context of the CORALIE (Udry et al. 2000a) extrasolar planet search program analyzing the stellar parameters (effective temperature, microturbulence, surface gravity and iron abundance) and also other element abundances. We need to know these parameters and abundances with very high accuracy to understand better the theoretical models. The study and precise characterization of high-mass

	HIPPARCOS	GAIA
Limiting magnitude(V)	~ 12 mag	20 mag
Completeness (V)	7.3–9.0 mag	20 mag
Number of objects	120000	1000 million
Accuracy (all five parameters)	1–2 mas	~ 9 –26 μ as

Table 1.1: A comparison between the scientific capabilities of Gaia with those of Hipparcos.

planets help us to understand better the statistical properties of extrasolar planets, the theory of gas giant planet formation and the formation and dynamical evolution of multiple-planet systems.

1.1 Gaia

The first step in the acquisition of astrometric data from space was represented by the Hipparcos project. The accuracies of the positions, annual proper motions and parallaxes were in the range of 1-2 milliarcsec. The next-generation space astrometry mission Gaia, launched in December 2013, will improve on all of five astrometric parameters (α , δ , μ_α , μ_δ , π) by two orders of magnitude (see Fig. 1.1). In Table 1.1 a comparative summary of the performances of Gaia and Hipparcos is shown.

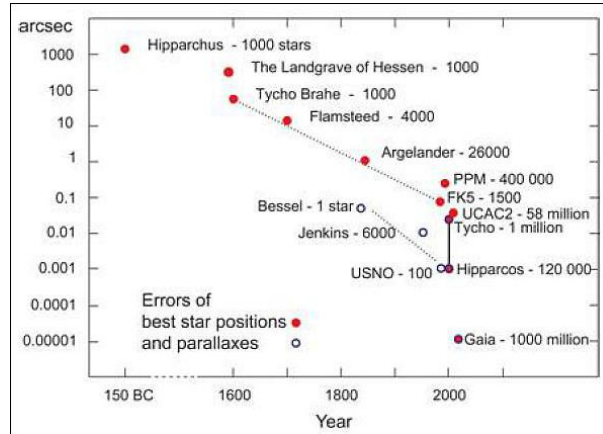


Figure 1.1: The development of astrometric accuracies over the past two thousand years, illustrating the advance made by the Hipparcos mission and the potential accuracies achievable by Gaia. From (<http://sci.esa.int/gaia/33840-progress-in-astrometric-accuracy/>)

Gaia will perform an all-sky survey in the V magnitude range between V=3 mag and V=20 mag. Its main method to acquire data will be high precision astrometry, backed with photometry and spectroscopy. It will observe about 1 billion stars, a few million galaxies, half a million quasars, and a few hundred thousands asteroids (Lindgren 2009). Gaia is in orbit around the

L2 point (second Lagrange point) of the Sun-Earth system, at about 1.5 million kilometers from Earth in the anti-Sun direction. The position was chosen for its advantages: the point offers uninterrupted observations and the entire celestial sphere will be observed and analyzed during five years. The speed of the spacecraft around its axis is constant (60 arcsec s^{-1}) and, therefore, during a period of six hours all objects located along the great circle perpendicular to the spin axis will be scanned. Each celestial object will be observed on average 70 times due to Gaia's scanning law pattern: a basic angle between the two fields of view of 106.5 degrees, the spin motion of six-hour period and a 63 day-precession period (de Bruijne 2012) of the spacecraft rotation axis placed at an angle of 45 degrees with respect to the Sun direction (see Fig. 1.2).

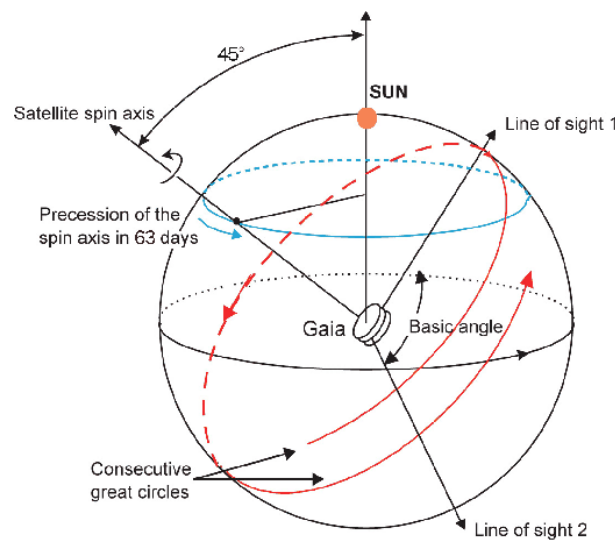


Figure 1.2: Gaia observation principle (de Bruijne 2012).

The spacecraft is composed of three functional modules: the payload module, the mechanical service module and the electrical service module. The payload has a single integrated instrument that includes three major functions (astrometry, photometry and spectrometry). The ultimate spacecraft contains the three functions into a single instrument by using common telescopes and a shared focal plane (<http://sci.esa.int/gaia/40129-payload-module/>):

- ASTRO: the Astrometric instrument which measures the five astrometric parameters giving the star position (2 angles, α and δ), the proper motion (derivatives of position) and the parallax (distance);
- the Photometric instrument which covers the band 320-1000 nm;
- the Radial Velocity Spectrometer (RVS) which gives the radial velocity data in the narrow band 847-874 nm.

From a technical viewpoint, the general values of Gaia are:

Δd (pc)	N_{star}	Δa (AU)	N_d	N_m
0–100	~61000	1.3–5.3	>1600	>640
100–150	~114000	1.8–3.9	>1600	>750
150–200	~295000	2.5–3.3	>1500	>750

Table 1.2: Number of giant planets that could be revealed by Gaia (N_d) and fraction of detected planets having accurate orbital elements determined (N_m) as a function of increasing distance from the Sun (Δd). A uniform frequency distribution of 1.3% planets per 1 AU bin is assumed. (Lattanzi et al. 2002)

- it is a continuously scanning, self-calibrating instrument that measures simultaneously the angular separations of several hundred star images with a field of view of about 1° diameter.
- it has a high angular resolution in the scanning direction;
- a wide-angle measuring capability;
- only after a few years of scanning we can have a complete separation of the astrometric parameters reporting the motions and distances of single stars.

1.2 Exoplanets: Gaia’s data combined with radial velocity.

One of the major scientific results in astronomy of the past decade was the discovery of extrasolar planets orbiting solar-type stars. The search of extrasolar planets has developed rapidly and with spectacular success after the first discovery by Mayor and Queloz [1995] of a planet orbiting the solar type star 51 Peg, followed soon by the detection of planets around 47 Uma (Butler and Marcy 1996) and 70 Vir (Marcy and Butler 1996). Today, more than 1700 planets have been found orbiting stars using five different exoplanet detection techniques (radial velocity, astrometry, transit, microlensing, imaging). Fig. 1.3 shows the temporal development of the detections.

Thanks to this high and increasing number, it was possible to investigate the statistical properties of the derived orbital features and stellar-host characteristics, and to search for constraints for the different planet formation and evolution scenarios (e.g. Mayor et al. 2014).

The fraction of F, G and K stars with giant planets is fairly well studied, out to orbital periods of several years that can be probed with current data, with good agreement between different surveys: this population at orbital distances of 1-5 AU, minimum mass $> 50 M_E$ and orbital period < 10 years is characterized by an occurrence rate of about 15%. It shows a peak at 1-2 M_J with a ‘brown dwarf desert’ above 10-20 M_J , a wide distribution of orbital eccentricities and a high metallicity of the host stars (e.g. Udry and Santos 2007, Cumming et al. 2008, Mayor et al. 2014).

Nowadays, thanks to the high resolution, high-precision spectrographs (like HARPS, Pepe et al. 2002) and projects under development (like ESPRESSO, Pepe et al. 2010), we can push down

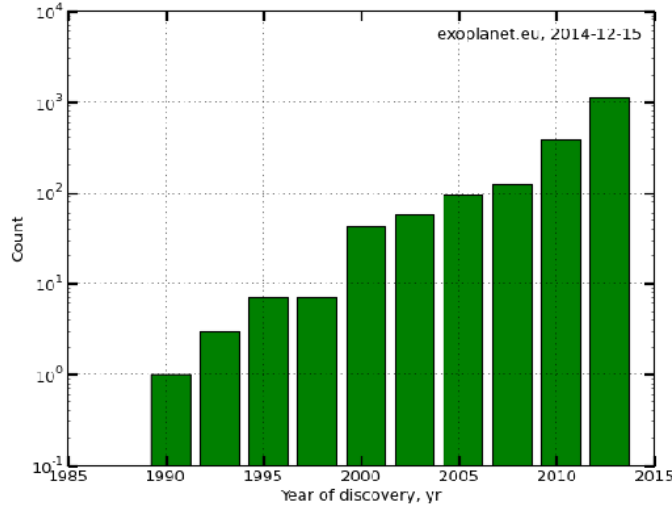


Figure 1.3: Number of the detected extrasolar planets as a function of the year of the discovery. From "The Extrasolar Planet Encyclopaedia" (<http://exoplanet.eu/>)

the limits in RV and improve our knowledge of the close-in low-mass planet population with precise radial velocity measurements until 10 cm s^{-1} .

Thanks to HARPS and the Keck-HIRES, for example, it was discovered a large number of Neptunes and super-Earths. They show, around FGK stars, a occurrence rate of 0.33 ± 0.05 planets per stars with a minimum mass between 3 and $30 M_E$ and period < 50 days. In particular, at least 70 % of the systems with Neptune or super-Earth are multi-planet systems (e.g. Lovis et al. 2009, Howard et al. 2010, Mayor et al. 2011).

Moreover, over the last few years, it has been increased the number of exoplanets found also by the transit method; for example, from the Kepler mission thousands more transiting planet candidates have been observed (e.g. Batalha et al. 2013).

This is an exciting time in exoplanet statistics!

In the upcoming years, we will learn much more because the sample will increase further and new regions of the mass-orbital period plane will be investigated. A wider range of stellar properties will be explored also thanks to the future astrometry space mission (Gaia) which should detect a significant number of planets.

Gaia can potentially discover several thousands (possibly $10 - 20 \times 10^4$, see Table 1.2) of gas giant planets at orbital radii 0.5 AU and 4-5 AU around solar-type stars out to $d \sim 500 \text{ pc}$, and 1000-1500 planets around M dwarfs out to $\sim 100 \text{ pc}$ (Perryman et al. 2014, Sozzetti 2015).

The main potentiality of Gaia will be its ability to measure astrometrically actual masses and orbital parameters for possibly thousands of giant planets, and to determine the degree of coplanarity in possibly hundreds of multiple-planet systems (Casertano et al. 2008). Gaia will observe millions of main sequence stars and brown dwarf companions within a few AU from their host stars, but Sozzetti [2014] have demonstrated that Gaia will detect also thousands of ultra-cool

dwarfs in the vicinity of the Sun.

Furthermore, it's important to remember that, because of the nature of the radial-velocity method, only some orbital parameters and a lower limit on the planet mass are known from spectroscopic measurements alone (Udry and Santos 2007). Instead, the astrometry determines other parameters of the planet orbit and in particular the inclination of the orbital plane with respect to the plane of the sky which is unresolved in radial velocity. For this reason, combining radial velocity with astrometry we could measure, for example, the mass of the planet and hence with Gaia we expect to improve the current landscape by adding thousands of new planets.

And not only! Thanks to this project (Gaia mission), we could study better longer period systems. Consequently, we could cover better the period distribution on the detected exoplanets: Gaia will probe a parameters space (long periods) that is not covered by RVs or transits.

1.3 Exoplanets: Gaia and the importance of ground based spectroscopic follow-up

Astrometry in synergy with other techniques can characterize more completely planetary systems. The two techniques used in this PhD project are spectroscopy and astrometry. For spectroscopy, we consider the Doppler optical spectroscopy, known as radial velocity method, and the techniques to derive the atmospheric parameters of the stars analyzing the spectrum (the stellar characterization).

1.3.1 RV and astrometry

The RV method and astrometry are complementary. We know that with the RV method we can only calculate a lower limit to the mass of the planet ($m \sin i$) because the RV measurements cannot determine either the inclination i of the orbital plane with respect to the plane of the sky or the position angle Ω of the line of nodes in the plane of the sky. But with the astrometry, that can derive the 2 parameters i and Ω , we can solve it and determine the real mass of the companion (Lattanzi et al. 2002). The synergy of these two methods is really useful to study exoplanets (e.g. Lattanzi et al. 2002, Sozzetti 2009, Sozzetti 2010). Astrometry searches for long-period planets around nearby stars of all spectral types. The spectral type and the rotational velocity of the star do not strongly condition the astrometric precision; moreover, the astrometry is less sensitive to noise from spots or other disturbances in the stellar photosphere, unlike the RV method (e.g. Hatzes 1999, Martínez-Arnáiz et al. 2010, Lagrange et al. 2010, Dumusque et al. 2011). Therefore, astrometry can detect giant planets around active young stars, while for the RV, in principle, it is more difficult due to the noise in the spectrum, stellar jitter such as starspots (Desort et al. 2007).

Moreover, the combination of astrometry with RVs also helps to increase the sample, since Gaia will not be observing the stars for many years: the duration of the mission is of about 5 years. For this reason, RVs will complement and improve the phase coverage of the orbits and increase the number of data points, helping us to refine the orbital solutions.

Furthermore, astrometry can complement RV because the two signals of the methods are opposite. The first one is more sensitive to planets far from the star (signal scales linearly with the

semimajor axis (a)), while the second one is more sensitive to planets close to the star (signal scales with $1/\sqrt{a}$). Also, thanks to the astrometry, we can determine whether multiple systems are coplanar or not. Many of the known exoplanets have highly eccentric orbits. It's possible that these eccentricities are due to the strong gravitational interaction between two or several massive planets (Lin and Ida 1997). If we know masses and mutual inclinations of the planets this can help us to study deeper the dynamical modelling of multiple systems including such fundamental issues as the dynamical stability and orbital resonances (e.g. Winn et al. 2010, Schlaufman 2010, Albrecht et al. 2012, Figueira et al. 2012). On the contrary, the radial velocity method is more sensitive than astrometry in detecting low-mass planets, particularly thanks to the new generation of high-precision instruments, such as HARPS and HARPS-N (Pepe and Lovis 2008, Cosentino et al. 2012).

1.3.2 Stellar characterization and Gaia

To derive several fundamental stellar parameters such as the effective temperature, surface gravity, metallicity¹ and the elemental abundances, we should analyze the observed spectrum of the star. For a precise characterization of planet it is very important to precisely characterize their parent stars because planets were formed as a result of the star formation process. Therefore, the star formation and planet formation are closely related (Cameron 1962, Shu et al. 1987 and see Sect. 1.4.1).

Thanks to Gaia, we could have new several thousand of giant planets detections and knowing well the properties of the parent stars from the spectroscopy and astrometry, we will be able to investigate their behaviour as a function of stellar mass, metallicity, age, etc.. Therefore, we can test the theoretical models and the role of metallicity in connection with the planets (e.g. Gonzalez 1997, Santos et al. 2004, Fischer and Valenti 2005, Johnson et al. 2010, Mayor et al. 2011).

Furthermore, the role of Gaia will be important also for the large sample of nearby M dwarfs which, in combination with the follow-up spectroscopic measurements can help us to answer to many key questions about their formation (in comparison also with giant planet formation), their parameters (mass, temperature, age), their atmospheric elements and the probability to have planetary systems (Sozzetti 2010, Sozzetti 2014).

Moreover, Gaia's data can help the analysis of the spectroscopic data, providing an accurate parallax that can help us to calculate the surface gravity with less uncertainties (Sozzetti et al. 2007, Mortier et al. 2013b).

One of the most important example of high-resolution follow-up for Gaia to determine stellar parameters and chemical compositions of the stars is the Gaia-ESO Survey (<http://www.gaia-eso.eu/>). The Gaia-ESO Survey is a public spectroscopic survey with the goal to analyze $\geq 10^5$ stars to understand the history of our Galaxy; it is the first survey that allow us to have a homogenous dataset for large samples of field and also cluster stars. Its science includes the major components of the Milky Way (open clusters, star forming regions, halo, bulge and thin/thick discs) giving an overview of the distributions of kinematics and elemental abundances. We can analyze the history of galaxy having a map of the chemical elements,

¹In this thesis metallicity means iron abundance.

spatial distributions and kinematics which allow us to know the star formation, the structure and the dynamical histories (Pancino and Gaia-ESO Survey consortium 2012).

The detailed abundances determined thanks to the Gaia-ESO Survey will be complemented with the arrival of Gaia astrometry, because we will have also accurate distances and ages. Therefore, the combination of these data will help us to create the first stellar age-abundance-kinematics distribution and to estimate how galaxies and stars were formed. This survey will complete Gaia in the area where it shows limitations: spectroscopy.

1.4 Giant planet formation and observational properties.

In this section we briefly discuss the giant planet formation and the statistical properties of the observed planets, considering the open questions. Because of the main focus of my thesis, here I present mostly the giant planet formation, and some properties of these planets (like mass-period distribution, metallicity) due to the fact that Gaia will detect new several thousands of giant planets and therefore, will improve our knowledge on their formation and evolution.

1.4.1 Giant planet formation

Modern theories of star and planet formation are constrained by observations. There are two main models for the formation of giant planets: core accretion model (e.g. Pollack et al. 1996, Alibert et al. 2004) and disk instability model (e.g Boss 1997, Boss 2006, Mayer et al. 2002). The first is the traditional one where the initial phase of a giant planet's growth occur through an accumulation process of solid material (planetesimals formation), in the same way as terrestrial planet form. Hence, giant planets are formed by a runaway accretion of gas around previously formed rocky and/or icy core and continue to grow until there is no gas available within the planet's gravitational reach. The other model takes inspiration from gravitational collapse of interstellar clouds that form stars. The gas giant planets might form by the gas-phase gravitational instabilities (GIs) which conduct to fragmentation of a protoplanetary disk into bound, self-gravitating clumps. The formation of giant planet through disk instability takes shorter timescale because initially it is a rapid process, respect to core accretion. On the other hand, we need to answer to some open questions about when and where the condition of fragmentation can take place in protoplanetary disks (D'Angelo et al. 2011).

The correlation between the incidence of giant planets and the metallicity of the host star seems to be in agreement with core accretion planet formation theory (Santos et al. 2001, 2004, Fischer and Valenti 2005). Core accretion models offer a natural explanation for both the formation of heavy element cores and the accretion of massive gaseous envelopes. Therefore, until now, the observed correlation supports the core accretion model as the main mechanism responsible for the formation of giant planets.

1.4.2 Mass and orbital period distribution.

The details of the mass-orbital period distribution are important because they include information about the planet formation process. In Fig. 1.4 we show the mass-orbital period

distribution in logarithm scale.

From this figure we can observe that we do not find Neptune-mass planets with period larger than about 1000 days. This lack of planets can be due to the detection bias: it is more difficult to do measurements for low masses and long orbital periods because of their small radial-velocity signal (Mayor et al. 2011, Udry et al. 2003). However, with the increasing of the radial velocity precision, large numbers of Neptunes and super-Earths with a minimum mass lower than $30M_E$ on short-period orbits ($P < 50$ days) have been discovered (Mayor et al. 2014).

For the giant planets, their frequency increases with the logarithm of the orbital period (Fig. 1.5), and they cover a range of periods from few days to several thousands of days (Mayor et al. 2011); Cumming et al. [2008] fitted this rise with a power-law distribution. But there is a "period valley" in the distribution showing a deficit of planets at orbital periods of ~ 10 and 100 days (e.g. Udry et al. 2003, Burkert and Ida 2007). Furthermore, it was found a "pile-up" of planets at orbital periods of 1–3 days, the "very hot Jupiters", and at orbital periods of 3–9 days, the "hot Jupiters" (e.g. Udry et al. 2002, 2003, Gaudi et al. 2005) (see Fig. 1.4).

As we observe from the Fig. 1.4, we can expect that most giant planets are in long period orbits and therefore, Gaia will have many candidates.

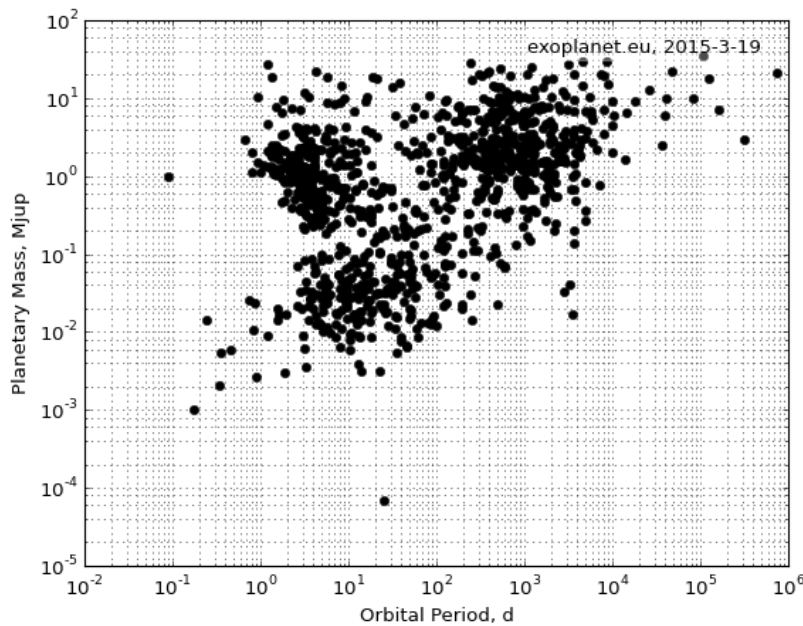


Figure 1.4: The mass-orbital period distribution in logarithmic scale. From "The Extrasolar Planet Encyclopaedia" (<http://exoplanet.eu/>, Schneider et al. 2011)

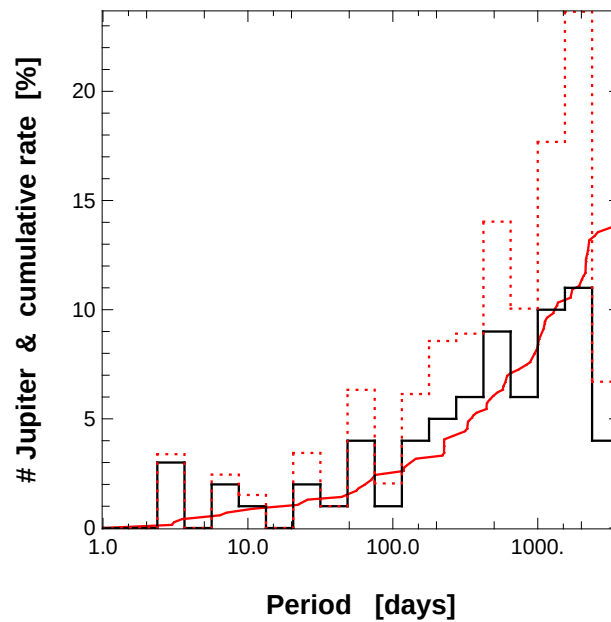


Figure 1.5: Histogram of the planet frequency for planets with minimum masses above 50 Earth masses. The observed distribution is represented by continuous black line and the bias-corrected distribution is represented by dash red line. From Mayor et al. [2011].

1.4.3 Metallicity of stars with planets

With the increase frequency of planets discoveries, many studies have been done on the correlation between the stars hosting planets and the host star metallicity.

Exoplanet data show a strong correlation between stellar metallicity and frequency of giant planet detection (Udry and Santos 2007): $\sim 25\%$ of stars whose metallicity is twice that of the Sun host a gas giant (within a few AU). This percentage reduces to only $\sim 5\%$ for solar-metallicity stars. Therefore, there is higher probability of forming a giant planet in a metal-rich environment (e.g. Santos et al. 2004, Fischer and Valenti 2005, Sousa et al. 2011). However, the discovery of several planets orbiting metal-poor objects (e.g. Cochran et al. 2007, Santos et al. 2008a,b) shows that giant planet formation is not completely inhibited in the metal-poor regime (Santos et al. 2004, 2011).

Despite these results, it was proposed that the metallicity-giant planet correlation may not be present for intermediate mass stars hosting giant planets (Pasquini et al. 2007). On the contrary, the recent work of Reffert et al. [2014] affirms that there is a planet-metallicity correlation among giant stars hosting planets compatible with the observed planet metallicity correlation for main sequence hosts. Anyway, we need more observations and measurements to settle this issue (Mortier et al. 2013a). A deeper understanding of this fact may have crucial consequences for our understanding of giant planet formation.

Furthermore, it seems that there is no correlation between lower mass Neptunian and super-Earth planets and high $[\text{Fe}/\text{H}]$ stars (Mayor and Udry 2008, Sousa et al. 2008, Ghezzi et al. 2010b).

For low-mass planets the metallicity distribution appears flat (Mayor et al. 2011, Buchhave et al. 2012). Anyway, also in this case, it is required to improve the sample of low-mass planets to be sure of the existence of this non-correlation.

Other elements

Abundance trends of chemical species other than iron can help us to solve the questions on the planet formation, too. The core-accretion scenario predict a relation between stars hosting planets and stellar metallicity (not only iron). Some studies showed no significant differences in the trends of $[X/Fe]$ between stars with and without planets (e.g. Takeda 2007, Neves et al. 2009, González Hernández et al. 2010, Delgado Mena et al. 2010), while some works have found possible enrichment in some species (e.g. Santos et al. 2000, Fischer and Valenti 2005, Gilli et al. 2006, Adibekyan et al. 2012b). Adibekyan et al. [2012a] found that in the metal-poor regime the stars hosting planets have higher abundances of α elements (Mg, Si and Ti) than the stars without planets. Adibekyan et al. [2012a] analyzed the abundances of 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn and V) for stars hosting Neptunian, Jovian and stars without planets. In general, they found that the increase of $[X/Fe]$ for stars hosting low-mass planets starts at higher metallicities respect to stars hosting giant planets. They measured an enhancement in the abundances of some elements for stars with and without planets: they found higher values of Mg, Al, Si, Sc and Ti for stars with giant planets compared to non hosting targets and higher abundances of Ti, Si, Al, Co, V, Sc, Mg and Na in Neptunian hosts compared to stars without planets. These results show that some elements might contribute particularly to form low-mass planets.

1.4.4 Planets around evolved stars

Stellar mass may have a strong influence on the formation of giant planets. It is now known that the frequency of giant planets around (low-mass) M dwarfs is considerably smaller than the one found for FGK dwarfs (Endl et al. 2003, 2006), although contradictory results exist (Kornet et al. 2006, Laughlin et al. 2004). One of the most effective ways to study the frequency of planets around higher mass stars is to search for the planets around giants because it is not easy to have precise radial-velocities for massive main sequence stars due to their few sharp absorption lines (high T_{eff}), rapid rotation and pulsation (Jones et al. 2014). Unfortunately, much effort is also required to derive the mass for giant stars because they have strong oscillation modes which introduce noise in the RV measurements. This makes difficult to study the "stellar mass-frequency of planets" relation for these objects.

Properties of giant planets around evolved stars

By now, more than 50 giant planets have been discovered around giant stars, allowing us to study some properties of exoplanets around evolved stars. These properties show some differences from the properties of giant planets around dwarf stars.

First, it was found a paucity of short-period systems: there are not planets around giant stars at orbital distances below ~ 0.5 AU due to the fact that closer-in planets were swallowed up.

Second, between ~ 0.5 and 0.9 AU there is an overabundance of exoplanets (Jones et al. 2014). Moreover, Döllinger et al. [2009] observed that around more massive stars more massive planets are found ($M_p \gtrsim 3M_J$) compared with those discovered in solar-type stars confirming the core accretion model.

However, the reason of this observational trend is still in debate (Jones et al. 2014).

Therefore, we need to improve the observations and the study of planets around giant stars to have more statistics, in order to confirm the observed trends and to explain the properties of these systems.

1.5 The outline of this work

We have to answer still many outstanding questions discussed in the previous sections. Therefore we need to study the stars in very high detail. Thanks to Gaia, we will know precisely the positions, distances, space motion and changes in brightness of a thousand million stars in our Galaxy. It is expected to discover hundreds of thousands of new celestial objects, such as extrasolar planets and failed stars called brown dwarfs. The high-precision global astrometric measurements by Gaia will provide deep insights on the science of extrasolar planets. Therefore, combining these measurements with high precision radial velocities we expect to change the current landscape of exoplanets science. In the planet context, Gaia, with RVs follow-up, will help us to detect and to have a full characterization of planetary systems, and therefore to improve and deepen our knowledge on the planet formation and evolution.

In Chapter 2 we discuss the two methods (RV and astrometry) and the developed tool to carry out simultaneous radial velocity and astrometric orbital fits which allow us to derive precise orbital parameters (period, time of the periastron, eccentricity, semimajor axis, inclination and ω). In Chapter 3 we present the study on 8 binary systems in a metal poor sample of solar type stars. Using statistical methods to effectively combine Hipparcos astrometry and radial velocities we find a possible range of solutions for the mass of the companion and its orbital period. Chapter 4 shows the analysis of giant stars, from the study of precise stellar parameters to the abundances for 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn and V). Finally, in Chapter 5 we summarise the results obtained in this PhD project and mention some of the work to be carried out in the future.

CHAPTER 2

Putting together RV and astrometry in view of Gaia

In this chapter we will present our first approach to the two methods (RV and astrometry described in the section 2.1) analyzing stars already studied by different authors. From the basic way (HD162020 and Alpha Centauri A & B) to conclude with the analysis of HD43848. For this last star we'll also analyze its Hipparcos data because the data are unidimensional like Gaia and, therefore, the procedure to analyze them are similar. We'll combine them with the RV analysis. At the end, we'll try to use the same method to study other two stars (HD134113 and HD219828) but without success because of lack of accuracy of Hipparcos data.

2.1 The two methods

Several different detection techniques can discover exoplanets. In this PhD thesis project we deal with two of these methods: radial velocity and astrometry. In this section we describe them.

2.1.1 Radial velocity

The radial velocity method to detect exoplanets is based on the detection of variations in the velocity of the central star, due to the changing direction of the gravitational pull from an exoplanet as it orbits the star. The method consists in interpreting the measurements of radial velocities of these systems (binary stars or star plus exoplanets) to derive the parameters of the orbits. Hilditch [2001] describes how to obtain the orbital parameters from measured radial velocity and below we show how to derive them.

Figure 2.1 shows the binary orbit in space relative to the line of sight of the observer (O) and the tangent plane of the sky. The polar coordinates of the star (celestial body) with respect to O are $(r, \nu + \omega)$, which can be determined into two components in the orbital plane: $r \cos(\nu + \omega)$ along the line of nodes, and $r \sin(\nu + \omega)$ at a right angle to the line of nodes. Therefore, projecting this second quantity into the line of sight, it is obtained

$$z = r \sin(\nu + \omega) \sin i \quad (2.1)$$

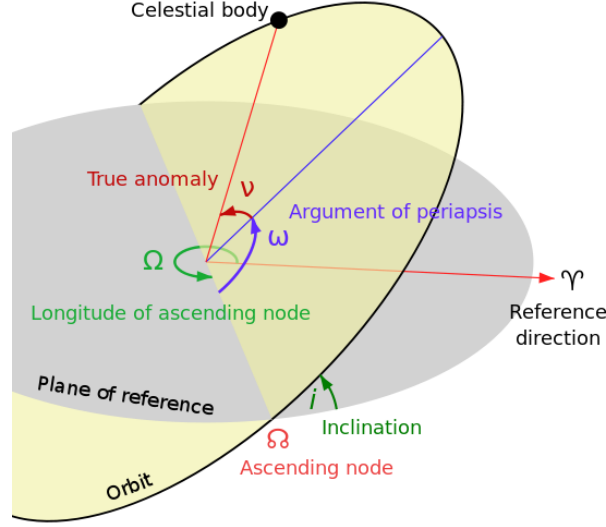


Figure 2.1: The relative orbit of a binary located in three dimensions and defined by the angles Ω , i , and ω . The orbital plane intersects a reference plane. The intersection is called line of nodes, as it connects the center of mass with the ascending and descending nodes.(from Wikipedia)

Consequently, we have the observed radial velocity due to the orbital motion:

$$V_{rad} = \dot{z} = \sin i [\sin(\nu + \omega) \dot{r} + r \cos(\nu + \omega) \dot{\nu}] \quad (2.2)$$

$\dot{r}$ and $\dot{\nu}$ can be determined using the polar equation for an ellipse, $r = a(1 - e^2)/(1 + e \cos \nu)$ to give $\dot{r} = \frac{e \sin(\nu) \dot{\nu}}{1 + e \cos \nu}$ and the Kepler's second law, $r^2 \dot{\nu} = 2\pi a^2 (1 - e^2)^{1/2} / P$. So, the final result is:

$$V_{rad} = \frac{2\pi a \sin i}{P(1 - e^2)^{1/2}} [\cos(\nu + \omega) + e \cos \omega] \quad (2.3)$$

This equation can be written in another form:

$$V_{rad} = K(\cos(\nu + \omega) + e \cos \omega) + \gamma \quad (2.4)$$

where $K = \frac{2\pi a \sin i}{P(1 - e^2)^{1/2}}$ is the semiamplitude of the velocity curve, and γ is the systemic velocity, or the radial velocity of the centre of mass of the binary system. If the quantities γ , K , e , and ω are constant, the radial velocity V_{rad} has a maximum, A , or a minimum, B , when $(\nu + \omega) = 0$ or π , respectively. Therefore, we have $A = \gamma + K e \cos(\omega + K)$, $B = \gamma + K e \cos(\omega - K)$ and as a result $K = (A - B)/2$. In Fig. 2.2 we can see a cosine curve which is given by the equation (2.4), when $e = 0$. Increasing e , the velocity curve becomes increasingly skew-symmetric (Hilditch 2001).

When we can see the velocity curves of the both components (double-lined spectroscopic binary), we can derive from the semiamplitude K_1 or K_2 the projected semimajor axis $a_1 \sin i$ or $a_2 \sin i$ using this equation (Hilditch 2001):

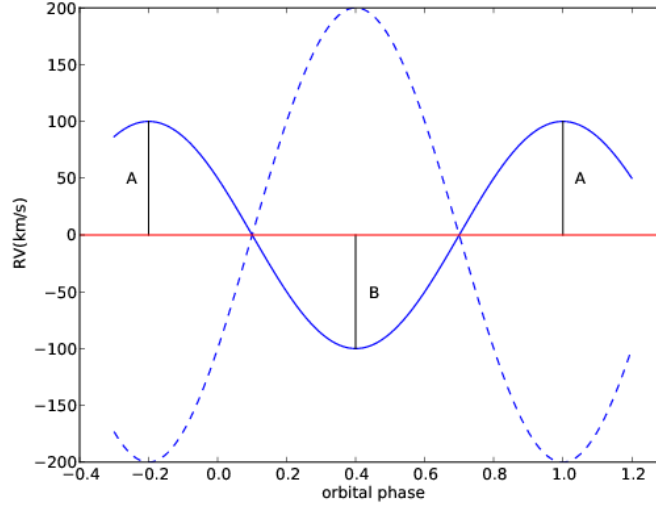


Figure 2.2: The radial-velocity curves for the two stars in a binary system with a circular orbit. The semi-amplitudes are $K_1 = 100 \text{ km s}^{-1}$ and $K_2 = 200 \text{ km s}^{-1}$, giving a mass ratio $q = m_2/m_1 = 0.5$. The systemic velocity is $\gamma = 0 \text{ km s}^{-1}$. (Hilditch 2001)

$$a_{1,2} \sin i = \frac{(1 - e^2)^{1/2}}{2\pi} K_{1,2} P \quad (2.5)$$

To derive the minimum masses $m_{1,2} \sin^3 i$ we can use this relationship (Hilditch 2001):

$$m_{1,2} \sin^3 i = \frac{1}{2\pi G} (1 - e^2)^{3/2} (K_1 + K_2)^2 K_{2,1} P \quad (2.6)$$

It is important to note that this equation provides the true masses only for orbits with $i = 90$ degrees (planes in our line of sight), otherwise, for inclined orbits, we can derive only the lower limit for the mass of each component (Hilditch 2001).

2.1.2 Astrometry.

Astrometry consists of precisely measuring a star's position in the sky and observing how that position changes over time. We should consider the relative motion of star 2 about star 1 at the origin O (Figure 2.3). The three coordinates that describe the motion can be described in relationship with the radius vector r , which is seen at time t to be at an angular position ν relative to the position of periastron, like (Hilditch 2001):

$$\begin{aligned} x &= r[\cos \Omega \cos(\nu + \omega) - \sin \Omega \sin(\nu + \omega) \cos i] \\ y &= r[\sin \Omega \cos(\nu + \omega) + \cos \Omega \sin(\nu + \omega) \cos i] \end{aligned} \quad (2.7)$$

The component z is described in the Eq. (2.1). ω , Ω , i are, respectively, the longitude of periastron, the longitude of the ascending node and the inclination of the orbit.

In Fig.2.3 we can observe the binary motion in function of the projected separation ρ between the two components, 1 and 2, and the position angle θ .

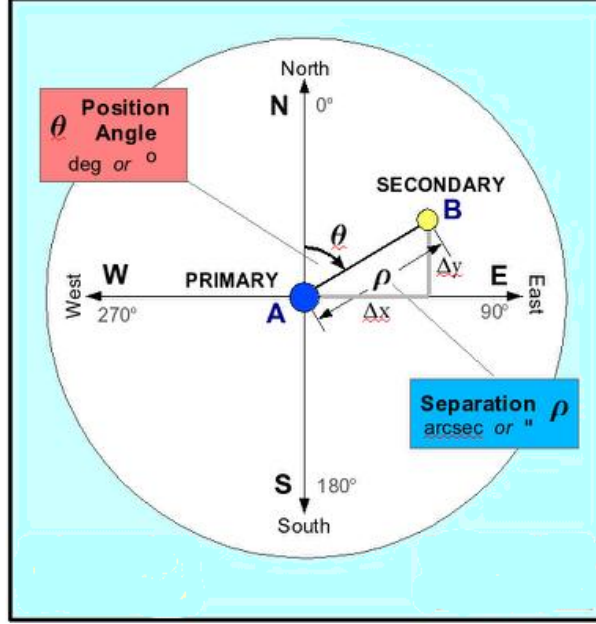


Figure 2.3: Orientation of Double Stars: Representation of Position Angle and Separation.

The separation and position angle (ρ, θ) at time t are in relation with the projected quantities (x, y) using the equations $\Delta\delta = x = \rho \cos \theta$ and $\Delta\alpha \cos \delta = y = \rho \sin \theta$ (Hilditch 2001).

Introducing the Thiele-Innes constants, A, B, F, G , defined as:

$$\begin{aligned} A &= a[\cos \Omega \cos \omega - \sin \Omega \sin \omega \cos i] \\ B &= a[\sin \Omega \cos \omega + \cos \Omega \sin \omega \cos i] \\ F &= a[-\cos \Omega \sin \omega - \sin \Omega \cos \omega \cos i] \\ G &= a[-\sin \Omega \sin \omega + \cos \Omega \cos \omega \cos i] \end{aligned} \quad (2.8)$$

and defining the elliptical rectangular coordinates, $x_p = \cos E - e$ and $y_p = (1 - e^2)^{1/2} \sin E$, so that $r^2 = a^2(1 - e \cos E)^2 = a^2(x_p^2 + y_p^2)$ and $r \cos \nu = ax_p$, $r \sin \nu = ay_p$, we have:

$$\begin{aligned} \Delta\delta &= \rho \cos \theta = Ax_p + Fy_p \\ \Delta\alpha \cos \delta &= \rho \sin \theta = Bx_p + Gy_p \end{aligned} \quad (2.9)$$

The quantity E represents the eccentric anomaly and is the solution of the Kepler's equation:

$$E = \frac{2t\pi}{P} + e \sin E$$

Hence, the orbital period P and the time of periastron passage T_0 is provided by observations of (ρ, θ) over a complete orbit, or at least over a substantial fraction of an orbit. To note that the quantities P , T_0 and e (eccentricity) represent the dynamical elements, while the Thiele-Innes constants contain the geometrical elements (Ω (deg), ω (deg), i (deg), and a (semimajor axis of the ellipse in mas)).

We can describe the position of the central star in right ascension and declination ($X(t)$ and $Y(t)$ in μas) as a function of the time parameterizing the combination of proper motion, parallax and a Keplerian orbit, as follows:

$$\begin{aligned} X(t) &= c_x + \mu_\alpha t + \pi P_\alpha + A x_p + F y_p \\ Y(t) &= c_y + \mu_\delta t + \pi P_\delta + B x_p + G y_p \end{aligned} \quad (2.10)$$

where: c_x, c_y = RA and Dec orthonormal components, μ_α, μ_δ = proper motions (mas/years), π = parallax (mas) and P_α, P_δ = parallax factors (van de Kamp 1960). The formulae for the parallax factors in right ascension and declination are:

$$\begin{aligned} P_\alpha &= (\cos \varepsilon \cos \alpha \sin \odot - \sin \alpha \cos \odot) \\ P_\delta &= ((\sin \varepsilon \cos \delta - \cos \varepsilon \sin \alpha \sin \delta) \sin \odot - \cos \alpha \sin \delta \cos \odot) \end{aligned} \quad (2.11)$$

Where $\varepsilon = 23^\circ 27'$ is the obliquity of the ecliptic, and $\odot$ the Sun's true longitude and α and δ are the right ascension and declination of the star.

Hipparcos astrometry: briefly description

We start here to explain (more accurate explanation will be done in the section 2.4.2) the method to study the Hipparcos data because it's quite similar to the method applied for Gaia data. The Hipparcos catalogue contains the intermediate astrometric data (IAD) or abscissa residuals, which are the data from which the astrometric solutions were obtained. Therefore, in this case the basic astrometric measurements for a single stars are described by the one dimensional position measurements called 'abscissa data', collected over intervals set by the spin period of the satellite (10.6 hours) and referred to a reference great circle. Two independent data reduction consortia, NDAC and FAST, reduced independently the Hipparcos data, and each best final results are provided, but the final catalogue is formed by the merged results from the two consortia. In the IAD we can find some corrections (e.g. aberration, and satellite-attitude corrections). The abscissa residuals along a reference great circle are expressed in terms of the position in right ascension and declination in the equinox 2000.0 at the epoch 1991.25 (α_0, δ_0), the parallax (π), the proper motions in right ascension and declination (μ_α, μ_δ). For the Hipparcos catalogue $\alpha_0^* = \alpha_0 \cos \delta$ and $\mu_\alpha^* = \mu_\alpha \cos \delta$ are used instead of α_0 and μ_α (Pourbaix and Jorissen 2000). In order to look for evidence of orbital motion in the abscissa residuals, the aim is to build an objective function to minimize including the abscissa residuals. The objective function (χ^2) is expressed using this equation (Pourbaix and Jorissen 2000):

$$\chi^2 = (\Delta v - \sum_{k=1}^M \frac{\partial v}{\partial p_k} \Delta p_k)^t V^{-1} (\Delta v - \sum_{k=1}^M \frac{\partial v}{\partial p_k} \Delta p_k) \quad (2.12)$$

where the superscript t means transposed, Δv are the abscissa residuals, and $\frac{\partial v}{\partial p_k}$ is the partial derivative of the abscissa residuals with respect to the k th fitted parameters, Δp_k represents the relative correction, M is the number of parameters in the solution (5 astrometric parameters and the 4 Thiele-Innes constants in our case), and V^{-1} is the inverse of the covariance matrix of the observations given by (Pourbaix and Jorissen 2000):

$$V = \begin{pmatrix} V_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & V_n \end{pmatrix} \quad (2.13)$$

V_j is:

$$V_j = \begin{pmatrix} \sigma_{F_j}^2 & \rho \sigma_{F_j} \sigma_{N_j} \\ \rho \sigma_{F_j} \sigma_{N_j} & \sigma_{N_j}^2 \end{pmatrix} \quad (2.14)$$

where ρ , σ_{N_j} and σ_{F_j} are given in the IAD file and are, respectively, the correlation coefficient between FAST and NDAC abscissae, the standard error of the NDAC abscissa (mas) and the standard error of the FAST abscissa (mas).

If we consider both the two consortia (FAST and NDAC), the residuals obtained are correlated and V_j is the 2×2 variance-covariance matrix for measurement j . Otherwise, if we examine only one consortium V_j reduces to a diagonal matrix (with the estimated uncertainty σ_j of the measurement) (Pourbaix and Jorissen 2000). In detail we will explain better all the procedure when we will describe our study of the test case HD43848 (Sect. 2.4).

Combined radial velocity + astrometry solution

One way to combine radial velocity with astrometry solutions is to fit the Hipparcos IAD keeping four orbital elements fixed (P , e , T_0 , ω) to their spectroscopically determined values. In this way we can solve the inclination angle i and position angle of the ascending node Ω , putting an additional constraint on the astrometric semi-major axis as follows (Pourbaix and Jorissen 2000, Sozzetti and Desidera 2010):

$$a \sin i = 9.19 \times 10^{-8} P K \sqrt{1 - e^2} \pi_* \text{ mas} \quad (2.15)$$

where P is the period in days, the semiamplitude of the radial velocity curve K is in ms^{-1} and the orbital parallax π_* is in mas. Hence, the resulting fitting procedure has a total of 7 adjustable parameters: the five astrometric parameters plus i and Ω .

2.2 HD162020

We started from the study of the two methods one by one. Our first step was to plot the expected RV and astrometric curve of a planet, HD162020b, taken the data from "The Extrasolar Planet Encyclopedia" (<http://exoplanet.eu/>) for the RV method and from "SIMBAD" (<http://simbad.u-strasbg.fr/simbad/>) for the astrometry. Our goal was to acquaint ourselves with the two methods and with the programming language (python is the chosen programming language). For RV, we used the Keplerian function, Eq. (2.4), because it denotes the

radial-velocity variations caused by a planet in a generic Keplerian orbit around the star. Our sets of parameters were: P , e , γ , ω , K and T_0 . We made a small computer program to draw the shape of the keplerian function of HD162020b. We needed to calculate the true anomaly (ν). It is a function of t , e , P and T_0 and we computed it using the following algorithm:

1. for a given moment t , we calculated the mean anomaly, M :

$$M = 2\pi(t - T_0)/P \quad (2.16)$$

2. from the derived value of M , we computed the eccentric anomaly E by solving the Kepler's equation $M = E - e \sin(E)$. This equation is transcendental and we used a method called Lagrange Expansion to solve iteratively the eccentric anomaly E using the following procedure for 20 iterations:

$$\begin{aligned} E_0 &= M + e \sin M + \frac{e^2}{2} \sin 2M \\ M_0 &= E_0 - e \sin E_0 \\ E_1 &= E_0 + \frac{M - M_0}{1 - e \cos E_0} \\ M_1 &= E_1 - e \sin E_1 \end{aligned} \quad (2.17)$$

3. At the end, we calculated the true anomaly ν , considering the orbital eccentricity e and the derived value for E

$$\tan \frac{\nu}{2} = \sqrt{\frac{1+e}{1-e}} \tan \frac{E}{2} \quad (2.18)$$

The resulting plot is shown in Fig.2.4, where:

$$\begin{aligned} P &= 8.428 \pm 0.000056 \text{ days} \\ T_0 &= 51990.667 \pm 0.005 \text{ JD240000} \\ e &= 0.277 \pm 0002 \\ \gamma &= -27.328 \pm 0.002 \text{ km/s} \\ K &= 1.813 \pm 0.004 \text{ km/s} \\ \omega &= 28.40 \pm 0.23 \text{ deg} \end{aligned}$$

For the astrometric program, we used the orbital parameters aforementioned and assumed:

$$a_* = 0.06 \text{ mas}$$

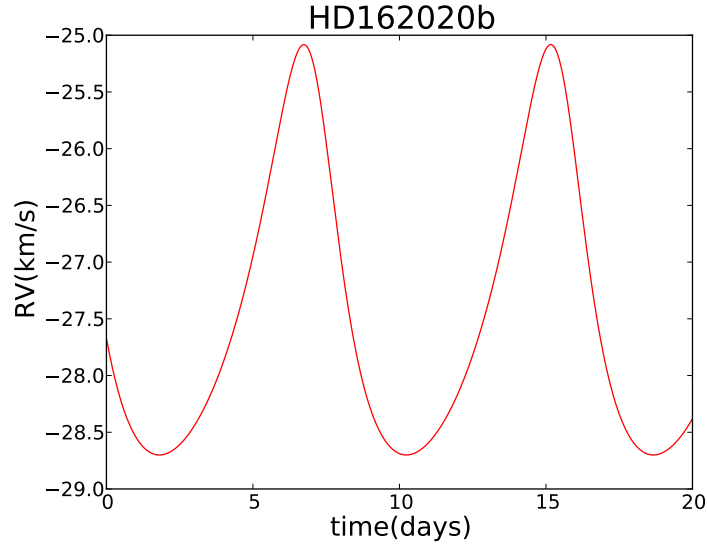


Figure 2.4: The RV curve of HD162020b.

$$i = 45 \text{ degrees}$$

$$\Omega = 180 \text{ degrees}$$

We thus calculated the Keplerian orbit (using the Thiele–Innes elements: A, B, G, F), described in Eq. (2.9) and then plotted the curves in Fig 2.5.

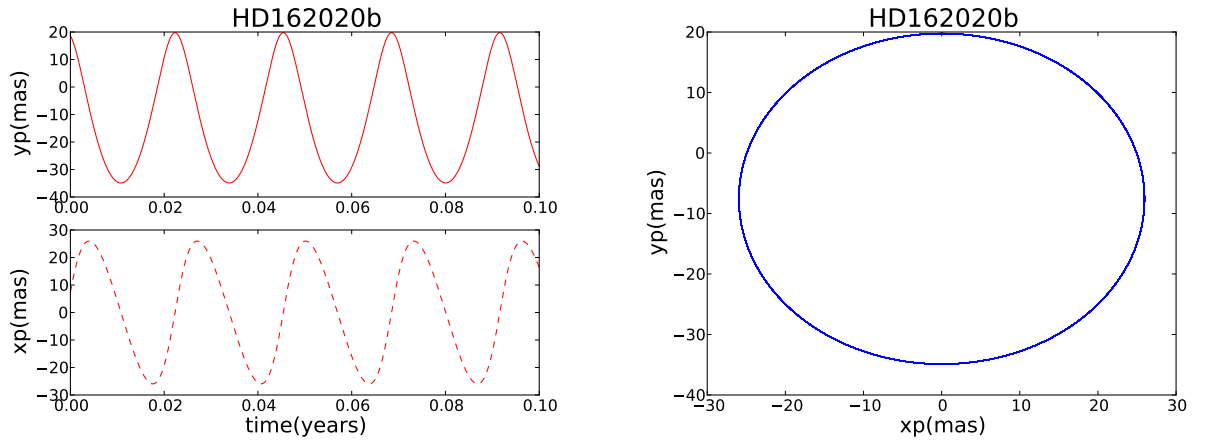


Figure 2.5: The astrometric orbital motion of HD162020b.

After that, the combination of proper motion, parallax and the keplerian orbit has been parameterized as defined in Eq. (2.10). We used the values taken from "SIMBAD" ([http:](http://)

//simbad.u-strasbg.fr/simbad/) for α , δ , the proper motion and the parallax, and calculated the parallax factors like in Eq. (2.11).

The distance (d) of the star was 31.26 pc and so, we calculated the parallax with the formula $\pi = 1/d$. The plot of the path of the star is shown in Fig. 2.6.

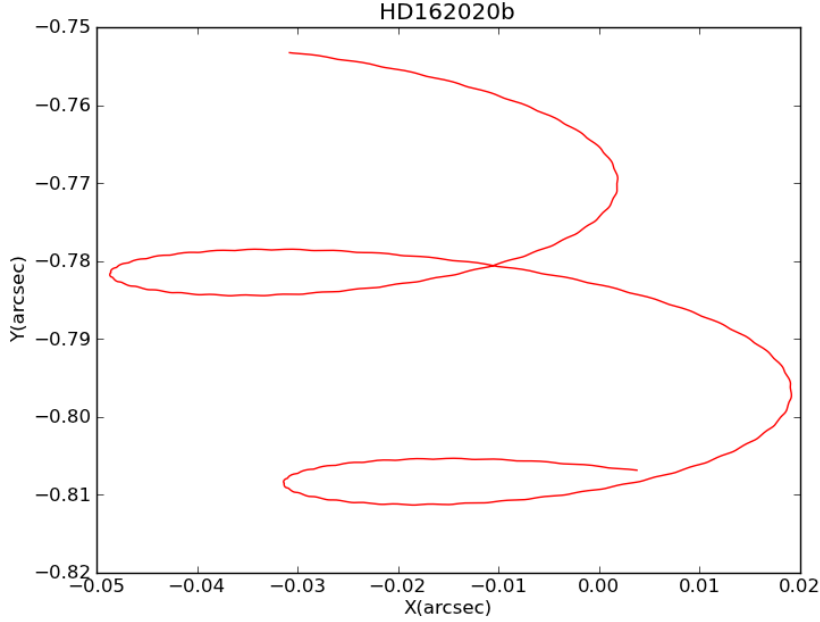


Figure 2.6: The path of the star HD162020.

2.3 Alpha Centauri A and B

Our second step was to fit the RV and astrometric data of alpha Centauri A and B, a binary star. Again, we started from the radial velocity. We took the data from several articles: Lunt [1918], Wesselink [1953], Murdoch et al. [1993], Endl et al. [2001] and Pourbaix et al. [2002]. Our procedure to make the program is as follows:

1. we created a model for the RV (using the procedure of our first program);
2. we read the datapoints and plotted;
3. we calculated the χ^2 for each dataset as:

$$\chi^2 = \sum_i \left(\frac{y_i - M_i}{\sigma_i} \right)^2$$

where y_i are the observations data and σ_i are the errors.

4. we minimized the sum of every χ^2 using the downhill simplex algorithm to recalculate the orbital parameters.

It's important to note that we added different shift array for each datapoints because we took data from different articles which had used different telescopes and so had different γ . Fig. 2.7 shows the final fit using these values (approximately from Pourbaix et al. 2002), like first guesses:

$$P = 29000 \text{ days}$$

$$e = 0.5$$

$$\gamma = -22 \text{ km/s}$$

$$\omega = 230 \text{ degrees}$$

$$K_A = 5 \text{ km/s}$$

$$K_B = 6 : \text{ km/s}$$

$$T_0 = 1800 \text{ days}$$

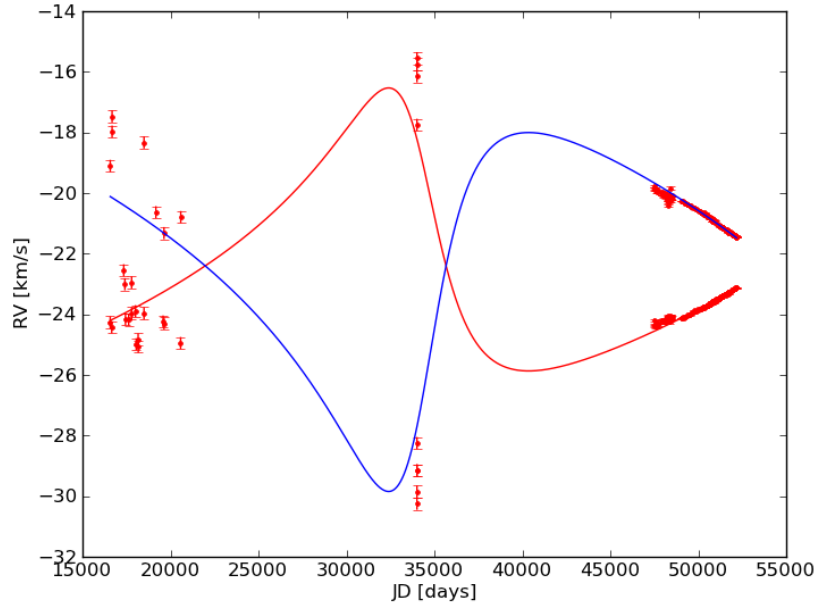


Figure 2.7: RV curve of Alpha Centauri A and B

For the astrometric part of the study of Alpha Centauri A and B we took the data from the WDS catalogue (<http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/WDS>). In this catalogue the relative position of the fainter secondary star referred to the

brighter primary is yielded by visual observations in polar coordinates, so we had the distance (ρ) and the position angle (θ). We rejected the data older than year 1900 for the low quality. Our first step was to convert the polar coordinates in cartesian coordinates to construct the orbit diagram using the equations:

$$x_p = \rho \sin \theta$$

$$y_p = \rho \cos \theta$$

Therefore we fit the orbit diagram (Fig. 2.8, Fig. 2.9). After that, we did the motion of one

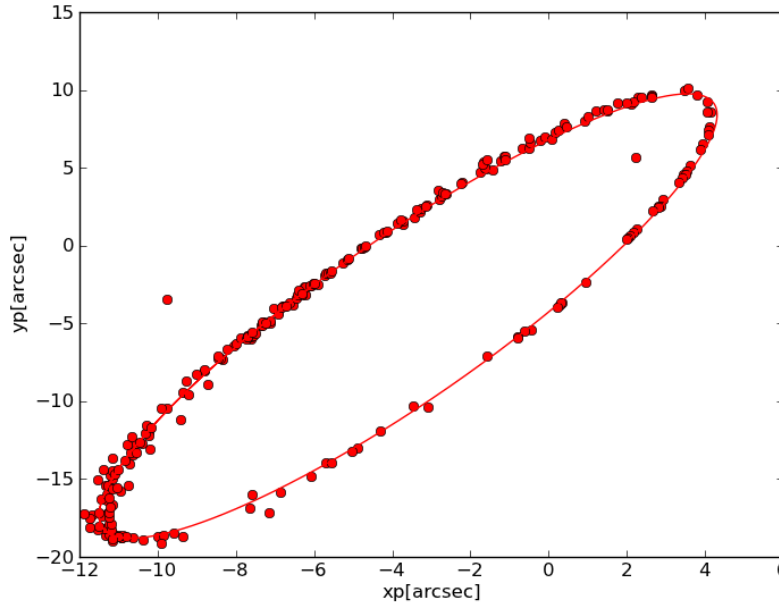


Figure 2.8: Resulted astrometric orbit of Alpha Centauri A and B

component of the binary star using the parallax, proper motion taken the values from "SIMBAD" (<http://simbad.u-strasbg.fr/simbad/>), and errors (that we created random between 0 and 0.005), and we put a planetary perturbation, too, using the Eq. (2.10).

For the planetary perturbation we decided to use these values:

$$M_p = 1.5 * 10^{-2} M_{\odot}$$

$$M_s = 1 M_{\odot}$$

$$a = 1.2 AU$$

$$d = 1.347 pc$$

$$a_p = \frac{M_p}{M_s} * \frac{a}{d}$$

$$P = \sqrt{\frac{a^3}{1 * (M_p + M_s)}}$$

$$e = 0.3$$

$$i = \text{random}(0, \pi/2)$$

$$\omega = \text{random}(0, 2\pi)$$

$$\Omega = \text{random}(0, \pi)$$

$$T_0 = \text{random}(0, P)$$

where we considered the orbit of the planet as prograde (inclination less than 90 degrees) and as visual binary the position angle of the node is less than 180 degrees because it is not known if this is ascending or descending node.

Fig. 2.9 shows the resulted simulated motion of the binary. Finally we studied the residuals

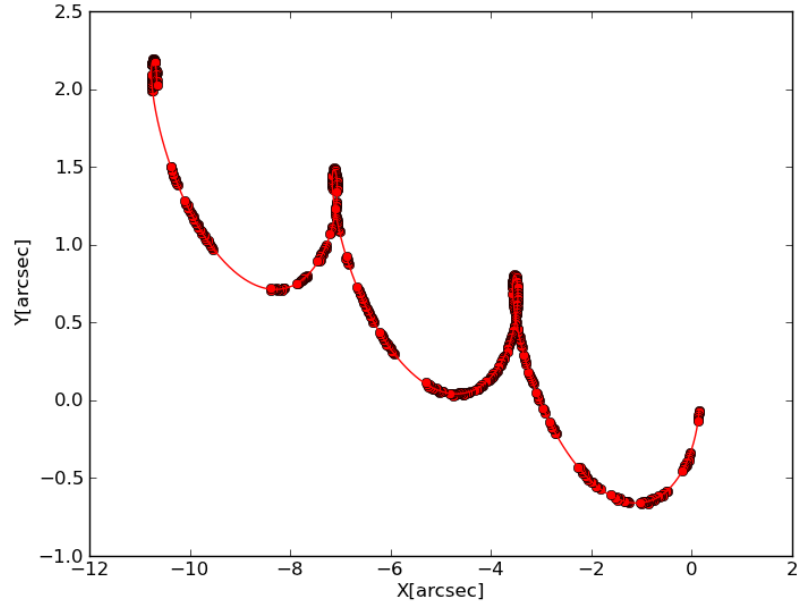


Figure 2.9: Resulted simulated motion of Alpha Centauri.

to understand the differences between those obtained taking into account the planetary perturbation in the fit and those obtained without modeling the planetary motion. We calculated the difference between the data and the model: X-fit and Y-fit. First, we plotted the residuals considering the planetary perturbation in the fit (Fig 2.10). Then, we considered the residuals without the planetary perturbation in the fit (Fig. 2.11). It's possible to notice the difference between the plots: in the case in which we didn't consider the planetary perturbation we had larger and more correlated residuals with respect the other case, in which the residuals are uncorrelated and of

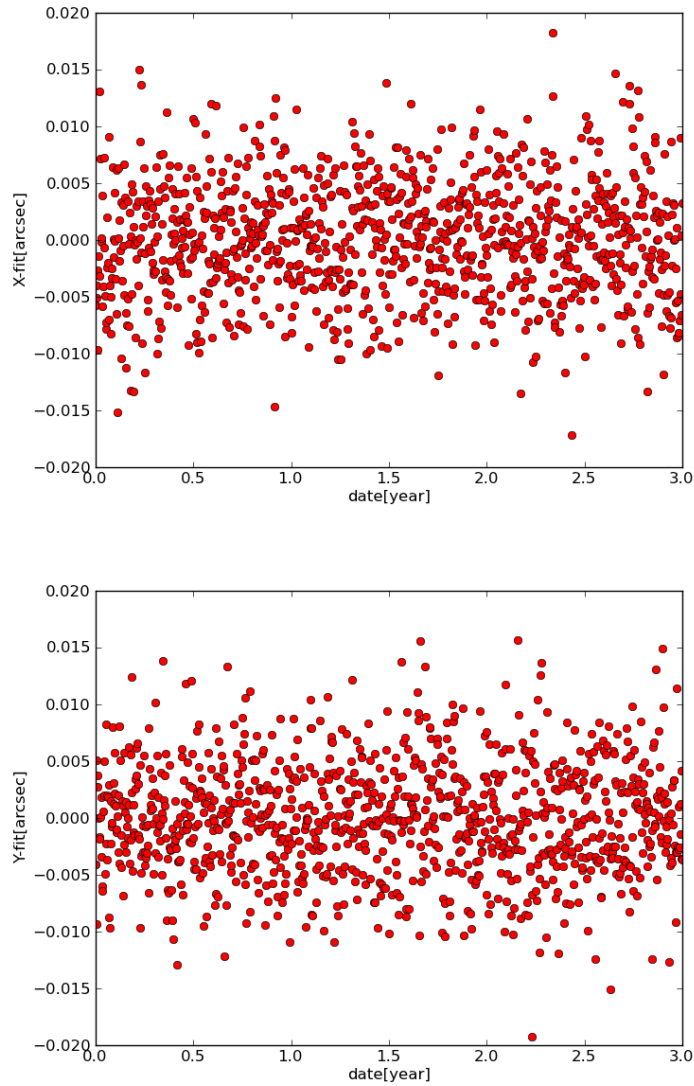


Figure 2.10: Residuals considering the planetary perturbation.

magnitude comparable to the observational errors. So, from the study of residuals it's possible to infer the presence of additional motion induced by a companion, also of planetary mass.

2.4 HD43848: a test case

The Hipparcos telescope represented the first step in the acquisition of astrometric data from space. Positions, annual proper motions and parallaxes have been determined with accuracies in the range 1-2 milliarcsecond. Gaia will provide improvements with orders of magnitude better

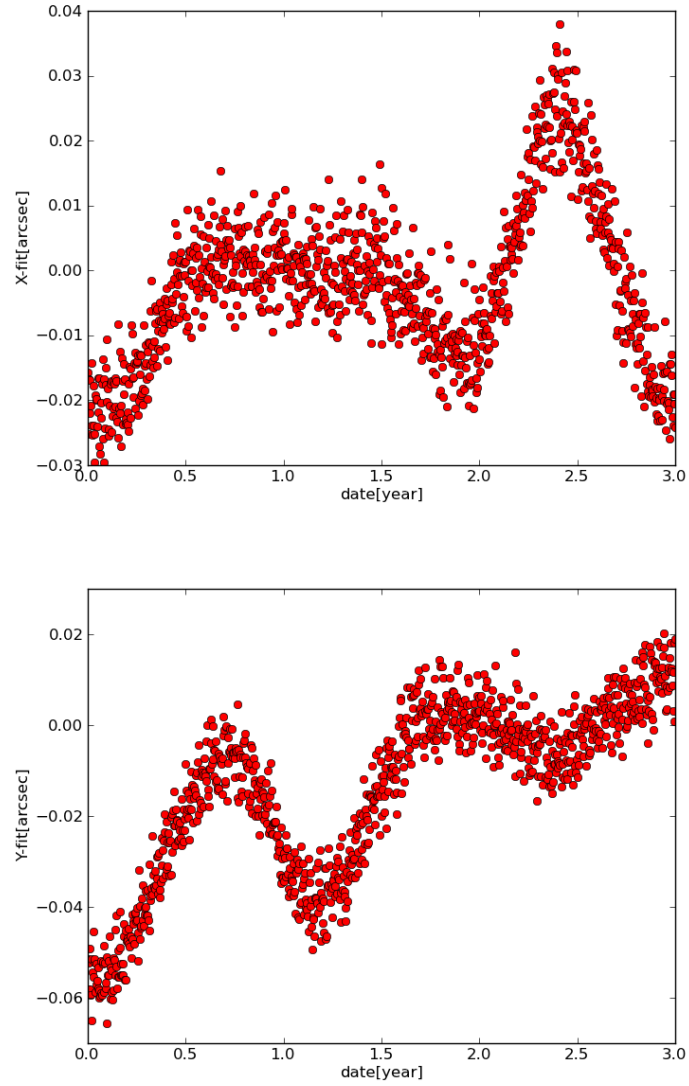


Figure 2.11: Residuals without the planetary perturbation.

for all these parameters.

We start to work with the Hipparcos data because its IAD already defined (Intermediate Astrometric Data) are one-dimensional like the Gaia data. Then, we will study HD 43848 analyzing its Hipparcos data and combining them with the RV method. We chose this star because it was already studied by other authors (Sahlmann et al. 2011, Minniti et al. 2009 and Sozzetti and Desidera 2010) and so we could certify and test our software code. This analysis will be preparatory work for Gaia data.

2.4.1 RV analyses

We examined the Doppler measurements taken with the MIKE echelle spectrograph on the 6.5 m Magellan II telescope by Minniti et al. [2009] combined with the published measurements of the CORALIE instrument before and after its upgrade in 2007 (Ségransan et al. 2010). We fitted these data to adjust the model described by the Keplerian function. The Keplerian orbit solution is found by imposing the model function with 6 parameters (K , e , ω , T_0 , P and γ) to the radial velocities of the star. The uncertainties of the measurements are not larger than 10 m s^{-1} . The resulted RV curved is shown in Fig. 2.12 and the fitted parameters are:

Period = 2349.925079 days

Eccentricity = 0.71375

$\gamma = 214.3185 \text{ m/s}$

$\omega = 227.8790 \text{ degrees}$

$K = 597.4410 \text{ m/s}$

$T_0 = 5592.4172 \text{ JD}240000$.

Sahlmann et al. [2011] obtained the distribution of e through the Monte Carlo simulations and found two possible solutions. However, from their study, the lower eccentricity orbit ($e \lesssim 0.78$) is more probable (77%) than the high-eccentricity one ($e \lesssim 0.96$).

Comparing our results with work of Sahlmann et al. [2011] my parameters confirm that the best and more probable eccentricity is the lowest one.

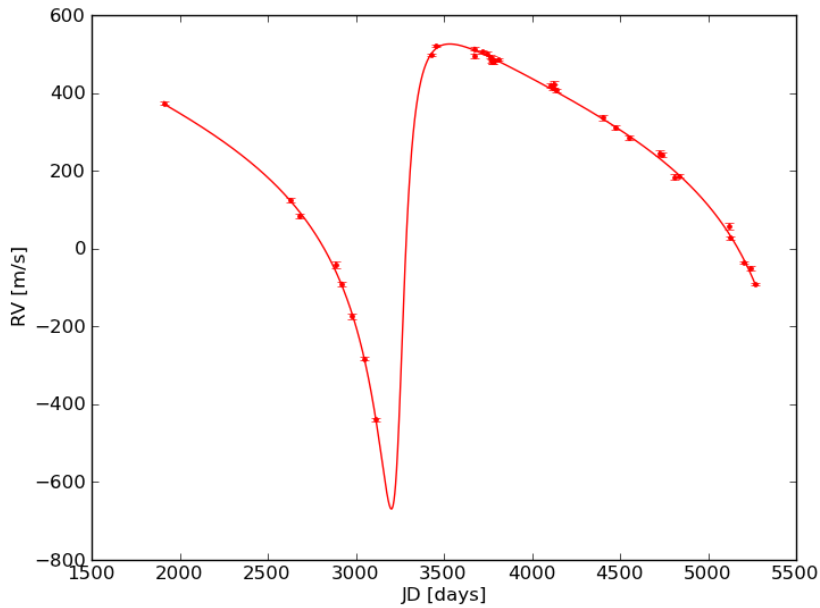


Figure 2.12: Resulted RV curve of HD43848

2.4.2 Astrometry analyses

For the astrometry, we retrieved the data from the official website of Hipparcos. As first step when we need to solve any data fitting problem, we set up an objective function in order to compare different solutions. To do that, it is usually necessary that the lowest value of this function corresponds to the best solution. The IAD gives us the abscissa residuals along a reference great circle for the Hipparcos 5-parameter solution ($\alpha_0, \delta_0, \pi, \mu_\alpha, \mu_\delta$). The purpose is to further reduce the abscissa residual $\Delta\nu$ below the values obtained from the Hipparcos 5-parameter model. So, we created the objective function for the Hipparcos Intermediate Astrometric Data which is the χ^2 expressed by (Pourbaix and Jorissen 2000):

$$\chi^2 = (\Delta\nu - \sum_{k=1}^M \frac{\partial\nu}{\partial p_k} \Delta p_k)^t V^{-1} (\Delta\nu - \sum_{k=1}^M \frac{\partial\nu}{\partial p_k} \Delta p_k) \quad (2.19)$$

where $\Delta\nu$ are the abscissa residuals provided by the IAD file and corresponding to the Hipparcos 5 parameter-solution and $\frac{\partial\nu}{\partial p_k}$ is the partial derivate of the abscissa residual varies when a correction Δp_k is applied to the value of the k -th parameter with respect to the Hipparcos solution. M is the number of parameters retained in the solution, and V^{-1} is the inverse of the covariance matrix of the observations. We use only one consortium of the observation j , so we created V_j as a diagonal matrix with the estimated uncertainty σ_j of the measurement. $\Delta\nu$, together with $\frac{\partial\nu}{\partial p_k}$ ($k = 1$ to 5 , with $p_1 = \alpha_0, p_2 = \delta_0, p_3 = \pi, p_4 = \mu_\alpha, p_5 = \mu_\delta$) and the original astrometric parameters as well as ρ, σ_{F_j} and σ_{N_j} are provided in the IAD file. To estimate χ^2 (Eq. 2.19) for an orbital model, it is required to have partial derivatives of ν with respect to the orbital parameters.

They are expressed as a function of the partial derivatives of ν with respect to α_0 and δ_0 as follows:

$$\frac{\partial\nu}{\partial o} = \frac{\partial\nu}{\partial\alpha_0} \frac{\partial\xi}{\partial o} + \frac{\partial\nu}{\partial\delta_0} \frac{\partial\eta}{\partial o} \quad (2.20)$$

where o is any orbital parameter and $\xi = \alpha_0 + \mu_\alpha(t - t_0) + P_\alpha\pi + y, \eta = \delta_0 + \mu_\delta(t - t_0) + P_\delta\pi + x$. In the above expression, P_α and P_δ are the parallax factors, while ξ and η represent the Cartesian coordinates of the observed component on the plane tangent to the sky at the position (α_0, δ_0) . They combine the displacements due to the proper motion, the orbital motion and the parallax.

The apparent orbit around the center of mass of the system is described by the variables x and y . They are expressed using the Thiele-Innes constants of the photocentric orbit as $x = AX + FY$ and $y = BX + GY$ with $X = \cos E - e$ and $Y = \sqrt{1 - e^2} \sin E$ where E is the eccentric anomaly and (X, Y) are the coordinates in the true orbit.

We used the Thiele-Innes representation of a photocentric orbit to carry out a linear least squares fit over a large grid of periods, while keeping fixed e and T_0 to their spectroscopic values. The fitted model is fully linear in 9 parameters (Eq. 2.19 with $M=9$), i.e. the five astrometric ones and the four Thiele-Innes constants A, B, F and G (Sozzetti and Desidera 2010).

Therefore, in that case the derivatives for the Thiele-Innes parameters are $\frac{\partial\nu}{\partial\alpha} \frac{\partial x}{\partial A} A, \frac{\partial\nu}{\partial\alpha} \frac{\partial x}{\partial F} F, \frac{\partial\nu}{\partial\delta} \frac{\partial y}{\partial B} B, \frac{\partial\nu}{\partial\delta} \frac{\partial y}{\partial G} G$ with $\frac{\partial\nu}{\partial\alpha}$ and $\frac{\partial\nu}{\partial\delta}$ given in the IAD file; $\frac{\partial x}{\partial A}$ and $\frac{\partial y}{\partial B}$ represent X, $\frac{\partial x}{\partial F}$ and $\frac{\partial y}{\partial G}$ represent Y.

In this way we calculated the variation of χ^2 as a function of a trial period (a periodogram). The outcome is shown in Fig. 2.13.

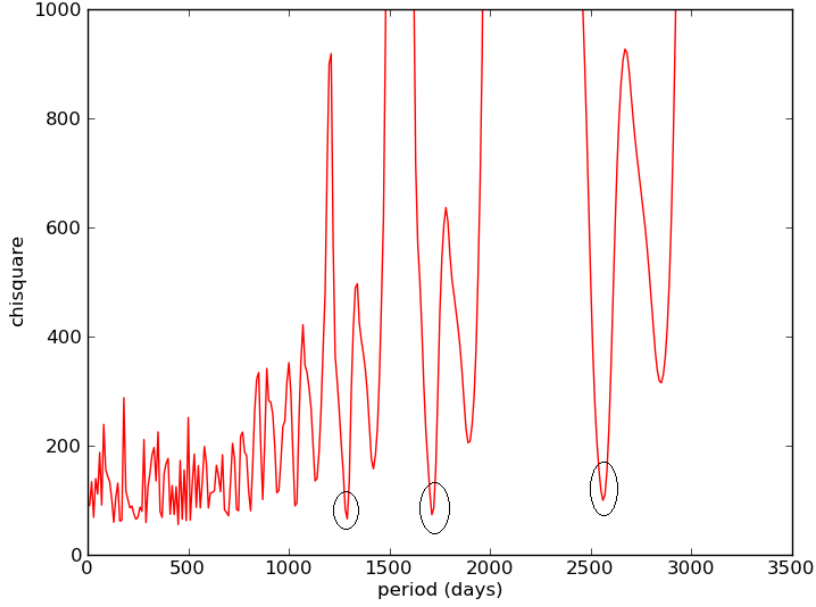


Figure 2.13: Periodogram of HD43848: a long-period trend in the data emerges in agreement with the RV analyses and the paper of Sozzetti and Desidera [2010]

A long-period trend in the data emerges from the plot in agreement with the RV analyses and the work by Sozzetti and Desidera [2010]. Hipparcos only covered a fraction of the period (the duration of the mission was 3 years) but the periodogram has 3 local minima (circled) after 1000 days that confirm the presence of a long period companion.

Then, we derived the upper mass limit from the astrometry of the planet for HD43848, while the radial velocity analysis gives the lower limit. Fixing e , T_0 and P to their spectroscopic values, we derived, first, the inclination from only the Thiele-Innes analysis using the Eq. (2.21) and after the semi-major axis from Eq. (2.22) (Pourbaix and Arenou 2001):

$$i = 2(\arctan \sqrt{\frac{(G - A)^2 + (B + F)^2}{(A + G)^2 + (B - F)^2}}) \quad (2.21)$$

$$a^2 = \frac{1}{\cos i} (A * G - F * B) \quad (2.22)$$

Then we could calculate the upper limit in mass for the planet using the following equation:

$$M_p = \frac{a(arcsec) * (M_s^{\frac{2}{3}} * d(pc) * \sqrt{1 - e^2})}{P^{\frac{2}{3}}} \quad (2.23)$$

The result is $310.069M_J$ and it's not far from the error bars of the paper by Sozzetti and Desidera [2010]. They discovered that it is a late M dwarf with a companion of mass $M_c = 120_{-43}^{+167}M_J$.

With the milliarcsec astrometry we cannot reach the sensitivity of radial velocity measurements for inclined orbits and for secondaries of order $1 - 10M_J$. The astrometric signature due to the primary's reflex motion doesn't depend on the inclination, on the contrary smaller orbital inclinations lead to smaller radial velocities. For this reason the astrometry constraints the upper limit of the secondary's mass. But the astrometric sensitivity of Hipparcos can only determine orbits for brown dwarf companions of nearby stars, if they exist. Therefore, Gaia opens exciting perspectives to study and to know the true mass of brown dwarfs and high-mass planets, which can give us the possibility to study the formation mechanisms of objects with similar mass and their chemical composition.

2.4.3 Unresolved cases

We tried to analyze other 2 stars, HD134113 and HD219828 to derive the upper mass limit similarly to what we found for the previous star. For HD134113, we took the spectroscopic parameters from Santos et al. [2011]. They found an orbital period of 201.674 ± 0.008 days and a minimum mass of $M_p \sin i = 48M_J$. Therefore, as a first step with the astrometric data from Hipparcos, we fitted the model to search for the period (Fig. 2.14). We could observe a deep around 0.4 years that fits well with RV orbital period. After that, we calculated the upper mass, but the resulted value was $604.69 M_J$. This bad result is due to the small dataset and the high distance of the star, limiting the conclusions that can be drawn due to the lack of Hipparcos accuracy.

For the star HD219828 the outcome was even less constraining. We knew the spectroscopic parameters from the paper of Melo et al. [2007]. But, unfortunately, Hipparcos, in this case, observed nothing (the periodogram is shown in Fig. 2.15) always due to the high distance of the star (Parallax = $13.83 mas$). Therefore, we computed the astrometric signature (α) using the Eq. (2.24) that for this star is 8.3 microarcsec. With the target mission accuracy of $20 \mu as$, Gaia will be able to easily measure the mass of objects such as those around HD 134113 and HD 219828.

$$\alpha = \frac{M_p}{M_s} * \frac{a_p(AU)}{d(pc)} \quad (2.24)$$

2.4.4 Summary and future work

In this chapter, we presented the study of the two methods (radial velocity and astrometry) for different stars. We described the procedure and the results; we developed a programming code which seems to perform well. With the same code for Hipparcos data we tried to analyze two new stars but without success. In the future, we need to implement a new task to allow also

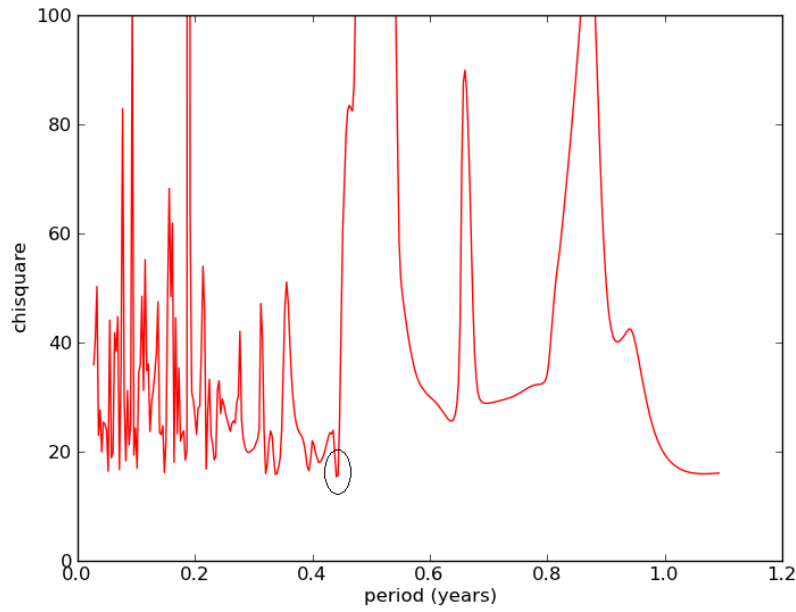


Figure 2.14: Periodogram of HD134113

the measurement of the inclination (i), to be able to calculate the true mass of planets and to perform a method to calculate also the errors for the RV method. With the arrival of Gaia data, we could use the same software code to calculate the true mass of thousands of brown dwarfs and high-mass planets and therefore to improve our knowledge about extrasolar planets.

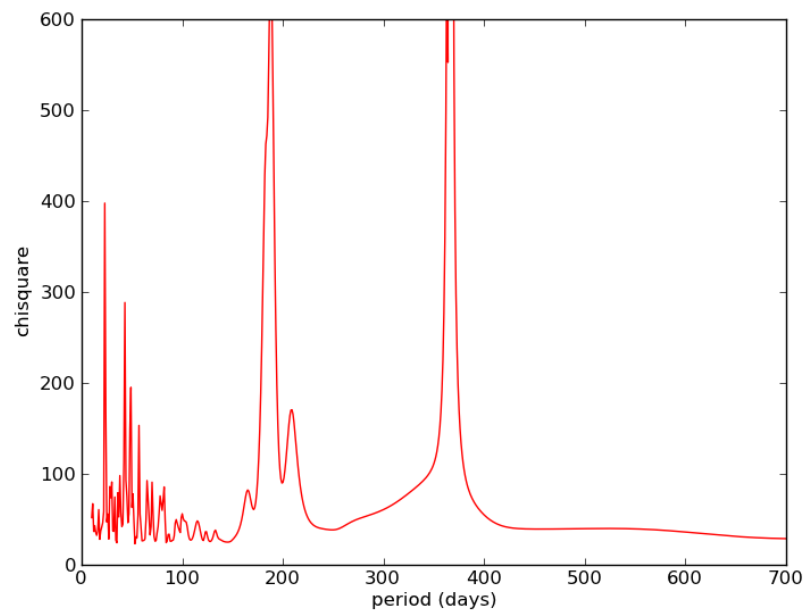


Figure 2.15: Periodogram of HD219828

CHAPTER 3

Binary systems in a metal-poor sample.

This chapter describes the work done for the analysis of 8 metal-poor binary systems (SB1 – Benamati et al. 2013).

The theories of planet formation and evolution are still under discussion and the study to find some strong correlation of giant planet frequency with stellar metallicity $[Fe/H]$ is still open. It seems easier to find a planet around a metal-rich star than around metal-poor object. In this context, Sozzetti et al. [2009] and Santos et al. [2011] were motivated to design the RV surveys focus on the search for planets orbiting metal-deficient stars. In these sample unsuitable targets for a planet search were found for different reasons. Some of these stars, in particular, are binary stars (SB1). Our work focused on these metal-poor binary stars.

The differences between binary frequencies for metal-poor and metal-rich stars has a long story. Some studies have showed that metal-poor stars are deficient in binaries, others that they have the same frequency of binaries as metal-rich stars.

Abt [2008, 2009] showed that the metal-poor binaries have few short periods and many long ones, while for the metal-rich binaries the opposite is true. The reasons of this different period distribution can due to the equipment used or to the formation process. First, the low-resolution spectrographs help us to detect many of the short period binaries but not many of the long-period binaries and therefore we can conclude that the metal-poor stars are deficient in binaries. On the contrary, with the use of higher resolution we can detect many more binaries and so conclude that there is no differences in binary frequency between metal-poor and metal-rich stars. Second reason, if binaries are formed in three-body interactions in clusters and, as n-body simulations show, the longer they remain in dense cluster environments, the harder (shorter periods) they become.

On the other hand, Latham et al. [2002] found that the period distribution are the same for the halo and disk suggesting that metallicity have little influence over the fragmentation process that leads to short-period binaries. Furthermore, Latham et al. [2002] discovered that all the binaries with periods shorter than 10 days have nearly circular orbits, while the binaries with periods longer than 20 days exhibit a wide range of eccentricities and a median value of about 0.37. Finally, if we compare these results with the parent stars in systems harboring planets, it seems

that the stellar companions and planetary companions form and/or evolve by two different processes, because the frequency and orbital characteristics of stellar companions does not depend on metallicity. The results are in disagreement and need more investigation.

Another study focused on the mass ratio distribution for the binaries. The conclusions regarding the mass ratio distribution of solar-type binaries are discrepant due to the difficulties to detect low-mass companions. The studies proposed a distribution flat or bimodal or monotonically increasing toward low- q systems (Trimble 1990). In Duquennoy and Mayor [1991] the distribution shows a peak around $q \approx 0.3$, instead Raghavan et al. [2010] demonstrated that the distribution is flat down to $q \approx 0.1$ with the exception of a marginally significant peak at $q \gtrsim 0.95$. Duchêne and Kraus [2013] found a difference in the ratio between short- and long- period binaries: the first one are characterized by a strong peak at $q \approx 1$ and a slowly declining $f(q)$ function toward low-mass ratios, while the long-period binaries have a single peak around $q \approx 0.3$. Even for extreme mass ratio systems ($q \lesssim 0.1$) the discussion and the interest are still open, in the context of the search for planetary-mass companions and of the difficulty for binary formation models to produce them (Bate 2012). In Fig. 3.1 deficit of low- q systems, especially among (very) low-mass objects is shown. The extremely low frequency of BD (Brown dwarf) companions among solar-type SBs (e.g. Grether and Lineweaver 2006) is inconsistent with extrapolations of both the binary mass function and the planetary mass function (e.g. Reffert and Quirrenbach 2011, Sahlmann et al. 2011). It is called BD "desert" but it is not completely arid: the BD companions are rare but not absent (Janson et al. 2012b). Therefore, we need further and more analysis. Finally, the way this trend depends on $[\text{Fe}/\text{H}]$ has never been explored in detail because of the relatively small numbers of known binars among metal-poor stars.

In this context, using different statistical methods we try to find in binary systems a range of solutions for the period and the mass of the companion based on the available radial velocities and the combination of Hipparcos and Tycho astrometry.

3.1 Sample and data

The stars in this sample originally belongs to the Doppler surveys described in Santos et al. [2011] and Sozzetti et al. [2009]. Once they discovered that these objects were SB1 spectroscopic binaries, they were removed. The list of the entire sample analyzed is presented in Table 3.1 and the detailed set of properties can be found in the mentioned papers. For the most part of the stars (except CD-436810 and G135-46) was not found acceptable orbital solution with the available RV data. The RV measurements were obtained with the HARPS Spectrograph at La Silla (Mayor et al. 2003) from Santos et al. [2011] and with the HIRES Spectrograph on the Keck 1 telescope at Mauna Kea in Hawaii (Vogt et al. 1994) from Sozzetti et al. [2009].

The HARPS data for CD-436810 and HD16784 were obtained with a $2 - 3 \text{ m s}^{-1}$ precision, during approximately three and one year respectively. A complete and more detail description of the data and observing strategy is given in Santos et al. [2011]. For the other stars, the RV data were collected using HIRES (see Sozzetti et al. 2009 for details) over a timespan of about three years (2003-2006). The precision of this data is typically $5 - 10 \text{ m s}^{-1}$. Further lower-precision RV time-series for all binaries (except CD-436810 and HD16784) were gathered with the CfA Digital Speedometers (Latham 1992) and with TRES Echelle Spectrograph at the 1.5 meter Tillinghast

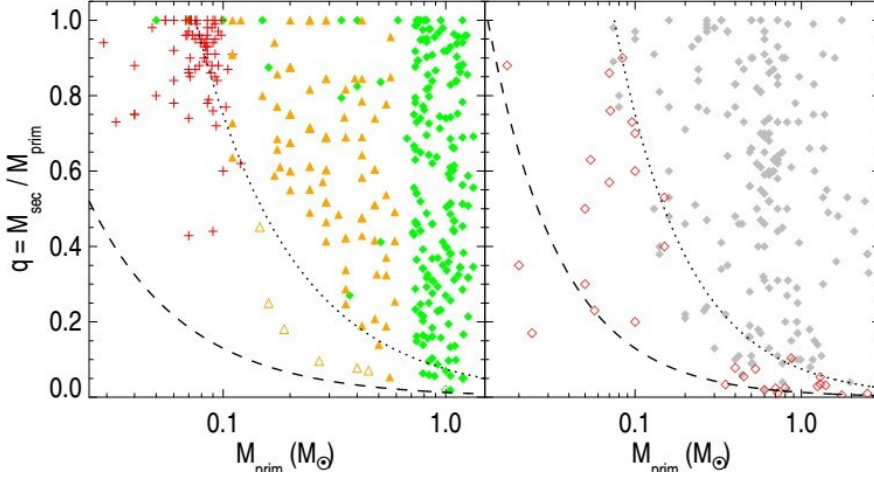


Figure 3.1: (*Left:*) Distribution of mass ratios as a function of mass for nearby field objects with $M_{\star} \leq 1.5 M_{\odot}$. The black dotted and dashed curves indicate constant companion masses at the substellar and planetary regime limits (0.075 and $0.013 M_{\odot}$), respectively. Data for solar-type stars (green diamonds), low-mass stars (orange triangles) and very low-mass (VLM) objects (red plus signs) are taken from Raghavan et al. [2010], the RECONS survey and Janson et al. [2012a], and the VLM binary database, respectively. Brown dwarf companions to low-mass stars identified outside of large-scale surveys are shown as open orange triangles. The few systems with $M_{prim} \leq 0.5 M_{\odot}$ from Raghavan et al. [2010] correspond to lower mass subsystems in hierarchical multiple systems. (*Right:*) Similar plot for star-forming regions and young associations. Shown as gray diamonds in this plot are companions to Class II/III objects in Taurus, Upper Scorpius, and Chamaeleon I using the large surveys from Kraus et al. [2008, 2011], Kraus and Hillenbrand [2012] and Lafrenière et al. [2008]. In addition, red open diamonds represent objects discovered via small-scale surveys or pointed observations with a particular emphasis on VLM primaries and/or companions (the figure is taken from Duchêne and Kraus [2013]).

telescope on Mt. Hopkins in Arizona. Typical velocities precision for TRES is on the order of 100 m s^{-1} , while for CfA DS is $\sim 0.5 \text{ km s}^{-1}$ (see Table 3.2), but have a long duration between ~ 10 years and more than 27 years. Using data from different spectrograph, we accounted for differences in the RV zero-points between datasets. The full set of RV time-series is presented in the various panels of Fig. 3.2. The relative HIRES measurements for each stars were shifted by the mean of the RV data from CfA and TRES (Table 3.2) in order to bring them close to the common CfA DS + TRES system and small residual velocity offsets between the three systems were determined as free parameters in the best-fit orbital solutions presented in Table 3.3. All HIRES, HARPS, CfA DS and TRES data are available in Appendix A of this thesis.

Table 3.1.: The sample of metal-poor spectroscopic binaries included in this study.

Star	Comment	$[Fe/H]$ (dex)	M_1 ($M_\odot$)	source of RVs	source of $[Fe/H]$	source of M_1
CD-436810	SB1	-0.44	0.91	HARPS Spectrograph	Adibekyan et al. [2012b]	Sousa et al. [2011]
HD16784	SB1	-0.65	0.83	HARPS Spectrograph	Sousa et al. [2011]	Sousa et al. [2011]
G27-44	SB1	-0.78	0.85	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]
G63-5	SB1	-0.62	0.83	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]
G135-46	SB1	-0.62	0.84	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]
G237-84	SB1	-0.66	0.79	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]
HD7424	SB1	-0.76	0.82	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]
HD192718	SB1	-0.63	0.88	HIRES Spectrograph	Sozzetti et al. [2009]	Sozzetti et al. [2009]

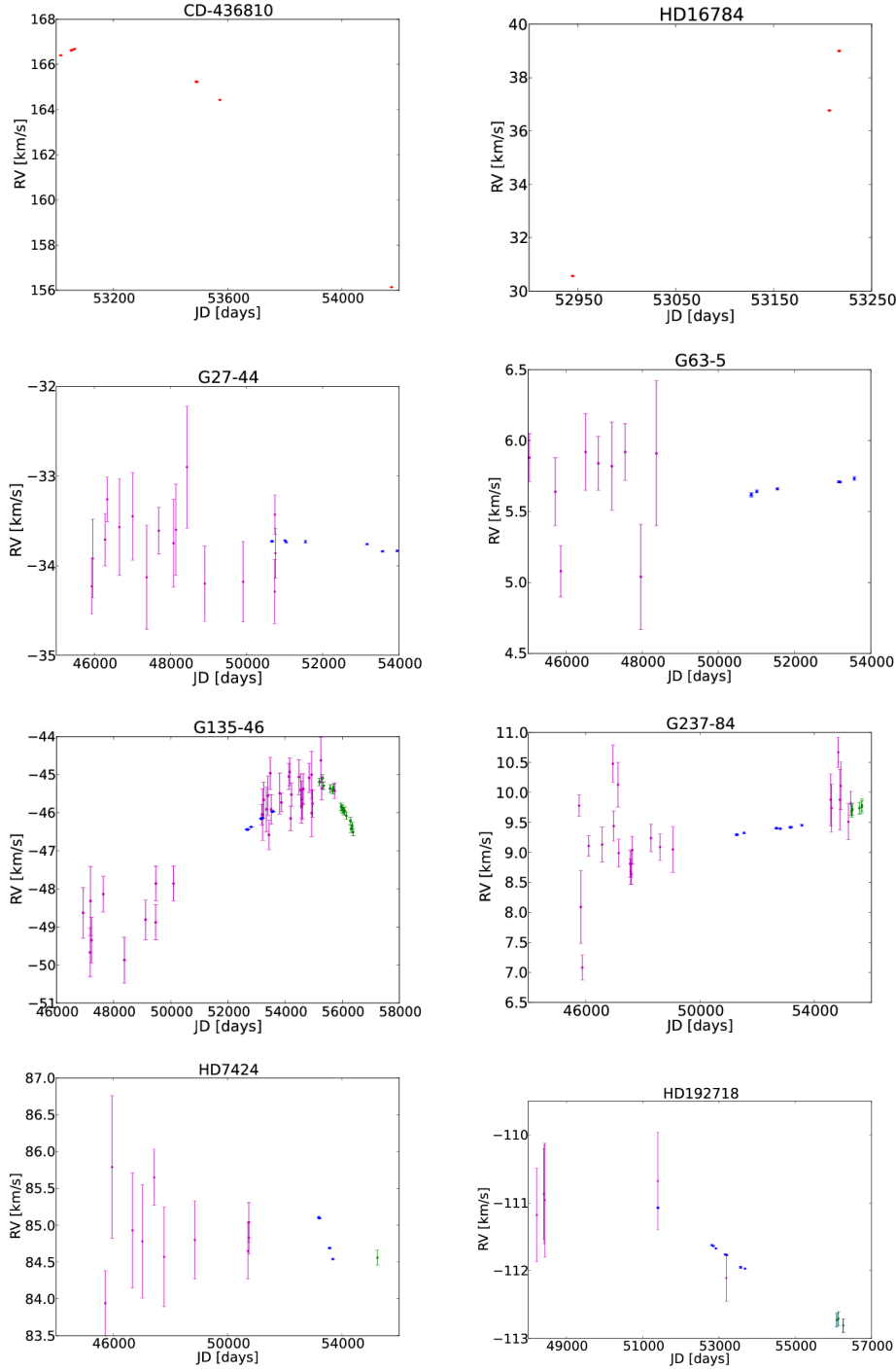


Figure 3.2: RV measurements for the metal-poor binaries: red points indicate HARPS measurements, blue points HIRES data, magenta points the CfA DS measurements and green points the TRES velocities.

Table 3.2: List of the sample with available radial-velocity RMS and mean RV from the CfA DS + TRES.

Star	RMS (km s ⁻¹)	Mean RV (km s ⁻¹)
G27-44	0.39	-33.76
G63-5	0.36	5.67
G237-84	0.73	9.38
HD7424	0.51	84.87
HD192718	0.92	-111.66

Table 3.3: Elements of the fitted orbit for the binaries G135-46 and CD-436810

	G135-46	CD-436810	
P	10378.14963 ± 343.58878	1702.706837 ± 983.189055	days
e	0.24669 ± 0.03726	0.244466 ± 0.311647	
γ	-47.1821 ± 0.1555	162.4862 ± 0.7259	km s ⁻¹
ω	107.73555 ± 8.28467	-138.691965 ± 32.953857	deg
K	1970.701 ± 143.278	5373.413773 ± 588.369727	m s ⁻¹
T ₀	56969.75177 ± 182.83846	54307.191445 ± 750.931749	JD
ΔRV _{T-CfA}	+0.316 ± 0.252		km s ⁻¹
ΔRV _{H-CfA}	-0.3114 ± 0.223		km s ⁻¹

3.2 Statistical methods

In this section we describe the methods used to analyze the binary systems. Looking at the Fig. 3.2 we clearly notice that for most systems in our sample the high-precision RV data allow us only to identify the existence of long-term (mostly linear) trends, and the low-precision Doppler measurements (when available) usually cannot improve significantly the situation when we combine them to derive full-fledged spectroscopic orbital solutions. Therefore, to obtain some insight on the range of companion masses and periods for these systems, we used, in addition to standard keplerian orbit fitting algorithms, when possible, other 'non-standard' statistical methods taking advantage of not only the RV data but also, when available, Hipparcos and Tycho-2 astrometry.

The statistical methods used are:

1. the method described by Makarov and Kaplan [2005] was used to calculate the differences between the measured proper motion of Hipparcos and Tycho-2 ($\Delta\mu$), in addition to values for the acceleration in the proper motion ($\dot{\mu}$), when measured and reported in the Hipparcos catalogue. We tried to estimate the physical parameters of the systems, in particular the period and the mass of the secondary star, using the statistical approach discussed by these authors.
2. the method described by Torres [1999] was used to derive an estimate for the mass of the companion and the orbital period, when only a simple acceleration was detected in the

Doppler studies (i.e. a linear RV trend).

Finally, to obtain tighter limits on the ranges of period and mass for the companions, fitting with the available data, we combined the relatively loose constraints from each individual method.

3.2.1 Radial velocity

Here we describe the methods using the available RV data.

Orbital solution

First, we fitted the radial velocity data with a Keplerian function to try to find a possible orbital solution. Unfortunately, only for two of the systems (G135–46 and CD–436810) we found a satisfactory Keplerian fit (see Sect. 3.3).

The Keplerian function (from Hilditch 2001) used for the measured radial velocity of the primary star is:

$$vr = \gamma + K[e * \cos \omega + \cos(\omega + \nu)] \quad (3.1)$$

where ω is the longitude of the periastron of the companion, ν is the true anomaly (both in degrees), e is the eccentricity, K the radial velocity semi-amplitude and γ is the velocity of the center of mass of the system (both in m s^{-1}). Then, we calculated the minimum mass of the companion using the following equation and the orbital parameters calculated before:

$$M_{\min}(M_J) = \frac{1}{203.255} * M_1^{2/3}(M_\odot) * P^{1/3}(d) * K(m/s) * \sqrt{1 - e^2} \quad (3.2)$$

d(RV)/dt method

As already mentioned, we adopted another method using the acceleration in the RV curve to estimate, from a statistical point of view, the mass of the companion. When the detected RV variation is in a good approximation a linear trend, we used the method fully described in Torres [1999]. This situation is verified when the period is very long and only a linear acceleration (a slope), $d(RV)/dt$, can be determined. However, to complete our study, we have also decided to apply this method to the cases of G135-46 and in part for CD436810, but only considering the data in the linear part of the curve. In these cases, we use the expression for the secondary mass in terms of the measured RV acceleration, the distance estimate (D) and the angular separation (ρ):

$$M_2 = 5.341 * 10^{-6} (D\rho)^2 \left| \frac{d(RV)}{dt} \right| \Phi(i, e, \omega, \varphi) \quad (3.3)$$

Here, Φ is a function of the inclination angle (i), the eccentricity (e), the longitude of periastron (ω) and the phase of the orbit (φ), all of which are unknown in principle (together with the

angular separation):

$$\Phi(i, e, \omega, \varphi) = |(1 - e)(1 + \cos E)\{ (1 - e \cos E) * [1 - \sin^2(\nu + \omega) \sin^2 i] \sin(\nu + \omega)(1 + \cos \nu) \sin i \}^{-1}| \quad (3.4)$$

where the eccentric anomaly E is related to the true anomaly ν through the relation:

$$\tan \frac{\nu}{2} = \sqrt{\frac{1+e}{1-e}} \tan \frac{E}{2}. \quad (3.5)$$

The orbital phase is linked to the true anomaly ν and to the eccentric anomaly E through Kepler's equation,

$$E - e \sin E = 2\pi\varphi \quad (3.6)$$

If the acceleration is measured in $\text{m s}^{-1} \text{ yr}^{-1}$, the angular separation in arcsec, and the distance in pc, the companion mass results in solar units.

Therefore, as first step, we computed the slope from the RV data presented in Fig. 3.2. We decided to exclude the CfA DS data because they have a much lower RV precision. For the cases of CD-436810 and G135-46 we used only data that are on the linear part of the RV curve. For the remaining cases (G27-44, G63-5, G237-84, HD16784, HD7424 and HD192718) we used the linear slope of the RV data (summarized for all targets in Table 3.5), which indicates the presence of a distant companion orbiting with a period greatly exceeding the duration of the observations. After that, we calculated the distance to the star using the parallax value from Hipparcos. Therefore, we have only two quantities, $d(RV)/dt$ and D , as observables. The separation, ρ , and the orbital elements are unknown. Consequently, we applied a numerical Monte Carlo approach to have information on the secondary mass. We adopted a random uniform distribution for the inclination angle (in deg, between 0 and 1), the longitude of the periastron (in deg, between 0 and 2π) and the phase (between 0 and 2π). For the eccentricity, we set a circular orbit for the case of CD-436810, because the solution found from the Keplerian fit is close to circular, and for the others binaries we set a random eccentricity in the range $[0, 0.95]$. For the orbital period, we decided to adopt a random, uniform distribution with the maximum to 100 years, while the minimum value was set from the total timespan of the RV measurements. The projected separation was calculated using Kepler's third law and using the known Hipparcos distance and the random orbital period assuming a reasonable approximation for the total system mass of $1 M_{\odot}$. In such way, we calculated the secondary mass from the Eq. (3.3). From the results we accepted only values that satisfy the condition $M_2 < M_1$ (these binaries are single-lined spectroscopic and by definition the companion star cannot be as massive as the primary, otherwise a secondary spectrum would have been detected in the spectroscopic data). This implies that not all the values of ρ are accepted (see Eq. (3.3)) and therefore the orbital period, too. At the end of this analysis, therefore, we can obtain a possible range of solutions for the orbital period and the mass of the detected companion (see, as an example, the histogram of Fig. 3.3).

An estimate for the upper limit of the minimum mass

From our RV datasets, the CfA DS data are those with less precision and largest error bars. However, they span a period much larger than the ones obtained with HARPS or HIRES. There-

fore, we decided to use the CfA DS RVs to estimate an upper limit for the minimum mass of the companion and the range of orbital periods. We used the Eq (3.2) to calculate the value of the minimum mass fixing K at the value RMS observed in the RV data and listed in Table 3.2. We decided to use this upper limit for the minimum mass as an additional constraint to the results will be presented for each target.

3.2.2 Astrometry

In this section we describe the methods used with the astrometric data. Whenever possible, we used the old (Perryman and ESA 1997a) and the new reduction (van Leeuwen 2007) of Hipparcos catalogue data and the proper motion values from Tycho-2 Catalogue (Høg et al. 2000).

Periodogram

We ran the periodogram analysis on the intermediate astrometric data of Hipparcos, following the method used in Sozzetti and Desidera [2010] and described in the Chapter 2. Briefly, it is supposed a circular orbit and the chisquare over a large grid of periods was calculated. We used both the old and new reductions of the Hipparcos data, when differences existed. The evaluated fitted model is fully linear in 9 parameters: the five astrometric ones and the four Thiele-Innes constants A , B , F and G that represent the orbit of one component around the center of mass (Pourbaix and Jorissen 2000, Sozzetti and Desidera 2010). The purpose of the periodograms is to find evidence for any short or long-period trends in the astrometric data.

$\Delta\mu$ method

Having astrometric data with low accuracy, we could not continue the analysis with the Hipparcos data. For this reason, for every star we compared the proper motion components, μ_{RA} and μ_{Dec} , of Hipparcos (Perryman and ESA 1997a, van Leeuwen 2007) and Tycho-2 (Høg et al. 2000) and, when possible, the difference between them was calculated (Table 3.5). We used this methodology to estimate a value for the mass of the companion, because the two catalogues are based on observations with different timescales. The Hipparcos catalogue is based on observations collected during a relatively short time, therefore includes short-term proper motions, while the Tycho-2 catalogue is based on long-term observations of star positions. In binaries that have sufficiently long-period data, the reflex orbital motion of the primary will be captured in the observed short-term proper motions. The long-term proper motion, on the other hand, will be closer to the true center of mass motion of the system. Thus, we define $\Delta\mu$ binaries as stars that have instantaneous (or short-term) proper motions significantly different from the quasi-inertial motion of the center of mass (Makarov and Kaplan 2005). For those stars that have a significant $\Delta\mu$ (in mas yr^{-1}) respect more than twice its error. The $\Delta\mu$ is a powerful instrument in discovering new binary systems because the binaries with a significant orbital motion can be revealed even if the companion is invisible or unresolved, like our stars.

To estimate the mass of the companion M_2 , we used the formula described in Makarov and Kaplan [2005]:

$$\Delta\mu \leq \frac{2\pi\Pi R_0 M_2}{M_{tot}^{2/3} P^{1/3}}, \quad (3.7)$$

where π is the parallax in mas, P is the orbital period in years, M_2 is the secondary mass, and M_{tot} is the total mass of the system (both in $M_\odot$). The R_0 parameter is an orbital phase factor that we considered constant and equal to 1, under the assumption of circular orbits.

Therefore, we calculated the difference between the proper motions of Hipparcos and Tycho-2 (see Table 3.5) and we compared this number with the $\Delta\mu$ calculating for a range of combination of periods (in days) and masses of the companion. The possible solutions for the systems accepting only values for the mass of the companion that satisfy the condition of $M_2 < M_1$ were valued being these single-lined spectroscopic binaries in which only the lines from one of the stars can be seen.

$\dot{\mu}$ method

For about 2.2 % of stars in the *Hipparcos* catalogue (Perryman and ESA 1997b) it was necessary a more complex model of seven free parameters, that includes the acceleration of the proper motion components ($\dot{\mu}$). These stars cannot be accurately described in the Hipparcos astrometry by a five-parameter model (two position components, two components of proper motion, and parallax as unknowns) owing to their orbital motion around a companion star. Makarov and Kaplan [2005] collected all currently known $\dot{\mu}$ binaries in the Hipparcos catalogue and found a relation that links the expected $\dot{\mu}$ (mas yr⁻²) with a function of a range of orbital periods (days) and masses for the companion ($M_\odot$).

$$\dot{\mu} \leq \frac{(2\pi R_1)^2 \Pi M_2}{M_{tot}^{2/3} P^{4/3}} \quad (3.8)$$

We accepted, as before, the values satisfying the condition $M_2 < M_1$ and that provided a value higher or equal to the observed $\dot{\mu}$. Under the assumption of circular orbits we kept R_1 , which is the orbital phase factor, constant and equal to 1.

Unfortunately, only for one of our stars (CD-436810) an acceleration solution in the Hipparcos data is available. This is due to a combination of long orbital periods and large distances for the binary sample investigated here.

3.3 Results

In this section I present the results derived from the different methodology steps explained above, of our binary systems one by one.

3.3.1 HD16784

For this star, we used only the method of Torres [1999]. The calculated slope of the RV data ($N_{mes} = 3$) is $10525.488 \pm 6169.67 \text{ m s}^{-1} \text{ yr}^{-1}$. The huge error of the slope due to the limited number of measurements (Fig. 3.2) and the actual non-linearity of the RV trend translate in a not

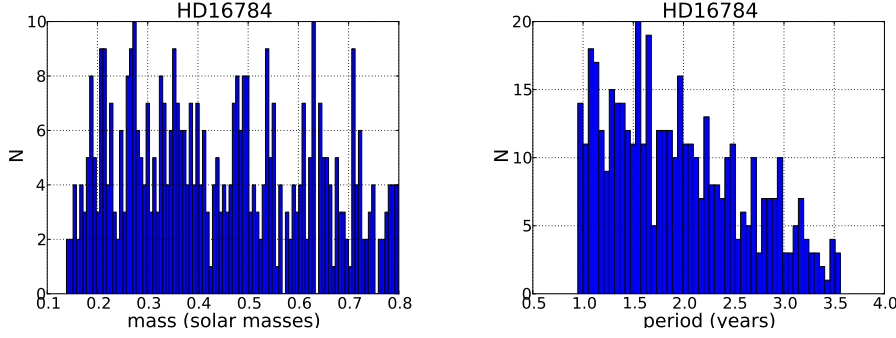


Figure 3.3: Limits on the orbital period and the mass of the companion to HD16784.

well-constrained RV slope. Moreover, the timespan is only of 272 days (< 1 years). From the analysis, we did not find a very definite result for the mass of the companion, but the histogram shows that it seems to be $> 0.13 M_{\odot}$. The orbital period results between 1 year and below 3 years and half with 1σ (68 %) at 2.2 years and 2σ (95 %) at 3.2 years (Fig. 3.3). For this case, we did not observe a significant $\Delta\mu$ (Table 3.5) and therefore we did not use the $\Delta\mu$ method. Moreover, we did not find any signal doing the periodogram and no $\dot{\mu}$ is available.

3.3.2 G27-44

In Fig. 3.2 we can observe that the data have a total timespan of 3200 days ($N_{\text{mes}}=23$), but still the radial velocity curve is not complete. For this reason, we can only know that the period of the star is longer than ~ 8 years. Moreover the RV data show a clear deviation from a straight line model (as can be seen from a visual inspection of Fig. 3.2). For this case, we analyzed the slope ($-11.20 \pm 0.78 \text{ m s}^{-1} \text{ yr}^{-1}$) of the RV data, using the method of Torres [1999] to estimate the mass of the companion and its period. For the orbital period the analysis did not provide any clear conclusion: it was found at $1-\sigma$ confidence that the period should be shorter than 61 years. However, it is important to remember, as mentioned above, that the periods analysis is limited to 100 years (Fig. 3.4). On the other hand we find a very interesting result regarding the mass of the companion. In Fig. 3.4 it is shown that at $1-\sigma$ confidence level the mass of the companion is $< 0.05 M_{\odot}$ and $M_{\odot} < 0.25$ at $2-\sigma$. The lowest allowed value of the secondary mass from the histogram is $0.002 M_{\odot}$. In this case, we have also the CfA DS data and from their analysis ($\text{RMS} = 0.39 \text{ km s}^{-1}$) we can conclude that the upper limit of the $M \sin i$ is $0.03 M_{\odot}$ for a period of ~ 16 years (the time span of the CfA DS data). For this star, it is not found a significant $\Delta\mu$ (Table 3.5) and $\dot{\mu}$ is not available, therefore we did not use the two methods of Makarov and Kaplan [2005]. Moreover, the periodogram from the Hipparcos data did not show any trend.

3.3.3 G63-5

Only a straight linear trend is observed from 16 measurements obtained for this star during a timespan of ~ 7 years (2700 days). We analyzed the slope ($12.37 \pm 1.07 \text{ m s}^{-1} \text{ yr}^{-1}$) and we found, at 68 % and 95 % of confidence levels, a mass for the companion $< 0.07 M_{\odot}$ and 0.28

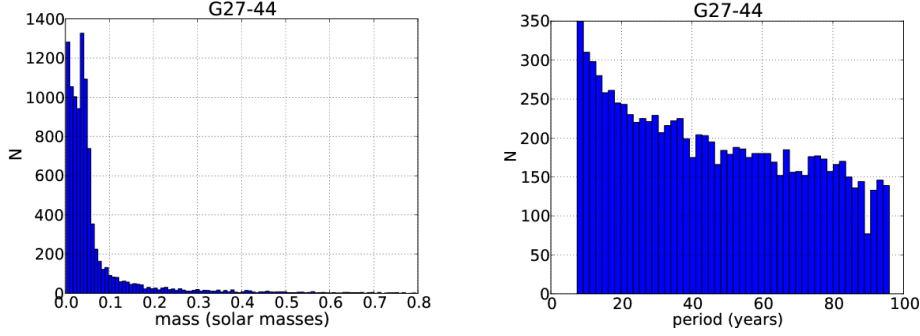


Figure 3.4: Limits on the orbital period and the mass of the companion to G27-44.

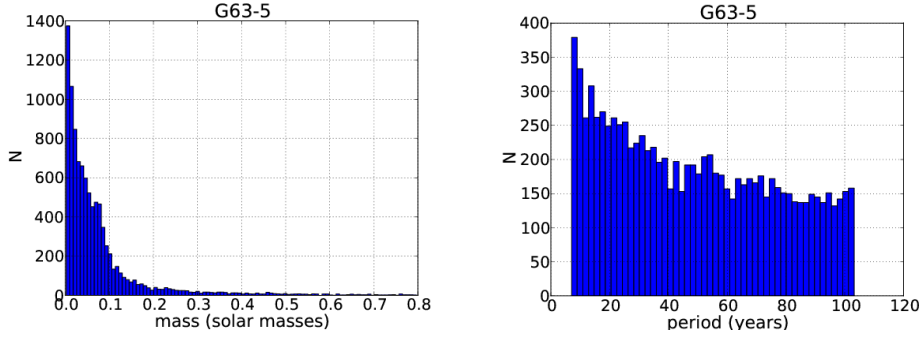


Figure 3.5: Limits on the orbital period and the mass of the companion to G63-5.

$M_{\odot}$, respectively (Fig. 3.5) and a minimum mass of $0.002 M_{\odot}$. We cannot observe any definite result for the period. We obtained an upper limit for the minimum mass of $0.025 M_{\odot}$ for a period of ~ 8 years (the span of the TRES RV data; $\text{RMS} = 0.36 \text{ km s}^{-1}$). Also for this case, we did not use the $\Delta\mu$ and $\dot{\mu}$ method (Table 3.5: no significant $\Delta\mu$ and not available $\dot{\mu}$) and no trend from the periodogram in the Hipparcos data appears.

3.3.4 G237-84

In this case, we have a significant value for $\Delta\mu$ in addition to the slope ($23.58 \pm 1.72 \text{ ms}^{-1}\text{yr}^{-1}$) of the RV data ($N_{\text{mes}}=38$). From the slope analysis we found at 68 % the mass $< 0.10 M_{\odot}$ and at 95 % $< 0.35 M_{\odot}$ and the minimum mass of the companion found in the histogram is $0.004 M_{\odot}$. The period is found to be > 6 years (2300 days) but from the histogram we cannot take any firm conclusions (Fig. 3.6).

From the study of the maximum minimum mass ($\text{RMS} = 0.73 \text{ km s}^{-1}$) we obtained a value $< 0.07 M_{\odot}$. Moreover, we tried to find some further constraints for the mass of the companion depending on its orbital period using the significant value for $\Delta\mu$ that corresponds to the right-ascension component of the proper motion (the larger one; Table 3.5). But, unfortunately, this study did not allow us to add other information. No $\dot{\mu}$ is available and no trend in the Hipparcos

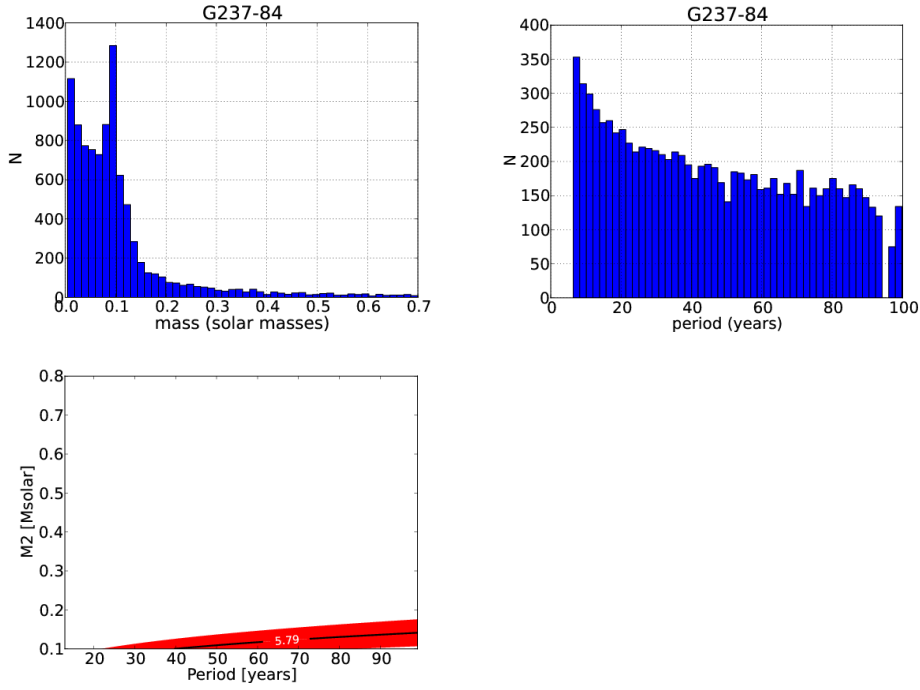


Figure 3.6: Limits on the orbital period and the mass of the companion of G237-84 and the study of $\Delta\mu$ (the black line represents the measured value of $\Delta\mu$).

data, doing the periodogram, is found for this star.

3.3.5 HD7424

For this star we used also the $\Delta\mu$ and the slope ($-417.02 \pm 4.66 \text{ m s}^{-1} \text{ yr}^{-1}$ in 500 days) methods. Unfortunately from the $\Delta\mu$ analysis we could not find any further and strong constraints for the mass. We observed interesting limits from the slope analysis: the mass results to be $> 0.008 M_\odot$ and at $1 \sigma < 0.43 M_\odot$. For the period we found a value between 1 and 40 years, with a maximum of 19-years at a 68 % ($1-\sigma$) confidence level (Fig. 3.7). Compared with the cases discussed above, for this star we found stronger constraints and no allowed values above 40 years exist due to the companion upper mass constraint used in our simulations. The maximum value for the minimum mass of the companion is $0.07 M_\odot$ calculated from the analysis of the dispersion of the CfA DS data ($\text{RMS} = 0.51 \text{ km s}^{-1}$). Moreover, no trend from the periodogram in the Hipparcos data was observed and no $\dot{\mu}$ is available.

3.3.6 HD192718

For this star, we could apply only the method of Torres [1999] with the slope ($-144.65 \pm 1.40 \text{ m s}^{-1} \text{ yr}^{-1}$) of the RV measurements ($N_{\text{mes}}=20$). The period is longer than 5 years because the data cover 2200 days. From the analysis, we could observe that the mass seems to be > 0.02

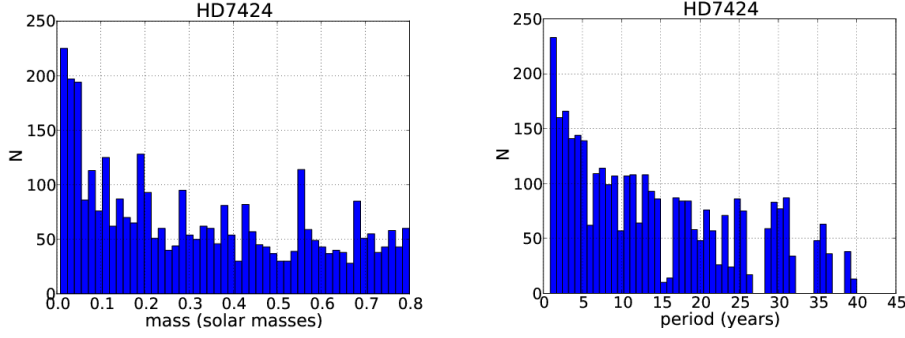


Figure 3.7: Limits on the orbital period and the mass of the companion to HD7424.

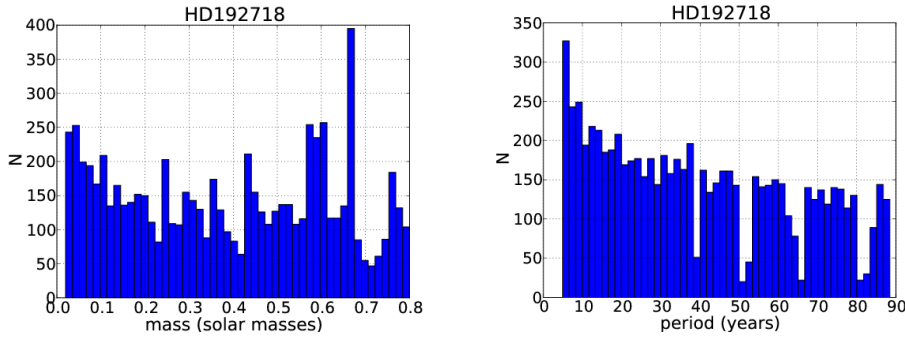


Figure 3.8: Limits on the orbital period and the mass of the companion to HD192718.

$M_{\odot}$, while at 1 and 2 σ confidence levels it is < 0.55 and $0.75 M_{\odot}$, respectively. For the period we obtained a value < 53 years at 1 σ and < 83 years at 2 σ (Fig. 3.8). We used also the CfA DS data (RMS = 0.92 km s^{-1}) finding $0.08 M_{\odot}$ as the upper limit for the minimum mass of the companion. No $\dot{\mu}$ is available, the $\Delta\mu$ does not present any significant value and no trend in the Hipparcos data emerges. Considering the TRES data we observed that the orbital period is expected to be longer than 13.5 years (5000 days) and the results from the keplerian fit are compatible with the analysis, with an orbital period around 46.5 years (~ 17000 days).

3.3.7 G135-46

For this star we could almost complete one cycle in the RV curve thanks to the CfA DS and TRES data. First, we applied the Torres' method using only the slope of the Keck data (Nmes= 9 in 900 days) but unfortunately we could not found any strong constraints for the mass of the companion and for the orbital period of the system. In Fig. 3.9 we can only deduce that the mass of the companion is $< 0.54 M_{\odot}$ at 68 % and < 0.73 at 95 %; for the period we found that it is shorter than 70 years, while at 1 and at 2 σ levels its value is 39 years and 63 years, respectively. However, with the new data we could fit the RV curve and derive the orbital properties of the binary system and the minimum mass of the companion. The results are shown in Table 3.3 and

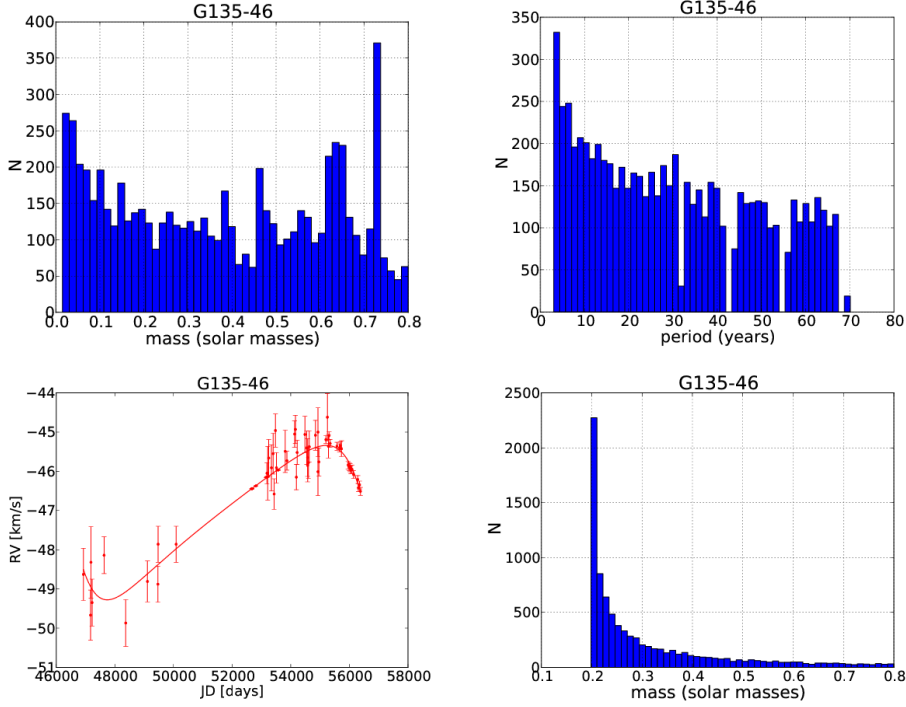


Figure 3.9: *Upper panels:* Limits on the mass and the orbital period of the companion to G135–46. *Lower panels:* RV data with overplotted the best-fit Keplerian orbit (*left*). Histogram of the mass fixing the period at the orbital fit value (*right*).

the minimum mass results to be $0.2 M_{\odot}$. With this value, we decided to use again the Torres’ method but imposing the period of 27 years resulting from the keplerian fit and the actual mass results to be $> 0.2 M_{\odot}$. With this extra constraint, we obtained at 1 and 2σ limits a mass of $< 0.30 M_{\odot}$ and $< 0.63 M_{\odot}$, respectively (Fig. 3.9). For this star, it is not observed a significant value for $\Delta\mu$ and no $\dot{\mu}$ is also available. Moreover no trend appears in the Hipparcos data, doing the periodogram.

3.3.8 CD-436810

This binary is interesting because it has two contrasting results between the old and the new reduction of the Hipparcos Intermediate Astrometric Data (IAD). Moreover, the solution found with 7 (old reduction) and 5 (new reduction) parameters provides different parallax values: 6.83 mas for the old and 9.27 mas for the new reduction. This star has also RV data (even if not complete: $N_{\text{mes}} = 9$ with a timespan of 3 years and half) and significant values of $\Delta\mu$ and $\dot{\mu}$. We followed the method described in Sozzetti and Desidera [2010] to make the periodogram analysis and the data from the old reduction highlighted the presence of a significant long-term trend (Fig. 3.10). This star is the only one for which a periodogram analysis provided validating evidence in the Hipparcos data of the presence of a wide-separation companion. In addition,

Table 3.4: Summary of the results for the binary system CD-436810 based on the old and new Hipparcos reduction

Star	Mass ($M_{\odot}$)		Minimum Mass ($M_{\odot}$)	Period (years)		Minimum Period (years)
	1 σ	2 σ		1 σ	2 σ	
CD-436810 old	0.63	0.78	0.29	4.8	6	2.9
CD-436810 new	0.67	0.77	0.32	4.8	5.8	3.2

we applied the F-test and we found that the addition of four parameters to the model of the Hipparcos IAD improved significantly the fit: $P(F) = 0.0005$. With the RV data, we derived the parameters of the keplerian fit and they are shown in Table 3.3. The obtained orbital period is ~ 1702 days (~ 4.6 years), while the derived minimum mass for the companion is $\sim 0.28 M_{\odot}$. The solution is not optimal because the full orbit is not covered, and, therefore, it is used as a consistency check in support of the attempt at constraining the mass and orbital period of the companion to this particular star. Having the possibilities, we added more constraints using the other methods already mentioned above and making use of the available astrometric data. For the old Hipparcos reduction, the observed $\Delta\mu$ shows that the mass of the companion is above $0.3 M_{\odot}$. With the value of $\dot{\mu}$ we also find that the orbital period is $\sim 4 - 8$ years ($\sim 1500 - 3000$ days) (Fig. 3.10), since higher values would imply companion masses above $0.8 M_{\odot}$.

Doing the same procedure, but with the new Hipparcos reduction, we found a possible lower mass. In Fig. 3.10 we compared the two reduction for the $\Delta\mu$ and we could note the difference in the solution. We calculated the mass of the companion and the period using the method of the slope ($-4885.42 \pm 46.15 \text{ m s}^{-1} \text{ yr}^{-1}$) and we found also different results depending on whether we use the old or new reduction parallax results. For the old reduction, the period results between 2.9 years and below 6.3 years with the 1 σ threshold at 4.8 years (Fig. 3.11) and the derived secondary mass is between $> 0.29 M_{\odot}$ and $< 0.80 M_{\odot}$ with the 68 % confidence limit being $< 0.63 M_{\odot}$ (Fig. 3.11). For the new reduction, the possible values for the period slightly increase to between 3.2 years and 6.3 years with $P < 4.8$ years at 1 σ confidence level (Fig. 3.11) and the companion mass also changes to values between $0.32 M_{\odot}$ and $0.80 M_{\odot}$, with $M_2 < 0.67 M_{\odot}$ at 68 % confidence (Fig. 3.11). In Table 3.4 the summary of the results for this star is given.

3.4 Summary

In this chapter, we presented a multi-technique analysis of 8 metal-poor SB1 binary systems taken from the rejected targets of the sample of Santos et al. [2011] and Sozzetti et al. [2009]. For these stars, no previously determined orbital solutions and companion mass were estimated. We found a range of solutions for the secondary masses and for the orbital period of the systems. Because of the lack of complete radial velocity and accuracy of astrometry data we used different statistical methods. With the RV measurements, we started to try to find an orbital solution, then we used the statistical method described by Torres [1999] utilizing the $d(RV)/dt$ with Monte Carlo simulations. With the astrometric data, we used the method of $\Delta\mu$ (differ-

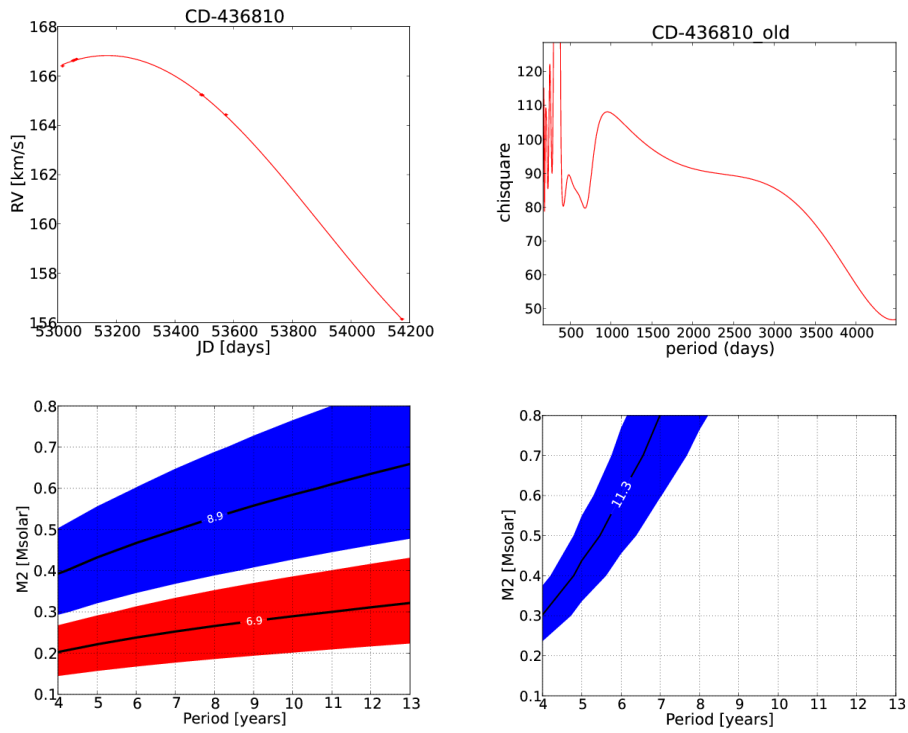


Figure 3.10: *Upper left:* The Keplerian orbital fit to the CD-436810 RV data. *Upper right and bottom:* The periodogram analysis of the Hipparcos old reduction data and the study of $\Delta\mu$ and $\dot{\mu}$ for the case of CD-436810. The results for the old Hipparcos reduction are in blue (with 1σ of confidence level), while in red the results for the new reduction of Hipparcos data are reported. The black lines represent the measured values of $\Delta\mu$ and $\dot{\mu}$.

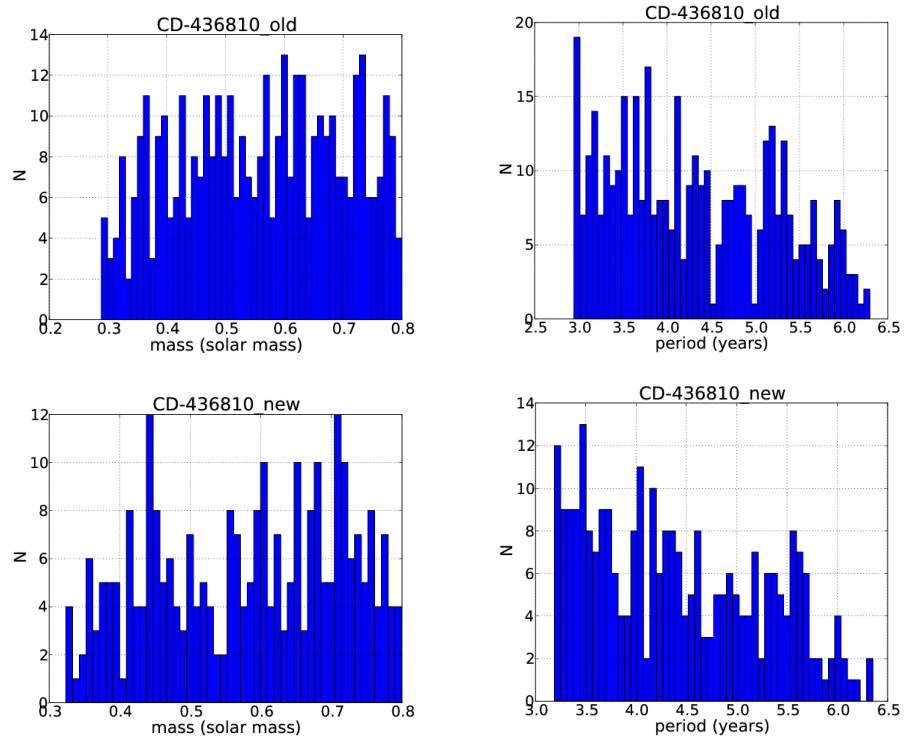


Figure 3.11: *Upper panels:* Limits on the mass and the orbital period of the companion to CD-436810 using the old Hipparcos reduction. *Lower panels:* Limits on the mass and the orbital period of the companion to CD-436810 based on the new Hipparcos reduction.

ences between the measured proper motion of Hipparcos and Tycho-2) and $\dot{\mu}$ (the acceleration of proper motion) described by Makarov and Kaplan [2005] because our sample is composed of spectroscopic binaries with invisible or unresolved companions that create problems in the data reduction of a large and accurate astrometric catalog. For the examined systems we can conclude that for 3 of them the most likely values for the companion mass are below $0.2 M_{\odot}$. Two of these systems (G27-44 and G63-5) show possible masses at 1σ of confidence level of ≈ 0.07 solar masses, putting them as candidate brown dwarf companions. Within the other 5 binaries we have 4 systems (HD192718, G135-46, HD16784 and CD-436810) where it is more likely that the mass of the companion is higher. These stars are thus likely orbited by M dwarf companions. A particular case is CD-436810, a binary system with a short orbital period (≥ 6 years) and a mass above $0.28 M_{\odot}$, for which we find a very interesting result using the two different reductions of the Hipparcos data. The results found using the information in the slope of the RV data seem to be more compatible with the $\Delta\mu$ and the presence of the acceleration solution ($\dot{\mu}$) using the old Hipparcos reduction. The parallax found with the new reduction is 25 % higher. Therefore, the perturbation due to the companion should be more evident. Rather than a case of spurious acceleration (e.g., Tokovinin et al. 2012, 2013) this may point to a problem with the new Hipparcos data reduction for this specific star.

3.5 Conclusions and future work

Our analysis is based on a small number of stars and the range found for the companion masses and orbital periods is unfortunately not well constrained. Therefore, it was difficult to compare the observed results with the mass distribution of the previous studies, like, for example, Duquennoy and Mayor [1991]. At the same time, it is interesting to note that among the 8 targets, two seems to have very low mass companions. However, even if this fits into the mass distribution of Duquennoy and Mayor [1991], it is not possible to affirm absolutely the mass and the period but only a possible range of solutions. The future with *Gaia* will help us to put much better constraints and to find the exact mass and orbital parameters for the systems studied here. For example, it will be possible to solve the binary system CD-436810 because this system has a period (~ 6.5 years) likely not significantly exceeding the *Gaia* mission duration (5 years). Moreover, the fraction of astrometric binaries will also dramatically increase when the *Gaia* catalogue will be published with about billion of stars. In addition, we will be able to apply the same methods described in this chapter to study extrasolar planets detected both astrometrically using the μas -level precision of *Gaia* data and with Doppler measurements.

Table 3.5: List of the binaries with the values of proper motion, $\Delta\mu$, and $\dot{\mu}$ based on Hipparcos and Tycho-2 data, and the RV slopes based on available Doppler information.

NAME	π (mas)	μ Hipp (mas yr ⁻¹)	μ Hipp new (mas yr ⁻¹)	μ Tycho-2 (mas yr ⁻¹)	$\Delta\mu$ (mas yr ⁻¹)	$\dot{\mu}$ (mas yr ⁻²)	slope (m s ⁻¹ yr ⁻¹)
CD-436810	9.27	-27.20 ± 1.07	-25.22 ± 0.94	-18.3 ± 1.6	8.9 ± 1.9	11.29 ± 2.16	-4885.42 ± 46.15
HD7424	8.64	198.43 ± 2.06	197.59 ± 1.87	201.3 ± 1.6	2.87 ± 2.61		-417.02 ± 4.66
G237-84	29.07	-108.32 ± 1.82	-110.10 ± 1.49	-114.8 ± 1.5	6.48 ± 2.36		23.58 ± 1.72
G63-5	16.36	-294.31 ± 0.63	-294.40 ± 0.57	-300.1 ± 1.1	5.79 ± 1.27		12.37 ± 1.07
G135-46	12.96	244.42 ± 0.66	244.96 ± 0.51	246.5 ± 1.1	2.08 ± 1.28		198.65 ± 2.14
HD192718	17.28	-520.57 ± 1.13	-520.03 ± 1.03	-521.5 ± 1.1	0.93 ± 1.58		-144.65 ± 1.40
G27-44	23.66	267.23 ± 0.81	267.36 ± 0.68	269.4 ± 1.1	2.17 ± 1.36		-11.20 ± 0.78
HD16784	15.67	-334.28 ± 1.16	-333.73 ± 1.14	-334.0 ± 0.9	0.28 ± 1.47		10525.488 ± 6169.67
		-73.27 ± 1.02	-73.97 ± 1.10	-71.1 ± 0.9	2.17 ± 1.36		
		313.17 ± 1.20	314.39 ± 0.90	311.9 ± 1.5	1.27 ± 1.92		
		-129.31 ± 0.78	-129.51 ± 0.61	-133.1 ± 1.5	3.79 ± 1.69		
		150.64 ± 1.11	151.6 ± 0.69	150.60 ± 1.0	0.04 ± 1.49		
		331.61 ± 0.75	331.35 ± 0.55	332.4 ± 1.1	0.79 ± 1.33		
		569.90 ± 0.95	569.56 ± 0.98	570.0 ± 1.2	0.1 ± 1.5		
		75.41 ± 0.90	75.63 ± 0.86	75.1 ± 1.2	0.31 ± 1.5		

CHAPTER 4

The giant stars sample.

This chapter describes the work done for the derivation of the stellar parameters and the determination of the chemical abundances of 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn and V) for a sample of giant stars that are part of the CORALIE program to search for planets around giants (Alves et al. 2015, in press; and Adibekyan et al. 2015 accepted).

The properties of giant planets around (low-mass) M dwarfs and solar-type stars are quite well studied: for FGK stars, it seems easier to find a planet around metal-rich star than around a metal-poor object (Santos et al. 2004), but not excluding completely the presence of planets around metal-poor stars. Moreover, it is known that the frequency of giant planets around (low-mass) M dwarfs is considerably smaller than the one found for FGK dwarfs (Endl et al. 2003, 2006).

Because of the huge difficulties to obtain precise radial-velocities for massive main sequence stars, the stellar metallicity-giant planet correlation for evolved stars is still not well studied. By now, more than 50 giant planets have been found around giant stars, revealing contrasting properties compared to the giant planets discovered around dwarf stars. Pasquini et al. [2007] proposed that the metallicity-giant planet correlation may not be present for giants hosting exoplanets (Fig. 4, *left panel*). Although this conclusion is not unanimous (see Hekker and Meléndez 2007), the question is now being debated (Ghezzi et al. 2010a, Maldonado et al. 2013, Mortier et al. 2013a). It should also be noted that even though evolved planet hosts are on average more metal-poor than planet-hosting dwarfs¹, there seems to be no metallicity enhancement for red giants with planets regarding to red giants without planets detected (Mortier et al. 2013b, and references therein).

If confirmed, however, the results of Pasquini et al. [2007] would cast doubts in the planet-metallicity relation observed for dwarf stars, or at least in the way this relation has been interpreted. These authors suggest that such a difference between main sequence and evolved stars is due to pollution, which is more effective for stars in the main sequence than for evolved giant

¹However, it should be considered the possibility that giant stellar samples that are searched for planets may be biased. Hence, the comparison of dwarf stars with giant stars should be done cautiously. This issue will be discussed later on throughout the thesis.

stars where the convective zone enlarges and mixes a large fraction of the stellar gas. Other explanations are also possible: giants are on average more massive than main sequence stars surveyed for planet search, therefore the frequency of planets around giants could be explained with more sophisticated models that take into account the dependence of the snow line with the stellar mass. It may produce a large increase of giant planets frequency with the stellar mass (Kennedy and Kenyon 2008). In this scenario only the total amount of metals present (and not their percentage) is relevant, therefore more massive metal-poor stars (with more massive disks) may still produce many planets. In fact, recent studies suggest that radial velocity surveys of giant stars are biased with respect to metal-poor stars, once most of those programs select their stellar samples with a cut-off in the $(B-V)$ colour, set to be less than or equal to 1.0. This $(B-V)$ cut-off in a sample of cool stars results in a lack of high-metallicity, low-gravity components, creating a bias that may explain why planets are rather found around metal-poor giants (Mortier et al. 2013b, Fig. 4, *right panel*). In addition, Santos et al. [2009] have shown that the methods to derive stellar parameters should be considered as another explanation, since the way the absorption lines are chosen may have a determining role for the derivation of metallicities for giant stars.

Therefore, we need to understand better the planet-metallicity relation and, as a consequence, we will know better the giant planet formation. To settle this issue, and to understand the exact way that metallicity influences planet formation, it is extremely important a derivation of uniform and precise parameters for giants in planet search samples.

Given the huge difficulties of obtaining precise radial-velocities for massive main sequence stars, one of the most effective ways to access the frequency of planets around higher mass stars is to search for planets around giants. Unfortunately, it is not easy to derive the mass for a highly evolved field star because during the red giant phase, red giant branch and horizontal branch stars with different ages, masses and metallicities occupy a similar position in the Hertzsprung-Russell (HR) diagram, the so called mass-age-metallicity degeneracy, and therefore the mass and evolutionary status cannot be determined simply by comparing their effective temperature and luminosity with isomass tracks (Jones et al. 2011b). Thus, it is more difficult to study the "stellar mass-frequency of planets" relation for giant stars. A more accurate derivation of uniform and precise parameters for the giants in planet search samples is needed if we want to overcome this problem (Santos et al. 2009), specially the determination of accurate stellar masses.

The precise chemical and kinematic characterization of intermediate-mass, evolved stars is very important for different fields of both Galactic and stellar astronomy, and the emerging field of planetary sciences. Many studies observed significant differences in chemical abundances between main sequence dwarf and evolved stars (e.g., Friel et al. 2003; Jacobson et al. 2007; Villanova et al. 2009; Santrich et al. 2013). While these differences for some elements might be by astrophysical, having a stellar evolutionary character (e.g., Tautvaišienė et al. 2005, for sodium), several authors however suggested that the differences may arise also in the analysis, being dependent on the particular method and line-list used (e.g., Santos et al. 2009). Moreover, one should also consider the non local thermodynamic equilibrium (non-LTE) effects which are stronger for giants than for dwarfs and may influence the analysis (e.g., Bergemann et al. 2013, 2014; Alexeeva et al. 2014).

The goals of this work was to characterize the sample of evolved stars from a planet-search pro-

gram and to study the galactic chemical evolution in the solar-neighborhood using the evolved stars. We derived, first, precise stellar parameters (T_{eff} , $\log g$, ξ and $[Fe/H]$) for the entire sample (257 stars) using precise radial-velocity measurements. These results will be useful, when some planets will be detected, to study the frequency of planets as a function of the different stellar parameters, including their chemical composition and mass, and compare the results with model predictions.

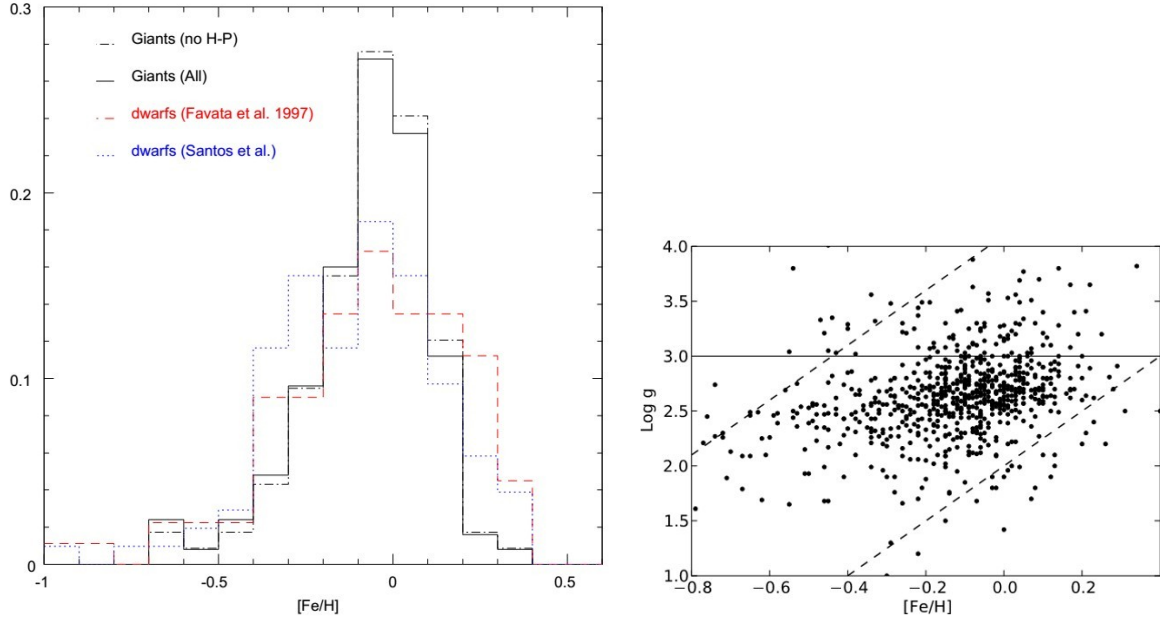


Figure 4.1: *Left panel*

: Metallicity distribution of the giants compared to the distribution of main sequence stars (Pasquini et al. [2007]). *Left panel*: Surface gravity versus metallicity for the giant comparison sample used by Mortier et al. [2013b].

4.1 Spectroscopic analysis

The study of stellar spectra is required to understand the nature of the stellar atmospheres. When we observe regular stellar spectra, it is easy to note the presence of many absorption lines, which correspond to electronic transitions among the different levels of atoms and molecules. Moreover, the stellar temperature, the surface gravity and chemical composition have a important role on the strength or equivalent width of spectral absorption lines. For this reason, studying the stellar spectrum we can derive the basic atmospheric parameters, like the effective temperature T_{eff} , the surface gravity $\log g$, the metallicity $[Fe/H]$ and the microturbulence ξ . A good and easy approximation for the stellar atmospheres theory is the local thermodynamic equilibrium (LTE) condition, which considers that collisions dominate the excitation of the atoms present in the gas. In this case, we can apply the Boltzmann equation that represents the ratio between the

number of atoms in different energy levels:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-(E_u - E_l)/kT}, \quad (4.1)$$

where n_i is the number of atoms in the energy level i , g_i the degeneracy of the level i and E_i the excitation potential of the level i (u and l denote upper and lower levels of energy), k is the Boltzmann constant and T the temperature.

Moreover, the Saha equation can be used to deal with the ionisation state of the elements for a collision dominated gas (Eq. (4.2)).

$$\frac{n_+}{n_l} = \frac{2}{n_e} \frac{g_+}{g_l} \left(\frac{2\pi m_e kT}{h^2} \right)^{(3/2)} e^{-\chi_l/kT}, \quad (4.2)$$

where n_+ is the number of atoms in a ionized state, n_l the number of neutral atoms, m_e the electron mass, h the Planck constant and χ_l the ionization potential. Thermodynamic equilibrium is obtained when the temperature, pressure and chemical potential of a system are constant. LTE is assumed when these parameters are varying slowly enough in space and time, and therefore each point emits like a black body with a given temperature (T).

The most basic quantity measured in a spectral line is its profile or shape: more photons will be absorbed stronger will be the shape of the absorption line. The measurement of a total absorption in a line is called "equivalent width", EW, and described as:

$$EW = \int_0^\infty \frac{F_c - F_\nu}{F_c} d\nu, \quad (4.3)$$

where F_c is the continuum flux and F_ν the flux in the spectral line (Fig. 4.3).

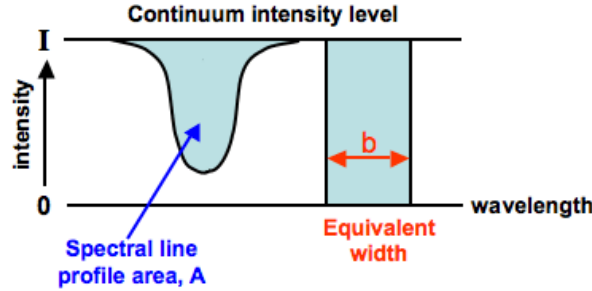


Figure 4.2: The area, A , of a spectral line measured below the continuum level is related to a rectangular line profile with the same area, and equivalent width, b . (From: <http://astronomy.swin.edu.au/cosmos/>)

Thanks to the Boltzmann and Saha equations (Eq. (4.1), (4.2)) we can understand the important role of temperature (but also of surface gravity, elemental abundance and microturbulence) in the atom populations and in the absorption line strengths and, therefore, the influence of them in the EW of the spectral lines. The LTE approximation is valid only for weak lines ($EW \leq$

150 mÅ). For stronger lines we should consider the dependence of other factors and the influence of NLTE effects. Following the descriptions presented by Gray [2008] we can study the dependence of the line strength on temperature, surface gravity, microturbulence and elemental abundance.

- **EFFECTIVE TEMPERATURE:** we can determine the effective temperature computing abundances for several lines of the same element, normally iron, because it is the same for each absorption line with different excitation potentials.
- **SURFACE GRAVITY:** the ionized species are more sensitive to changes in the pressure than the neutral species. Both gas pressure and electron pressure are controlled by the surface gravity, g , ($P_g \propto g^{(2/3)}$ and $P_e \propto g^{(1/3)}$), therefore to obtain the pressure or more commonly surface gravity it is necessary to force the neutral and ionized lines of the same species to give the same abundance.
- **ELEMENTAL ABUNDANCE:** the abundance of the species (number of atoms) is connected with the line strength which increases with increasing abundance. However, this relation is not always linear, but, for the weak line regime, the curve of growth is linear and the EW is proportional to the abundance.
- **MICROTURBULENCE:** the line absorption coefficient is influenced by the microturbulent velocity. The EWs of the saturated lines are greater for stars with greater microturbulent velocities. In the dependence of the curve of growth with the microturbulence, we can observe a retardation of the saturation for increasing values of the microturbulence. We thus can derive the microturbulence assuming no dependence of the species abundances on the reduced EWs (EW/ λ).

4.2 Stellar sample and observations

The stars of this sample belong to the CORALIE program settled down to search for planets around giant stars observing a large sample of giant stars and obtaining the spectra with the CORALIE spectrograph (Swiss Euler Telescope, La Silla) (Udry et al. 2000b). Most stars of this sample have a large number of measurements spread over the last 3 years. The first results of this survey already suggest a good number (> 30) of planet candidates. For our analysis, we used 256 K & G evolved stars observed with the high resolution ($\lambda/\Delta\lambda \sim 110000$) and high signal-to-noise (S/N) spectra obtained with the UVES spectrograph (VLT Kueyen Telescope, Paranal, Chile) between April and December 2010 (ESO programs 085.C-0062 and 086.C-0098). High S/N and resolution are needed since K-giants have crowded spectra with lots of blended lines. The observations were done using the UVES standard setup Red 580 ($R = 47\,000$, spectral range: 480–680 nm). The final spectra cover the wavelength domain between 4780 and 6805 Å, and have a typical S/N of ~ 150 . All spectra for each individual star were combined using the IRAF² SCOMBINE task. The spectra were reduced using the UVES pipeline.

²IRAF is distributed by National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation, USA.

Fig. 4.3 presents the distribution of these stars through the HR diagram. In this figure, the (B-V) color index was taken from Hipparcos (Perryman et al. 1997) and the surface luminosity $\log L/L_{\odot}$ was computed from the estimated Hipparcos parallaxes and V magnitude following the calibrations presented by Flower [1996], and revisited by Torres [2010]. The evolutionary tracks are from Ekström et al. [2012], for an initial metallicity of $Z=0.014$. This plot confirms that our sample is composed only by giant stars. As we can see in this figure, our sample has stellar masses between 1.5 and 4.0 solar masses. Of these stars, up to now, only one has a known planet (HD11977), while the others are giant stars without planets.

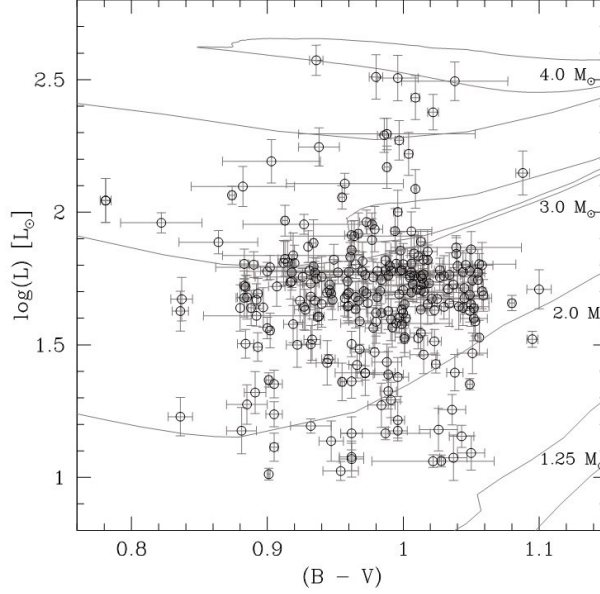


Figure 4.3: Hertzsprung-Russell diagram for our stellar sample. Evolutionary tracks are from Ekström et al. [2012], for an initial abundance of metals set to $Z = 0.014$.

4.2.1 Methods

We used the ARES³ code (Automatic Routine for line Equivalent widths in stellar Spectra - Sousa et al. 2007) to measure automatically the equivalent width (EW) of iron absorption lines (FeI and FeII). ARES needs an atomic linelist because stellar parameters may depend on line-list choice (see, e.g., Santos et al. 2009). For our sample, we decided to use three different linelist:

- the large linelist from Sousa et al. [2008]: a stable linelist with 263 FeI and 36 weaker FeII lines, with a large range of excitation potentials (SO08);
- the small linelist made specifically for giant stars from Hekker and Meléndez [2007] and composed by 16 FeI and 6 FeII lines (HM07);

³The ARES code can be downloaded at <http://www.astro.up.pt/sousasag/ares>

- the linelist built specifically for cool stars (with $T_{\text{eff}} \leq 5200$ K) from Tsantaki et al. [2013]. This linelist is based on the linelist by Sousa et al. [2008], but as this linelist showed unsatisfactory results for cool stars ($T_{\text{eff}} < 5200$ K, the temperature were too high compared with other methods) it consists of 120 FeI and 17 weaker FeII lines (TS13). The TS13 line-list provides results in good agreement with the expected values (Mortier et al. 2013b).

ARES needs a set of input parameters. Most of these parameters are fixed and given in Sousa et al. [2008]: $\text{smoothder} = 4$, $\text{space} = 3$, $\text{lineresol} = 0.07$, $\text{miniline} = 2$. The only parameter we changed was rejt . The parameters determines the calibration of the continuum position, strongly depends on the S/N of the spectra. The S/N adopted is given as a root sum square of the S/N of the order related to 6000 Å (see UVES ETC⁴), for each spectrum, extracted in the header of the fits reduced spectra. The Table C.1 shows the used values of rejt for each stars. Assuming ionization and excitation equilibrium, the parameters were derived through an iterative process until the slope of the relation between the abundances given by individual FeI lines and both the excitation potential (χ_I) and reduced equivalent width ($\log EW/\lambda$) were zero, and until the FeI and FeII lines provided the same average abundance. The spectroscopic analysis was completed assuming local thermodynamic equilibrium (LTE) with a grid of ATLAS model atmospheres (Kurucz [1993]), and making use of the 2002 version of the MOOG⁵ radiative transfer code (Snedden [1973]). All the values of stellar parameters derived for our stars are listed in Table C.2. Note that no viable solution could be found for HD74006 using the HM07 line-list. Due to the fact that most of stars in our sample have temperatures lower than 5200 K, we adopt as final the parameters derived using the TS13 line-list.

In Fig. 4.4 we present the distribution of the atmospheric stellar parameters derived in our work, using respectively the HM07 (left panel), SO08 (middle panel), and TS13 (right panel) linelists. We can see a general agreement for the results found for the three cases (HM07, SO08 and TS13 line-lists). The results from TS13 and SO08 are compatible in terms of metallicity, but in effective temperature they show an offset, specially for the cooler stars, as expected and discussed in Tsantaki et al. [2013] and Mortier et al. [2013a]. The uncertainties are illustrated in the boxplot in Fig. 4.5 which shows the median and quartiles for all parameters derived with the HM07 (left panel), SO08 (middle panel), and TS13 (right panel) line-lists. As we can see in this figure, HM07 results show a much higher dispersion on the uncertainties, as expected given their smaller number of lines. These relatively small number of lines (16 FeI & 6 FeII) decrease the statistical strength of the determined stellar parameters, increasing the internal dispersion, especially for FeII. For instance, the metallicity derived using this linelist presents unrealistically high values for the errors, with an average of about 0.24 dex, and $\sigma [\text{Fe}/\text{H}] > 1.0$ dex for 9 stars (see Table C.2). This may due to no reduced equivalent width (R.W.) statistics was done for the Fe I lists.

Fig. 4.6 shows the comparison between the results obtained using the HM07 and SO08 line-lists with those obtained using the TS13 line-list which we adopt as final parameters. Between the results of TS13 and HM07 we found an average difference (defined as TS13 - HM07 results) of 54 K, -0.019 dex, 0.075 km s^{-1} , and -0.032 dex for effective temperature, surface gravity,

⁴<http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=UVES+INS.MODE=spectro>

⁵<http://www.as.utexas.edu/chris/moog.html>

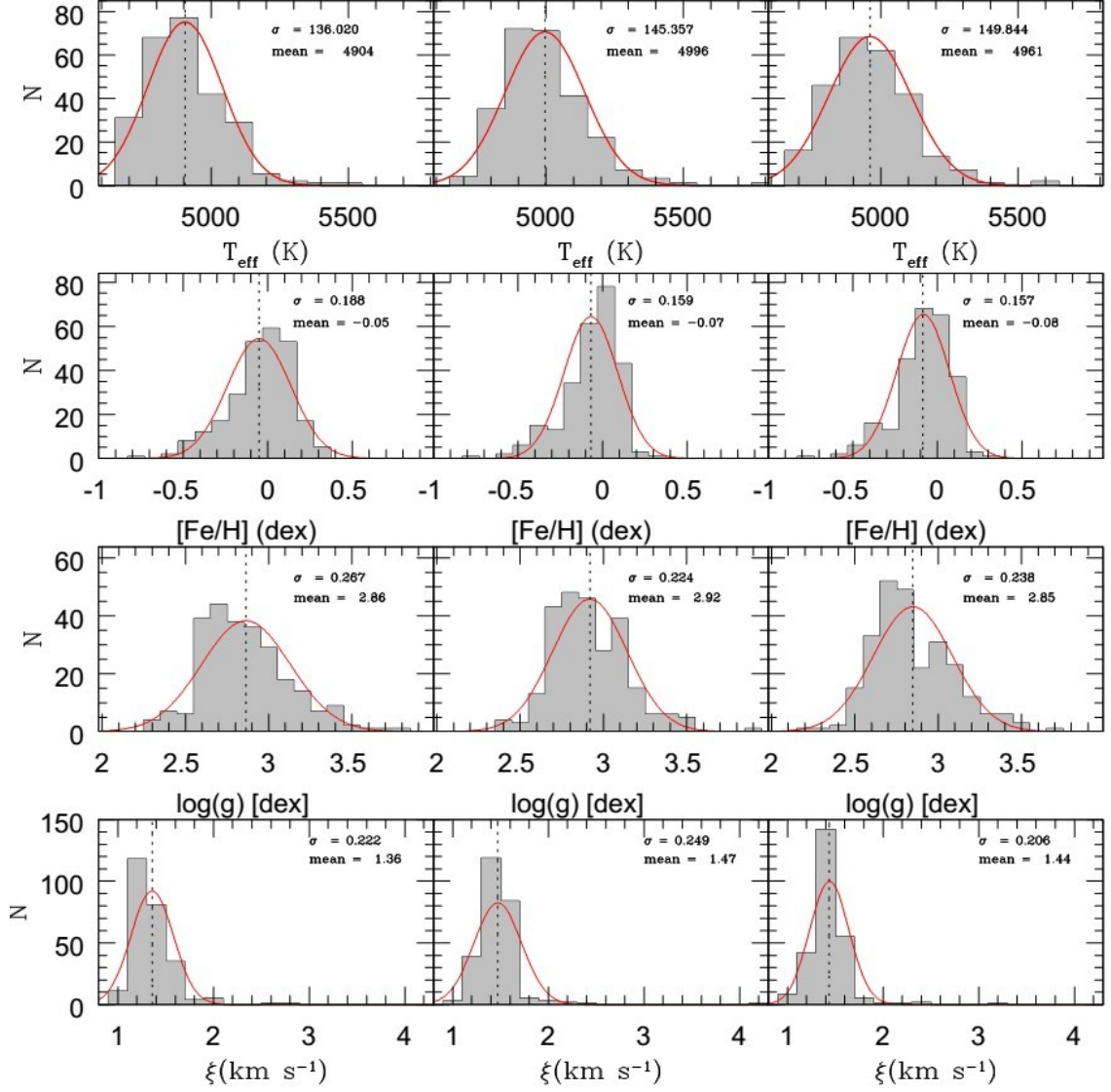


Figure 4.4: Distribution of the atmospheric parameters derived using the HM07 (*left panels*), SO08 (*middle panels*), and TS13 (*right panels*) line-lists. In each plot, the Gaussian fits to the distribution, together with the values of the mean (dotted line) and the standard deviation σ are also shown.

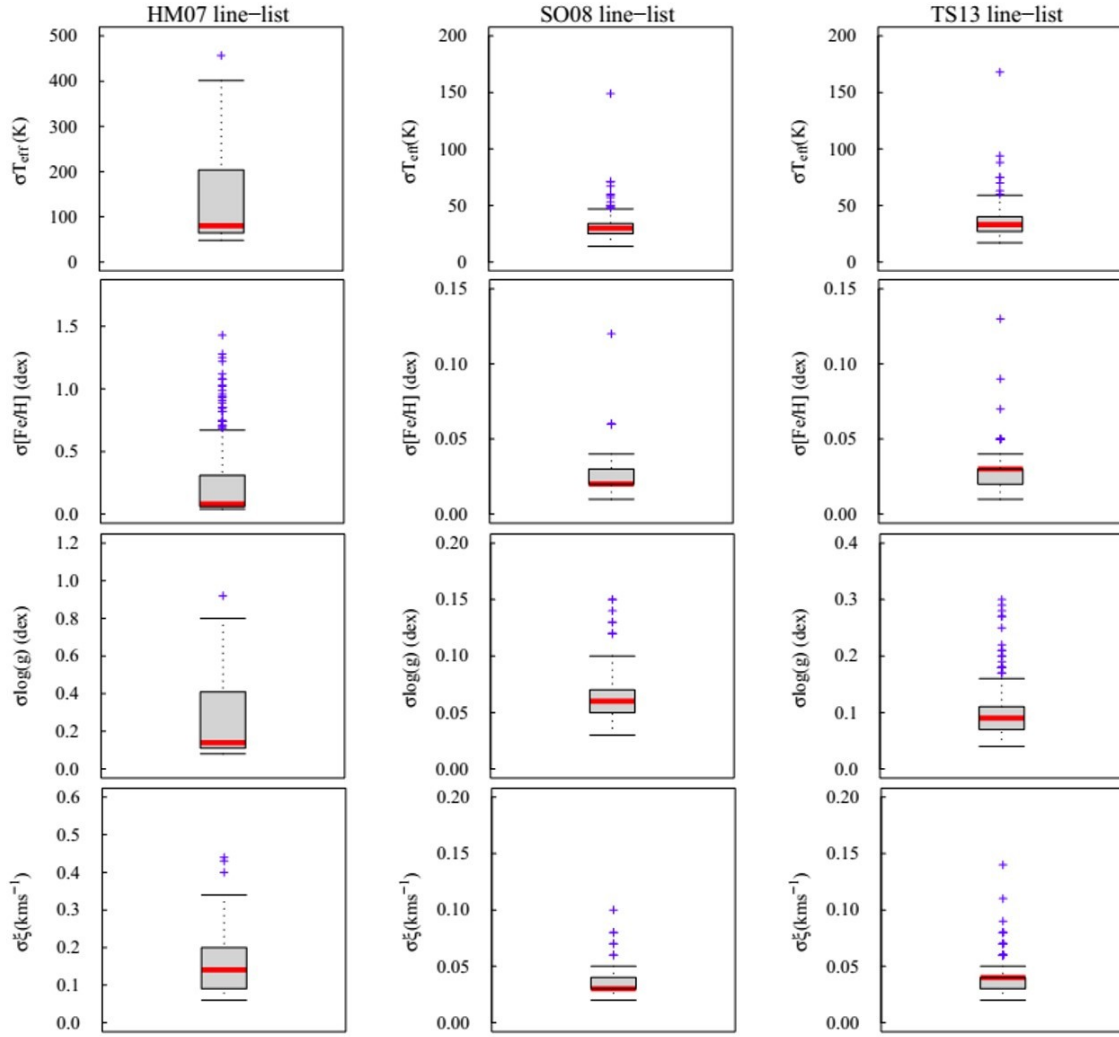


Figure 4.5: Boxplot showing the median (solid horizontal red lines), lower and upper quartiles (box), range of datapoints within 1.5x (75% - 25%) range (whiskers), and outliers (individual blue crosses) of the errors for derived parameters presented in Fig. 4.4.

microturbulence, and metallicity, respectively, while between the results of TS13 and SO08 the average differences (defined as TS13 - SO08 results) are -35 K, -0.071 dex, -0.033 km s^{-1} , and -0.015 dex, respectively. Microturbulence of TS13 compares very well with SO08 line-list, but the results found with HM07 line-list are slightly higher than the other values, but still within the error bar.

4.2.2 Results

Comparison with previous works

The large majority of the giant stars studied in this paper do not have any previous metallicity estimate derived from high-resolution spectroscopy. In order to compare our results with previous ones, we used several works (Foy 1981; Gratton and Ortolani 1986; McWilliam 1990; Luck 1991; Jones et al. 1992; di Benedetto 1998; Randich et al. 1999; Thorén et al. 2004; da Silva et al. 2006; Hekker and Meléndez 2007; Liu et al. 2007; Meléndez et al. 2008; Soubiran et al. 2010; Jones et al. 2011a,b) to compile a list of literature data for a set of 74 stars in our sample. The literature values of the atmospheric parameters for these common sample are listed in Table C.3. Note that only 67 of these stars have all four parameters already calculated in previous works (Table C.3), hence we are providing here new precise spectroscopic atmospheric parameters for 190 stars. Indeed, five stars HD 96566, HD 94890, HD 24160, HD 116243, HD 134505 in this sample have only values of effective temperature taken from di Benedetto [1998]. Fig. 4.7 shows the comparison between our results obtained for the TS13 linelist, with those presented in these earlier works. As we can see in the panels of this figure, our results present a good agreement with those listed in the literature.

The atmospheric parameters taken from the literature for the 74 stars presented in Table C.3 can also be found in the PASTEL catalog (Soubiran et al. 2010) but not the microturbulence velocity. Compared to the PASTEL catalog (Soubiran et al. 2010) we found an average difference (defined as TS13 - literature data) of 108 K, -0.02 dex, and 0.03 dex for effective temperature, surface gravity, and metallicity, respectively. The common sample presented in Table C.3 is composed by values taken from 13 different works. In order to test our results against samples homogeneously characterized, we checked our results, separately, against those from Jones et al. [2011b], Liu et al. [2007], McWilliam [1990], and da Silva et al. [2006] due to the significant number of stars in common with these works. Fig. 4.8 shows the comparison of our stellar parameters with those from these works. We found an average difference of 20 K, -0.17 dex, -0.032 km s^{-1} , and -0.072 dex, respectively, for effective temperature, surface gravity, microturbulence, and metallicity when we compare our results with those from da Silva et al. [2006], and -26 K, 0.085 dex, 0.048 km s^{-1} , and -0.0088 dex compared to Jones et al. [2011b]. We have 20 stars in common with McWilliam [1990] whom analysed 671 GK giant spectra, and derived effective temperatures with empirical and semi-empirical methods, involving an IR flux calibration. For this set of stars, the average difference on effective temperature is 119 K, with a standard deviation of 81.1 K, and it is less than 0.12 dex in metallicity, with a standard deviation of 0.07 dex. Besides the effective temperature and the metallicity from McWilliam [1990] are marginally higher than the one derived in our work, the two other parameters compare quite well, with an average difference of -0.21 dex and -0.65 km s^{-1} for surface gravity and microtur-

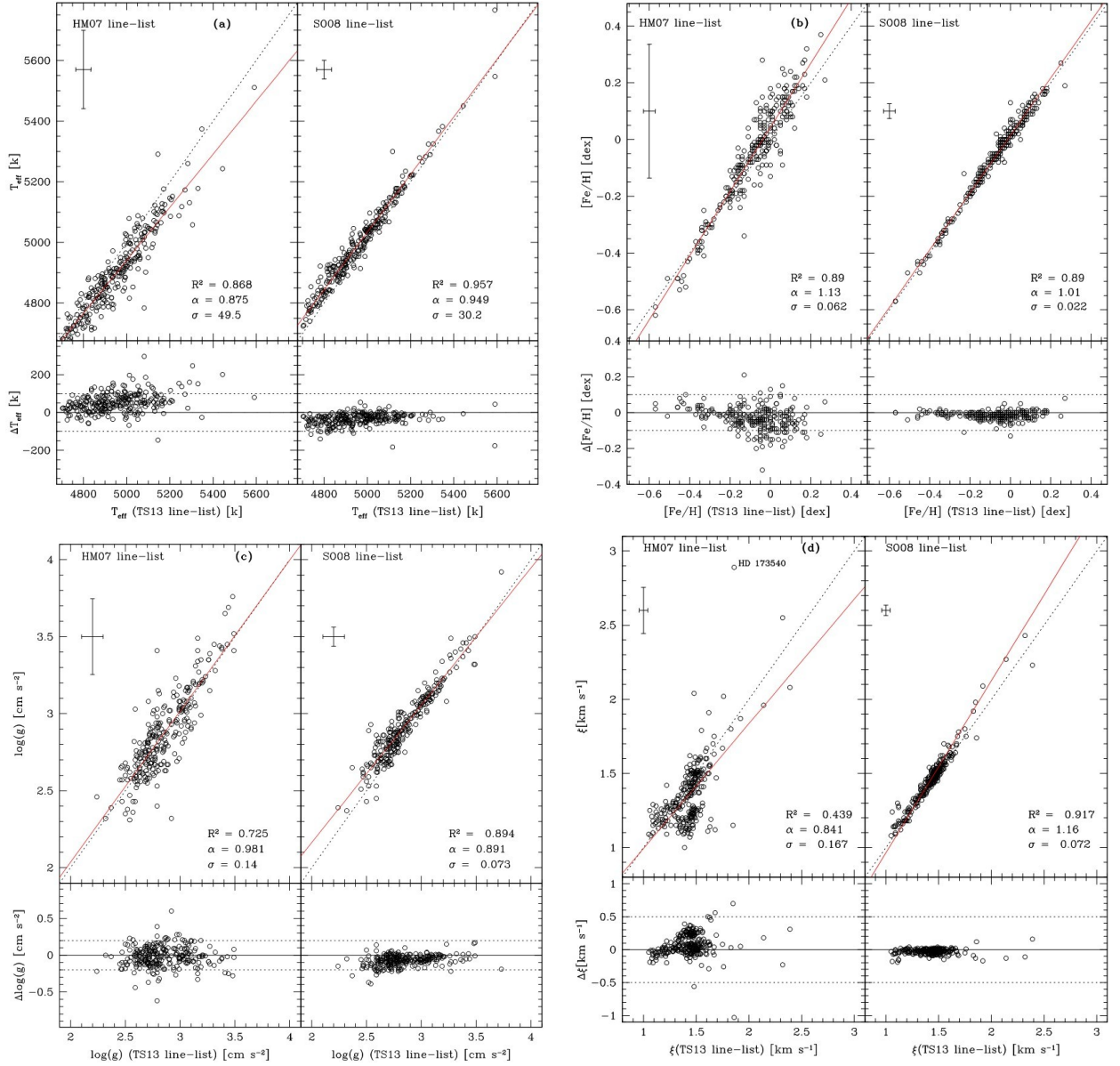


Figure 4.6: Comparison between the results found using the TS13, SO8, and HM07 line-lists. **(a)** Effective temperature, **(b)** metallicity, **(c)** surface gravity, and **(d)** microturbulence velocity derived using the HM07 (*left plot*) and SO8 (*right plot*) line-lists compared to those derived using the TS13 line-list. In each panel, the lower plot compares the differences from perfect agreement. The differences refer to the abscissa minus the ordinate of the corresponding upper plot. The dotted line shows the one-to-one relation, and the solid line is the linear fit, for which the values of the R-squared (R^2), the slope calculated by the regression α , and the residual standard deviation σ are given. The average error is also plotted. HD 74006 is not shown in the plots because it does not present the results using the HM07 line-list.

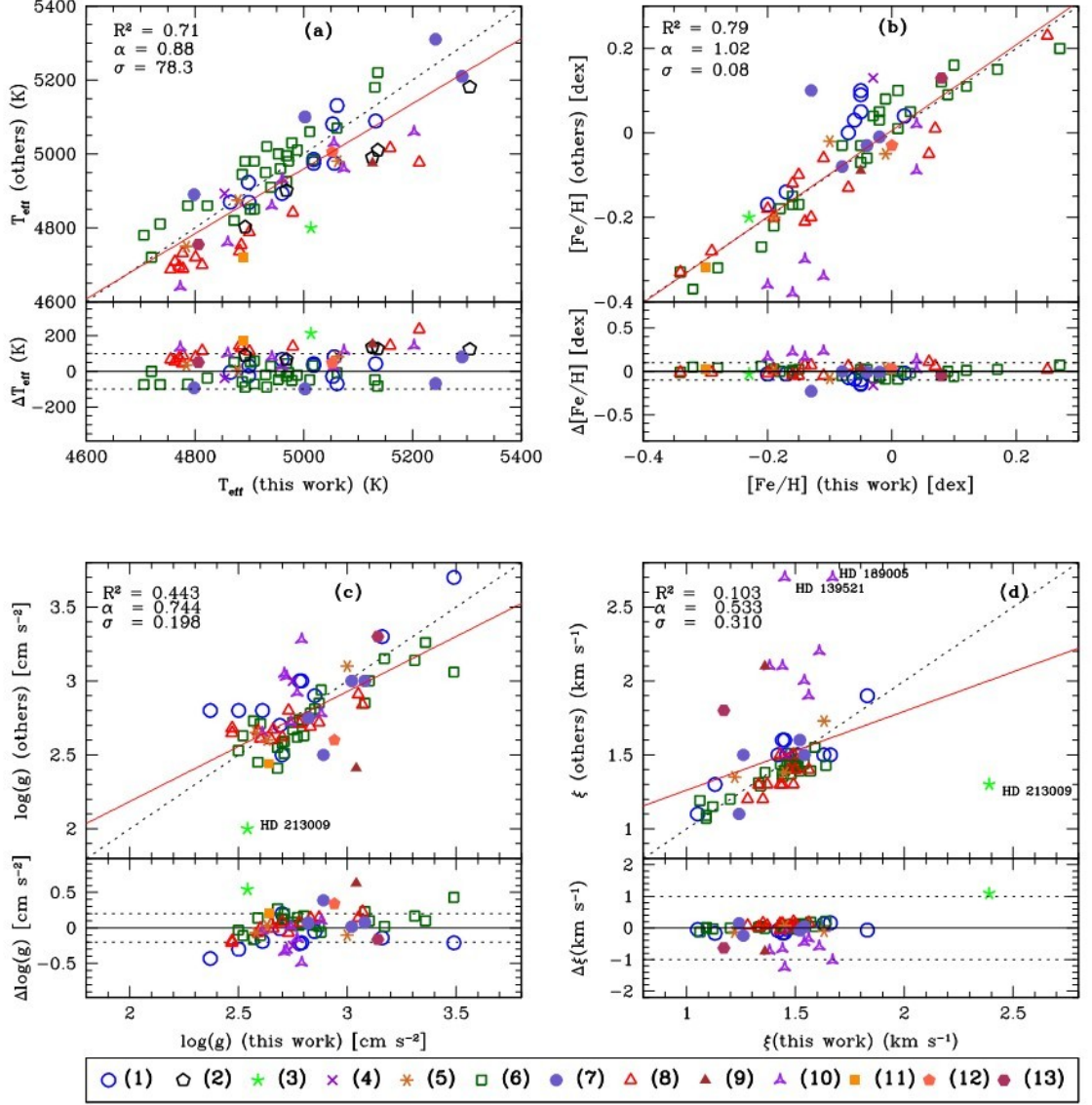


Figure 4.7: Comparison of the results of this work obtained for the TS13 line-list with available literature data for (a) effective temperature, (b) metallicity, (c) surface gravity, and (d) microturbulence. The dotted line shows the one-to-one relation, and the solid line is the linear fit, for which the values of the R-squared (R^2), the slope calculated by the regression α , and the residual standard deviation σ are given. Each symbol indicates a reference given in Table C.3, as enumeration reported in the legend, i. e., (1): da Silva et al. [2006]; (2): di Benedetto [1998]; (3): Foy [1981]; (4): Gratton and Ortolani [1986]; (5): Hekker and Meléndez [2007]; (6): Jones et al. [2011b]; (7): Jones et al. [1992]; (8): Liu et al. [2007]; (9): Luck [1991]; (10): McWilliam [1990]; (11): Meléndez et al. [2008]; (12): Randich et al. [1999]; (13): Thorén et al. [2004].

bulence, respectively.

The comparison of our atmospheric parameters with those from Liu et al. [2007], with whom we have 14 stars in common, is also presented in Fig. 4.8. The average differences are 108 K, 0.017 dex, 0.016 dex, and 0.089 km s^{-1} , for effective temperature, metallicity, surface gravity, and microturbulence, respectively. One of the major advantage of our work is to present a homogeneous measurement of spectroscopic parameters for a set of giant stars that have been already surveyed for exoplanets research, thus presenting a solid sample of comparison for future researches.

4.2.3 Concluding remarks

We have derived the stellar atmospheric parameters (the effective temperature, the surface gravity, the microturbulence, and the metallicity) for a sample of 257 field giant stars that are being surveyed for planets using precise radial-velocity measurements. Those parameters were derived by using three different line-lists of Fe I and Fe II (SO08, TS13, and HM07). All parameters derived in this work are listed in Table C.2, and we adopt as final the parameters derived with the TS13 line-list. We compared the results found by using the different linelists and we found small dispersion for most of the stars. HM07 results to show a much higher dispersion as expected because the linelist is small. The results from TS13 and SO08 are compatible in terms metallicity, but in T_{eff} they show an offset specially for the cooler stars. Even in this case this behaviour is expected because the SO08 linelist for cool stars presents unsatisfactory (too high) results in T_{eff} compared with other methods (Mortier et al. 2013a, Tsantaki et al. 2013). In the present catalog (Table C.2) we are providing new precise spectroscopic measurements of atmospheric parameters for 190 stars for which the given four parameters had not yet been found or published in previous works. Additionally, we also provide new measurements for 67 stars with previous published results of all parameters, but with the major advantage that they are now calculated homogeneously, providing a more suitable analysis. The comparison of our results with those presented in the literature shows that our derivations are solid, and it will be very useful to future studies of frequency of planets as a function of the different stellar parameters. Since the first discovery of a substellar companion orbiting a giant star (HD 137759 Frink et al. 2002), more than 100 evolved stars are known to host planets according to the available data at the Extrasolar Planets Encyclopaedia⁶, but it is still missing a homogeneous sample that allows to perform studies on the properties of giant stars hosting planets. Note that one star in our sample is already known to have an orbiting planet (HD 11977 - Setiawan et al. 2005). The parameters for this star are $T_{\text{eff}} = 5018 \pm 27 \text{ K}$, $\log g = 2.85 \pm 0.07 \text{ cm s}^{-2}$, $\xi = 1.44 \pm 0.03 \text{ km s}^{-1}$, $[\text{Fe}/\text{H}] = -0.17 \pm 0.03 \text{ dex}$ (TS13 line-list), showing that its iron content is a bit less than that of the Sun. Low iron abundance has been also found in other giants hosting planets suggesting that planet-hosting giant stars are on average metal-poor compared to planet-hosting dwarfs. However, as pointed out by Mortier et al. [2013a], it may be due to a bias in samples of evolved stars used to detect planets. In the present catalog, the red giant branch star HD 135760 is the most metal-rich ($[\text{Fe}/\text{H}] = +0.27 \pm 0.05 \text{ dex}$), which is in agreement with previous result presented by Jones et al. [2011b], while HD 7082 is the most metal-poor ($[\text{Fe}/\text{H}] = -0.74 \pm$

⁶<http://exoplanet.eu>

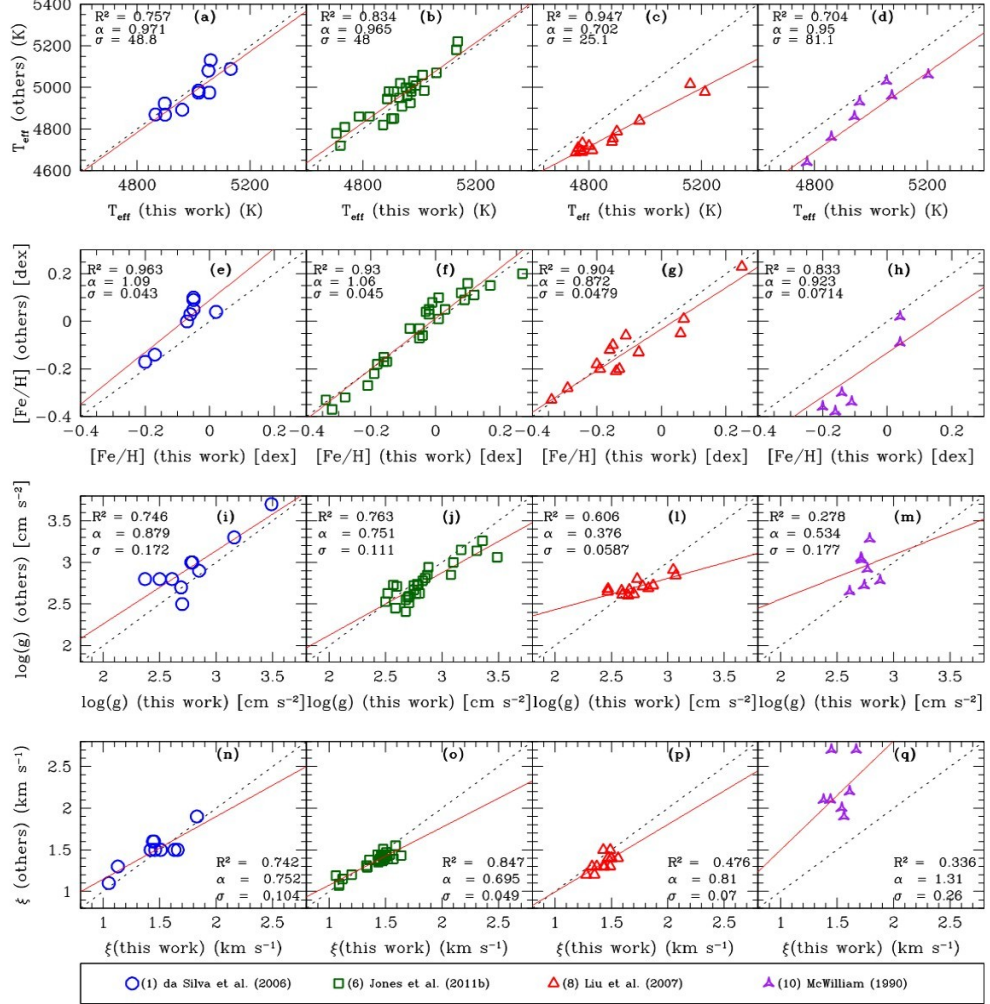


Figure 4.8: Comparison between our results with those from da Silva et al. [2006], Jones et al. [2011b]; Liu et al. [2007], and McWilliam [1990]. The dotted line shows the one-to-one relation, and the solid line is the linear fit, for which the values of the R-squared (R^2), the slope calculated by the regression α , and the residual standard deviation σ are given. Each symbol indicates a reference reported in Table C.3, as enumeration given in the legend.

Table 4.1: The coefficients of the linear fits ($y = a \times X + b$) of the relations between the stellar parameters, along with the correlation coefficient and the significances. The number of stars is 251.

Elem	a	b	R ²	z-score
$\xi_t - T_{eff}$	0.120±0.065	0.825±0.326	0.013	1.7
$\log g - T_{eff}$	0.847±0.089	-1.356±0.441	0.266	7.9
$[Fe/H] - T_{eff}$	0.280±0.069	-1.472±0.343	0.061	3.9
$[Fe/H] - \log g$	0.234±0.041	-0.751±0.116	0.116	5.4
$\xi_t - \log g$	-0.440±0.029	2.673±0.083	0.476	10.8
$\xi_t - [Fe/H]$	-0.154±0.057	1.407±0.010	0.027	2.6

0.02 dex), amongst with three other stars that have $[Fe/H] < -0.5$ dex. Most stars of our sample have already a large number of measurements of precise radial velocities with the CORALIE spectrograph spread over the last years. Once a significant sample of planets will be found in the present sample, we will be able to study the planet frequency as a function of metallicity and stellar mass. Until then, we can use our accurate and uniform stellar parameters as control sample to others studies that compare stars hosting planets with stars without detected planets. The importance of this work is to present homogeneous measurements of spectroscopic parameters for a huge set of evolved stars, selected in a planet search program. This study will be a solid sample of comparison for future researches.

4.3 Abundances

The next step, after the measurements of precise stellar parameters, was to determine the elemental abundances for 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn and V). We decided to adopt the stellar parameters derived from the linelist of Tsantaki et al. [2013], because it is designed specifically to analyze cool stars. The stars in the sample have effective temperatures $4700 \lesssim T_{eff} \lesssim 5600$ K, surface gravities $2.2 \lesssim \log g \lesssim 3.7$ dex, microturbulences $1 \lesssim \xi_t \lesssim 3.2$ km s⁻¹ and they lie in the metallicity range of $-0.75 \lesssim [Fe/H] \lesssim 0.30$ dex. The interdependence of the fundamental parameters are presented in Fig. 4.9. The figure reveals several interesting correlations between the parameters, for instance one can see that the metallicity correlates with the surface gravity and also stars with higher T_{eff} (above 5100 K) show higher metallicity. Microturbulent velocity strongly correlates with $\log g$. The significance of the observed correlations is estimated following the method described in Figueira et al. [2013] and Adibekyan et al. [2013] and the parameters of the linear relations are presented in Table 4.1. We note that five stars classified as outliers in the ξ_t - $\log g$, were excluded from the estimation of the significance of the correlations (see next Section for details).

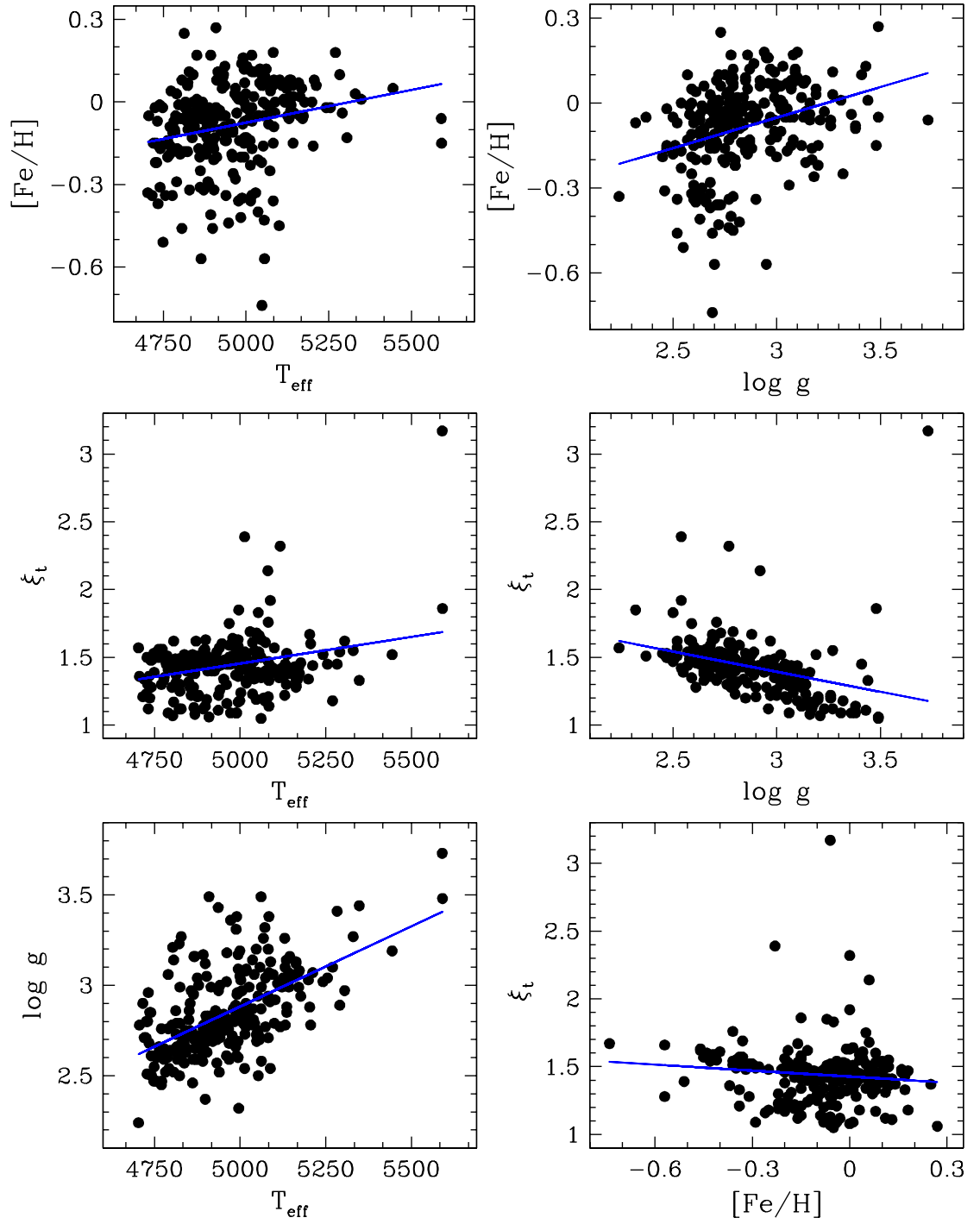


Figure 4.9: Interdependence of the stellar atmospheric parameters of the sample stars. The blue solid lines depict the linear fits of the data.

4.3.1 The microturbulence relationship

Sometimes, when the number of iron lines is not large enough, a correct determination of microturbulence becomes very difficult because of the small EW/λ range of the FeI lines (e.g., Mortier et al. 2013a). In these cases, one uses empiric relations between microturbulence and other stellar parameters. Several studies have shown that for FGK dwarf stars, microturbulent velocity depends on $\log g$ and T_{eff} (e.g., Nissen 1981; Allende Prieto et al. 2004; Adibekyan et al. 2012a; Tsantaki et al. 2013; Ramírez et al. 2013). Takeda et al. [2008] has already suggested that the microturbulence correlates with the surface gravity, however the authors did not provide any analytic form of the relation. To find out the parameters the ξ_t correlates with, we first applied a linear fit for three pairs of data-sets: ξ_t -[Fe/H], ξ_t - $\log g$, ξ_t - T_{eff} . Then we evaluated the significance of the correlation as it was done in Figueira et al. [2013]. As expected the strongest correlation is observed with $\log g$ (5.7σ), $\approx 4\sigma$ in case of T_{eff} , and $\approx 1.8\sigma$ for [Fe/H]. However, the fits can be affected by the presence of several outliers as can be seen in Fig. 4.9. To remove the outliers we used the ξ_t - $\log g$ relation (since it shows the strongest correlation), by applying a 2σ -clipping (two times of residual standard deviation). Then, after cleaning the data from outliers we again fitted the data and evaluated the significance of the relations. We found that microturbulence significantly correlates with the surface gravity (at about 11σ level), and with the metallicity but with less degree of significance. Therefore, the five outliers were responsible for the "strong" relation observed between ξ_t and T_{eff} . After this test, we decided to present the relation of microturbulence only with $\log g$ and [Fe/H], which has the following functional form:

$$\xi_t = 2.72(\pm 0.08) - 0.457(\pm 0.031) \times \log g + 0.072(\pm 0.044) \times [Fe/H] \quad (4.4)$$

We note, that this empirical relation is valid only for the range of stellar parameters that the stars in our sample span.

4.3.2 Linelist and test case: Arcturus star

To build a linelist for the 12 elements we tested the linelist and atomic data taken from Adibekyan et al. [2012b]. Since the spectra of cool evolved stars are more line crowded (which cause strong blending) compared to their unevolved hotter counterparts, we aimed to carefully select a subset of unblended lines from Adibekyan et al. [2012b]. For this purpose we used the spectrum of the K-giant Arcturus star taken from the archive of the NARVAL spectrograph at the 2m Bernard Lyot Telescope in Toulouse, France. This star has a very good quality spectrum, with both high resolution and high signal to noise to be an excellent reference star for giants. We measured the equivalent widths (EWs) of the selected lines both manually, using a Gaussian fitting procedure within the IRAF splot task, and automatically, using the ARES code (Sousa et al. 2007). We calculated the mean relative difference $((EW_{ARES} - EW_{IRAF})/EW_{IRAF})$ and standard deviation of the relative difference of the EW measurements and applied a 2σ -clipping procedure second time after the outliers were excluded. Finally, 118 lines out of 164 were left with maximum relative difference in EW of about 15 %. These lines were once again checked by eye within IRAF to make sure that they are not blended and hence the correspondence between the EW measurements is not by chance (Fig. 4.10). The new linelist can be found in Table C.4.

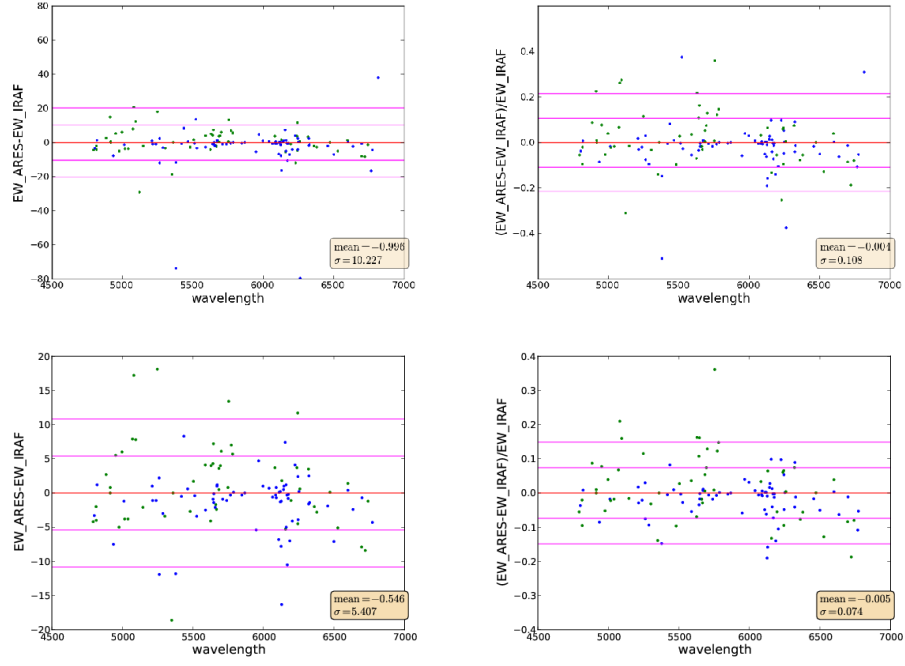


Figure 4.10: The comparison between the EW calculated with IRAF and ARES. At the *top* the first iteration and on the *bottom* the second iteration.

4.3.3 Abundances derivation

After, selecting the isolated lines for 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn, and V) in Arcturus, we could measure automatically the EWs with the ARES code for the stars in our sample. As done for the stellar parameters, we followed the same procedure discussed in Sousa et al. [2007] and in Mortier et al. [2013b]. We considered the LTE condition and the analysis was performed relative to the Sun 2010 version of the spectral synthesis code MOOG⁷ (Snedden [1973]) and a grid of Kurucz ATLAS9 plane-parallel model atmospheres (Kurucz [1993]) were used. The final abundance for each star and element was calculated as the average value of the abundances given by all lines detected in a given stellar spectrum. Individual lines for a given star and element with a line dispersion more than a factor of two higher than the *rms* were excluded. In this way we avoided the errors caused by bad pixels, cosmic rays or unknown effects.

4.3.4 Uncertainties

Since the abundances were determined via the measurement of EWs and using stellar parameters already determined, the errors might come from the EW measurements, from the errors in the atomic parameters, and from the uncertainties of the atmospheric parameters that were used to produce model atmosphere. In addition, one should add systematic errors that can occur due to NLTE or granulation (3D) effects. To minimize the errors, it is very important to use high-quality data and as many lines as possible for each element.

We followed Adibekyan et al. [2012b] for the calculation of the errors. In short, we first varied the model parameters by an amount of their one-sigma errors available for each star and calculated the abundance differences between the values obtained with and without varying the parameter. Then we evaluated the errors in the abundances of all elements $[X/H]$, adding quadratically the line-to-line scatter errors and the errors induced by uncertainties in the model atmosphere parameters. In cases when only one line was used to derive the abundances a typical 0.1 dex error for line-to-line scatter was assumed. For our sample stars the errors induced by uncertainties in the parameters of model atmosphere varies from about 0.02 dex (for SiI) to ≈ 0.06 dex (for VI) and in general are smaller than the line-to-line scatter errors. The final errors for the studied elements are smaller for AlI (≈ 0.04 dex) and larger for VI (≈ 0.14 dex).

4.3.5 Testing stellar parameters

Although Alves et al. (2015) have shown that the stellar parameters in general agree very well with the literature data, the consistency does not always imply correctness. Moreover the stellar parameters were derived through LTE abundance analysis and by using only iron lines. To check the validity limit of the adopted methodology in terms of stellar parameter ranges we tested our results in two ways (see also Adibekyan et al. 2012b).

First, in Fig. 4.11 we plot the $[CrI/CrII]$, $[ScI/ScII]$, and $[TiI/TiII]$ as a function of the stellar parameters to ensure that the ionization equilibrium enforced on the FeII lines (Alves

⁷The source code of MOOG can be downloaded at <http://www.as.utexas.edu/~chris/moog.html>

Table 4.2: Sample table of the derived abundances of the elements, rms, total error, and number of measured lines for each star.

Star	...	[SiI/H]	rms	err	[SiI/H] [*] _{corr}	n	[CaI/H]	rms	err	n	...
...	...	...	...	...	...	...	...	...	...	...	...
HD47001	...	-0.20	0.09	0.09	-0.26	14	-0.25	0.05	0.06	11	...
HD73898	...	-0.30	0.03	0.03	-0.28	14	-0.32	0.04	0.05	11	...
HD16815	...	-0.16	0.07	0.07	-0.20	15	-0.25	0.04	0.06	12	...
...	...	...	...	...	...	...	...	...	...	...	...

Notes: * The [X/H] abundances after correction for the T_{eff} trends.

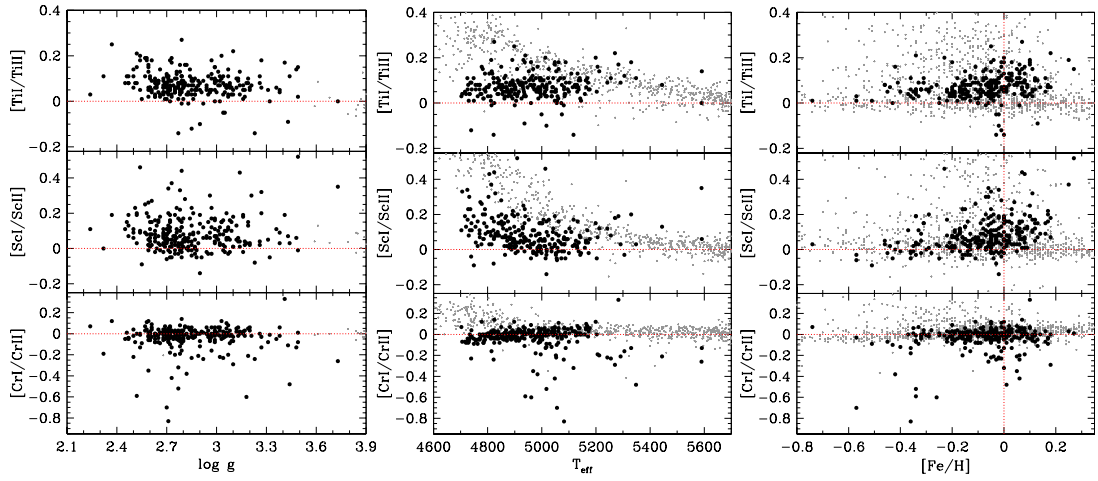


Figure 4.11: [CrI/CrII], [ScI/ScII], and [TiI/TiII] as a function of atmospheric parameters for our sample of evolved stars (black points) and for the sample of FGK dwarf stars from Adibekyan et al. [2012b] (grey dots).

et al. 2015) also is acceptable for other elements. For comparison, the field FGK dwarf stars from Adibekyan et al. [2012b] are presented. Most of the trends are nearly flat around zero in contradiction to their unevolved counterparts for which a gradually increase with decreasing of T_{eff} was observed. For our stars only an increase of [ScI/ScII] ratio can be seen with the decrease of T_{eff} . However, the results obtained for ScI and CrII should be considered with caution since their abundances have been derived by using only one line. From the figure one can notice a small offset from zero for [TiI/TiII] ratio and [ScI/ScII]. These positive offsets probably do not have relation to the NLTE effects as discussed in Bergemann [2011] for [TiI/TiII] and still need to be understood. These offsets could be connected with the use of not very precise surface gravity which is not well constrained using pure spectroscopy (e.g. Sozzetti et al. 2007, Mortier et al. 2013c). The dependence of the abundances of ionized and neutral species on the surface gravity is also discussed in Mortier et al. [2013c]. Tsantaki et al. [2013] showed that by correcting stellar parameters (mainly T_{eff}), using carefully selected line-list especially designed for cool stars, the observed trends of [XI/XII] with stellar parameters get flatter. For example, an overestimation of T_{eff} for cool stars might cause of the trends. Another way of testing the stellar parameters is to plot [X/Fe] against T_{eff} (Fig. 4.12). For comparison the dwarf sample of Adibekyan et al. [2012b] is also presented. Stellar evolutionary models do not suggest significant trends of these ratios with T_{eff} . However, for several elements we detected significant trends. To evaluate the significance of the trends we performed a linear fit and followed the procedure described in Figueira et al. [2013].

The significance of the trends and the slopes are presented in Table 4.3. From the figure, one can see that for most cases the trends are less steep compared to those observed for the dwarfs, which in turn speaks about the correctness of the stellar parameters used to derive the abundances.

Adibekyan et al. [2012b] already discussed several possible reasons of the observed trends of [XI/XII] with stellar parameters, and [X/Fe] with T_{eff} and concluded that the observed trends are probably not an effect of stellar evolution, and uncertainties in model atmospheres are the dominant effect in measurements. The authors afterwards removed the T_{eff} trend as it was done also in other works (e.g., Valenti and Fischer 2005; Petigura and Marcy 2011). Since by fitting the data and simply subtracting the fit would force the mean [X/Fe] to zero (which is a non-physical situation), Adibekyan et al. [2012b] added a constant term chosen so that the correction is zero at solar temperature. In our case the stars are cooler and their temperatures do not reach the solar temperature so we decided to apply another approach. In this case, the constant term was chosen so that the correction is zero at $T_{\text{eff}} = 4960$ K, which is the mean temperature of our sample stars. However, we appreciate the fact that this approach and the choice of the constant term is arbitrary. For this reason we decide to use the original (before detrending) chemical abundances for the rest of our study. The dependence of [X/Fe] on stellar gravity, microturbulence and metallicity is shown in Fig. 4.13, Fig. 4.14, and Fig. 4.15, respectively. For most of the species we did not observe a trend with ξ_t and $\log g$, and some of the observed trends probably reflect the correlation of T_{eff} with ξ_t , and T_{eff} with $\log g$ (see Fig. 4.9). As a final check, we compare our derived abundances with those obtained by Liu et al. [2007]. We note that this is the only literature source where we find enough stars (14 stars) in common to compare. We found very good agreement for all the species except vanadium: $\Delta[\text{Na}/H] = 0.02 \pm 0.12$,

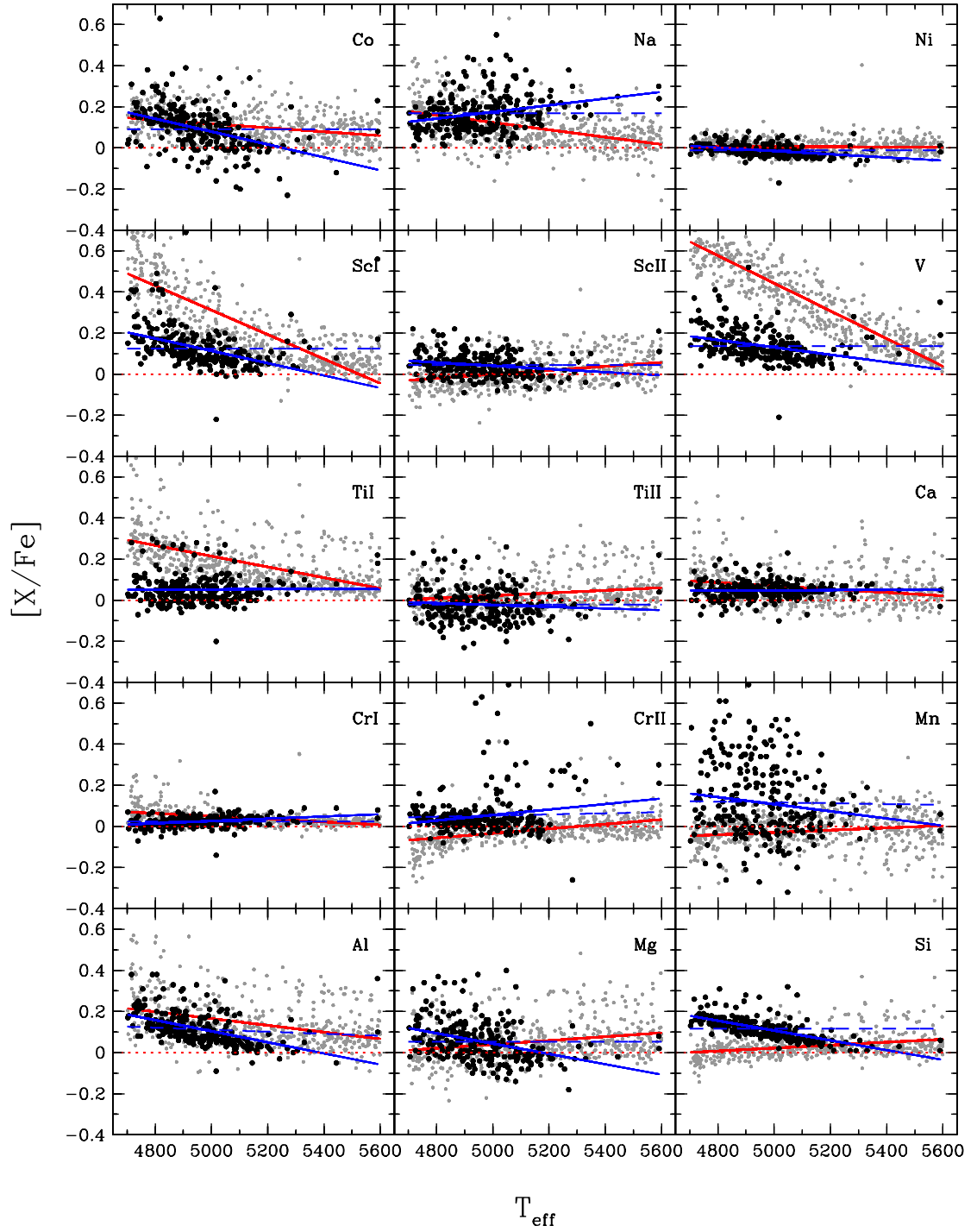


Figure 4.12: $[X/Fe]$ vs. T_{eff} plots. The black dots represent the stars of our sample and the gray small dots represent stars from Adibekyan et al. [2012b]. The blue and red solid lines depict the linear fits of the current data and the data from Adibekyan et al. [2012b], respectively. The blue dashed line is the fit of our data after correcting for the trend with T_{eff} . Each element is identified in the *upper right corner* of the respective plot.

Table 4.3: The slope, correlation coefficient, and the significance of the $[X/Fe]$ linear trends with the T_{eff} .

Elem	slope	R^2	N	z-score
NaI	$1.62 \pm 0.36 \times 10^{-4}$	0.72×10^{-1}	255	4.3
MgI	$-2.51 \pm 0.38 \times 10^{-4}$	0.14×10^0	256	6.1
AlI	$-2.69 \pm 0.29 \times 10^{-4}$	0.24×10^0	256	7.9
SiI	$-2.39 \pm 0.16 \times 10^{-4}$	0.45×10^0	256	11.0
CaI	$0.61 \pm 1.80 \times 10^{-5}$	0.44×10^{-3}	256	0.3
ScI	$-3.00 \pm 0.34 \times 10^{-4}$	0.23×10^0	254	7.6
ScII	$-0.78 \pm 0.23 \times 10^{-4}$	0.43×10^{-1}	256	3.2
TiI	$0.81 \pm 2.94 \times 10^{-5}$	0.29×10^{-3}	256	0.2
TiII	$-0.44 \pm 0.34 \times 10^{-4}$	0.64×10^{-2}	256	1.2
VI	$-1.79 \pm 0.29 \times 10^{-4}$	0.13×10^0	255	5.9
CrI	$0.56 \pm 0.10 \times 10^{-4}$	0.98×10^{-1}	256	4.9
CrII	$1.33 \pm 0.34 \times 10^{-4}$	0.57×10^{-1}	245	3.6
MnI	$1.33 \pm 0.34 \times 10^{-4}$	0.57×10^{-1}	246	2.3
CoI	$-3.12 \pm 0.37 \times 10^{-4}$	0.21×10^0	255	7.5
NiI	$-0.78 \pm 0.11 \times 10^{-4}$	0.16×10^0	256	6.3

$\Delta[Mg/H] = -0.06 \pm 0.12$, $\Delta[Al/H] = 0.05 \pm 0.04$, $\Delta[Ca/H] = 0.03 \pm 0.06$, $\Delta[Si/H] = 0.03 \pm 0.03$, $\Delta[Ti/H] = 0.04 \pm 0.08$, $\Delta[Ni/H] = -0.01 \pm 0.05$, and $\Delta[V/H] = 0.19 \pm 0.05$. The $[X/H]$ abundances of all stars are in Table C.5.

4.3.6 $[X/Fe]$ vs. $[Fe/H]$: Galactic chemical evolution

The $[X/Fe]$ vs. $[Fe/H]$ relation plot is traditionally used to study the Galactic chemical evolution because iron is a good chronological indicator of nucleosynthesis. In Fig. 4.15 we present the dependence of $[X/Fe]$ on metallicity for our sample of giant stars and for FGK dwarf stars from Adibekyan et al. [2012b]⁸. In the figure we also showed the average value of $[X/Fe]$ for stars with $[Fe/H] = 0.0 \pm 0.1$ dex, where the Galactic chemical evolution effects are small. As one can see, for all the elements the general behavior of $[X/Fe]$ with $[Fe/H]$ is similar for giant and dwarf stars, and reflects the Galactic chemical evolution in the solar neighborhood. However, one can also clearly notice that, for some elements (Co, Na, V, Mn, Al, and Si) while the Galactic chemical evolution trends are similar, they are shifted: for giant stars having higher $[X/Fe]$ values at a fixed metallicity. The largest offset is seen for Na and Mn, and a bit less in Si and Al. The Mn abundance was obtained by using only one line and it should be considered with caution. Moreover, the scatter in $[Mn/Fe]$ is very high, indicating unrealistic abundances for some fraction of the stars.

Overabundances of sodium and aluminum (also silicon in some cases) in open cluster giants

⁸Only stars with $T_{\text{eff}} = T_{\odot} \pm 500$ K are presented, because of the highest accuracy in the parameters and chemical abundances in these stars.

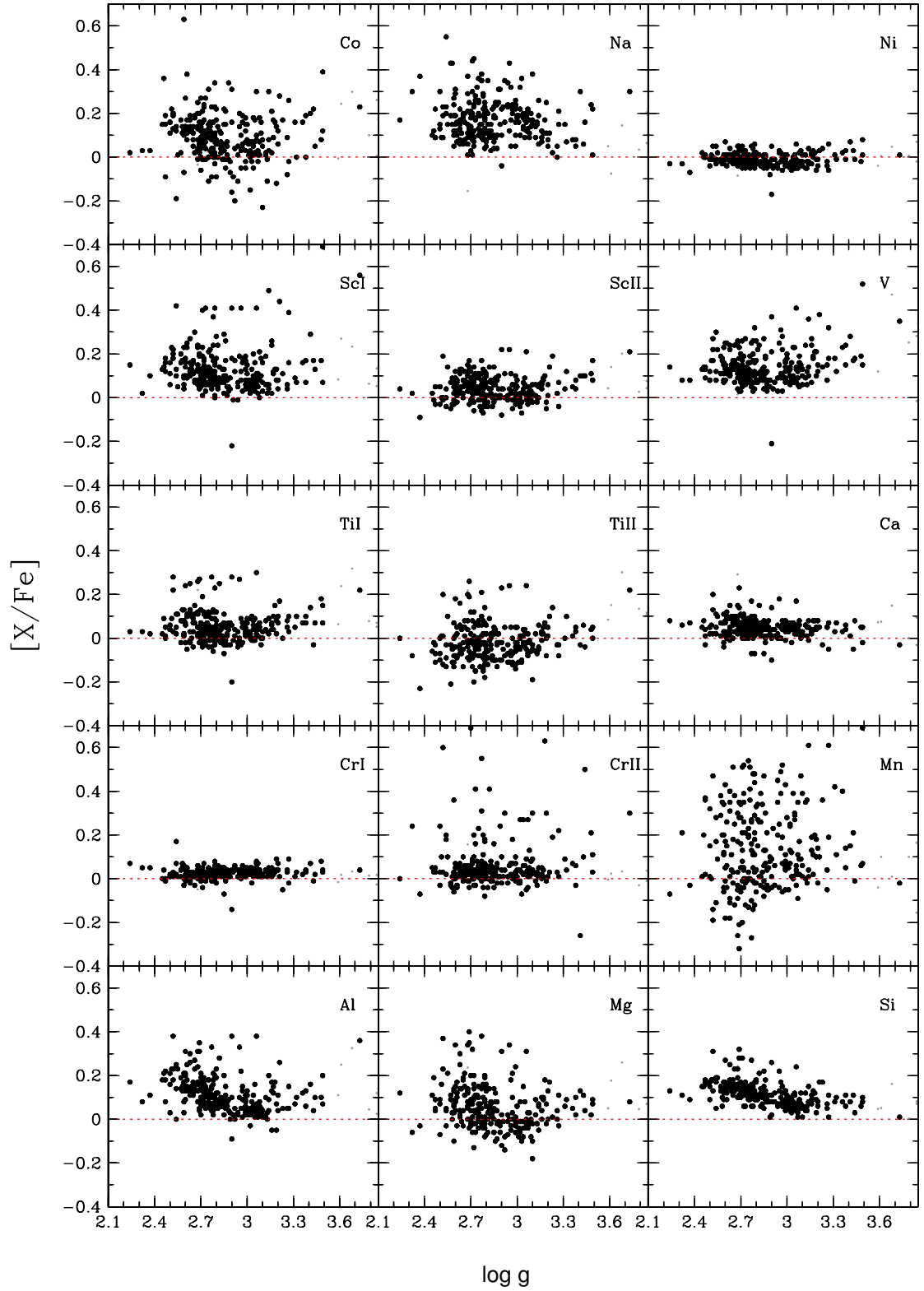


Figure 4.13: $[X/Fe]$ vs. $\log g$ plots. Each element is identified in the *upper right corner* of the respective plot. The black dots represent the stars of the sample and the gray small dots represent stars from Adibekyan et al. [2012b].

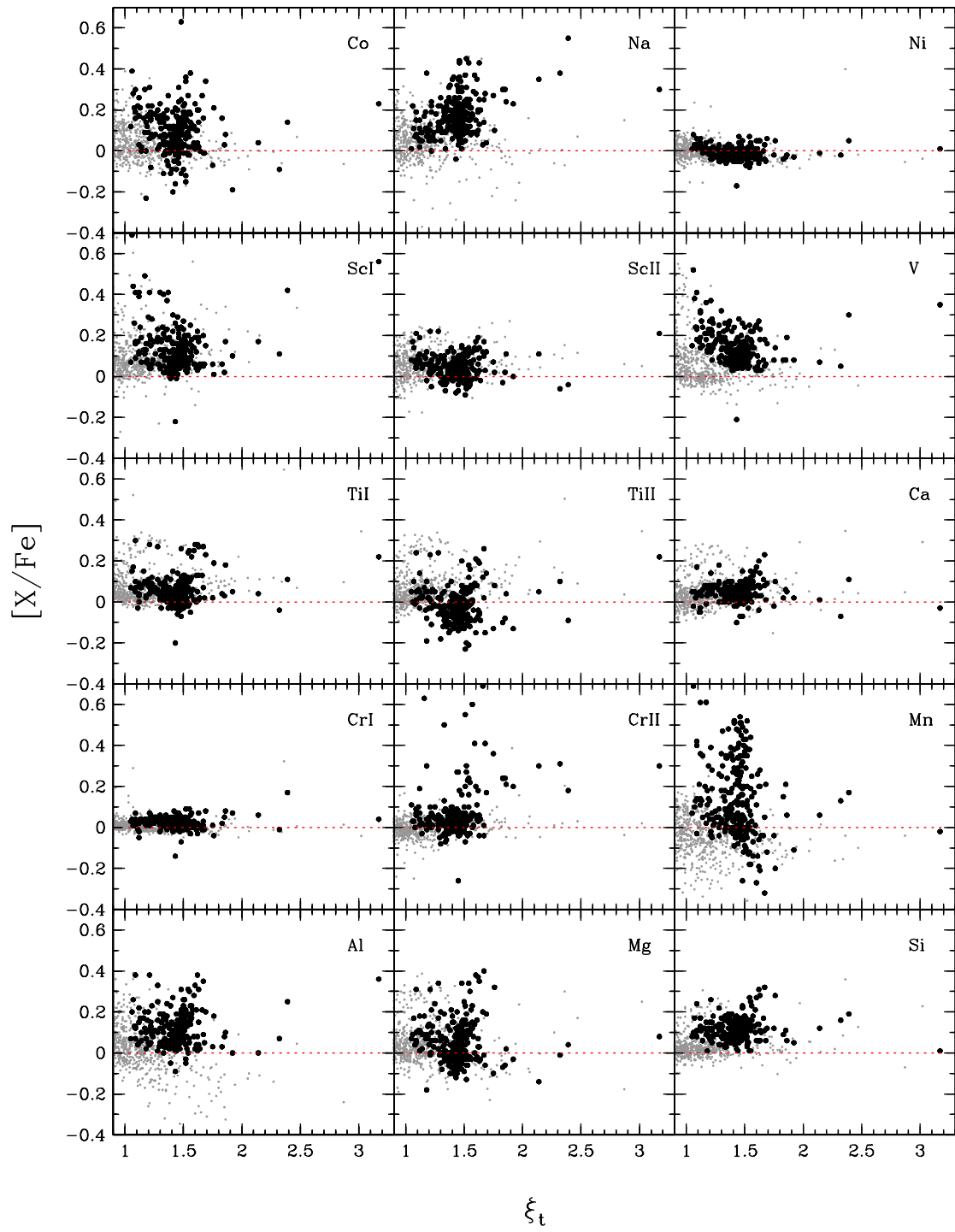


Figure 4.14: $[X/Fe]$ vs. microturbulence plots. Each element is identified in the *upper right corner* of the respective plot. The black dots represent the stars of the sample and the gray small dots represent stars from Adibekyan et al. [2012b].

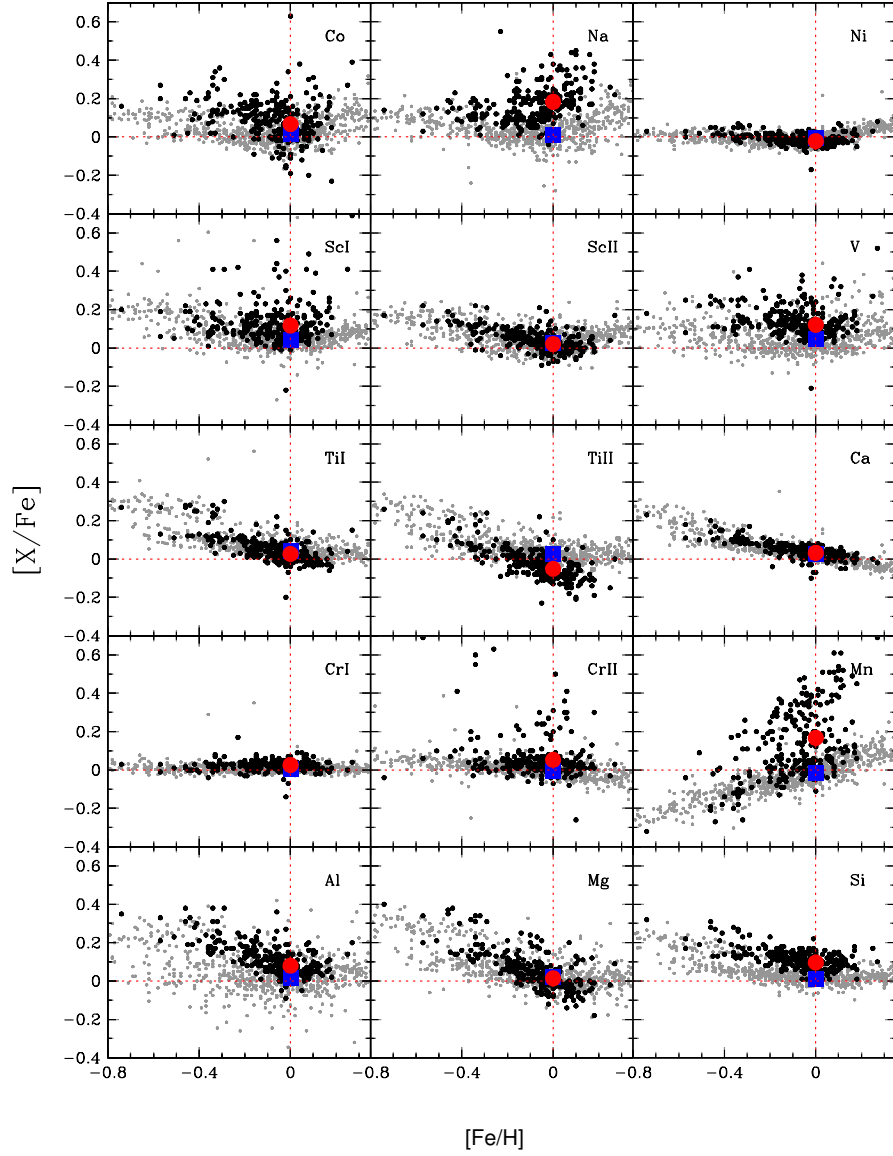


Figure 4.15: $[X/Fe]$ vs. $[Fe/H]$ plots. The black dots represent the stars of the sample and the gray small dots represent stars from Adibekyan et al. [2012b] with $T_{\text{eff}} = T_{\odot} \pm 500 \text{ K}$. The red circle and blue square show the average $[X/Fe]$ value of our and Adibekyan sample, respectively, with $[Fe/H] = 0.0 \pm 0.1 \text{ dex}$. Each element is identified in the *upper right corner* of the respective plot.

(compared to the abundances of dwarfs) were already observed by several authors (e.g., Friel et al. 2003, 2005; Tautvaišienė et al. 2005; Jacobson et al. 2007; Villanova et al. 2009; Santrich et al. 2013). In most of these studies, the trends were explained as a stellar evolutionary effect, due to the deep mixing produced by the hydrogen burning cycle, after stars have left the main sequence. For a complete picture, one should perform thorough analysis taking into account the non-LTE effects which are stronger for giants stars and also the systematic errors which might arise due to particular spectroscopic analysis method used. For example, it is well known that sodium lines suffer from non-LTE effects which lead to an overestimation of the Na abundances (e.g., Alexeeva et al. 2014). In our analysis we used two sodium lines (at 6154.23 Å and 6160.75 Å) which were studied for non-LTE effects in Alexeeva et al. [2014]. The average EWs of these lines were ~ 70 mÅ for 6154.23 Å, and ~ 80 mÅ for the 6160.75 Å line. According to Alexeeva et al. [2014], the non-LTE correction for our stars should be from -0.1 to -0.15 dex, which is close to the difference in [Na/Fe] between giants and dwarfs observed in this study.

4.3.7 Kinematics and stellar populations

The structure of the Milky Way (MW) has several stellar subsystems. The main three stellar populations of the MW are the thin disk, thick disk and the halo. These populations have different kinematic and chemical properties.

It is becoming increasingly clear that a separation of the Galactic stellar components based only on stellar abundances is superior to kinematic separation (e.g., Navarro et al. 2011; Lee et al. 2011; Adibekyan et al. 2011; Liu and van de Ven 2012; Recio-Blanco et al. 2014), because chemistry is a relatively more stable property of a star than its spatial positions and kinematics. However, as mentioned above, some changes in abundances of some elements are expected when the stars are evolving and leaving the main sequence. In this analysis, to separate the thin and thick disk stellar components, we used the position of the stars in the $[\alpha/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ plane (here α refers to the average abundance of Mg, Si, and Ti), but separately also a kinematics approach is applied. The space velocity components for 183 stars out of 256 were derived with respect to the local standard of rest (LSR), adopting the standard solar motion $(U_{\odot}, V_{\odot}, W_{\odot}) = (11.1, 12.24, 7.25)$ km s $^{-1}$ of Schönrich et al. [2010]. For the remaining 73 stars we did not calculate the velocities because of the deficit of astrometric literature data. The main source of the parallaxes and proper motions were the updated version of the Hipparcos catalog (van Leeuwen 2007). The radial velocities were taken from the SIMBAD Astronomical Database⁹. Combining the measurement errors in the parallaxes, proper motions, and radial velocities, the resulting average errors in the U, V, and W velocities are of about 2-3 km s $^{-1}$. To assess the likelihood of the stars being a member of different Galactic populations, we followed the prescriptions given by Reddy et al. [2006]. The probabilities that the stars belong to different stellar populations were calculated, having adopted both the Bensby et al. [2003] and Robin et al. [2003] population fractions. In these methods each of the three populations follows a Gaussian distribution of random velocities in each component. We considered that a probability in excess of 70 % suffices to assign a star to a concrete population. Stars with a probability less than 70 % were included in a transition population. The Galactic space velocity components and the probabilities to assign

⁹<http://simbad.u-strasbg.fr/simbad/>

the stellar population to which each star belongs to are shown in the Table C.6. According to the Bensby et al. [2003] criteria, among the 183 stars, we have 176 (96%) stars from the thin disk, 5 from the thick disk (3 %), and 2 stars are considered to be transition stars (1 %) that do not belong to any group. Adopting the criteria from Robin et al. [2003] gives 177 (97%) thin disk stars, 5 stars with kinematics suggesting a thick/thin disk transition, and one star with a classification of thick-disk/halo transition object. The distribution of the stars in the Tommre diagram is shown in Fig. 4.16.

As mentioned above, in addition to the difference in their kinematics, the thin and thick disk stars are also different in their α content at a given metallicity. This dichotomy in the chemical evolution allows one to separate different stellar populations. The $[\alpha/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ plot for the sample stars along with the dwarf stars from Adibekyan et al. [2012b] with $T_{\text{eff}} = T_{\odot} \pm 500$ K is depicted in Fig. 4.17¹⁰. As one can see from the figure the two samples show similar trends, with giant stars having on average higher $[\alpha/\text{Fe}]$ values at a fixed (low) $[\text{Fe}/\text{H}]$. Our chemical separation of the Galactic disks suggests that 23 stars (9%) in the sample show enhanced α abundances. In Adibekyan et al. [2011] and Adibekyan et al. [2013] the high- α stars were separated into two groups with a gap in both $[\alpha/\text{Fe}]$ and metallicity. It is interesting to see that the gap in $[\text{Fe}/\text{H}]$ for high- α stars can be also seen in our sample at the same metallicity ($\approx -0.2 / -0.3$ dex) and close to their $[\alpha/\text{Fe}]$ value (~ 0.2 dex). Following the same logic and definitions as in Adibekyan et al. [2013], the 10 stars with enhanced $[\alpha/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ below -0.3 dex can be classified as thick disk stars, and the remaining 13 stars as high- α metal-rich stars (HAMR). With this definition we see that 4% of the stars belong to the Galactic thick disk, as the kinematic separation was suggesting. We note that the current sample is small and we will avoid to give a definitive conclusion about the existence of the mentioned "gap" and the distinction of the two α -enhanced metal-poor and metal-rich populations. However, the fact that the two different homogeneously analyzed samples (the current one and the one from Adibekyan et al. [2011]) show quite similar features probably is more than just a hint about the existence of the HAMR stars as a distinct stellar family. However, we want to note that no similar gap was found in Bensby et al. [2014] where the authors suggested that the HAMR stars represent the metal-rich tail of the thick disk. As mentioned in Bensby et al. [2014], a large sample with well-controlled selection function (e.g., Gaia-ESO survey - Gilmore et al. 2012) would help us to understand the real nature of the HAMR stars.

Separation of the Galactic disks by α -enhancement

The separation of Galactic stellar populations by the chemical properties of the stars was done following the method presented in Adibekyan et al. [2011]. We first divided the sample into three $[\text{Fe}/\text{H}]$ bins: $[\text{Fe}/\text{H}] < -0.3$ dex, $[\text{Fe}/\text{H}] > 0.0$ dex, and stars in between. For the lowest and highest $[\text{Fe}/\text{H}]$ bins we easily identified the minima in the $[\alpha/\text{Fe}]$ histograms. For the stars with intermediate $[\text{Fe}/\text{H}]$, just plotting the $[\alpha/\text{Fe}]$ histogram will not reveal the minima, because the stars at these metallicities show a decrease of $[\alpha/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ (see Fig. 4.18). Thus, we first detrended the $[\alpha/\text{Fe}]$ by applying a linear fit and then subtracted it. Then in the $[\alpha/\text{Fe}]$ histogram we identified the minima and by adding them to the previously applied linear fit we obtained the

¹⁰The chemical dissection of the disks is presented in the next section.

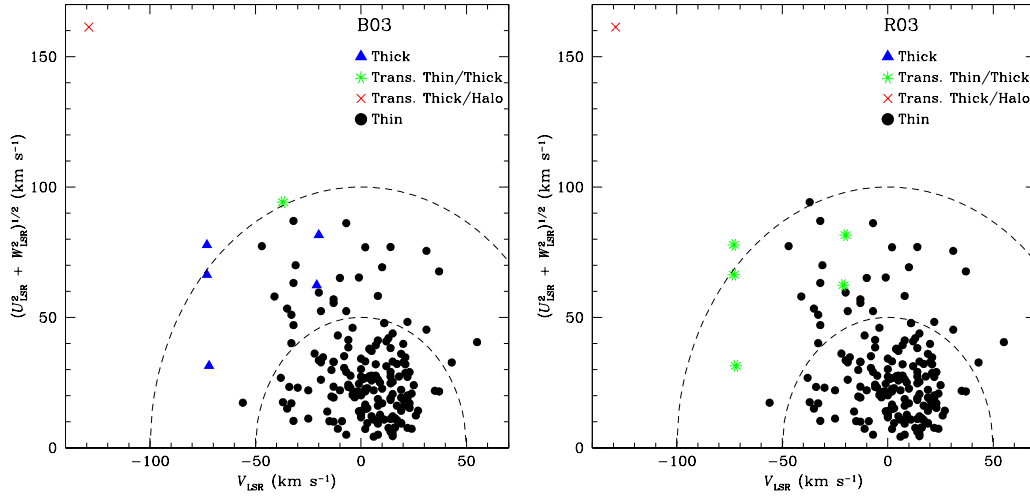


Figure 4.16: Toomre diagram for the entire sample. The *left* and *right* panels show the separation of the stellar groups according to the Bensby et al. [2003, B03] and Robin et al. [2003, R03] prescription, respectively. The symbols are explained in the figure.

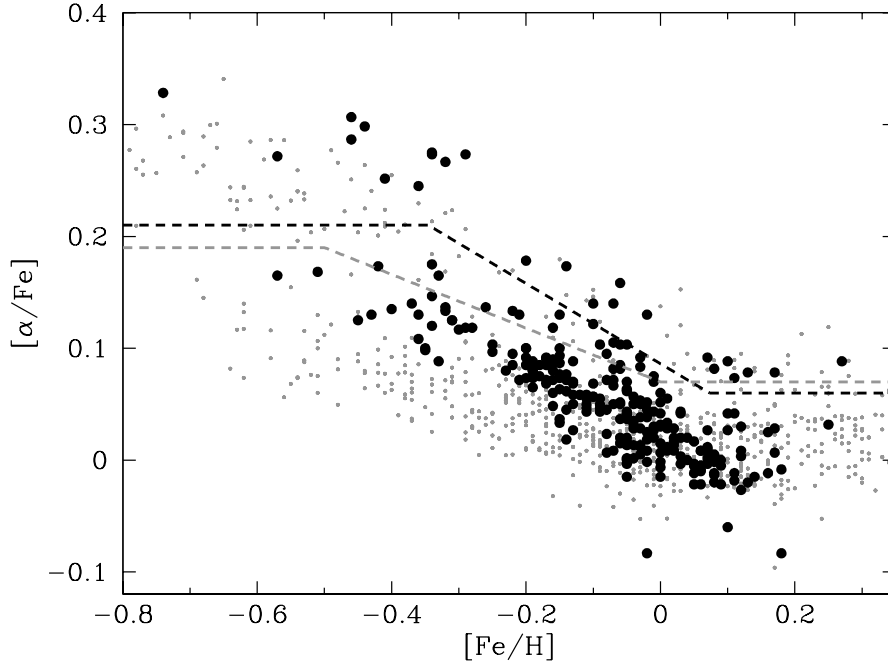


Figure 4.17: $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for the current sample (black dots) and for the stars from Adibekyan et al. [2012b] with $T_{\text{eff}} = T_{\odot} \pm 500 \text{ K}$ (gray small dots). The separation between the thick- and thin-disk stars for the two samples are presented in black and gray dashed lines.

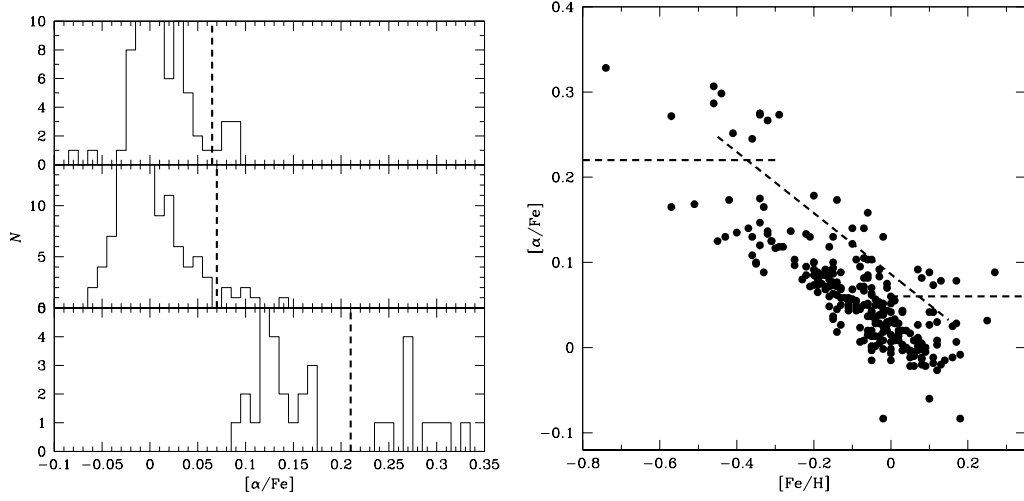


Figure 4.18: High- α and low- α separation histograms for the stars with $[\text{Fe}/\text{H}] < -0.3$ dex (*Left-top*), $-0.3 \leq [\text{Fe}/\text{H}] \leq 0.0$ dex (*left-middle*), and $[\text{Fe}/\text{H}] > 0.0$ dex (*left-bottom*). $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for the whole sample (*right*). The dashed lines are separate stars of the thin and thick disks.

line which separates the high- and low- α stars at $-0.3 \leq [\text{Fe}/\text{H}] \leq 0.0$ dex. The separation lines for each $[\text{Fe}/\text{H}]$ bin presented in Fig. 4.18.

4.4 Metallicity distribution

As mentioned above, several authors tried to understand the reason why the apparent giant-planet-metallicity correlation does not exist for evolved stars. As recently suggested by Mortier et al. [2013b], a possible reason might be a selection bias due to B-V colour cut-off. In Fig. 4.19, we plotted the relation between stellar metallicity and surface gravity for our targets. For comparison, the dwarf stars sample from Adibekyan et al. [2012b] is also presented. From the figure one can easily see that the giant stars sample lacks high metallicity and low-gravity stars, and also low-metallicity and high-gravity stars. This is again probably because of the selection criteria used to define the sample. To avoid the issues related to the selection effects, an unbiased giant sample with no colour cut-off and homogeneously derived parameters is needed to systematically search for planetary companions. However, it is still possible to overcome the effect of the B-V colour cut-off if one considers, for example, only stars in the "cut rectangle" shown in Fig. 4.19 (red rectangle), where the stars are equally distributed. However, these "cut rectangles" will consist of stars with narrower ranges of metallicities (from -0.25 to 0.15 dex in the example of Fig. 4.19), which is also an issue since the giant-planet-metallicity correlation is more pronounced at high metallicities (at least for dwarf stars). In the right panel of Fig. 4.19, we show the metallicity distribution of giant and dwarf stars where narrower $[\text{Fe}/\text{H}]$ distribution of giants is apparent. The figure also shows that the two distributions are peaked at almost solar metallicity. Several studies have already observed this tendency of evolved stars lacking

the metal-rich and very metal-poor tails (e.g., Taylor & Croxall 2005; Takeda et al. 2008; Luck & Heiter 2007; Ghezzi et al. 2010). The stars in this sample have stellar masses between 1.5 and $4.0 M_{\odot}$ (Alves et al. 2015), and hence should be on average younger than the dwarfs from Adibekyan et al. [2012b]. The younger age together with the age-metallicity dispersion relation (e.g., da Silva et al. 2006; Haywood 2008; Casagrande et al. 2011; Maldonado et al. 2013) might explain the narrower $[\text{Fe}/\text{H}]$ distribution of the giants. Young stars are mostly local since they do not have time to migrate within the Galaxy (Wang & Zhao 2013; Minchev et al. 2013). Radial migration in the disk makes the metallicity distribution wider, but does not change the mean abundance (Wang & Zhao 2013), as we see in Fig. 4.19. This is because mostly massive stars contribute to the chemical enrichment of the interstellar medium and they contribute mainly around their birth places because of their very short lifetime. The lack of very metal-rich giants can be understood along the same migration process, while most of the old stars which migrate would come from the inner, metal-rich disk (Wang & Zhao 2013; Minchev et al. 2013). In addition to the aforementioned astrophysical explanation, we would like to note again the selection effects which may arise in evolved star samples due to B-V colour cut-off. This selection bias may also make the metallicity distribution narrower.

4.5 Summary and conclusions

We have carried out a uniform abundance analysis for 12 refractory elements for a sample of 257 field G-, K-type evolved stars that are being surveyed for planets using precise radial-velocity measurements with the CORALIE spectrograph. The abundances were derived using a carefully selected line-list. We found that for all the elements Galactic chemical evolution trends are similar for giant and dwarf stars, while for some species $[\text{X}/\text{Fe}]$ values are shifted towards higher values at a fixed metallicity. Our analysis confirms the overabundance of Na (also Al and Si to a less degree) in giant stars compared to the field FGK dwarf stars from Adibekyan et al. [2012b]. This overabundance probably has a stellar evolutionary character, even though the possible departures from non-LTE may produce an enhancement of a similar degree (Alexeeva et al. 2014). To separate Galactic stellar populations, we applied both a purely kinematical approach and a chemical method. Our chemical separation suggests that 91% of the stars, being α -poor, belong to the thin disk and the remaining 9% of the stars show enhanced α -element abundances at a fixed $[\text{Fe}/\text{H}]$. This sample (while being not very large) also suggests a "gap" in $[\text{Fe}/\text{H}]$ for high- α stars as observed in Adibekyan et al. [2011]. Following the definition of the last authors, 4% of the stars were classified as thick-disk members (being metal-poor) and 5% as HAMR stars. The metallicity distribution of the giant stars is shown to be narrower than that of their non-evolved dwarf counterparts (see also Taylor and Croxall 2005; Takeda et al. 2008), but peaked at almost solar metallicity as in case of the dwarfs. The lack of very metal-rich and metal-poor stars can be explained by the fact that most of the stars are originated in the solar vicinity. Evolved stellar samples mostly consist of massive stars, which have shorter lifetime than the dwarfs, and therefore do not have enough time to migrate from further inner/outer disks (Wang and Zhao 2013; Minchev et al. 2013). Our present sample, as most of the giant star samples searched for planets, is affected by B-V colour cut-off which excludes low-logg stars with high- $[\text{Fe}/\text{H}]$ and high-logg stars with low metallicity. As discussed in Mortier et al. [2013b],

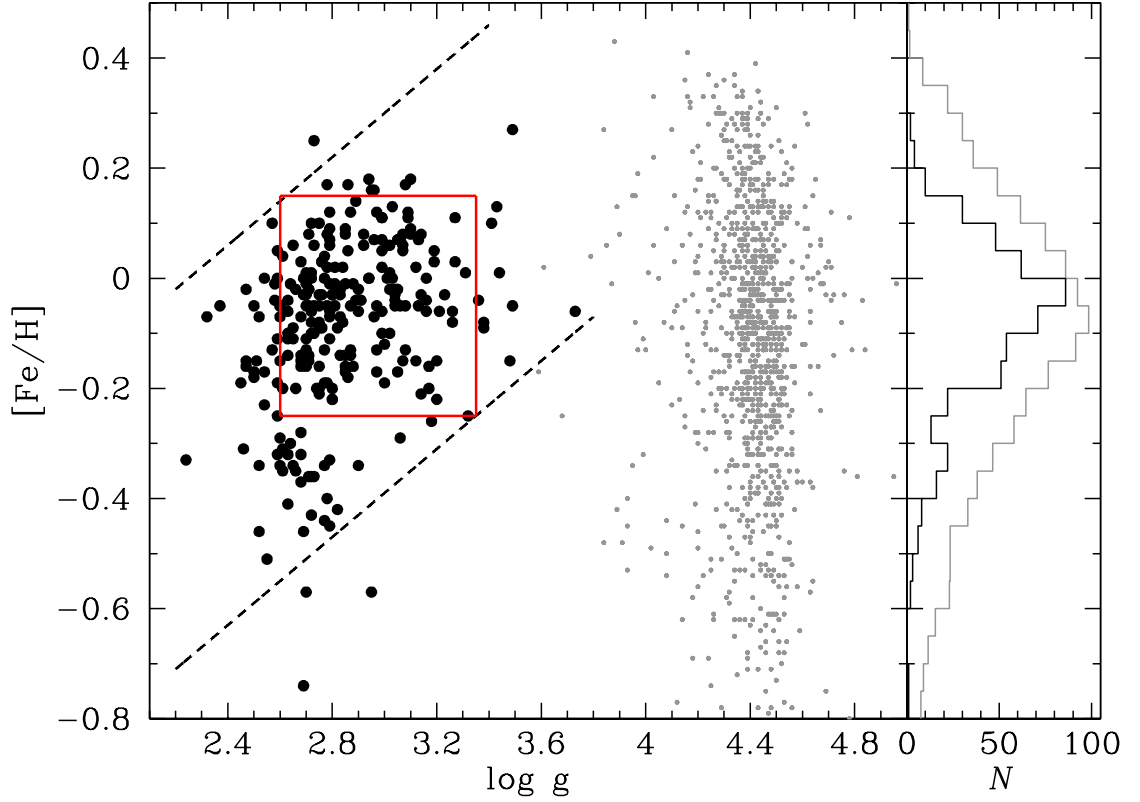


Figure 4.19: *Left panel:* $[\text{Fe}/\text{H}]$ vs. $\log g$ for the current sample (black dots) and for the stars from Adibekyan et al. [2012b] (gray dots). The two black dashed lines were drawn by eye and show the biases in the samples due to the $B - V$ cut-off. *Right panel:* $[\text{Fe}/\text{H}]$ distribution of the two aforementioned samples. The distribution of the giants stars (gray line) was multiplied by 2 for better visual comparison.

this selection bias might be the reason of the absence of the correlation between occurrence of giant planets and stellar metallicity. We suggest to use stars in a "cut-rectangle" in the $\log g$ -[Fe/H] diagram to overcome the aforementioned issue, if an unbiased sample is not available on hand. Although the current sample still contains only one star known to orbit a planetary companion (Setiawan et al. 2005), most of the stars have been already periodically observed over the last years. Before a significant number of planets will be detected, this sample can be used as a homogeneous comparison sample to study planet occurrence around giant stars. However, when exploring chemical peculiarities of planet-hosting giant stars, one should bear in mind the chemical properties of these evolved stars discussed in this thesis (e.g., enhancement in Na, Al, etc.).

We need to improve our knowledge on the planet-giant stars connection. With the arrival of *Gaia* data we will be able to constrain better surface gravity (an important parameter for the derivation of elemental abundances) and will kinematically characterize the stars with higher precision. The determination of very precise parallaxes from *Gaia* for all stars in the sample can improve further its characterization. *Gaia* was launched on December 2013 and the duration of the mission is 5 years. In this period *Gaia* will conduct an astronomical census of one billion stars giving the possibility to build up a picture of the way the Galaxy was born and subsequently evolved, together with the planet formation and evolution.

CHAPTER 5

Summary and Future work

In this chapter we will summarize the most important results and conclusions obtained in this thesis. Finally, we will outline some directions for future work that can be developed.

5.1 Summary

Gaia (launched in December 2013) is the present and the future for high-precision astrometry. In combination with present-day and future extrasolar planet search programs, Gaia will give a crucial contribution to several aspects of planetary systems astrophysics (formation theories, dynamical evolution, etc.) by determining high-accuracy astrometric orbits of giant planets, unbiased across all spectral types of stars up to $d < 200$ pc. To study the exoplanets and how planetary systems form and evolve, we need, not only, to detect and to know the orbital properties of the planet, but also to characterize the host star. In addition to a precise characterization of the planets, it is very important to collect information on their parent stars and having new several thousand of giant planets detections, thanks to Gaia, and, knowing well the properties of the parent stars from the spectroscopy and astrometry, we will be able to investigate their characteristics as a function of stellar mass, metallicity, age, etc.. It is indeed known that the stellar properties influence both frequency and properties of the planets, a fact that has important consequences for the models of planet formation and evolution.

The first part of the PhD project was focused on the development and testing of combinatory tools for the future analysis of Gaia data on extrasolar planets. The combination with radial-velocity (RV) measurements will allow us to derive much improved orbital and physical characteristics of the detected companions. As a matter of fact, the RV technique only allows to determine the minimum mass ($M \sin i$) of an orbiting object, while with astrometry we can measure directly the inclination (i) of orbit. Therefore, combining the two results we can calculate the real mass of the companion. To test our tools, we used the Hipparcos because its IAD (Intermediate Astrometric Data) are unidimensional like the Gaia data, although with typical measurement accuracies in excess of 1-2 milliarcsec. An initial training exercise based on the

combination of astrometry and RVs for two Doppler-detected giant planets around HD134113 and HD219828 failed to provide any significant constraint on the actual mass of the companions, because of the insufficient precision of Hipparcos data for the low expected astrometric signals (Chapter 2).

For this reason, we decided to test the effectiveness of the combination using binary systems. We focused on a sample of 8 metal-poor binaries discovered within the framework of two Doppler searches for planets around metal-poor stars carried out with the Keck/HIRES and HARPS spectrographs. Also in this case, the Hipparcos IAD (we utilized both the old and new reduction) did not give us the possibility to find well-constrained solutions in terms of companion mass. Therefore we decided to apply different statistical methods ($\Delta\mu$ and $\dot{\mu}$ described by Makarov and Kaplan [2005] and $d(RV)/dt$ described by Torres [1999]) using RV and astrometry data to find a range of possible solutions for the mass of the companion and its orbital period. For the examined systems, we concluded that for 3 of them the values for the most likely companion mass are below $0.2 M_{\odot}$. In particular, for 2 of these systems the possible companion at 1σ of confidence level is a brown dwarf. For the other 5 the mass of the companion probably lies in the stellar regime. A particular case is a binary system (CD-436810) with a short orbital period (around 6 years) and with a mass of the companion above $0.28 M_{\odot}$. For this binary we obtained different solution for the two different reductions of the Hipparcos IAD due to the fact that the parallax is 25 % higher with the new one and therefore the companion's perturbation should be more evident. We concluded that the more likely solution is the one obtained with the old reduction of the Hipparcos IAD, pointing to a possible problem in the new reduction for this particular star.

This work was published in Benamati, Sozzetti, Santos et al. 2013, PASP, 125, 1315

The second part of the PhD project was focused on the accurate determination of fundamental parameters of evolved stars that are searched for planets. To derive high precision stellar parameters and elemental abundances around evolved stars, high S/N and resolution spectra are needed since giants have crowded spectra with lots of blended lines. This work can help us to have a deeper understanding of the dependence between metallicity and the properties and occurrence rates of giant planets in evolved stars. We analyzed a sample of giant stars belonging to the CORALIE extrasolar planet search program. We derived precise stellar parameters using an appropriate line-list built for cool stars (< 5200 K), and then we determined the abundances for 12 elements (Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn and V). Our catalog of accurate physical parameters for a sample of 257 giant stars and their chemical composition was compared with results from the literature. We found good agreement with previous works. We found that for all the elements studied Galactic chemical evolution trends are similar for giant and dwarf stars, while for some species $[X/Fe]$ values of giants are shifted towards higher values at a fixed metallicity. Our analysis confirms the overabundance of Na (also Al and Si to a less degree) in giant stars compared to the field FGK dwarf stars from Adibekyan et al. [2012b]. Our homogeneous calculation of spectroscopic parameters and abundances for a set of giant stars that have been already surveyed for planets (and around which only one planet has been found so far) constitutes a solid and useful comparison sample for future analysis.

The work about stellar parameters will be published in Alves, Benamati et al. MNRAS (in press)

2015 and the work about elemental abundances has been submitted for publication to MNRAS (Adibekyan, Benamati, Santos et al. 2015)

5.2 Future work

The research carried out during this PhD project has attempted to address some of the relevant open questions in the extrasolar planet science in connection with the properties of their parent stars. I outline here some of the paths that could be taken to further improve our understanding of these topics, highlighting the strength of the combination of high-precision astrometric and spectroscopic datasets, as done in this thesis.

5.2.1 Exoplanets and brown dwarfs

The multi-technique analysis tools developed in this thesis can be applied systematically for the determination of the actual masses of planets and brown dwarfs with a two-fold approach: a) using RV time series of existing systems in combination with the upcoming Gaia data, and b) combining Gaia data of newly discovered systems with high-precision Doppler follow-up measurements. It will then be possible to characterize with unprecedented detail the mass distribution of giant planetary companions and that of the transition-region between giant planets and brown dwarfs. The Gaia data, in combination with new and existing RV measurements, will also allow to completely characterize the brown dwarf 'desert' (Grether and Lineweaver 2006), and its dependence on the stellar properties such as mass and metallicity helping us to improve our knowledge on the brown dwarf formation (Sozzetti 2014, Ma and Ge 2014).

5.2.2 Giant stars and their companions

The combination of Gaia astrometry and high-resolution, high-precision spectroscopy will also be instrumental to deepen our understanding of the properties and evolution of planetary systems around post-main-sequence stars.

- giant planets around giant stars – improving the statistics.
As discussed in this thesis, we analyzed a huge sample of giant stars belonging to a planet search program, but until now, only one planet has been discovered in this sample. Once a significant number of planets will be found in the present sample, one will be able to analyze the planet frequency as a function of mass and elemental abundance. However, our sample is affected by $B - V$ colour cut-off which excludes low-log g stars with high-[Fe/H] and high-log g stars with low metallicity. This selection bias could be the reason of the absence of the correlation between occurrence of giant planets and stellar metallicity. We can use stars in the "cut-rectangle" in the $\log g - [\text{Fe}/\text{H}]$ diagram to overcome the aforementioned issue, if an unbiased sample is not available on hand.
- trigonometric surface gravity – precise parallaxes from Gaia.
Surface gravity from spectroscopy is constrained with effective temperature and iron abundance and it is a very important stellar parameter also for the determination of other elemental abundances. If the determination of the surface gravity is inaccurate, it can affect

the determination of other stellar atmospheric parameters and also elemental abundances. Spectroscopic surface gravity is not well constrained as demonstrated in Sozzetti et al. [2007] and Mortier et al. [2013b]. Thanks to the very precise parallaxes from Gaia for billion of stars it will be possible to determine the surface gravity with much better precision. After that, fixing the astrometric surface gravity, the other atmospheric parameters and elemental abundances can be derived with high accuracy.

Moreover, in our study, we analyzed α elements and found a "gap" at $[\text{Fe}/\text{H}] \approx -0.3$ dex which divides the family of the high α stars in two: metal-poor high α stars and metal-rich high α stars (h α mr). Unfortunately, in this case, our sample is small and we cannot give a definite conclusion about the existence of this "gap" and about the distinction of the two α -enhanced metal-poor and metal-rich populations.

However, thanks to the Gaia-ESO survey, gathering elemental abundance information for a large stellar sample ($\geq 10^5$) with well-controlled selection functions, we will be able to understand the actual nature of these two populations.

APPENDIX A

Publications, meetings, conferences and communications related to the PhD

MEETINGS, SCHOOLS AND CONFERENCES:

- "Planetary Systems with Gaia: Near and Far" in Porto from 24 November 2011 to 25 November 2011.
- "GREAT School on the Science and Techniques of Gaia" in the Lorentz Center, Leiden, The Netherlands from 23 January 2012 until 27 January 2012. (Talk and poster)
- "Gaia Research for European Astronomy Training GREAT Management Course" in Noordwijk, The Netherlands from 30 January 2012 to 3 February 2012. This course was about the management: how to do plan, to evaluate the risks and to work in group.
- "International School of Astrophysics" in Teramo, Italy from 11 June 2012 until 15 June 2012, about the fundamental Cosmic Distance scale and the Transient Sky. This school was organized by "Francesco Lucchin" and GREAT-ITN project.
- "Planet formation and evolution 2012" in Munich, Germany, on September 3-7 2012. (Poster)
- XXII ENAA in Porto, Portugal, in September. (Poster)
- "Modelling the Milky Way" in Besançon, France, from 15th to 19th October 2012. This school was organized by GREAT-ITN Project.
- "Gaia and Exoplanets: GREAT Synergies on the Horizon" in Turin, Italy, from 5th until 7th November 2012. (Poster)
- "WP4+WP5 meeting" in Lund, Sweden, on November 21-22 2012. (Talk)
- "GREAT-ITN Mid-Term Review" in Bordeaux, France, 4-5 December 2012. (Talk)

- WP5 progress meeting (skyconference): "Gaia and the search for other planets: combining astrometry and RV". (Talk)
- "EWASS 2014" in Geneve, Switzerland, 30 June - 4 July 2014. (Talk)
- "GREAT-ITN Full meeting" in Geneve, Switzerland, 3 July 2014. (Talk)
- "The Milky Way Unravelling by Gaia" in Barcelona, Spain, 1-5 December 2014. (Talk)

PUBLICATIONS:

- **L. Benamati**, A. Sozzetti, N. C. Santos, and D. W. Latham, November 2013, A Combined Astrometric and Spectroscopic Study of Metal-Poor Binaries, PASP, Vol. 125, No. 933, pp. 1315-1328 DOI: 10.1086/674147
- N. C. Santos, A. Mortier, J. P. S. Faria, X. Dumusque, V. Zh. Adibekyan, E. Delgado Mena, P. Figueira, **L. Benamati** et al. 2014, The HARPS search for southern extra-solar planets. XXXV. The interesting case of HD41248: stellar activity, no planets?, Astronomy and Astrophysics DOI: 10.1051/0004-6361/201423808
- S. Alves, **L. Benamati**, N. C. Santos, V. Zh. Adibekyan, S.G. Sousa et al., Determination of the spectroscopic stellar parameters for 257 field giant stars, 2015, MNRAS to appear
- V. Zh. Adibekyan, **L. Benamati**, N. C. Santos, S. Alves et al., Chemical abundances and kinematics of 256 G-, K-type field giants. Setting a base for further analysis of giant-planets properties orbiting evolved stars., 2015, submitted.
- **L. Benamati**, V. Zh. Adibekyan, N. C. Santos, A. Sozzetti, Exoplanets: Gaia and the importance of ground based spectroscopy follow-up, 2015, EAS Publications Series to appear, arXiv:1502.00806

APPENDIX B

HIRES, HARPS, CfA DS and TRES data for the binary stars

Table B.1: HARPS, CfA and TRES radial velocity measurements.

BJD - 2400000	Radial Velocity (km s^{-1})	σ (km s^{-1})
CD-436810 (HARPS)		
53016.845925	166.40259	0.00314
53052.734014	166.61746	0.00304
53056.775907	166.63784	0.00240
53064.792500	166.68113	0.00273
53490.601963	165.23422	0.00248
53491.671209	165.22884	0.00253
53492.558667	165.22192	0.00165
53573.459353	164.42581	0.00357
54173.743325	156.14358	0.00221
HD16784 (HARPS)		
52944.692538	30.56387	0.00297
53206.921719	36.76851	0.00092
53216.891256	38.99693	0.00093
G27-44 (HIRES)		
50668.01562	0.0315	0.0073
Continued on next page		

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s ⁻¹)	σ (km s ⁻¹)
50670.01562	0.0322	0.0089
51008.06641	0.0414	0.0037
51038.98438	0.0229	0.0075
51545.72266	0.0266	0.0145
53162.06250	0.0	0.0064
53569.00781	-0.0801	0.0084
53952.08984	-0.0747	0.0107

G27-44 (CfA DS)

45934.6884	-34.23	0.31
45958.5819	-33.92	0.44
46282.7861	-33.71	0.29
46339.7367	-33.26	0.25
46659.6928	-33.57	0.54
47007.8692	-33.45	0.49
47375.8000	-34.13	0.58
47694.9712	-33.61	0.26
48082.8128	-33.75	0.49
48143.6573	-33.60	0.51
48435.8309	-32.90	0.68
48900.6157	-34.20	0.42
49908.8241	-34.18	0.45
50739.6310	-34.29	0.36
50742.6880	-33.43	0.22
50755.6097	-33.86	0.28

G63-5 (HIRES)

50864.03514	-0.0529	0.0142
50866.00624	-0.0480	0.0118
51007.80053	-0.0284	0.0090
51548.09345	-0.0096	0.0077
53161.89205	0.0389	0.0067
53191.82188	0.0376	0.0042
53568.77818	0.0625	0.0128

G63-5 (CfA DS)

Continued on next page

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s⁻¹)	σ (km s⁻¹)
45037.9649	5.88	0.17
45717.8215	5.64	0.24
45860.6643	5.08	0.18
46509.8467	5.92	0.27
46843.8410	5.84	0.19
47201.9465	5.82	0.31
47549.9644	5.92	0.20
47963.8947	5.04	0.37
48371.6681	5.91	0.51

G237-84 (HIRES)

51291.99768	-0.0776	0.0106
51293.96887	-0.0890	0.0146
51547.17281	-0.0534	0.0110
52679.05301	0.0261	0.0126
52680.04800	0.0224	0.0119
52811.76697	0.0167	0.0107
53161.78931	0.0386	0.0104
53191.73366	0.0426	0.0089
53568.74194	0.0735	0.0128

G237-84 (CfA DS)

45772.7879	9.78	0.18
45833.8371	8.09	0.61
45886.6972	7.08	0.21
46107.9933	9.11	0.17
46577.6817	9.13	0.29
46953.6721	10.48	0.31
46986.6346	9.44	0.25
47134.9914	10.13	0.37
47159.0571	8.99	0.23
47556.0699	8.81	0.22
47575.0687	8.68	0.21
47602.7910	8.64	0.17
47604.8590	8.81	0.22
47629.8029	9.04	0.23
48288.9797	9.24	0.23

Continued on next page

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s⁻¹)	σ (km s⁻¹)
48605.0531	9.09	0.22
49056.9222	9.05	0.38
54574.7592	9.88	0.43
54608.7376	9.74	0.40
54844.9614	10.67	0.25
54901.8969	9.88	0.50
54929.7681	10.11	0.40
55198.9976	9.51	0.30
55284.8971	9.82	0.20
G237-84 (TRES)		
55311.8115	9.69	0.10
55340.6311	9.72	0.10
55584.0480	9.74	0.10
55666.8658	9.79	0.10
55668.7458	9.76	0.10
HD7424 (HIRES)		
53192.10039	0.2411	0.0064
53209.12624	0.2252	0.0037
53210.11312	0.2249	0.0076
53569.11138	-0.1807	0.0085
53570.10677	-0.1781	0.0060
53684.76920	-0.3324	0.0078
HD7424 (CfA DS)		
45722.6160	83.94	0.44
45960.7864	85.79	0.97
46673.7901	84.93	0.78
47018.8042	84.78	0.77
47431.9151	85.65	0.38
47780.7328	84.57	0.68
48856.8328	84.80	0.53
50711.8584	84.65	0.38
50742.7854	85.04	0.27
50744.7392	84.83	0.22
Continued on next page		

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s ⁻¹)	σ (km s ⁻¹)
HD7424 (TRES)		
55242.5827	84.56	0.10
HD192718 (HIRES)		
51398.90265	0.5880	0.0080
51400.91461	0.5845	0.0119
52811.92588	0.0351	0.0110
52854.93152	0.0224	0.0086
52920.82402	-0.0128	0.0098
53162.04705	-0.1017	0.0085
53191.93307	-0.1096	0.0134
53208.94383	-0.1114	0.0095
53568.96500	-0.2887	0.0132
53569.97918	-0.2952	0.0103
53684.69217	-0.3106	0.0086
HD192718 (CfA DS)		
48220.4871	-111.18	0.69
48405.8449	-110.87	0.67
48415.8438	-110.87	0.73
48433.7621	-110.96	0.84
51395.7013	-110.68	0.72
53192.9203	-112.11	0.34
HD192718 (TRES)		
56087.9710	-112.73	0.10
56134.8973	-112.71	0.10
56260.5529	-112.81	0.10
G135-46 (HIRES)		
52678.12921	-0.2133	0.0066
52679.09727	-0.2103	0.0078
Continued on next page		

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s ⁻¹)	σ (km s ⁻¹)
52680.08853	-0.2124	0.0063
52811.80232	-0.1416	0.0041
53161.81140	0.0724	0.0060
53191.82815	0.0921	0.0049
53206.74503	0.0866	0.0063
53568.79557	0.2629	0.0063
53569.77774	0.2636	0.0055
G135-46 (CfA DS)		
46928.8399	-48.63	0.66
47174.9539	-49.67	0.64
47187.9622	-48.32	0.91
47225.0309	-49.35	0.60
47634.8100	-48.14	0.47
48374.7499	-49.87	0.60
49115.8432	-48.81	0.52
49470.8184	-48.88	0.46
49478.7951	-47.86	0.46
50093.9574	-47.86	0.46
53190.6938	-46.05	0.27
53216.6161	-46.05	0.68
53251.5128	-45.66	0.47
53343.9478	-45.91	0.59
53399.9381	-45.55	0.52
53434.8018	-46.58	0.39
53480.7413	-44.96	0.42
53513.8344	-45.91	0.39
53812.9219	-45.49	0.54
53871.8073	-45.73	0.24
54134.0428	-45.05	0.34
54160.0345	-44.93	0.36
54193.8909	-46.15	0.32
54219.8339	-45.52	0.31
54485.0612	-45.06	0.46
54548.9753	-45.40	0.43
54575.8548	-45.85	0.42
54575.9277	-45.65	0.48
54605.7664	-45.78	0.40
54632.7114	-45.37	0.40
Continued on next page		

Table B.1 – continued from previous page

BJD - 2400000	Radial Velocity (km s⁻¹)	σ (km s⁻¹)
54843.0356	-45.08	0.38
54929.8908	-46.01	0.61
54930.9282	-45.00	0.62
54961.8243	-45.76	0.36
55251.9779	-44.62	0.60
55284.9205	-45.36	0.30
55731.7849	-45.42	0.20
G135-46 (TRES)		
55200.0496	-45.19	0.10
55308.9105	-45.09	0.10
55344.7601	-45.29	0.10
55577.0259	-45.36	0.10
55665.8452	-45.40	0.10
55692.7503	-45.35	0.10
55960.0303	-45.84	0.10
55990.9158	-45.88	0.10
56024.8898	-45.91	0.10
56047.8309	-45.96	0.10
56089.6405	-45.95	0.10
56140.6684	-46.08	0.10
56288.0453	-46.21	0.10
56309.0569	-46.42	0.10
56348.0213	-46.35	0.10
56377.8662	-46.51	0.10

APPENDIX C

Table for giant stars analysis

Table C.1: List of the *rejt* parameters used for each stars.

Star	<i>rejt</i>
HD111295	0.985
HD120457	0.985
HD131376	0.985
HD160819	0.985
HD182893	0.985
HD213009	0.985
HD55151	0.985
HD55865	0.985
HD87896	0.985
HD101162	0.990
HD104704	0.990
HD116243	0.990
HD121853	0.990
HD127195	0.990
HD129462	0.990
HD132905	0.990
HD159558	0.990
HD160720	0.990
HD166063	0.990
HD207229	0.990
HD207883	0.990
HD210056	0.990
HD215682	0.990
HD56478	0.990
HD60060	0.990
HD61904	0.990
HD96566	0.990
HD100708	0.991
HD106572	0.991
HD110829	0.991
HD113778	0.991
HD114474	0.991
HD118338	0.991
HD119250	0.991
HD123151	0.991
HD125136	0.991
HD129893	0.991
HD133921	0.991
HD135760	0.991
Continued on next page	

Table C.1 – continued from previous page

Star	<i>re jt</i>
HD136672	0.991
HD139521	0.991
HD139980	0.991
HD140329	0.991
HD140861	0.991
HD148890	0.991
HD161814	0.991
HD166599	0.991
HD172875	0.991
HD174295	0.991
HD175145	0.991
HD175219	0.991
HD175401	0.991
HD177389	0.991
HD179433	0.991
HD181517	0.991
HD185075	0.991
HD189080	0.991
HD195569	0.991
HD198232	0.991
HD201852	0.991
HD208285	0.991
HD208737	0.991
HD210622	0.991
HD216210	0.991
HD30790	0.991
HD32436	0.991
HD32453	0.991
HD33285	0.991
HD3488	0.991
HD39720	0.991
HD41451	0.991
HD58540	0.991
HD59219	0.991
HD59894	0.991
HD60574	0.991
HD73468	0.991
HD770	0.991
HD84698	0.991
HD97344	0.991
Continued on next page	

Table C.1 – continued from previous page

Star	<i>re jt</i>
HD98732	0.991
HD10142	0.992
HD115310	0.992
HD11977	0.992
HD12055	0.992
HD12296	0.992
HD123569	0.992
HD12438	0.992
HD130650	0.992
HD136014	0.992
HD141832	0.992
HD14247	0.992
HD143009	0.992
HD143546	0.992
HD145621	0.992
HD146686	0.992
HD146690	0.992
HD14703	0.992
HD155276	0.992
HD157515	0.992
HD165135	0.992
HD165634	0.992
HD166949	0.992
HD168838	0.992
HD169767	0.992
HD169836	0.992
HD172211	0.992
HD173378	0.992
HD173540	0.992
HD1737	0.992
HD177222	0.992
HD18448	0.992
HD189005	0.992
HD189195	0.992
HD196171	0.992
HD19940	0.992
HD199951	0.992
HD21011	0.992
HD212953	0.992
HD214462	0.992
Continued on next page	

Table C.1 – continued from previous page

Star	<i>re jt</i>
HD215104	0.992
HD216742	0.992
HD216763	0.992
HD219507	0.992
HD219572	0.992
HD220790	0.992
HD221323	0.992
HD222433	0.992
HD223647	0.992
HD22366	0.992
HD223700	0.992
HD22382	0.992
HD224362	0.992
HD22532	0.992
HD22676	0.992
HD23549	0.992
HD23670	0.992
HD28093	0.992
HD28732	0.992
HD29085	0.992
HD29291	0.992
HD29399	0.992
HD29751	0.992
HD30185	0.992
HD34172	0.992
HD34266	0.992
HD34642	0.992
HD36189	0.992
HD37811	0.992
HD39640	0.992
HD40409	0.992
HD44880	0.992
HD44956	0.992
HD45145	0.992
HD45158	0.992
HD45553	0.992
HD46116	0.992
HD46262	0.992
HD46727	0.992
HD47001	0.992
Continued on next page	

Table C.1 – continued from previous page

Star	<i>re jt</i>
HD4737	0.992
HD47910	0.992
HD496	0.992
HD49947	0.992
HD51211	0.992
HD5457	0.992
HD55964	0.992
HD6080	0.992
HD6192	0.992
HD6245	0.992
HD636	0.992
HD63948	0.992
HD65638	0.992
HD67762	0.992
HD6793	0.992
HD67977	0.992
HD67990	0.992
HD69674	0.992
HD7082	0.992
HD70982	0.992
HD73887	0.992
HD73898	0.992
HD74006	0.992
HD75168	0.992
HD75451	0.992
HD77580	0.992
HD78883	0.992
HD79091	0.992
HD79846	0.992
HD80171	0.992
HD80934	0.992
HD81101	0.992
HD81136	0.992
HD83380	0.992
HD83465	0.992
HD85154	0.992
HD85250	0.992
HD85396	0.992
HD85612	0.992
HD8651	0.992
Continued on next page	

Table C.1 – continued from previous page

Star	<i>re jt</i>
HD87540	0.992
HD87627	0.992
HD88836	0.992
HD89015	0.992
HD90074	0.992
HD90317	0.992
HD90980	0.992
HD91437	0.992
HD9163	0.992
HD93410	0.992
HD9362	0.992
HD93773	0.992
HD94510	0.992
HD94890	0.992
HD9525	0.992
HD103462	0.993
HD13263	0.993
HD134505	0.993
HD14832	0.993
HD15414	0.993
HD156854	0.993
HD163652	0.993
HD16975	0.993
HD169916	0.993
HD17324	0.993
HD17374	0.993
HD17504	0.993
HD17652	0.993
HD17715	0.993
HD18023	0.993
HD18121	0.993
HD18292	0.993
HD18650	0.993
HD21430	0.993
HD23719	0.993
HD23931	0.993
HD23940	0.993
HD24160	0.993
HD29930	0.993
HD47973	0.993
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Table C.1 – continued from previous page

Star	<i>re_{jt}</i>
HD48758	0.993
HD64121	0.993
HD69123	0.993
HD69879	0.993
HD74772	0.993
HD81169	0.993
HD88323	0.993
HD12431	0.994
HD16815	0.994
HD62034	0.994
HD13940	0.995
HD87816	0.995
HD60666	0.996
HD61642	0.996
HD62412	0.996
HD62943	0.996
HD63295	0.996
HD63744	0.996

Table C.2: Stellar parameters determined from the iron lines by using HM07, SO08, and TS13 line-lists. The adopted parameters in our work is the one derived with the TS13 line-list.

HD number	HM07 line-list				SO08 line-list				TS13 line-list			
	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)
496	4881 ± 225	2.78 ± 0.45	1.21 ± 0.20	0.05 ± 0.18	4900 ± 39	2.79 ± 0.07	1.52 ± 0.04	-0.03 ± 0.03	4854 ± 40	2.75 ± 0.10	1.46 ± 0.04	-0.03 ± 0.03
636	4784 ± 202	2.86 ± 0.41	1.26 ± 0.20	0.24 ± 0.31	4903 ± 46	2.87 ± 0.09	1.50 ± 0.04	0.13 ± 0.03	4840 ± 43	2.75 ± 0.11	1.46 ± 0.04	0.10 ± 0.03
770	4800 ± 208	2.66 ± 0.42	1.25 ± 0.20	-0.03 ± 0.32	4841 ± 35	2.59 ± 0.07	1.57 ± 0.05	-0.13 ± 0.03	4771 ± 45	2.47 ± 0.10	1.50 ± 0.04	-0.16 ± 0.03
1737	4797 ± 203	2.36 ± 0.42	1.25 ± 0.20	0.13 ± 0.51	4998 ± 47	2.75 ± 0.08	1.57 ± 0.05	0.13 ± 0.04	4932 ± 50	2.57 ± 0.12	1.54 ± 0.05	0.10 ± 0.04
3488	4869 ± 63	2.87 ± 0.11	1.56 ± 0.09	-0.08 ± 0.06	4935 ± 30	2.83 ± 0.06	1.50 ± 0.03	-0.08 ± 0.03	4880 ± 34	2.72 ± 0.08	1.44 ± 0.04	-0.10 ± 0.03
4737	5146 ± 61	3.09 ± 0.09	1.14 ± 0.09	0.05 ± 0.06	5217 ± 26	3.20 ± 0.07	1.33 ± 0.03	0.01 ± 0.02	5199 ± 30	3.03 ± 0.10	1.34 ± 0.03	0.00 ± 0.03
5457	4682 ± 90	2.85 ± 0.18	1.36 ± 0.10	-0.02 ± 0.07	4718 ± 44	2.78 ± 0.09	1.36 ± 0.04	-0.05 ± 0.03	4706 ± 46	2.78 ± 0.10	1.36 ± 0.05	-0.05 ± 0.03
6080	5034 ± 70	3.43 ± 0.11	1.18 ± 0.10	-0.08 ± 0.06	5118 ± 25	3.46 ± 0.04	1.12 ± 0.03	-0.07 ± 0.02	5084 ± 24	3.38 ± 0.05	1.14 ± 0.03	-0.09 ± 0.02
6192	4995 ± 102	2.87 ± 0.16	1.51 ± 0.14	-0.04 ± 0.10	5124 ± 32	3.05 ± 0.07	1.45 ± 0.03	0.04 ± 0.03	5122 ± 26	2.99 ± 0.11	1.42 ± 0.03	0.05 ± 0.02
6245	5115 ± 62	3.21 ± 0.09	1.25 ± 0.09	0.04 ± 0.06	5179 ± 23	3.16 ± 0.05	1.33 ± 0.03	0.02 ± 0.02	5163 ± 26	3.12 ± 0.07	1.28 ± 0.03	0.02 ± 0.03
6793†	5178 ± 74	3.15 ± 0.13	1.41 ± 0.13	-0.02 ± 0.08	5367 ± 33	3.49 ± 0.10	1.70 ± 0.04	0.03 ± 0.03	5330 ± 42	3.27 ± 0.11	1.55 ± 0.04	0.03 ± 0.04
7082	4979 ± 93	2.75 ± 0.09	1.75 ± 0.44	-0.76 ± 0.11	5047 ± 18	2.70 ± 0.04	1.70 ± 0.03	-0.75 ± 0.02	5048 ± 21	2.69 ± 0.09	1.67 ± 0.04	-0.74 ± 0.02
8651	4739 ± 203	2.61 ± 0.41	1.28 ± 0.20	-0.11 ± 0.06	4798 ± 37	2.64 ± 0.07	1.58 ± 0.03	-0.19 ± 0.03	4763 ± 42	2.66 ± 0.11	1.56 ± 0.04	-0.20 ± 0.03
9163	4865 ± 59	3.20 ± 0.11	1.13 ± 0.08	-0.12 ± 0.04	4930 ± 27	3.18 ± 0.05	1.16 ± 0.03	-0.14 ± 0.02	4898 ± 29	3.12 ± 0.07	1.14 ± 0.03	-0.15 ± 0.02
9362	4824 ± 66	2.59 ± 0.11	1.46 ± 0.11	-0.30 ± 0.07	4895 ± 26	2.64 ± 0.04	1.50 ± 0.03	-0.28 ± 0.02	4885 ± 32	2.60 ± 0.07	1.49 ± 0.03	-0.29 ± 0.03
9525	4764 ± 214	3.08 ± 0.43	1.27 ± 0.20	0.12 ± 0.50	4808 ± 48	2.88 ± 0.09	1.42 ± 0.05	0.00 ± 0.03	4725 ± 70	2.71 ± 0.16	1.33 ± 0.07	-0.02 ± 0.04
10142	4727 ± 67	2.57 ± 0.13	1.51 ± 0.08	-0.14 ± 0.05	4815 ± 45	2.61 ± 0.09	1.53 ± 0.05	-0.11 ± 0.04	4755 ± 34	2.47 ± 0.09	1.50 ± 0.04	-0.15 ± 0.03
11977	4968 ± 98	2.88 ± 0.16	1.62 ± 0.17	-0.19 ± 0.10	5054 ± 21	2.90 ± 0.04	1.46 ± 0.02	-0.15 ± 0.02	5018 ± 27	2.85 ± 0.07	1.44 ± 0.03	-0.17 ± 0.03
12055†	5118 ± 204	2.84 ± 0.41	1.09 ± 0.20	-0.04 ± 0.63	5265 ± 30	3.11 ± 0.07	1.54 ± 0.03	-0.02 ± 0.03	5255 ± 27	3.04 ± 0.15	1.45 ± 0.03	-0.02 ± 0.02
12296	4751 ± 57	2.76 ± 0.12	1.49 ± 0.07	0.01 ± 0.05	4811 ± 32	2.65 ± 0.06	1.53 ± 0.03	0.00 ± 0.02	4787 ± 33	2.60 ± 0.09	1.51 ± 0.03	-0.05 ± 0.03
12431	4997 ± 71	2.90 ± 0.14	1.35 ± 0.10	0.04 ± 0.07	5049 ± 30	2.93 ± 0.06	1.43 ± 0.03	0.00 ± 0.02	5010 ± 36	2.83 ± 0.09	1.43 ± 0.04	-0.03 ± 0.03
12438	4956 ± 77	2.58 ± 0.09	1.70 ± 0.24	-0.62 ± 0.08	5050 ± 14	2.69 ± 0.04	1.64 ± 0.02	-0.57 ± 0.01	5056 ± 20	2.70 ± 0.04	1.66 ± 0.03	-0.57 ± 0.02
13263	5098 ± 67	3.06 ± 0.10	1.39 ± 0.12	-0.06 ± 0.07	5181 ± 21	3.09 ± 0.04	1.36 ± 0.02	-0.04 ± 0.02	5173 ± 25	3.08 ± 0.07	1.38 ± 0.03	-0.05 ± 0.02
13940	4996 ± 65	3.02 ± 0.11	1.35 ± 0.10	0.02 ± 0.06	5050 ± 25	2.99 ± 0.04	1.43 ± 0.03	0.00 ± 0.02	5017 ± 32	2.90 ± 0.07	1.43 ± 0.03	-0.02 ± 0.03
14247	4840 ± 55	3.12 ± 0.10	1.28 ± 0.07	-0.13 ± 0.05	4895 ± 28	3.05 ± 0.05	1.24 ± 0.03	-0.15 ± 0.02	4857 ± 30	2.97 ± 0.06	1.22 ± 0.03	-0.17 ± 0.03
14703	4966 ± 204	2.91 ± 0.42	1.17 ± 0.20	0.15 ± 0.43	5100 ± 25	3.13 ± 0.06	1.37 ± 0.03	0.12 ± 0.02	5058 ± 33	3.10 ± 0.10	1.38 ± 0.04	0.09 ± 0.03
14832	4826 ± 70	2.70 ± 0.13	1.50 ± 0.09	-0.23 ± 0.07	4890 ± 26	2.66 ± 0.05	1.50 ± 0.03	-0.23 ± 0.02	4862 ± 28	2.59 ± 0.06	1.48 ± 0.03	-0.25 ± 0.02
15414	4756 ± 60	3.21 ± 0.12	1.08 ± 0.07	-0.02 ± 0.04	4843 ± 34	3.23 ± 0.07	1.14 ± 0.04	-0.06 ± 0.02	4803 ± 39	3.21 ± 0.10	1.07 ± 0.05	-0.06 ± 0.03
16815	4739 ± 57	2.74 ± 0.11	1.33 ± 0.08	-0.32 ± 0.05	4794 ± 24	2.69 ± 0.06	1.35 ± 0.03	-0.34 ± 0.02	4777 ± 27	2.65 ± 0.10	1.33 ± 0.03	-0.34 ± 0.02
16975	5065 ± 201	2.88 ± 0.43	1.12 ± 0.20	0.15 ± 0.851	5162 ± 24	3.02 ± 0.04	1.41 ± 0.02	0.07 ± 0.02	5159 ± 25	3.05 ± 0.08	1.43 ± 0.03	0.07 ± 0.02
17324	4868 ± 68	3.15 ± 0.11	1.25 ± 0.10	-0.15 ± 0.05	4916 ± 27	3.11 ± 0.05	1.18 ± 0.03	-0.16 ± 0.02	4902 ± 30	3.05 ± 0.07	1.19 ± 0.03	-0.17 ± 0.02
17374	4881 ± 64	2.85 ± 0.11	1.37 ± 0.09	-0.02 ± 0.06	4923 ± 25	2.77 ± 0.04	1.47 ± 0.03	-0.08 ± 0.02	4899 ± 28	2.75 ± 0.06	1.45 ± 0.03	-0.09 ± 0.02
17504	4910 ± 57	3.20 ± 0.09	1.19 ± 0.09	-0.25 ± 0.05	4962 ± 21	3.18 ± 0.03	1.16 ± 0.02	-0.26 ± 0.02	4961 ± 24	3.18 ± 0.05	1.16 ± 0.03	-0.26 ± 0.02
17652	4820 ± 63	2.66 ± 0.10	1.51 ± 0.10	-0.30 ± 0.06	4868 ± 23	2.62 ± 0.05	1.51 ± 0.02	-0.32 ± 0.02	4872 ± 27	2.59 ± 0.06	1.51 ± 0.03	-0.32 ± 0.03
17715	4842 ± 56	2.67 ± 0.10	1.43 ± 0.07	-0.06 ± 0.05	4961 ± 33	2.83 ± 0.06	1.50 ± 0.03	-0.01 ± 0.03	4920 ± 31	2.69 ± 0.08	1.46 ± 0.03	-0.03 ± 0.03
18023	4686 ± 208	2.72 ± 0.42	1.31 ± 0.20	-0.30 ± 0.15	4770 ± 28	2.73 ± 0.07	1.29 ± 0.03	-0.28 ± 0.02	4740 ± 28	2.61 ± 0.12	1.28 ± 0.03	-0.31 ± 0.02
18121	4761 ± 63	2.62 ± 0.12	1.34 ± 0.08	-0.10 ± 0.06	4837 ± 37	2.65 ± 0.07	1.43 ± 0.04	-0.14 ± 0.03	4792 ± 43	2.54 ± 0.09	1.42 ± 0.04	-0.17 ± 0.03
18292	4818 ± 206	2.69 ± 0.41	1.24 ± 0.20	0.13 ± 0.40	5004 ± 34	2.94 ± 0.08	1.47 ± 0.04	0.13 ± 0.03	4930 ± 43	2.85 ± 0.10	1.45 ± 0.04	0.09 ± 0.03
18448	4724 ± 72	2.59 ± 0.13	1.50 ± 0.10	-0.31 ± 0.07	4791 ± 30	2.62 ± 0.08	1.60 ± 0.03	-0.33 ± 0.03	4756 ± 32	2.60 ± 0.09	1.54 ± 0.04	-0.34 ± 0.03
18650	4745 ± 206	2.62 ± 0.41	1.28 ± 0.20	0.15 ± 0.57	4912 ± 43	2.86 ± 0.08	1.47 ± 0.04	0.12 ± 0.03	4823 ± 35	2.65 ± 0.09	1.47 ± 0.04	0.06 ± 0.03
19940	4804 ± 218	2.95 ± 0.44	1.25 ± 0.20	-0.02 ± 0.56	4905 ± 38	2.97 ± 0.06	1.32 ± 0.04	-0.05 ± 0.03	4854 ± 41	2.90 ± 0.09	1.28 ± 0.04	-0.06 ± 0.03
21011	4885 ± 80	2.85 ± 0.13	1.39 ± 0.10	-0.04 ± 0.07	4972 ± 30	2.89 ± 0.05	1.47 ± 0.03	-0.06 ± 0.03	4934 ± 33	2.82 ± 0.07	1.46 ± 0.04	-0.09 ± 0.03
21430	4919 ± 72	2.61 ± 0.10	1.42 ± 0.14	-0.36 ± 0.07	4983 ± 18	2.67 ± 0.04	1.48 ± 0.02	-0.36 ± 0.02	4987 ± 21	2.66 ± 0.06	1.49 ± 0.03	-0.35 ± 0.02
22366	4678 ± 65	2.68 ± 0.12	1.40 ± 0.08	-0.36 ± 0.05	4740 ± 22	2.67 ± 0.04	1.35 ± 0.02	-0.37 ± 0.02	4751 ± 27	2.68 ± 0.06	1.36 ± 0.03	-0.37 ± 0.02
22382	4809 ± 215	2.72 ± 0.43	1.25 ± 0.20	0.10 ± 0.53	4920 ± 35	2.90 ± 0.07	1.49 ± 0.03	0.07 ± 0.03	4834 ± 38	2.72 ± 0.09	1.51 ± 0.04	0.01 ± 0.03
22532	4996 ± 73	3.22 ± 0.12	1.16 ± 0.12	-0.20 ± 0.07	5061 ± 18	3.22 ± 0.04	1.19 ± 0.02	-0.22 ± 0.02	5047 ± 19	3.20 ± 0.06	1.19 ± 0.02	-0.22 ± 0.02
22676	5045 ± 309	3.01 ± 0.62	1.13 ± 0.20	0.12 ± 0.22	5147 ± 32	3.11 ± 0.08	1.47 ± 0.04	0.06 ± 0.03	5109 ± 36	3.01 ± 0.09	1.40 ± 0.04	0.06 ± 0.03
23549	4885 ± 204	2.88 ± 0.41	1.21 ± 0.20	0.27 ± 0.20	5038 ± 33	2.99 ± 0.07	1.51 ± 0.03	0.18 ± 0.03	4992 ± 39	2.96 ± 0.10	1.48 ± 0.04	0.16 ± 0.03
23670	4877 ± 215	2.71 ± 0.45	1.21 ± 0.20	-0.06 ± 0.24	4883 ± 27	2.68 ± 0.05	1.48 ± 0.03	-0.16 ± 0.02	4884 ± 30	2.68 ± 0.07	1.48 ± 0.03	-0.16 ± 0.03
23719	4945 ± 206	2.63 ± 0.44	1.18 ± 0.20	0.17 ± 0.14	5103 ± 34	2.95 ± 0.05	1.52 ± 0.03	0.13 ± 0.03	5061 ± 31	2.87 ± 0.08	1.50 ± 0.03	0.12 ± 0.03
23931	4811 ± 207	2.75 ± 0.42	1.25 ± 0.20	0.01 ± 0.32	4853 ± 35	2.73 ± 0.07	1.48 ± 0.04	-0.08 ± 0.03	4785 ± 33	2.63 ± 0.09	1.47 ± 0.03	-0.11 ± 0.03
23940	4795 ± 60	2.57 ± 0.10	1.49 ± 0.11	-0.38 ± 0.06	4917 ± 24	2.59 ± 0.13	1.56 ± 0.03	-0.33 ± 0.02	4939 ± 26	2.52 ± 0.30	1.57 ± 0.03	-0.34 ± 0.03
24160	5047 ± 61	2.78 ± 0.10	1.37 ± 0.10	0.08 ± 0.07	5153 ± 25	2.94 ± 0.06	1.52 ± 0.03	0.08 ± 0.02	5136 ± 26	2.85 ± 0.08	1.53 ± 0.03	0.08 ± 0.02

Table C.2: continued.

HD number	HM07 line-list			SO08 line-list			TS13 line-list					
	T_{eff} (K)	$\log g$ (cm s $^{-2}$)	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s $^{-2}$)	ξ (km s $^{-1}$)	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s $^{-2}$)	ξ (km s $^{-1}$)	[Fe/H] (dex)	
64121	5018 ± 70	3.28 ± 0.12	1.19 ± 0.12	-0.24 ± 0.07	5077 ± 20	3.30 ± 0.04	1.18 ± 0.02	-0.25 ± 0.02	5072 ± 17	3.32 ± 0.05	1.18 ± 0.02	-0.25 ± 0.01
65638	4950 ± 49	2.93 ± 0.08	1.50 ± 0.08	0.02 ± 0.05	5015 ± 30	2.89 ± 0.05	1.44 ± 0.03	0.05 ± 0.03	4972 ± 30	2.81 ± 0.07	1.45 ± 0.03	0.02 ± 0.03
67762	4938 ± 204	3.44 ± 0.41	1.18 ± 0.20	-0.01 ± 0.49	5010 ± 28	3.42 ± 0.06	1.10 ± 0.03	-0.01 ± 0.02	4972 ± 30	3.36 ± 0.06	1.09 ± 0.04	-0.04 ± 0.02
67977	5057 ± 68	2.92 ± 0.08	1.37 ± 0.13	-0.18 ± 0.07	5165 ± 19	3.09 ± 0.04	1.40 ± 0.02	-0.13 ± 0.02	5142 ± 22	3.07 ± 0.06	1.41 ± 0.03	-0.15 ± 0.02
67990	4905 ± 63	2.90 ± 0.12	1.44 ± 0.08	-0.02 ± 0.06	5012 ± 30	2.92 ± 0.06	1.46 ± 0.03	0.00 ± 0.03	4925 ± 33	2.73 ± 0.09	1.40 ± 0.03	-0.05 ± 0.03
69123	4844 ± 56	3.13 ± 0.11	1.33 ± 0.07	0.07 ± 0.04	4883 ± 34	3.01 ± 0.07	1.35 ± 0.04	0.02 ± 0.03	4850 ± 40	2.81 ± 0.18	1.32 ± 0.04	-0.01 ± 0.03
69674	4789 ± 67	2.64 ± 0.11	1.55 ± 0.09	-0.20 ± 0.06	4888 ± 27	2.53 ± 0.05	1.59 ± 0.03	-0.17 ± 0.03	4871 ± 38	2.59 ± 0.08	1.62 ± 0.04	-0.19 ± 0.03
69879	4768 ± 53	2.43 ± 0.10	1.41 ± 0.07	-0.01 ± 0.04	4867 ± 36	2.71 ± 0.08	1.47 ± 0.03	-0.01 ± 0.03	4811 ± 35	2.65 ± 0.10	1.49 ± 0.04	-0.06 ± 0.03
70982	5037 ± 72	2.86 ± 0.12	1.43 ± 0.10	0.00 ± 0.07	5136 ± 27	2.89 ± 0.05	1.50 ± 0.03	0.02 ± 0.03	5132 ± 30	2.78 ± 0.13	1.45 ± 0.03	0.02 ± 0.03
73468	5000 ± 251	2.77 ± 0.50	1.15 ± 0.20	-0.06 ± 0.10	5032 ± 21	2.89 ± 0.04	1.48 ± 0.02	-0.13 ± 0.02	5012 ± 22	2.85 ± 0.07	1.46 ± 0.03	-0.14 ± 0.02
73887	4824 ± 54	2.73 ± 0.10	1.37 ± 0.07	0.04 ± 0.05	4927 ± 38	2.80 ± 0.07	1.51 ± 0.04	0.01 ± 0.03	4828 ± 43	2.60 ± 0.09	1.48 ± 0.04	-0.05 ± 0.04
73898	4958 ± 75	2.66 ± 0.10	1.60 ± 0.16	-0.48 ± 0.08	5034 ± 16	2.70 ± 0.04	1.53 ± 0.02	-0.44 ± 0.02	5065 ± 21	2.73 ± 0.06	1.54 ± 0.03	-0.43 ± 0.02
74006					5766 ± 149	3.92 ± 0.15	4.28 ± 0.42	-0.02 ± 0.12	5590 ± 168	3.73 ± 0.27	3.17 ± 0.49	-0.06 ± 0.13
74772 [†]	5131 ± 128	2.67 ± 0.15	1.22 ± 0.27	-0.09 ± 0.12	5290 ± 24	2.93 ± 0.07	1.62 ± 0.03	-0.07 ± 0.02	5291 ± 32	2.89 ± 0.11	1.54 ± 0.04	-0.04 ± 0.03
75168 [†]	5243 ± 80	2.99 ± 0.12	1.45 ± 0.16	-0.05 ± 0.09	5450 ± 27	3.23 ± 0.07	1.56 ± 0.03	0.06 ± 0.03	5444 ± 35	3.19 ± 0.14	1.52 ± 0.04	0.05 ± 0.03
75451	4819 ± 74	3.08 ± 0.14	1.18 ± 0.09	0.00 ± 0.05	4916 ± 31	3.12 ± 0.06	1.24 ± 0.04	-0.03 ± 0.03	4875 ± 31	3.04 ± 0.07	1.21 ± 0.03	-0.04 ± 0.02
77580	4850 ± 457	2.74 ± 0.92	1.23 ± 0.20	0.19 ± 0.06	5042 ± 43	3.01 ± 0.09	1.52 ± 0.04	0.16 ± 0.04	4991 ± 50	2.95 ± 0.10	1.46 ± 0.05	0.16 ± 0.04
78883	4840 ± 58	2.67 ± 0.09	1.65 ± 0.14	-0.52 ± 0.06	4994 ± 29	2.89 ± 0.07	1.69 ± 0.04	-0.42 ± 0.03	4984 ± 27	2.83 ± 0.12	1.59 ± 0.04	-0.42 ± 0.03
79091	4708 ± 59	2.94 ± 0.13	1.27 ± 0.07	-0.17 ± 0.04	4765 ± 26	2.86 ± 0.06	1.26 ± 0.03	-0.21 ± 0.02	4726 ± 33	2.80 ± 0.08	1.23 ± 0.04	-0.22 ± 0.02
79846	4983 ± 137	2.67 ± 0.30	2.55 ± 0.40	-0.13 ± 0.15	5300 ± 33	2.88 ± 0.15	2.43 ± 0.08	0.13 ± 0.06	5117 ± 75	2.97 ± 0.21	2.32 ± 0.11	0.00 ± 0.07
80171	4933 ± 202	2.94 ± 0.41	1.18 ± 0.20	0.22 ± 0.60	5034 ± 33	3.02 ± 0.08	1.48 ± 0.04	0.11 ± 0.03	5006 ± 47	2.97 ± 0.11	1.41 ± 0.05	0.12 ± 0.04
80934	4921 ± 201	3.04 ± 0.40	1.19 ± 0.20	0.22 ± 0.60	5042 ± 33	3.08 ± 0.07	1.42 ± 0.04	0.15 ± 0.03	5002 ± 46	3.03 ± 0.12	1.41 ± 0.05	0.13 ± 0.04
81101	4898 ± 79	2.65 ± 0.11	1.52 ± 0.15	-0.38 ± 0.08	4979 ± 19	2.75 ± 0.03	1.53 ± 0.02	-0.35 ± 0.02	4977 ± 24	2.72 ± 0.05	1.51 ± 0.03	-0.36 ± 0.02
81136 [†]	5141 ± 74	2.90 ± 0.10	1.60 ± 0.13	0.07 ± 0.08	5222 ± 26	2.81 ± 0.07	1.68 ± 0.03	0.07 ± 0.02	5206 ± 30	2.78 ± 0.11	1.60 ± 0.03	0.08 ± 0.03
81169	5072 ± 217	2.95 ± 0.43	1.11 ± 0.20	-0.01 ± 0.15	5131 ± 22	3.06 ± 0.04	1.38 ± 0.02	-0.05 ± 0.02	5126 ± 22	3.04 ± 0.06	1.36 ± 0.03	-0.05 ± 0.02
83380	4793 ± 202	2.74 ± 0.41	1.26 ± 0.20	0.10 ± 0.28	4920 ± 36	2.88 ± 0.07	1.47 ± 0.04	0.06 ± 0.03	4840 ± 47	2.72 ± 0.10	1.47 ± 0.05	0.00 ± 0.04
83465	4712 ± 84	2.58 ± 0.17	1.49 ± 0.10	-0.10 ± 0.07	4839 ± 31	2.67 ± 0.06	1.56 ± 0.03	-0.08 ± 0.03	4837 ± 43	2.72 ± 0.10	1.52 ± 0.04	-0.06 ± 0.03
84698	4846 ± 59	2.71 ± 0.12	1.37 ± 0.08	0.01 ± 0.05	4947 ± 32	2.81 ± 0.06	1.50 ± 0.03	0.01 ± 0.03	4870 ± 36	2.70 ± 0.08	1.46 ± 0.04	-0.03 ± 0.03
85154	4948 ± 204	2.97 ± 0.41	1.18 ± 0.20	0.09 ± 0.57	5085 ± 31	3.13 ± 0.06	1.32 ± 0.03	0.09 ± 0.03	5041 ± 39	3.06 ± 0.08	1.34 ± 0.04	0.07 ± 0.03
85250	5034 ± 60	3.17 ± 0.10	1.35 ± 0.09	0.10 ± 0.06	5119 ± 27	3.16 ± 0.05	1.35 ± 0.03	0.09 ± 0.02	5084 ± 28	3.07 ± 0.07	1.33 ± 0.03	0.08 ± 0.02
85396	5018 ± 64	3.20 ± 0.10	1.20 ± 0.10	-0.15 ± 0.06	5084 ± 18	3.22 ± 0.03	1.20 ± 0.02	-0.15 ± 0.01	5082 ± 19	3.20 ± 0.06	1.21 ± 0.02	-0.15 ± 0.02
85612	5028 ± 80	3.35 ± 0.14	1.14 ± 0.12	-0.04 ± 0.07	5108 ± 22	3.38 ± 0.04	1.18 ± 0.03	-0.05 ± 0.02	5068 ± 22	3.26 ± 0.09	1.20 ± 0.03	-0.08 ± 0.02
87540	4936 ± 223	2.93 ± 0.52	1.18 ± 0.20	0.11 ± 0.18	4959 ± 26	2.85 ± 0.06	1.45 ± 0.03	-0.02 ± 0.02	4914 ± 30	2.71 ± 0.09	1.43 ± 0.03	-0.05 ± 0.03
87627	4713 ± 48	2.60 ± 0.09	1.57 ± 0.06	-0.16 ± 0.04	4778 ± 31	2.56 ± 0.06	1.55 ± 0.03	-0.16 ± 0.03	4741 ± 39	2.50 ± 0.09	1.48 ± 0.04	-0.17 ± 0.03
87816	4904 ± 202	2.79 ± 0.42	1.20 ± 0.20	0.18 ± 0.45	4996 ± 50	2.88 ± 0.09	1.40 ± 0.05	0.13 ± 0.03	4987 ± 55	2.89 ± 0.11	1.37 ± 0.07	0.14 ± 0.04
87896 [†]	5260 ± 73	3.65 ± 0.15	1.52 ± 0.14	0.09 ± 0.07	5324 ± 37	3.46 ± 0.09	1.51 ± 0.04	0.13 ± 0.03	5283 ± 46	3.41 ± 0.10	1.45 ± 0.05	0.11 ± 0.04
88323	4953 ± 70	2.76 ± 0.11	1.45 ± 0.09	0.08 ± 0.07	5074 ± 35	2.80 ± 0.07	1.59 ± 0.04	0.09 ± 0.03	5048 ± 43	2.72 ± 0.12	1.52 ± 0.04	0.10 ± 0.04
88836	5047 ± 233	2.88 ± 0.47	1.13 ± 0.20	0.06 ± 0.40	5058 ± 22	2.95 ± 0.05	1.42 ± 0.02	-0.04 ± 0.02	4937 ± 26	2.84 ± 0.08	1.40 ± 0.03	-0.05 ± 0.02
89015	4783 ± 209	2.71 ± 0.42	1.26 ± 0.20	0.09 ± 0.06	4837 ± 36	2.71 ± 0.07	1.56 ± 0.04	-0.02 ± 0.03	4796 ± 38	2.67 ± 0.09	1.48 ± 0.04	-0.01 ± 0.03
90074	5128 ± 59	3.17 ± 0.09	1.22 ± 0.10	0.00 ± 0.06	5197 ± 19	3.17 ± 0.05	1.30 ± 0.02	-0.03 ± 0.02	5164 ± 23	3.06 ± 0.07	1.29 ± 0.03	-0.05 ± 0.02
90317	4890 ± 202	3.41 ± 0.40	1.21 ± 0.20	0.04 ± 0.31	4888 ± 24	3.15 ± 0.06	1.14 ± 0.03	-0.02 ± 0.02	4868 ± 30	3.16 ± 0.07	1.08 ± 0.03	0.00 ± 0.02
90980	4788 ± 201	2.71 ± 0.40	1.26 ± 0.20	0.17 ± 0.74	4967 ± 35	2.98 ± 0.07	1.45 ± 0.04	0.15 ± 0.03	4915 ± 46	2.99 ± 0.11	1.49 ± 0.05	0.11 ± 0.04
91437	5092 ± 63	3.03 ± 0.09	1.33 ± 0.09	0.04 ± 0.06	5178 ± 29	3.09 ± 0.04	1.40 ± 0.03	0.04 ± 0.03	5142 ± 27	2.99 ± 0.08	1.38 ± 0.03	0.02 ± 0.03
93410	4691 ± 69	2.82 ± 0.14	1.30 ± 0.08	-0.20 ± 0.05	4774 ± 33	2.80 ± 0.06	1.32 ± 0.03	-0.20 ± 0.02	4730 ± 35	2.80 ± 0.10	1.30 ± 0.03	-0.22 ± 0.02
93773	5018 ± 54	3.03 ± 0.10	1.47 ± 0.09	-0.02 ± 0.05	5055 ± 27	2.93 ± 0.06	1.42 ± 0.03	-0.05 ± 0.02	5018 ± 29	2.79 ± 0.08	1.42 ± 0.03	-0.07 ± 0.02
94510	4948 ± 65	3.15 ± 0.11	1.28 ± 0.09	-0.12 ± 0.06	5015 ± 24	3.14 ± 0.05	1.24 ± 0.03	-0.12 ± 0.02	5002 ± 24	3.08 ± 0.07	1.24 ± 0.03	-0.13 ± 0.02
94890	4787 ± 202	2.60 ± 0.41	1.26 ± 0.20	0.06 ± 0.31	4911 ± 34	2.76 ± 0.06	1.53 ± 0.03	-0.03 ± 0.03	4892 ± 42	2.76 ± 0.09	1.52 ± 0.04	-0.03 ± 0.03
96566	4910 ± 120	2.56 ± 0.18	1.67 ± 0.18	0.05 ± 0.12	4914 ± 48	2.45 ± 0.10	1.80 ± 0.05	0.00 ± 0.04	4968 ± 49	2.59 ± 0.17	1.75 ± 0.05	0.05 ± 0.05
97344	5009 ± 63	2.96 ± 0.10	1.48 ± 0.11	-0.05 ± 0.06	5130 ± 28	3.09 ± 0.06	1.44 ± 0.03	0.00 ± 0.03	5074 ± 32	3.04 ± 0.12	1.40 ± 0.04	-0.03 ± 0.03
98732	4732 ± 203	3.08 ± 0.41	1.29 ± 0.20	-0.31 ± 0.29	4815 ± 28	3.07 ± 0.05	1.14 ± 0.03	-0.29 ± 0.02	4790 ± 25	3.06 ± 0.05	1.09 ± 0.03	-0.29 ± 0.02
100708	4717 ± 82	2.94 ± 0.15	1.15 ± 0.09	-0.01 ± 0.06	4828 ± 38	3.01 ± 0.07	1.33 ± 0.04	-0.07 ± 0.03	4798 ± 36	2.82 ± 0.16	1.26 ± 0.04	-0.08 ± 0.026
101162	4889 ± 65	2.91 ± 0.11	1.46 ± 0.08	0.08 ± 0.05	4925 ± 32	2.81 ± 0.06	1.47 ± 0.04	0.05 ± 0.03	4936 ± 31	2.79 ± 0.17	1.48 ± 0.03	-0.04 ± 0.03
103462	4950 ± 92	2.53 ± 0.11	1.41 ± 0.43	-0.53 ± 0.10	5068 ± 15	2.75 ± 0.04	1.56 ± 0.02	-0.47 ± 0.01	5100 ± 21	2.79 ± 0.06	1.57 ± 0.03	-0.45 ± 0.02

Table C.2: continued.

HD number	HM07 line-list			SO08 line-list			TS13 line-list		
	T_{eff} (K)	$\log g$ (cm s^{-2})	$[\text{Fe}/\text{H}]$ (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	$[\text{Fe}/\text{H}]$ (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	$[\text{Fe}/\text{H}]$ (dex)
104704	4716 ± 86	3.04 ± 0.17	1.23 ± 0.10	4775 ± 30	2.93 ± 0.06	1.24 ± 0.03	4736 ± 40	2.85 ± 0.09	1.20 ± 0.04
106572	4722 ± 110	2.38 ± 0.18	1.50 ± 0.32	4825 ± 26	2.53 ± 0.05	1.61 ± 0.03	4806 ± 27	2.52 ± 0.07	1.62 ± 0.03
110829	4883 ± 202	3.41 ± 0.40	1.21 ± 0.20	4844 ± 43	3.01 ± 0.09	1.30 ± 0.04	4824 ± 44	2.79 ± 0.22	1.30 ± 0.05
111295	4853 ± 101	2.40 ± 0.15	1.47 ± 0.34	5049 ± 27	2.88 ± 0.06	1.78 ± 0.03	5029 ± 34	2.79 ± 0.12	1.69 ± 0.05
113778	4736 ± 118	2.62 ± 0.22	1.49 ± 0.16	4842 ± 32	2.72 ± 0.07	1.52 ± 0.03	4821 ± 38	2.60 ± 0.10	1.49 ± 0.04
114474	4831 ± 82	3.02 ± 0.15	1.34 ± 0.10	4842 ± 41	2.83 ± 0.07	1.47 ± 0.04	4790 ± 48	2.76 ± 0.10	1.41 ± 0.05
115310	5079 ± 94	3.15 ± 0.13	1.41 ± 0.16	5097 ± 28	2.97 ± 0.05	1.43 ± 0.03	5011 ± 34	2.80 ± 0.07	1.45 ± 0.04
116243 [†]	5058 ± 101	2.69 ± 0.12	1.91 ± 0.33	5325 ± 22	3.02 ± 0.05	1.63 ± 0.03	5305 ± 32	2.97 ± 0.10	1.62 ± 0.04
118338	5031 ± 397	2.90 ± 0.80	1.13 ± 0.20	5178 ± 25	3.13 ± 0.05	1.47 ± 0.03	5131 ± 32	3.10 ± 0.13	1.44 ± 0.04
119250	4821 ± 97	2.68 ± 0.16	1.44 ± 0.13	4882 ± 27	2.67 ± 0.05	1.50 ± 0.03	4823 ± 37	2.50 ± 0.10	1.47 ± 0.04
120457	4916 ± 203	2.95 ± 0.41	1.19 ± 0.20	5042 ± 32	3.09 ± 0.07	1.39 ± 0.03	5017 ± 42	3.08 ± 0.08	1.33 ± 0.05
121853	4934 ± 67	2.76 ± 0.10	1.50 ± 0.14	4985 ± 23	2.77 ± 0.04	1.57 ± 0.03	4968 ± 24	2.68 ± 0.06	1.50 ± 0.03
123151	4864 ± 66	2.72 ± 0.10	1.42 ± 0.09	4971 ± 29	2.80 ± 0.05	1.51 ± 0.04	4957 ± 35	2.77 ± 0.10	1.48 ± 0.04
123569	4981 ± 202	2.94 ± 0.40	1.16 ± 0.20	5104 ± 27	3.12 ± 0.05	1.37 ± 0.03	5089 ± 31	3.13 ± 0.08	1.38 ± 0.03
125136	4781 ± 163	2.96 ± 0.30	1.42 ± 0.21	4949 ± 33	3.15 ± 0.06	1.18 ± 0.04	4937 ± 37	2.97 ± 0.20	1.22 ± 0.04
127195	4947 ± 66	3.42 ± 0.11	1.10 ± 0.10	5006 ± 23	3.37 ± 0.04	1.09 ± 0.03	4990 ± 24	3.38 ± 0.05	1.09 ± 0.03
129462	4915 ± 165	3.00 ± 0.25	2.04 ± 0.31	4985 ± 27	2.84 ± 0.04	1.57 ± 0.03	4953 ± 26	2.75 ± 0.06	1.48 ± 0.03
129893	4914 ± 59	2.91 ± 0.10	1.43 ± 0.08	4974 ± 31	2.88 ± 0.05	1.44 ± 0.03	4917 ± 35	2.80 ± 0.08	1.40 ± 0.04
130650	4940 ± 71	2.79 ± 0.11	1.51 ± 0.12	5027 ± 24	2.78 ± 0.04	1.54 ± 0.03	5009 ± 28	2.79 ± 0.07	1.51 ± 0.03
131376	5052 ± 234	3.01 ± 0.47	1.12 ± 0.20	5126 ± 26	3.11 ± 0.06	1.43 ± 0.03	5096 ± 34	3.06 ± 0.08	1.42 ± 0.03
132905	4876 ± 66	2.54 ± 0.09	1.46 ± 0.12	4954 ± 22	2.69 ± 0.05	1.53 ± 0.02	4989 ± 22	2.61 ± 0.18	1.55 ± 0.03
133921 [†]	5173 ± 60	3.10 ± 0.11	1.15 ± 0.09	5283 ± 31	3.10 ± 0.09	1.24 ± 0.03	5270 ± 38	3.10 ± 0.12	1.18 ± 0.04
134505	5101 ± 247	2.92 ± 0.50	1.10 ± 0.20	5156 ± 24	3.07 ± 0.04	1.44 ± 0.03	5126 ± 23	3.01 ± 0.06	1.42 ± 0.03
135760	4801 ± 201	3.41 ± 0.40	1.25 ± 0.20	4891 ± 71	3.32 ± 0.14	1.24 ± 0.07	4909 ± 94	3.49 ± 0.19	1.46 ± 0.09
136014	4807 ± 73	2.57 ± 0.12	1.56 ± 0.13	4925 ± 21	2.73 ± 0.04	1.62 ± 0.02	4899 ± 23	2.69 ± 0.07	1.63 ± 0.03
136672	4763 ± 266	2.59 ± 0.53	1.27 ± 0.20	4842 ± 31	2.68 ± 0.06	1.53 ± 0.03	4829 ± 27	2.68 ± 0.09	1.48 ± 0.03
139521	4888 ± 52	2.76 ± 0.09	1.52 ± 0.08	4954 ± 24	2.75 ± 0.04	1.50 ± 0.03	4960 ± 27	2.79 ± 0.07	1.45 ± 0.03
139980	4885 ± 212	2.67 ± 0.44	1.21 ± 0.20	4944 ± 28	2.87 ± 0.06	1.47 ± 0.03	4936 ± 25	2.83 ± 0.08	1.45 ± 0.03
140329	4991 ± 201	3.45 ± 0.40	1.15 ± 0.20	5043 ± 30	3.40 ± 0.07	1.15 ± 0.04	4988 ± 32	3.31 ± 0.10	1.09 ± 0.04
140861	5032 ± 87	2.76 ± 0.13	2.02 ± 0.26	5069 ± 18	2.69 ± 0.04	1.75 ± 0.02	5082 ± 20	2.71 ± 0.08	1.76 ± 0.03
141832	4972 ± 202	3.45 ± 0.40	1.16 ± 0.20	5046 ± 43	3.41 ± 0.07	1.30 ± 0.05	4936 ± 50	3.43 ± 0.25	1.11 ± 0.06
143009	5029 ± 224	2.63 ± 0.45	1.14 ± 0.20	5067 ± 27	2.77 ± 0.05	1.68 ± 0.03	4994 ± 36	2.69 ± 0.12	1.63 ± 0.04
143546 [†]	5152 ± 222	3.05 ± 0.45	1.07 ± 0.20	5223 ± 28	3.11 ± 0.06	1.57 ± 0.03	5212 ± 39	3.07 ± 0.12	1.44 ± 0.04
145621	4754 ± 53	2.76 ± 0.12	1.54 ± 0.07	4854 ± 44	2.75 ± 0.08	1.56 ± 0.04	4739 ± 42	2.85 ± 0.27	1.48 ± 0.04
146686	4755 ± 204	2.88 ± 0.41	1.28 ± 0.20	4914 ± 71	2.95 ± 0.12	1.44 ± 0.07	4813 ± 75	2.73 ± 0.16	1.37 ± 0.08
146690	4938 ± 201	2.75 ± 0.40	1.18 ± 0.20	5050 ± 28	2.91 ± 0.05	1.46 ± 0.03	5023 ± 31	2.84 ± 0.07	1.46 ± 0.03
148890	5037 ± 204	2.87 ± 0.41	1.13 ± 0.20	5069 ± 26	2.91 ± 0.05	1.45 ± 0.03	5039 ± 31	2.81 ± 0.08	1.47 ± 0.03
155276	4717 ± 237	2.63 ± 0.47	1.29 ± 0.20	4943 ± 53	2.96 ± 0.10	1.51 ± 0.05	4851 ± 60	2.86 ± 0.13	1.43 ± 0.06
156854	4863 ± 343	2.79 ± 0.69	1.22 ± 0.20	4981 ± 32	2.90 ± 0.06	1.53 ± 0.04	4883 ± 42	2.70 ± 0.12	1.44 ± 0.04
157515	4885 ± 57	3.27 ± 0.10	1.17 ± 0.08	4911 ± 26	3.19 ± 0.06	1.16 ± 0.03	4892 ± 25	3.17 ± 0.07	1.12 ± 0.03
159558	4825 ± 66	2.65 ± 0.11	1.59 ± 0.11	4889 ± 22	2.64 ± 0.04	1.55 ± 0.03	4861 ± 25	2.46 ± 0.13	1.52 ± 0.03
160720	5125 ± 92	3.11 ± 0.13	1.50 ± 0.15	5233 ± 30	3.08 ± 0.06	1.51 ± 0.03	5177 ± 29	2.94 ± 0.10	1.46 ± 0.03
160819	4877 ± 205	3.24 ± 0.41	1.21 ± 0.20	4893 ± 30	3.08 ± 0.06	1.28 ± 0.03	4822 ± 47	3.23 ± 0.29	1.12 ± 0.05
161814	4853 ± 204	2.70 ± 0.41	1.23 ± 0.20	4955 ± 36	2.80 ± 0.06	1.47 ± 0.03	4911 ± 42	2.71 ± 0.10	1.46 ± 0.04
163652	4944 ± 75	2.68 ± 0.11	1.61 ± 0.18	5011 ± 16	2.73 ± 0.03	1.53 ± 0.02	5014 ± 19	2.73 ± 0.04	1.54 ± 0.02
165135	4774 ± 59	2.68 ± 0.11	1.39 ± 0.08	4875 ± 29	2.79 ± 0.05	1.40 ± 0.03	4860 ± 32	2.74 ± 0.07	1.38 ± 0.03
165634	4950 ± 62	2.58 ± 0.09	1.55 ± 0.10	5061 ± 25	2.73 ± 0.06	1.62 ± 0.03	5062 ± 26	2.58 ± 0.10	1.63 ± 0.03
166063	5009 ± 207	2.32 ± 0.42	1.15 ± 0.20	5033 ± 34	2.37 ± 0.08	1.98 ± 0.04	4996 ± 42	2.32 ± 0.12	1.85 ± 0.05
166599	5088 ± 221	3.14 ± 0.44	1.10 ± 0.20	5076 ± 28	3.01 ± 0.05	1.39 ± 0.03	5052 ± 27	2.94 ± 0.08	1.39 ± 0.03
166949	5123 ± 210	3.35 ± 0.42	1.09 ± 0.20	5166 ± 21	3.27 ± 0.05	1.27 ± 0.02	5130 ± 22	3.26 ± 0.12	1.22 ± 0.03
168338	4817 ± 206	2.66 ± 0.41	1.24 ± 0.20	5028 ± 36	2.99 ± 0.07	1.57 ± 0.04	4930 ± 42	2.79 ± 0.10	1.43 ± 0.04
169767	4782 ± 65	2.94 ± 0.13	1.30 ± 0.08	4821 ± 30	2.84 ± 0.06	1.33 ± 0.03	4801 ± 39	2.78 ± 0.09	1.28 ± 0.04
169836	4870 ± 205	2.70 ± 0.48	1.22 ± 0.20	4993 ± 27	2.86 ± 0.05	1.48 ± 0.03	4934 ± 34	2.75 ± 0.08	1.48 ± 0.04

Table C.2: continued.

HD number	HM07 line-list			SCO08 line-list			TS13 line-list					
	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)	T_{eff} (K)	$\log g$ (cm s^{-2})	ξ (km s^{-1})	[Fe/H] (dex)
169916	4793 ± 317	3.03 ± 0.63	1.26 ± 0.20	0.04 ± 1.12	4801 ± 32	2.81 ± 0.07	1.35 ± 0.03	-0.08 ± 0.03	4778 ± 37	2.59 ± 0.18	1.35 ± 0.04	-0.11 ± 0.03
172211	4996 ± 202	2.85 ± 0.40	1.15 ± 0.20	0.32 ± 1.08	5150 ± 34	2.99 ± 0.06	1.53 ± 0.03	0.17 ± 0.03	5082 ± 34	2.94 ± 0.09	1.47 ± 0.04	0.18 ± 0.03
172875	4975 ± 78	3.04 ± 0.12	1.43 ± 0.12	0.08 ± 0.07	5070 ± 33	3.04 ± 0.06	1.46 ± 0.04	0.11 ± 0.03	5026 ± 45	2.99 ± 0.09	1.38 ± 0.05	0.11 ± 0.04
173378	4926 ± 62	3.19 ± 0.10	1.23 ± 0.09	-0.21 ± 0.05	5005 ± 19	3.17 ± 0.04	1.18 ± 0.02	-0.20 ± 0.02	4994 ± 20	3.17 ± 0.04	1.17 ± 0.02	-0.20 ± 0.02
173540 [†]	5511 ± 123	3.76 ± 0.15	2.89 ± 1.46	-0.24 ± 0.18	5547 ± 31	3.32 ± 0.07	1.74 ± 0.04	-0.15 ± 0.03	5591 ± 46	3.68 ± 0.12	1.86 ± 0.08	-0.15 ± 0.04
174295	4854 ± 72	2.67 ± 0.12	1.39 ± 0.09	-0.19 ± 0.07	4974 ± 24	2.84 ± 0.06	1.44 ± 0.03	-0.17 ± 0.02	4960 ± 28	2.61 ± 0.14	1.46 ± 0.03	-0.20 ± 0.03
175145 [†]	5374 ± 163	3.69 ± 0.23	1.20 ± 0.32	0.16 ± 0.17	5382 ± 25	3.49 ± 0.06	1.41 ± 0.03	0.02 ± 0.02	5348 ± 28	3.44 ± 0.12	1.33 ± 0.04	0.01 ± 0.03
175219	4800 ± 63	2.56 ± 0.10	1.49 ± 0.09	-0.31 ± 0.06	4896 ± 25	2.71 ± 0.05	1.50 ± 0.03	-0.29 ± 0.02	4888 ± 30	2.64 ± 0.06	1.52 ± 0.04	-0.30 ± 0.03
175401	5009 ± 86	2.98 ± 0.14	1.79 ± 0.15	0.04 ± 0.08	5102 ± 37	2.97 ± 0.06	1.57 ± 0.04	0.16 ± 0.03	5042 ± 42	2.79 ± 0.12	1.55 ± 0.04	0.12 ± 0.04
177222	4914 ± 59	3.00 ± 0.09	1.28 ± 0.08	-0.03 ± 0.06	4993 ± 26	3.00 ± 0.06	1.38 ± 0.03	-0.06 ± 0.02	4952 ± 32	2.84 ± 0.13	1.34 ± 0.03	-0.08 ± 0.03
177389	5049 ± 67	3.52 ± 0.10	1.09 ± 0.10	-0.01 ± 0.05	5102 ± 24	3.50 ± 0.04	1.08 ± 0.03	-0.03 ± 0.02	5061 ± 26	3.49 ± 0.09	1.05 ± 0.03	-0.05 ± 0.02
179433	5291 ± 220	3.49 ± 0.44	1.00 ± 0.20	0.28 ± 0.57	5168 ± 22	3.15 ± 0.04	1.38 ± 0.02	-0.02 ± 0.02	5145 ± 31	3.16 ± 0.08	1.39 ± 0.04	-0.04 ± 0.03
181517	4965 ± 209	2.95 ± 0.42	1.17 ± 0.20	0.18 ± 0.29	5050 ± 33	2.99 ± 0.06	1.47 ± 0.03	0.08 ± 0.03	4996 ± 41	2.96 ± 0.08	1.44 ± 0.05	0.07 ± 0.03
182893	4913 ± 201	3.04 ± 0.49	1.19 ± 0.20	0.19 ± 0.37	5043 ± 30	3.13 ± 0.06	1.38 ± 0.03	0.14 ± 0.02	4994 ± 40	3.09 ± 0.09	1.36 ± 0.04	0.12 ± 0.03
185075 [†]	4703 ± 64	2.58 ± 0.11	1.39 ± 0.10	-0.49 ± 0.06	4792 ± 27	2.67 ± 0.05	1.41 ± 0.03	-0.47 ± 0.02	4749 ± 23	2.55 ± 0.05	1.39 ± 0.03	-0.51 ± 0.02
189005 [†]	5086 ± 72	2.67 ± 0.09	1.63 ± 0.15	-0.21 ± 0.08	5222 ± 20	2.90 ± 0.04	1.69 ± 0.02	-0.15 ± 0.02	5203 ± 25	2.88 ± 0.07	1.67 ± 0.03	-0.16 ± 0.03
189080	4716 ± 201	2.81 ± 0.40	1.29 ± 0.20	-0.09 ± 0.31	4791 ± 34	2.81 ± 0.06	1.40 ± 0.03	-0.13 ± 0.02	4720 ± 34	2.71 ± 0.10	1.34 ± 0.03	-0.15 ± 0.02
189195	4864 ± 60	2.75 ± 0.10	1.44 ± 0.09	-0.10 ± 0.06	4936 ± 24	2.78 ± 0.05	1.47 ± 0.03	-0.11 ± 0.02	4887 ± 29	2.68 ± 0.07	1.47 ± 0.03	-0.14 ± 0.03
195569	4852 ± 77	2.84 ± 0.15	1.39 ± 0.10	0.00 ± 0.06	4948 ± 31	2.84 ± 0.06	1.46 ± 0.03	-0.02 ± 0.03	4909 ± 33	2.83 ± 0.08	1.44 ± 0.03	-0.02 ± 0.03
196171	4859 ± 57	2.79 ± 0.10	1.43 ± 0.08	-0.06 ± 0.05	4941 ± 33	2.83 ± 0.05	1.44 ± 0.03	-0.05 ± 0.03	4900 ± 43	2.83 ± 0.10	1.43 ± 0.04	-0.07 ± 0.03
198232	4877 ± 63	2.39 ± 0.25	1.43 ± 0.09	-0.01 ± 0.07	4948 ± 35	2.65 ± 0.07	1.59 ± 0.04	-0.02 ± 0.03	4898 ± 43	2.37 ± 0.18	1.51 ± 0.04	-0.05 ± 0.04
199951 [†]	5088 ± 91	2.81 ± 0.15	1.37 ± 0.18	-0.09 ± 0.10	5279 ± 30	3.06 ± 0.09	1.62 ± 0.04	-0.01 ± 0.03	5242 ± 32	3.02 ± 0.15	1.52 ± 0.04	-0.02 ± 0.03
201852	5025 ± 243	3.02 ± 0.48	1.14 ± 0.20	0.11 ± 0.13	5038 ± 24	3.01 ± 0.05	1.42 ± 0.03	0.00 ± 0.02	4999 ± 34	3.05 ± 0.10	1.41 ± 0.04	-0.02 ± 0.03
207229	4896 ± 210	2.83 ± 0.42	1.20 ± 0.20	0.11 ± 0.15	4947 ± 34	2.83 ± 0.06	1.52 ± 0.04	0.00 ± 0.03	4887 ± 39	2.71 ± 0.09	1.46 ± 0.04	-0.02 ± 0.03
207883	4822 ± 61	2.61 ± 0.10	1.47 ± 0.09	-0.22 ± 0.06	4934 ± 25	2.74 ± 0.05	1.53 ± 0.03	-0.20 ± 0.02	4911 ± 28	2.75 ± 0.06	1.49 ± 0.03	-0.20 ± 0.02
208285	4850 ± 72	2.67 ± 0.12	1.67 ± 0.15	-0.50 ± 0.07	4953 ± 21	2.80 ± 0.04	1.62 ± 0.02	-0.43 ± 0.02	4947 ± 25	2.77 ± 0.05	1.60 ± 0.03	-0.44 ± 0.02
208737	4888 ± 75	2.56 ± 0.13	1.60 ± 0.10	-0.02 ± 0.07	5025 ± 32	2.71 ± 0.06	1.62 ± 0.03	0.05 ± 0.03	4968 ± 34	2.96 ± 0.10	1.59 ± 0.04	0.03 ± 0.03
210056	4819 ± 234	3.02 ± 0.47	1.24 ± 0.20	-0.06 ± 0.28	4870 ± 34	3.00 ± 0.07	1.31 ± 0.03	-0.10 ± 0.02	4824 ± 29	2.99 ± 0.10	1.25 ± 0.03	-0.10 ± 0.02
210622	4953 ± 201	3.35 ± 0.40	1.17 ± 0.20	0.06 ± 0.85	5033 ± 26	3.34 ± 0.06	1.18 ± 0.03	0.05 ± 0.02	4999 ± 31	3.19 ± 0.14	1.18 ± 0.04	0.03 ± 0.02
212953	4812 ± 77	2.62 ± 0.11	1.52 ± 0.13	-0.43 ± 0.07	4896 ± 23	2.68 ± 0.05	1.56 ± 0.03	-0.41 ± 0.02	4893 ± 24	2.63 ± 0.08	1.55 ± 0.03	-0.41 ± 0.02
213009	4816 ± 146	2.47 ± 0.26	2.08 ± 0.25	-0.22 ± 0.14	5045 ± 59	2.93 ± 0.12	2.23 ± 0.08	-0.12 ± 0.06	5013 ± 88	2.54 ± 0.28	2.39 ± 0.14	-0.23 ± 0.09
214462	4762 ± 53	2.86 ± 0.11	1.28 ± 0.06	-0.03 ± 0.04	4831 ± 36	2.88 ± 0.06	1.35 ± 0.03	-0.07 ± 0.03	4770 ± 34	2.76 ± 0.10	1.30 ± 0.04	-0.09 ± 0.03
215104	4755 ± 83	2.55 ± 0.15	1.61 ± 0.12	-0.20 ± 0.08	4918 ± 30	2.77 ± 0.06	1.51 ± 0.03	-0.11 ± 0.02	4882 ± 34	2.70 ± 0.07	1.49 ± 0.04	-0.13 ± 0.03
215682	4715 ± 55	2.64 ± 0.10	1.50 ± 0.07	-0.09 ± 0.05	4795 ± 38	2.66 ± 0.07	1.51 ± 0.04	-0.10 ± 0.03	4728 ± 43	2.59 ± 0.10	1.50 ± 0.04	-0.15 ± 0.03
216210	5095 ± 60	3.19 ± 0.09	1.28 ± 0.10	-0.01 ± 0.06	5166 ± 20	3.22 ± 0.03	1.28 ± 0.02	0.00 ± 0.02	5135 ± 26	3.14 ± 0.07	1.30 ± 0.03	-0.03 ± 0.02
216742	4825 ± 66	3.05 ± 0.11	1.30 ± 0.09	-0.11 ± 0.05	4836 ± 32	2.90 ± 0.06	1.34 ± 0.03	-0.18 ± 0.02	4812 ± 34	2.86 ± 0.07	1.31 ± 0.04	-0.18 ± 0.02
216763	4902 ± 65	2.80 ± 0.11	1.50 ± 0.09	-0.18 ± 0.06	4984 ± 23	2.86 ± 0.05	1.46 ± 0.03	-0.14 ± 0.02	4980 ± 32	2.87 ± 0.08	1.47 ± 0.03	-0.14 ± 0.03
219507	4711 ± 56	2.71 ± 0.11	1.47 ± 0.07	-0.09 ± 0.04	4819 ± 35	2.73 ± 0.07	1.50 ± 0.04	-0.10 ± 0.03	4763 ± 44	2.63 ± 0.10	1.50 ± 0.04	-0.14 ± 0.03
219572	5055 ± 58	3.02 ± 0.10	1.49 ± 0.10	-0.04 ± 0.06	5112 ± 23	2.97 ± 0.06	1.44 ± 0.03	-0.03 ± 0.02	5087 ± 28	2.91 ± 0.08	1.44 ± 0.03	-0.04 ± 0.02
220790	4847 ± 204	2.64 ± 0.41	1.23 ± 0.20	-0.17 ± 0.29	4940 ± 25	2.80 ± 0.06	1.51 ± 0.03	-0.19 ± 0.02	4902 ± 27	2.75 ± 0.08	1.48 ± 0.03	-0.21 ± 0.02
221323	4839 ± 205	2.81 ± 0.41	1.23 ± 0.20	0.15 ± 0.06	4919 ± 34	2.82 ± 0.06	1.51 ± 0.04	0.00 ± 0.03	4842 ± 44	2.65 ± 0.09	1.47 ± 0.04	-0.04 ± 0.03
222433	4913 ± 65	2.81 ± 0.10	1.39 ± 0.09	-0.09 ± 0.06	4956 ± 25	2.78 ± 0.06	1.43 ± 0.03	-0.12 ± 0.02	4941 ± 30	2.71 ± 0.07	1.44 ± 0.03	-0.14 ± 0.03
223647	4930 ± 74	2.71 ± 0.11	1.51 ± 0.14	-0.36 ± 0.08	5034 ± 19	2.82 ± 0.04	1.54 ± 0.02	-0.33 ± 0.02	5017 ± 25	2.77 ± 0.07	1.51 ± 0.03	-0.34 ± 0.03
223700	4995 ± 237	3.17 ± 0.47	1.15 ± 0.20	0.17 ± 0.59	5024 ± 30	3.08 ± 0.06	1.33 ± 0.03	0.10 ± 0.02	4788 ± 36	2.99 ± 0.09	1.31 ± 0.04	0.11 ± 0.03
224362	4732 ± 99	2.65 ± 0.20	1.40 ± 0.11	-0.02 ± 0.08	4922 ± 42	2.89 ± 0.08	1.56 ± 0.04	0.02 ± 0.03	5012 ± 42	2.57 ± 0.10	1.51 ± 0.04	-0.01 ± 0.03

[†] For this star the parameters derived with the SCO08 line-list may also be adopted as final.

Table C.3: Stellar parameters taken from the literature of 74 stars in common with our sample. References are provided in the last column.

HD number	T_{eff} (K)	$\sigma(T_{eff})$ (K)	$\log g$ (cm s^{-2})	$\sigma(\log g)$ (cm s^{-2})	[Fe/H] (dex)	$\sigma([\text{Fe}/\text{H}])$ (dex)	ξ (km s^{-1})	$\sigma(\xi)$ (km s^{-1})	Ref.
496	4893	—	3.00	—	0.13	—	1.50	—	(1)
770	4696	100	2.68	0.10	-0.12	0.10	1.40	0.2	(2)
1737	5020	—	2.73	—	0.16	0.12	1.44	—	(3)
5457	4780	—	2.74	—	-0.07	0.14	1.38	—	(3)
8651	4708	100	2.67	0.10	-0.18	0.10	1.40	0.2	(2)
9362	4754	100	2.61	0.10	-0.28	0.10	1.30	0.2	(2)
10142	4688	100	2.65	0.10	-0.1	0.10	1.40	0.2	(2)
11977	4975	70	2.90	0.20	-0.14	0.05	1.60	—	(4)
12296	4860	—	2.71	—	-0.03	0.14	1.47	—	(3)
12438	4975	70	2.50	0.20	-0.54	0.05	1.50	—	(4)
16815	4732	100	2.60	0.10	-0.33	0.10	1.30	0.2	(2)
16975	5015	100	2.91	0.10	0.01	0.10	1.30	0.2	(2)
17652	4820	—	2.45	—	-0.37	0.08	1.42	—	(3)
23719	5070	—	2.85	—	0.11	0.11	1.43	—	(3)
23940	4910	—	2.63	—	-0.33	0.11	1.39	—	(3)
24160	5010	—	—	—	—	—	—	—	(5)
29085	4875	—	3.10	—	-0.2	—	1.35	—	(6)
29291	4960	—	2.92	—	-0.09	—	2.20	—	(7)
32436	4640	—	2.65	—	0.02	—	1.90	—	(7)
34266	5030	—	2.58	—	0.10	0.10	1.43	—	(3)
34642	4870	70	3.30	0.20	0.03	0.05	1.30	—	(4)
36189	5081	70	2.80	0.20	0.05	0.05	1.90	—	(4)
37811	5220	—	2.94	—	0.08	0.10	1.39	—	(3)
40409	4755	—	3.30	—	0.13	—	1.80	—	(8)
60666	4750	—	2.60	—	-0.02	—	1.38	—	(6)
67762	4980	—	3.26	—	-0.06	0.07	1.07	—	(3)
70982	5089	70	3.00	0.20	0.04	0.05	1.60	—	(4)
73898	5030	—	3.03	—	-0.49	—	2.00	—	(7)
74772	5210	—	2.50	—	-0.03	—	1.50	—	(9)
81169	4975	—	2.41	—	-0.09	—	2.10	—	(10)
93773	4985	70	3.00	0.20	0.00	0.05	1.50	—	(4)
94510	5100	—	3.00	—	0.10	—	1.10	—	(9)
94890	4802	—	—	—	—	—	—	—	(5)
96566	4901	—	—	—	—	—	—	—	(5)
100708	4890	—	2.75	—	-0.08	—	1.50	—	(9)
104704	4810	—	2.81	—	-0.15	0.08	1.20	—	(3)
115310	5060	—	2.63	—	0.04	0.09	1.39	—	(3)
116243	5181	—	—	—	—	—	—	—	(5)
118338	5180	—	3.00	—	0.12	0.08	1.37	—	(3)
119250	4860	—	2.53	—	-0.18	0.10	1.43	—	(3)
120457	4985	—	2.85	—	0.15	0.08	1.31	—	(3)
121853	4925	—	2.55	—	-0.32	0.09	1.44	—	(3)
123151	4960	—	2.62	—	-0.22	0.09	1.51	—	(3)
129462	5000	—	2.72	—	-0.03	0.10	1.41	—	(3)
134505	4990	—	—	—	—	—	—	—	(5)
135760	4850	—	3.06	—	0.20	0.13	1.19	—	(3)
136014	4869	70	2.70	0.20	-0.39	0.05	1.50	—	(4)
139521	4930	—	3.28	—	-0.34	—	2.70	—	(7)
140329	5010	—	3.14	—	0.01	0.09	1.09	—	(3)
143546	4977	100	2.84	0.10	-0.05	0.10	1.30	0.2	(2)
146686	4699	100	2.80	0.10	0.23	0.10	1.30	0.2	(2)
157515	4980	—	3.15	—	-0.17	0.08	1.15	—	(3)
165135	4760	—	2.72	—	-0.36	—	2.10	—	(7)
165634	4980	—	2.65	—	-0.05	—	1.73	—	(6)
166599	5005	50	2.60	0.25	-0.03	0.09	—	—	(11)
168838	4950	—	2.73	—	0.09	0.09	1.44	—	(3)
169767	4720	100	2.71	0.10	-0.2	0.10	1.20	0.2	(2)
169916	4689	100	2.66	0.10	-0.06	0.10	1.20	0.2	(2)
174295	4893	70	2.80	0.20	-0.17	0.05	1.50	—	(4)
175219	4720	—	2.44	—	-0.32	—	—	—	(12)
177389	5131	70	3.70	0.20	0.09	0.05	1.10	—	(4)
189005	5060	—	2.78	—	-0.38	—	2.70	—	(7)
189080	4720	—	2.51	—	-0.17	0.10	1.29	—	(3)
195569	4980	—	2.78	—	0.05	0.10	1.35	—	(3)
196171	4788	100	2.69	0.10	-0.13	0.10	1.50	0.2	(2)
198232	4923	70	2.80	0.20	0.10	0.05	1.50	—	(4)
199951	5310	—	3.00	—	-0.01	—	1.60	—	(9)
207229	4945	—	2.59	—	0.03	0.10	1.43	—	(3)
208737	4995	—	2.41	—	0.05	0.10	1.55	—	(3)
213009	4800	—	2.00	—	-0.2	—	1.30	—	(13)
215104	4737	100	2.62	0.10	-0.2	0.10	1.50	0.2	(2)
216763	4841	100	2.72	0.10	-0.21	0.10	1.40	0.2	(2)
220790	4850	—	2.67	—	-0.27	0.13	1.37	—	(3)
222433	4860	—	3.05	—	-0.3	—	2.10	—	(7)

(1) Gratton and Ortolani [1986]; (2) Liu et al. [2007]; (3) Jones et al. [2011b]; (4) da Silva et al. [2006]; (5) di Benedetto [1998]; (6) Hekker and Meléndez [2007]; (7)

McWilliam [1990]; (8) Thorén et al. [2004]; (9) Jones et al. [1992]; (10) Luck [1991]; (11) Randich et al. [1999]; (12) Meléndez et al. [2008]; (13) Foy [1981]

Table C.4: The new linelist.

λ (Å)	(eV)	loggf	Elements	Z	EW_{sun} (mÅ)
6154.23	2.10	-1.622	NaI	11	36.6
6160.75	2.10	-1.363	NaI	11	54.3
5711.09	4.35	-1.777	MgI	12	105.6
6319.24	5.11	-2.300	MgI	12	25.2
6696.03	3.14	-1.571	AlI	13	36.2
6698.67	3.14	-1.886	AlI	13	21.1
5645.61	4.93	-2.068	SiI	14	35.8
5684.49	4.95	-1.642	SiI	14	61.2
5701.11	4.93	-2.034	SiI	14	37.7
5753.64	5.62	-1.333	SiI	14	45.7
5948.54	5.08	-1.208	SiI	14	85.4
6125.02	5.61	-1.555	SiI	14	31.7
6142.49	5.62	-1.520	SiI	14	33.1
6145.02	5.62	-1.425	SiI	14	38.8
6195.46	5.87	-1.666	SiI	14	17.1
6237.33	5.61	-1.116	SiI	14	61.1
6243.82	5.62	-1.331	SiI	14	44.8
6244.48	5.62	-1.310	SiI	14	46.2
6527.21	5.87	-1.227	SiI	14	38.9
6721.85	5.86	-1.156	SiI	14	44.0
6741.63	5.98	-1.625	SiI	14	15.5
5260.39	2.52	-1.836	CaI	20	0.
5261.71	2.52	-0.677	CaI	20	97.7
5349.47	2.71	-0.581	CaI	20	94.6
5512.98	2.93	-0.559	CaI	20	84.8
5867.56	2.93	-1.592	CaI	20	25.1
6156.02	2.52	-2.497	CaI	20	9.6
6161.29	2.52	-1.313	CaI	20	60.6
6166.44	2.52	-1.155	CaI	20	69.9
6169.04	2.52	-0.800	CaI	20	92.2
6455.60	2.52	-1.404	CaI	20	56.3
6471.67	2.53	-0.825	CaI	20	91.2
6499.65	2.52	-0.917	CaI	20	85.8
5671.82	1.45	0.533	ScI	21	14.6
5526.82	1.77	0.140	ScII	21	76.3
5657.88	1.51	-0.326	ScII	21	66.9
5667.14	1.50	-1.025	ScII	21	33.9
5684.19	1.51	-0.946	ScII	21	37.2
6245.62	1.51	-1.022	ScII	21	34.9

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Table C.4 – continued from previous page

WL	Excit	loggf	elements	num	ewsun
6320.84	1.50	-1.863	ScII	21	8.1
4820.41	1.50	-0.429	TiI	22	43.1
4913.62	1.87	0.068	TiI	22	50.2
4997.10	0.00	-2.174	TiI	22	31.6
5016.17	0.85	-0.657	TiI	22	63.2
5039.96	0.02	-1.199	TiI	22	75.3
5071.49	1.46	-0.797	TiI	22	28.8
5145.47	1.46	-0.622	TiI	22	37.0
5503.90	2.58	-0.218	TiI	22	12.3
5648.57	2.49	-0.410	TiI	22	10.1
5662.16	2.32	-0.123	TiI	22	23.5
5739.48	2.25	-0.781	TiI	22	7.7
5965.84	1.88	-0.492	TiI	22	26.7
6064.63	1.05	-1.941	TiI	22	8.3
6091.18	2.27	-0.445	TiI	22	15.0
6126.22	1.07	-1.416	TiI	22	22.1
6258.11	1.44	-0.435	TiI	22	51.5
6599.12	0.90	-2.069	TiI	22	9.3
5211.54	2.59	-1.490	TiII	22	32.8
5418.77	1.58	-2.104	TiII	22	49.5
5670.85	1.08	-0.482	VI	23	18.8
6039.73	1.06	-0.747	VI	23	12.4
6081.45	1.05	-0.692	VI	23	14.1
6090.21	1.08	-0.150	VI	23	33.5
6119.53	1.06	-0.451	VI	23	21.6
6243.11	0.30	-1.067	VI	23	27.8
6251.83	0.29	-1.431	VI	23	15.0
4801.03	3.12	-0.251	CrI	24	49.6
4936.34	3.11	-0.343	CrI	24	5.6
5214.14	3.37	-0.784	CrI	24	16.4
5238.97	2.71	-1.427	CrI	24	15.9
5247.57	0.96	-1.618	CrI	24	82.0
5287.18	3.44	-0.954	CrI	24	10.4
5480.51	3.45	-0.997	CrI	24	9.5
4884.61	3.86	-2.069	CrII	24	23.4
5377.62	3.84	-0.068	MnI	25	40.8
4792.86	3.25	-0.080	CoI	27	32.7
4813.48	3.22	0.177	CoI	27	45.9
5301.05	1.71	-1.950	CoI	27	19.5
5359.20	4.15	0.040	CoI	27	9.6

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Table C.4 – continued from previous page

WL	Excit	loggf	elements	num	ewsun
5647.24	2.28	-1.594	CoI	27	14.0
4814.60	3.60	-1.670	NiI	28	16.7
4913.98	3.74	-0.661	NiI	28	55.7
4952.29	3.61	-1.261	NiI	28	32.3
4976.33	1.68	-3.002	NiI	28	37.7
5010.94	3.63	-0.901	NiI	28	48.8
5081.11	3.85	0.064	NiI	28	93.5
5094.41	3.83	-1.108	NiI	28	30.3
5435.86	1.99	-2.432	NiI	28	51.7
5462.50	3.85	-0.880	NiI	28	41.0
5587.87	1.93	-2.479	NiI	28	52.9
5589.36	3.90	-1.148	NiI	28	26.7
5625.32	4.09	-0.731	NiI	28	37.8
5628.35	4.09	-1.316	NiI	28	14.7
5641.88	4.11	-1.017	NiI	28	24.1
5643.08	4.16	-1.234	NiI	28	15.1
5694.99	4.09	-0.629	NiI	28	43.1
5748.36	1.68	-3.279	NiI	28	28.0
5847.00	1.68	-3.410	NiI	28	23.0
5996.73	4.24	-1.010	NiI	28	20.3
6086.29	4.27	-0.471	NiI	28	43.5
6108.12	1.68	-2.512	NiI	28	65.0
6111.08	4.09	-0.823	NiI	28	34.2
6119.76	4.27	-1.316	NiI	28	10.9
6128.98	1.68	-3.368	NiI	28	25.3
6130.14	4.27	-0.938	NiI	28	22.1
6175.37	4.09	-0.534	NiI	28	49.0
6176.82	4.09	-0.266	NiI	28	63.7
6186.72	4.11	-0.888	NiI	28	30.5
6204.61	4.09	-1.112	NiI	28	22.0
6223.99	4.11	-0.954	NiI	28	27.7
6322.17	4.15	-1.164	NiI	28	18.4
6327.60	1.68	-3.086	NiI	28	38.6
6360.81	4.17	-1.145	NiI	28	18.5
6378.26	4.15	-0.830	NiI	28	31.8
6598.60	4.24	-0.914	NiI	28	24.9
6635.13	4.42	-0.779	NiI	28	23.6
6767.78	1.83	-2.136	NiI	28	79.2
6772.32	3.66	-0.963	NiI	28	49.2

Table C.5: The table of the $[X/H]$ abundances for all stars before the correction for the T_{eff} trends.

star	T_{eff}	$\log g$	$[Fe/H]$	v_{tur}	v_{rot}	Na	Mg	Al	Si	Ca	Sc	Sr	Ti	Ti2	VI	Cr	Cr2	Mn	Co	Ni
496	4854	2.75	-0.03	1.46	0.993	0.23	0.02	0.05	0.11	-0.03	0.08	0.01	-0.04	-0.08	0.07	-0.02	0.02	0.00	0.10	-0.05
636	4840	2.75	0.10	1.46	0.992	0.46	0.10	0.20	0.24	0.12	0.31	0.12	0.06	0.02	0.22	0.12	0.16	0.64	0.41	0.10
770	4771	2.47	-0.16	1.50	0.993	0.06	-0.12	0.02	0.01	-0.15	-0.04	-0.11	-0.15	-0.23	-0.07	-0.17	-0.13	0.21	-0.25	-0.16
1737	4932	2.57	0.10	1.54	0.992	0.53	0.19	0.24	0.25	0.03	0.11	0.30	0.08	-0.11	0.21	0.14	0.07	0.18	0.12	0.09
3488	4880	2.72	-0.10	1.44	0.993	-0.03	0.10	0.02	0.03	-0.03	-0.01	-0.02	-0.04	-0.09	0.00	-0.07	-0.06	0.06	0.01	-0.12
4737	5199	3.03	0.00	1.34	0.994	0.19	-0.01	0.03	0.10	0.06	0.08	-0.07	0.10	-0.10	0.08	0.05	-0.07	0.01	-0.02	-0.06
5457	4706	2.78	-0.05	1.36	0.992	0.07	-0.07	0.13	0.03	0.05	0.32	-0.01	-0.03	-0.07	0.21	-0.06	0.01	0.43	-0.01	-0.04
6080	5084	3.38	-0.09	1.14	0.994	-0.04	-0.07	-0.03	-0.03	-0.03	-0.02	-0.05	-0.02	-0.06	0.06	-0.06	-0.12	-0.04	-0.09	-0.10
6192	5122	2.99	0.05	1.42	0.993	0.31	0.02	0.08	0.09	0.09	0.09	0.06	0.07	-0.01	0.13	0.08	0.05	0.11	0.00	0.01
6245	5163	3.12	0.02	1.28	0.994	0.16	0.04	0.03	0.06	0.08	0.08	0.03	0.06	-0.04	0.11	0.06	0.01	0.02	0.03	-0.03
6793	5330	3.27	0.03	1.55	0.994	0.24	0.00	0.04	0.10	0.19	-0.01	0.19	-0.01	0.13	0.25	0.12	0.25	0.01	-0.03	-0.03
7082	5048	2.69	-0.74	1.67	0.995	-0.60	-0.34	-0.39	-0.42	-0.51	-0.54	-0.57	-0.47	-0.48	-0.56	-0.71	-0.78	-1.06	-0.58	-0.71
8651	4763	2.66	-0.20	1.56	0.994	-0.12	0.01	0.03	0.03	0.03	-0.17	-0.12	-0.14	-0.09	-0.12	-0.03	-0.14	0.05	-0.02	-0.18
9163	4898	3.12	-0.15	1.14	0.994	-0.06	-0.06	-0.05	-0.03	-0.09	0.04	-0.09	-0.07	-0.13	0.09	-0.11	-0.13	0.20	-0.13	-0.14
9362	4885	2.60	-0.29	1.49	0.994	-0.17	-0.14	-0.09	-0.12	-0.21	-0.19	-0.20	-0.23	-0.28	-0.16	-0.28	-0.28	-0.30	-0.15	-0.28
9525	4725	2.71	-0.02	1.33	0.992	0.18	-0.01	0.17	0.14	-0.02	0.38	0.04	0.00	-0.11	0.24	-0.01	0.06	0.11	0.06	-0.04
10142	4755	2.47	-0.15	1.50	0.993	-0.06	-0.06	0.07	0.03	-0.11	0.03	-0.10	-0.10	-0.18	-0.01	-0.15	-0.10	0.21	0.04	-0.14
11977	5018	2.85	-0.17	1.44	0.994	0.01	-0.12	-0.09	-0.06	-0.11	-0.10	-0.09	-0.11	-0.14	-0.09	-0.12	-0.14	-0.25	-0.14	-0.20
12055	5255	3.04	-0.02	1.45	0.994	0.18	-0.10	0.03	0.03	0.05	0.08	0.00	0.06	-0.05	0.08	0.02	0.25	-0.01	-0.01	-0.05
12296	4787	2.60	-0.05	1.51	0.992	0.14	-0.01	0.09	0.08	-0.03	0.13	-0.02	-0.07	-0.13	0.10	-0.04	0.02	0.38	0.09	-0.05
12431	5010	2.83	-0.03	1.43	0.994	0.07	-0.01	0.05	0.03	0.04	0.05	-0.01	0.01	-0.06	0.09	0.02	-0.04	0.23	0.04	-0.07
12438	5056	2.70	-0.57	1.66	0.996	-0.54	-0.37	-0.36	-0.40	-0.46	-0.51	-0.44	-0.44	-0.45	-0.49	-0.58	0.12	-0.61	-0.30	-0.57
13263	5173	3.08	-0.05	1.38	0.994	0.06	-0.06	-0.02	0.00	0.01	-0.05	-0.03	0.00	-0.06	0.00	-0.01	-0.04	0.12	-0.04	-0.09
13940	5017	2.90	-0.02	1.43	0.993	0.06	-0.14	-0.11	0.00	-0.12	-0.24	-0.10	-0.22	-0.12	-0.23	-0.16	-0.04	-0.01	-0.18	-0.19
14247	4857	2.97	-0.17	1.22	0.994	0.07	-0.07	-0.02	-0.02	-0.11	0.01	-0.11	-0.09	-0.12	-0.17	0.05	-0.10	-0.10	0.02	-0.16
14703	5058	3.10	0.09	1.38	0.993	0.26	-0.01	0.13	0.14	0.11	0.16	0.15	0.09	0.06	0.19	0.10	0.13	0.48	0.17	0.07
14832	4862	2.59	-0.25	1.48	0.994	-0.13	-0.12	-0.08	-0.08	-0.18	-0.16	-0.18	-0.23	-0.25	-0.14	-0.24	-0.25	-0.31	-0.12	-0.24
15414	4803	3.21	-0.06	1.07	0.993	0.05	0.11	0.20	0.11	-0.01	0.38	0.08	0.11	0.04	0.32	-0.05	-0.03	0.04	0.22	-0.03
16815	4777	2.65	-0.34	1.33	0.994	-0.15	-0.15	-0.17	-0.16	-0.25	-0.23	-0.26	-0.25	-0.29	-0.17	-0.32	-0.31	-0.16	-0.20	-0.34
16975	5159	3.05	0.07	1.43	0.993	0.24	0.03	0.08	0.12	0.11	0.10	0.09	0.07	0.03	0.14	0.09	0.09	0.34	0.09	0.02
17324	4902	3.05	-0.17	1.19	0.994	-0.08	-0.09	-0.01	-0.05	-0.11	-0.01	-0.11	-0.08	-0.15	0.06	-0.14	-0.15	0.13	0.00	-0.16
17374	4899	2.75	-0.09	1.45	0.993	0.10	-0.08	0.03	0.03	-0.05	0.02	0.00	-0.04	-0.10	0.04	-0.06	-0.07	0.14	-0.09	-0.12
17504	4961	3.18	-0.26	1.16	0.994	-0.09	-0.08	-0.09	-0.14	-0.18	-0.13	-0.16	-0.11	-0.19	-0.05	-0.23	0.37	-0.06	-0.10	-0.24
17652	4872	2.59	-0.32	1.51	0.994	-0.27	-0.18	-0.11	-0.15	-0.21	-0.22	-0.27	-0.19	-0.25	-0.16	-0.32	-0.30	-0.21	-0.20	-0.32
17715	4920	2.69	-0.03	1.46	0.993	0.09	-0.03	0.02	0.07	0.01	0.02	-0.06	-0.05	-0.13	0.06	0.00	-0.04	0.32	0.03	-0.07
18023	4740	2.61	-0.31	1.28	0.994	-0.21	-0.14	-0.06	-0.17	-0.21	-0.08	-0.23	-0.20	-0.29	-0.06	-0.26	-0.30	-0.05	-0.14	-0.30
18121	4792	2.54	-0.17	1.42	0.993	0.03	-0.12	-0.03	0.00	-0.12	-0.04	-0.13	-0.15	-0.20	-0.05	-0.15	-0.15	0.11	-0.05	-0.18
18292	4930	2.85	0.09	1.45	0.992	0.28	0.03	0.17	0.20	0.10	0.22	0.09	0.06	-0.01	0.23	0.11	0.11	0.56	0.12	0.07
18448	4756	2.60	-0.34	1.54	0.994	-0.19	-0.09	-0.19	-0.07	-0.23	-0.18	-0.22	-0.10	-0.16	-0.09	-0.35	-0.29	-0.52	-0.07	-0.27
18650	4823	2.65	0.06	1.47	0.992	0.24	0.03	0.17	0.20	0.06	0.22	0.06	0.02	-0.07	0.19	0.07	0.11	0.57	0.11	0.05
19940	4854	2.90	-0.06	1.28	0.993	0.16	-0.04	0.04	0.05	-0.06	0.12	-0.02	0.00	-0.08	0.15	-0.02	-0.02	0.03	0.10	-0.07
21011	4934	2.82	-0.09	1.46	0.993	0.03	-0.04	-0.01	0.02	-0.04	0.00	-0.05	-0.07	-0.10	0.02	-0.06	-0.06	0.17	-0.03	-0.12
21430	4987	2.66	-0.35	1.49	0.994	-0.15	-0.24	-0.21	-0.22	-0.25	-0.28	-0.27	-0.28	-0.30	-0.28	-0.33	-0.34	-0.47	-0.33	-0.37
22366	4734	2.68	-0.37	1.36	0.994	-0.26	-0.24	-0.13	-0.18	-0.27	-0.14	-0.25	-0.25	-0.29	-0.12	-0.33	-0.33	-0.20	-0.17	-0.35
22382	4851	2.72	0.01	1.51	0.993	0.25	0.05	0.15	0.12	0.01	0.19	0.03	-0.01	-0.07	0.14	0.03	0.04	0.40	0.13	-0.01
22532	5047	3.20	-0.22	1.19	0.994	-0.14	-0.09	-0.11	-0.14	-0.14	-0.14	-0.16	-0.12	-0.17	-0.07	-0.18	-0.21	-0.08	-0.10	-0.23
22676	5109	3.01	0.06	1.40	0.993	0.25	0.02	0.10	0.12	0.09	0.14	0.04	0.08	-0.05	0.18	0.10	0.04	0.11	0.12	0.03
23549	4992	2.96	0.16	1.48	0.992	0.33	0.11	0.21	0.23	0.16	0.28	0.19	0.13	0.08	0.27	0.16	0.23	0.65	0.26	0.14
23670	4884	2.68	-0.16	1.48	0.993	0.13	-0.11	0.01	0.00	-0.09	-0.03	-0.10	-0.11	-0.20	-0.02	-0.12	-0.14	-0.21	-0.12	-0.16
23719	5061	2.87	0.12	1.50	0.992	0.36	0.03	0.18	0.21	0.13	0.17	0.12	0.09	-0.01	0.18	0.13	0.10	0.16	0.11	0.09
23931	4785	2.63	-0.11	1.47	0.993	-0.05	-0.10	0.02	0.04	-0.10	0.00	-0.06	-0.12	-0.14	0.01	-0.13	-0.05	0.20	0.01	-0.12
23940	4939	2.52	-0.34	1.57	0.995	-0.25	-0.11	-0.11	-0.16	-0.21	-0.16	-0.35	-0.12	-0.33	0.26	-0.33	0.26	-0.48	-0.21	-0.35
24160	5136	2.85	0.08	1.53	0.993	0.31	0.02	0.10	0.13	0.12	0.10	0.06	0.08	-0.02	0.12	0.10	0.04	0.07	0.07	0.03
28093	4994	2.60	-0.15	1.58	0.994	0.14	-0.07	0.06	-0.02	-0.08	-0.01	-0.07	-0.09	-0.19	-0.01	-0.13	-0.14	0.02	-0.04	-0.16
28732	4928	2.86	0.05	1.44	0.992	0.23	-0.05	0.10	0.14	0.05	0.15	0.06	0.04	-0.05	0.16	0.05	0.08	0.12	0.00	0.03

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Table C.5 – continued from previous page

star	teff	logg	feh	vturn	rejt	NaI	MgI	AlI	SiI	CaI	ScI	ScII	TiI	TiII	VI	CrI	CrII	MnI	CoI	NiI
29085	4879	3.00	-0.19	1.22	0.994	0.00	-0.13	-0.06	-0.08	-0.13	-0.04	-0.11	-0.10	-0.14	0.01	-0.17	-0.18	0.09	-0.04	-0.18
29291	5074	2.77	0.04	1.61	0.993	0.39	0.02	0.26	0.10	0.07	0.08	0.05	0.04	-0.04	0.09	0.06	0.08	0.30	0.06	0.00
29399	4828	3.27	0.11	1.12	0.992	0.26	0.22	0.26	0.22	0.06	0.50	0.18	0.14	0.08	0.43	0.09	0.12	0.72	0.37	0.17
29751	5052	2.75	-0.16	1.53	0.994	0.09	-0.06	-0.03	-0.05	-0.09	-0.09	-0.06	-0.10	-0.16	-0.09	-0.13	0.07	-0.29	-0.07	-0.16
29930	4748	2.47	-0.02	1.53	0.992	0.07	0.03	0.06	0.14	-0.05	0.14	-0.05	-0.02	-0.13	0.11	-0.03	0.01	0.00	0.13	-0.02
30185	4905	2.77	-0.13	1.40	0.993	0.22	-0.12	-0.03	0.02	-0.06	-0.05	-0.07	-0.11	-0.12	-0.02	-0.11	-0.05	0.14	-0.09	-0.13
30790	4817	2.59	0.00	1.48	0.992	0.19	0.03	0.13	0.14	0.03	0.29	0.02	0.01	-0.05	0.15	0.06	0.09	0.19	0.42	0.00
32436	4773	2.61	0.04	1.56	0.992	0.20	0.01	0.18	0.20	0.04	0.29	0.02	-0.01	-0.05	0.15	0.06	0.09	0.19	0.42	0.00
32453	5171	2.99	-0.06	1.43	0.994	0.17	-0.12	-0.02	0.02	0.02	0.02	-0.02	0.01	-0.08	0.01	-0.05	-0.03	-0.11	-0.08	-0.09
33285	5088	2.54	0.00	1.92	0.993	0.23	-0.03	0.00	0.05	0.02	0.10	0.00	0.05	-0.13	0.08	0.07	0.20	-0.11	-0.19	-0.03
34172	5140	3.02	0.06	1.38	0.993	0.38	0.05	0.08	0.11	0.11	0.13	0.05	0.06	-0.05	0.16	0.10	0.04	0.13	0.09	0.03
34266	4978	2.70	0.01	1.64	0.992	0.21	-0.02	0.03	0.11	0.04	0.07	-0.01	0.03	-0.08	0.04	0.02	0.05	-0.03	0.01	-0.03
34642	4865	3.16	-0.06	1.13	0.993	0.03	0.04	0.11	0.05	-0.03	0.18	0.00	0.01	-0.04	0.21	-0.02	-0.04	0.07	0.15	-0.05
36189	5053	2.50	-0.05	1.83	0.993	0.25	-0.12	-0.02	0.04	-0.03	0.01	-0.08	-0.01	-0.15	0.03	-0.03	0.19	0.10	0.11	-0.09
37811	5136	2.88	-0.01	1.52	0.994	0.30	-0.02	0.03	0.07	0.04	0.02	0.03	0.03	-0.03	0.04	0.01	0.00	-0.06	0.33	-0.04
39640	4932	2.70	-0.11	1.43	0.993	0.10	-0.11	-0.04	0.01	-0.05	-0.04	-0.08	-0.07	-0.13	-0.01	-0.07	-0.09	0.17	-0.02	-0.14
39720	4770	2.45	-0.19	1.53	0.993	0.09	-0.08	-0.01	-0.04	-0.14	-0.06	-0.17	-0.17	-0.25	-0.06	-0.19	-0.14	-0.18	-0.04	-0.17
40409	4806	3.14	0.08	1.17	0.992	0.27	0.15	0.28	0.23	0.07	0.57	0.14	0.17	0.04	0.44	0.10	0.09	0.69	0.38	0.12
41451	4893	2.78	0.17	1.45	0.992	0.46	0.13	0.28	0.33	0.19	0.41	0.19	0.11	0.03	0.34	0.16	0.20	0.29	0.33	0.21
44880	5036	3.14	-0.21	1.23	0.994	-0.15	-0.12	-0.13	-0.13	-0.15	-0.16	-0.16	-0.12	-0.15	-0.07	-0.18	-0.20	-0.20	-0.13	-0.23
44956	5163	3.13	-0.05	1.33	0.993	0.10	-0.07	-0.05	-0.01	0.00	-0.03	-0.07	-0.02	-0.12	0.01	-0.02	-0.08	-0.07	-0.16	-0.10
45145	4891	2.58	-0.04	1.49	0.993	0.11	-0.04	0.09	0.06	0.03	0.13	-0.07	0.04	-0.15	0.13	0.01	-0.03	0.31	0.07	-0.07
45158	5062	2.99	0.07	1.35	0.993	0.29	0.05	0.13	0.14	0.11	0.20	0.04	0.10	-0.05	0.19	0.12	0.06	0.11	0.14	0.06
45553	5168	3.07	0.05	1.34	0.993	0.22	0.02	0.09	0.08	0.09	0.13	0.02	0.09	-0.02	0.14	0.09	0.01	0.40	0.08	0.01
46116	4903	2.63	-0.32	1.51	0.994	-0.16	-0.18	-0.06	-0.15	-0.23	-0.21	-0.19	-0.20	-0.26	-0.19	-0.31	-0.31	-0.43	-0.18	-0.31
46262	4716	2.90	-0.34	1.21	0.994	-0.24	-0.03	0.04	-0.08	-0.20	0.07	-0.12	-0.06	-0.11	0.03	-0.31	-0.24	-0.38	-0.03	-0.29
46727	4922	2.73	-0.10	1.46	0.993	0.07	-0.06	0.01	0.05	-0.03	0.00	-0.05	-0.04	-0.13	0.02	-0.07	-0.09	-0.12	0.02	-0.12
47001	4703	2.24	-0.33	1.57	0.993	-0.16	-0.21	-0.16	-0.20	-0.25	-0.18	-0.29	-0.30	-0.33	-0.19	-0.26	-0.33	-0.40	-0.31	-0.36
47910	4844	2.65	-0.09	1.40	0.993	0.03	0.09	0.06	0.05	0.03	0.08	-0.07	-0.06	-0.14	0.07	-0.07	0.01	-0.06	-0.01	-0.11
47973	5048	2.73	0.06	1.68	0.993	0.34	0.00	0.11	0.12	0.07	0.12	0.09	0.08	-0.09	0.12	0.05	0.47	0.27	0.05	0.01
48758	4864	2.95	-0.27	1.28	0.995	-0.45	-0.23	-0.24	-0.35	-0.39	-0.38	-0.35	-0.30	-0.33	-0.32	-0.54	-0.51	-0.61	-0.37	-0.54
49947	4984	2.80	-0.20	1.49	0.994	-0.12	-0.04	-0.08	-0.11	-0.14	-0.12	-0.13	-0.12	-0.18	-0.09	-0.18	-0.17	-0.26	-0.12	-0.22
55151	4814	2.79	-0.01	1.46	0.992	0.12	0.07	0.07	0.16	-0.08	0.11	0.08	-0.04	-0.03	0.11	0.01	0.17	0.02	-0.04	0.01
55865	4866	2.70	-0.01	1.47	0.992	0.17	-0.03	0.18	0.09	0.02	0.12	0.04	0.03	-0.09	0.19	0.02	0.01	0.15	0.13	0.02
55964	4941	3.00	-0.12	1.26	0.994	0.06	-0.06	-0.01	-0.03	-0.05	-0.01	-0.07	-0.05	-0.14	0.06	-0.07	-0.08	-0.07	-0.04	-0.15
56478	4897	2.68	-0.15	1.56	0.993	0.06	-0.03	0.01	0.01	-0.08	-0.03	-0.09	-0.10	-0.16	0.00	-0.09	-0.10	-0.12	-0.01	-0.14
58540	4732	2.96	-0.07	1.12	0.993	-0.02	0.11	0.15	0.10	-0.02	0.34	0.04	0.02	-0.02	0.24	-0.05	0.00	0.07	-0.04	-0.05
59219	5081	2.92	0.06	2.14	0.993	0.41	-0.08	0.06	0.18	0.07	0.23	0.17	0.10	0.11	0.13	0.12	0.36	0.12	0.10	0.05
59894	4996	2.87	-0.13	1.45	0.994	-0.03	-0.05	-0.05	-0.04	-0.06	-0.05	-0.05	-0.08	-0.11	-0.01	-0.09	-0.06	0.08	-0.06	-0.15
60060	4882	2.72	-0.08	1.46	0.993	-0.03	0.02	0.03	0.03	-0.03	0.07	-0.05	-0.05	-0.10	0.05	-0.01	-0.08	-0.04	0.16	-0.09
60574	5036	2.78	-0.40	1.61	0.994	-0.32	-0.24	-0.19	-0.26	-0.32	-0.28	-0.27	-0.27	-0.32	-0.30	-0.41	-0.29	-0.54	-0.30	-0.39
60666	4784	2.63	-0.10	1.45	0.993	-0.02	-0.06	0.01	0.06	-0.11	0.00	-0.06	-0.12	-0.14	0.00	-0.11	-0.03	-0.09	0.02	-0.11
61642	4868	2.65	-0.11	1.38	0.993	0.09	-0.07	0.01	0.00	-0.04	0.01	-0.06	0.04	-0.13	0.04	-0.08	-0.12	-0.13	0.00	-0.14
61904	5102	2.92	0.08	1.41	0.993	0.24	0.00	0.13	0.16	0.12	0.20	0.08	0.09	0.00	0.15	0.13	0.12	0.05	-0.12	0.04
62034	4836	2.68	-0.07	1.47	0.993	-0.01	-0.01	0.06	0.07	-0.05	0.08	0.00	-0.05	-0.09	0.05	-0.06	-0.05	0.23	-0.08	-0.09
62412	4966	2.76	0.03	1.45	0.993	0.18	0.02	0.08	0.12	0.06	0.10	-0.01	0.02	-0.10	0.11	0.05	0.03	0.44	0.06	-0.02
62943	5114	3.02	0.01	1.35	0.994	0.11	0.00	0.04	0.06	0.05	0.03	0.01	0.03	-0.04	0.07	0.03	0.00	0.25	0.01	-0.04
63295	4837	2.57	-0.13	1.44	0.993	0.06	-0.02	0.06	0.00	-0.06	0.03	-0.06	-0.05	-0.16	0.06	-0.12	-0.15	0.16	0.04	-0.15
63744	4815	2.66	-0.02	1.41	0.992	0.14	0.13	0.25	0.14	0.05	0.28	0.10	0.13	-0.01	0.22	-0.01	0.36	0.17	-0.03	0.17
63948	4960	3.02	-0.10	1.30	0.993	0.00	-0.02	-0.05	-0.02	-0.06	-0.05	-0.08	-0.09	-0.09	0.03	-0.08	-0.06	0.15	-0.03	-0.14
64121	5072	3.32	-0.25	1.18	0.995	-0.18	-0.16	-0.15	-0.15	-0.18	-0.18	-0.13	-0.15	-0.15	-0.15	-0.22	-0.21	-0.14	-0.25	-0.26
65638	4972	2.81	0.02	1.45	0.993	0.37	0.02	0.08	0.13	0.05	0.07	0.03	0.01	-0.07	0.09	0.04	0.05	0.36	0.08	-0.01
67762	4972	3.36	-0.04	1.09	0.993	0.04	0.01	0.08	0.04	-0.01	0.12	0.01	0.03	-0.03	0.19	-0.02	0.03	0.36	0.12	-0.02
67977	5142	3.07	-0.15	1.41	0.994	-0.02	-0.12	-0.11	-0.10	-0.09	-0.13	-0.10	-0.11	-0.11	-0.09	-0.11	-0.11	-0.24	-0.13	-0.20
67990	4925	2.73	-0.05	1.40	0.993	0.13	-0.02	0.02	0.07	0.00	-0.02	-0.03	-0.08	-0.10	0.03	-0.05	-0.02	-0.05	-0.01	-0.08
69123	4850	2.81	-0.01	1.32	0.992	0.14	0.02	0.11	0.09	0.03	0.23	-0.05	0.03	-0.13	0.21	0.02	-0.05	0.14	0.13	-0.03

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Table C.5 – continued from previous page

star	teff	logg	feh	vturn	rejt	NaI	MgI	AlI	SiI	CaI	ScI	TiI	Ti2	VI	CrI	Cr2	MnI	CoI	NiI
69674	4871	2.59	-0.19	1.62	0.994	-0.09	-0.12	-0.11	-0.05	-0.23	-0.15	-0.17	-0.18	-0.23	-0.22	-0.16	0.01	-0.09	-0.20
69879	4811	2.63	-0.06	1.49	0.993	0.16	-0.02	0.06	0.09	-0.04	0.07	-0.03	-0.08	-0.11	-0.04	-0.02	0.34	0.07	-0.07
70982	5132	2.78	0.02	1.45	0.993	0.24	0.01	0.06	0.08	0.09	0.11	-0.05	0.06	0.07	0.06	-0.02	0.01	0.02	-0.02
73468	5012	2.85	-0.14	1.46	0.994	-0.04	-0.10	-0.05	-0.04	-0.06	-0.06	-0.08	-0.07	-0.12	-0.05	-0.12	-0.18	-0.08	-0.17
73887	4828	2.60	-0.05	1.48	0.993	0.26	0.04	0.04	0.10	-0.04	0.05	-0.03	-0.07	-0.13	-0.03	-0.03	0.00	0.07	-0.06
73898	5055	2.72	-0.43	1.54	0.995	-0.20	-0.29	-0.24	-0.30	-0.05	-0.32	-0.29	-0.31	-0.31	-0.32	-0.33	-0.43	-0.34	-0.41
74006	5590	3.73	-0.06	3.17	0.994	0.24	0.02	0.30	-0.05	-0.09	0.50	0.15	0.16	0.16	-0.02	0.24	-0.08	0.17	-0.05
74772	5291	2.89	-0.04	1.54	0.994	0.11	-0.07	-0.04	0.03	0.00	0.00	-0.03	0.03	-0.06	0.01	0.20	0.04	-0.06	-0.12
75168	5444	3.19	0.05	1.52	0.994	0.30	0.03	0.00	0.08	0.10	0.13	0.00	0.13	0.05	0.15	0.35	0.15	-0.07	-0.01
75451	4875	3.04	-0.04	1.21	0.993	0.09	-0.05	0.07	0.04	0.00	0.16	0.00	0.00	-0.03	-0.03	-0.02	0.35	0.14	-0.04
77580	4991	2.95	0.16	1.46	0.992	0.59	0.16	0.26	0.29	0.16	0.35	0.20	0.16	0.05	0.31	0.17	0.41	0.30	0.18
78883	4984	2.82	-0.42	1.59	0.995	-0.33	-0.28	-0.14	-0.21	-0.27	-0.28	-0.28	-0.17	-0.33	-0.18	-0.01	-0.41	-0.30	-0.41
79091	4726	2.80	-0.22	1.23	0.994	-0.15	-0.09	0.01	-0.04	-0.15	0.06	-0.11	-0.10	-0.16	-0.04	-0.16	-0.18	0.00	-0.20
79846	5117	2.77	0.00	2.32	0.993	0.38	-0.01	0.07	0.16	-0.07	0.11	-0.06	-0.04	0.10	0.05	-0.01	0.31	0.13	-0.09
80171	5006	2.97	0.12	1.41	0.992	0.35	0.12	0.21	0.20	0.16	0.28	0.11	0.10	0.00	0.22	0.13	0.64	0.18	0.11
80934	5002	3.03	0.13	1.41	0.992	0.49	0.03	0.21	0.23	0.11	0.26	0.11	0.12	0.02	0.29	0.11	0.25	0.20	0.11
81101	4977	2.72	-0.36	1.51	0.994	-0.27	-0.20	-0.19	-0.21	-0.27	-0.28	-0.26	-0.25	-0.31	-0.25	-0.16	-0.40	-0.13	-0.36
81136	5206	2.78	0.08	1.60	0.993	0.36	0.05	0.10	0.14	0.11	0.14	0.07	0.09	-0.07	0.11	0.09	0.28	0.19	0.09
81169	5126	3.04	-0.05	1.36	0.993	0.09	-0.09	0.01	0.02	0.01	-0.01	-0.03	0.01	-0.07	0.03	-0.01	-0.03	-0.05	-0.10
83380	4840	2.72	0.00	1.47	0.993	0.12	-0.02	0.10	0.15	0.01	0.13	-0.02	0.00	-0.07	0.11	0.02	0.05	0.11	-0.02
83465	4837	2.72	-0.06	1.52	0.993	0.03	0.03	0.08	0.08	-0.04	0.11	0.01	0.00	-0.09	0.13	-0.06	0.02	0.29	0.11
84698	4870	2.70	-0.03	1.46	0.992	0.11	0.01	0.07	0.08	0.01	0.07	-0.04	-0.03	-0.10	-0.04	0.00	0.02	-0.09	-0.05
85154	5041	3.06	0.07	1.34	0.993	0.23	0.05	0.13	0.14	0.09	0.16	0.06	0.09	0.02	0.21	0.10	0.09	0.13	0.15
85250	5084	3.07	0.08	1.33	0.993	0.29	0.04	0.11	0.12	0.10	0.13	0.07	0.09	0.06	0.17	0.09	0.10	0.06	0.04
85396	5082	3.20	-0.15	1.21	0.994	-0.10	-0.15	-0.11	-0.09	-0.07	-0.11	-0.14	-0.08	-0.14	-0.03	-0.14	-0.17	-0.09	-0.19
85612	5068	3.26	0.00	1.20	0.994	-0.03	-0.04	-0.03	-0.01	-0.03	-0.02	-0.06	0.00	-0.11	-0.05	-0.05	-0.04	0.01	-0.10
87540	4914	2.71	-0.05	1.43	0.993	0.03	0.04	0.02	0.07	0.01	0.06	-0.05	-0.03	-0.12	0.07	0.00	-0.05	-0.06	0.04
87627	4741	2.50	-0.17	1.48	0.993	-0.02	-0.10	0.04	0.00	-0.12	-0.01	-0.12	-0.11	-0.17	-0.05	-0.14	0.15	-0.01	-0.18
87816	4987	2.89	0.14	1.37	0.992	0.45	0.08	0.17	0.22	0.16	0.23	0.14	0.11	0.04	0.22	0.15	0.24	0.07	0.11
87896	5283	3.41	0.10	1.45	0.993	0.40	0.23	0.26	0.18	0.11	0.39	0.20	0.24	0.07	0.38	0.17	0.25	0.30	0.17
88323	5048	2.72	0.10	1.52	0.992	0.55	-0.03	0.18	0.16	0.14	0.23	0.05	0.08	-0.10	0.21	0.13	0.07	0.62	0.16
88836	5037	2.87	-0.05	1.40	0.992	0.05	-0.01	0.01	0.03	-0.01	-0.04	-0.05	-0.04	-0.07	-0.02	-0.01	-0.04	-0.08	-0.10
89015	4796	2.64	-0.01	1.48	0.992	0.10	-0.02	0.12	0.12	-0.01	0.14	0.01	-0.01	-0.08	0.14	0.00	0.01	0.03	0.12
90074	5164	3.06	-0.05	1.29	0.994	0.07	-0.06	-0.02	-0.01	0.01	0.01	-0.04	0.00	-0.07	0.02	0.00	-0.10	-0.03	-0.10
90317	4868	3.16	0.00	1.08	0.993	0.07	0.04	0.13	0.09	0.02	0.26	0.07	0.06	-0.01	0.24	0.01	0.00	0.13	0.21
90980	4915	2.99	0.11	1.49	0.992	0.21	0.12	0.19	0.24	0.10	0.28	0.17	0.12	0.07	0.25	0.12	0.18	0.54	0.26
91437	5142	2.99	0.02	1.38	0.993	0.18	0.02	0.04	0.07	0.08	0.08	0.01	0.06	-0.04	0.11	0.05	0.04	0.07	0.05
93410	4730	2.80	-0.22	1.30	0.993	-0.17	-0.16	-0.03	-0.05	-0.18	-0.04	-0.12	-0.19	-0.20	-0.05	-0.24	-0.17	-0.18	-0.05
93773	5018	2.79	-0.07	1.42	0.993	0.13	0.01	-0.02	0.03	-0.01	-0.07	-0.07	-0.06	-0.14	-0.03	-0.05	0.14	-0.07	-0.12
94510	5002	3.08	-0.13	1.24	0.994	-0.04	-0.10	-0.05	-0.04	-0.05	-0.05	-0.10	-0.06	-0.14	0.03	-0.10	-0.08	-0.11	-0.06
94890	4892	2.76	-0.03	1.52	0.993	0.09	0.04	0.10	0.08	0.00	0.06	0.00	-0.01	-0.11	0.07	-0.02	0.00	-0.03	0.13
96566	4968	2.59	0.05	1.75	0.993	0.32	-0.05	0.08	0.17	0.03	0.11	0.12	0.07	-0.08	0.13	0.06	0.41	0.01	-0.02
97344	5074	3.04	-0.03	1.40	0.993	0.15	0.12	0.03	0.08	0.02	0.03	0.04	-0.04	0.01	-0.01	0.03	-0.03	0.02	-0.04
98732	4790	3.06	-0.29	1.09	0.994	-0.10	0.02	0.09	-0.05	-0.12	0.12	-0.08	0.01	-0.05	0.12	-0.22	-0.20	-0.32	0.01
101162	4936	2.79	0.06	1.48	0.992	0.23	-0.02	0.12	0.17	0.08	0.22	0.07	0.07	-0.04	0.17	0.09	0.06	0.17	0.05
103462	5100	2.79	-0.45	1.57	0.995	-0.27	-0.30	-0.26	-0.32	-0.35	-0.35	-0.33	-0.33	-0.38	-0.34	-0.45	-0.38	-0.47	-0.44
104704	4736	2.85	-0.16	1.20	0.993	-0.09	-0.02	0.04	-0.01	-0.08	0.13	-0.10	-0.05	-0.14	-0.11	-0.14	-0.11	-0.03	0.06
106572	4806	2.52	-0.46	1.62	0.994	-0.27	-0.09	-0.08	-0.15	-0.26	-0.24	-0.27	-0.18	-0.26	-0.19	-0.44	9.99	-0.65	-0.26
110829	4824	2.79	0.07	1.30	0.992	0.29	0.27	0.26	0.19	0.12	0.48	0.04	0.16	-0.11	0.39	0.13	-0.01	0.25	0.30
111295	5029	2.79	-0.33	1.69	0.993	-0.29	-0.14	-0.13	-0.21	-0.24	-0.18	-0.21	-0.10	-0.19	-0.17	-0.25	-0.16	-0.45	0.01
113778	4821	2.60	-0.07	1.49	0.993	0.05	0.01	0.06	0.00	-0.04	0.09	-0.02	0.00	-0.11	0.08	-0.06	-0.07	-0.02	0.07
114474	4790	2.76	0.03	1.41	0.992	0.22	0.08	0.14	0.17	0.04	0.25	0.02	0.03	-0.10	0.19	0.05	0.10	0.54	0.15
115310	5011	2.80	-0.03	1.45	0.993	0.18	0.03	0.06	0.08	0.05	0.03	-0.02	-0.01	-0.08	0.05	0.01	-0.02	-0.05	0.03
116243	5305	2.97	-0.13	1.62	0.994	0.07	-0.10	-0.12	-0.07	-0.05	-0.10	-0.07	-0.08	-0.20	-0.11	-0.05	-0.19	-0.09	-0.19
118338	5131	3.10	0.08	1.44	0.993	0.23	0.06	0.09	0.14	0.09	0.11	0.10	0.08	0.03	0.14	0.10	0.17	0.09	0.13
119250	4823	2.50	-0.18	1.47	0.993	-0.05	-0.09	-0.02	-0.03	-0.13	-0.07	-0.13	-0.14	-0.25	-0.10	-0.17	-0.21	-0.17	-0.07

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Table C.5 – continued from previous page																				
star	teff	logg	feh	vturn	rejt	NaI	MgI	AlI	SiI	CaI	ScI	TiI	Ti2	VI	CrI	Cr2	MnI	CoI	NiI	
120457	5017	3.08	0.17	1.33	0.992	0.34	0.16	0.23	0.25	0.19	0.38	0.22	0.22	0.15	0.36	0.21	0.30	0.26	0.35	0.19
121853	4968	2.68	-0.28	1.50	0.994	-0.13	-0.14	-0.11	-0.14	-0.20	-0.20	-0.18	-0.17	-0.24	-0.17	-0.25	-0.29	-0.37	-0.15	-0.28
123151	4957	2.77	-0.19	1.48	0.993	-0.10	-0.14	-0.05	-0.07	-0.14	-0.10	-0.11	-0.10	-0.18	-0.07	-0.17	-0.20	-0.03	-0.08	-0.20
123569	5089	3.13	0.07	1.38	0.993	0.23	0.05	0.10	0.13	0.08	0.13	0.07	0.10	0.01	0.19	0.08	0.10	0.43	0.06	0.05
125136	4937	2.97	-0.05	1.22	0.993	0.17	0.16	0.08	0.07	0.01	0.13	-0.10	0.02	-0.16	0.23	0.01	-0.05	0.14	0.11	-0.05
127195	4990	3.38	-0.08	1.09	0.994	0.00	0.02	0.05	0.03	-0.04	0.09	0.00	0.02	-0.03	0.16	-0.04	-0.02	0.06	0.11	-0.05
129462	4953	2.75	-0.08	1.48	0.993	0.12	-0.12	-0.01	0.01	-0.03	-0.01	-0.06	-0.06	-0.16	0.00	-0.04	-0.05	-0.08	-0.19	-0.12
129893	4917	2.80	-0.03	1.40	0.993	0.08	-0.10	0.04	0.06	-0.01	0.06	0.02	0.03	-0.06	0.04	-0.02	0.03	0.30	-0.12	-0.06
130650	5009	2.79	-0.06	1.51	0.993	0.12	-0.05	0.05	0.05	-0.02	0.02	0.00	-0.05	-0.09	0.04	-0.05	-0.05	0.23	0.02	-0.07
131376	5096	3.06	0.07	1.42	0.993	0.25	0.07	0.14	0.14	0.12	0.18	0.12	0.11	0.05	0.20	0.15	0.10	0.11	0.06	0.06
132905	4989	2.61	-0.35	1.55	0.994	-0.23	-0.25	-0.17	-0.23	-0.23	-0.26	-0.28	-0.25	-0.30	-0.24	-0.32	-0.38	-0.29	-0.24	-0.36
133921	5270	3.10	0.18	1.18	0.993	0.56	0.00	0.20	0.19	0.21	0.34	0.16	0.21	-0.01	0.31	0.19	0.48	0.24	-0.05	0.19
134505	5126	3.01	0.00	1.42	0.994	0.16	-0.08	0.02	0.08	0.04	0.04	-0.01	0.03	-0.04	0.07	0.03	0.04	-0.05	0.01	-0.04
135760	4909	3.49	0.27	1.06	0.991	0.49	0.36	0.47	0.37	0.25	0.96	0.44	0.42	0.27	0.79	0.31	0.30	0.96	0.66	0.35
136014	4899	2.69	-0.46	1.63	0.995	-0.33	-0.11	-0.15	-0.18	-0.32	-0.27	-0.32	-0.19	-0.27	-0.23	-0.45	9.99	-0.67	-0.26	-0.41
136672	4829	2.68	-0.32	1.48	0.994	-0.31	0.02	-0.01	-0.09	-0.17	-0.08	-0.17	-0.06	-0.12	-0.06	-0.30	-0.26	-0.58	-0.07	-0.27
139521	4960	2.79	-0.11	1.45	0.994	-0.03	-0.02	-0.06	-0.02	-0.06	-0.10	-0.05	-0.07	-0.18	0.00	-0.05	-0.06	-0.13	-0.04	-0.14
139980	4936	2.83	-0.14	1.45	0.993	-0.11	-0.07	-0.04	-0.02	-0.09	-0.07	-0.06	-0.08	-0.12	-0.02	-0.10	-0.06	-0.17	-0.12	-0.17
140329	4988	3.31	0.01	1.09	0.993	0.16	0.07	0.08	0.09	0.04	0.10	0.05	0.06	0.01	0.19	0.02	0.10	0.43	0.17	0.02
140861	5082	2.71	-0.36	1.76	0.994	-0.26	-0.04	-0.18	-0.08	-0.26	-0.35	-0.34	-0.17	-0.28	-0.22	-0.40	0.43	-0.56	-0.15	-0.31
141832	4936	3.43	0.13	1.11	0.992	0.19	0.24	0.17	0.24	0.08	0.30	0.23	0.10	0.19	0.30	0.12	0.23	0.34	0.35	0.16
143009	4994	2.69	0.00	1.63	0.993	0.25	-0.04	0.04	0.11	0.03	0.04	0.03	0.01	-0.06	0.03	0.01	0.06	0.28	0.02	-0.03
143546	5212	3.07	0.06	1.44	0.993	0.28	0.03	0.07	0.07	0.11	0.17	0.05	0.12	-0.02	0.18	0.13	0.33	0.17	0.07	0.01
145621	4739	2.85	-0.01	1.48	0.992	0.03	-0.01	0.07	0.21	-0.08	0.09	0.13	-0.08	0.04	0.03	-0.08	0.15	0.05	0.14	0.00
146686	4813	2.73	0.25	1.37	0.991	0.51	0.23	0.39	0.42	0.25	0.66	0.29	0.29	0.10	0.52	0.25	0.22	0.97	0.52	0.28
146690	5023	2.84	0.02	1.46	0.993	0.24	0.05	0.08	0.12	0.06	0.10	0.02	0.03	-0.08	0.10	0.05	0.01	0.05	0.07	-0.02
148890	5039	2.81	-0.05	1.47	0.993	0.15	-0.11	0.00	0.04	0.00	-0.01	-0.07	-0.04	-0.11	0.03	0.01	-0.05	0.22	-0.05	-0.08
155276	4851	2.86	0.17	1.43	0.992	0.42	0.29	0.28	0.35	0.15	0.43	0.23	0.14	0.07	0.35	0.16	0.19	0.30	0.38	0.18
156854	4883	2.70	-0.05	1.44	0.993	0.09	-0.07	0.01	0.06	-0.03	0.00	-0.06	-0.06	-0.14	0.02	-0.03	0.01	0.29	-0.01	-0.08
157515	4892	3.17	-0.16	1.12	0.994	-0.05	-0.06	-0.01	-0.03	-0.12	-0.04	-0.08	-0.12	-0.14	0.03	-0.14	-0.12	-0.05	0.01	-0.13
159558	4861	2.46	-0.31	1.52	0.993	-0.19	-0.12	-0.10	-0.16	-0.23	-0.17	-0.32	-0.22	-0.33	-0.17	-0.27	-0.28	-0.11	0.05	-0.31
160720	5177	2.94	0.00	1.46	0.993	0.23	0.02	0.03	0.07	0.06	0.05	-0.01	0.03	-0.03	0.09	0.04	-0.02	0.20	0.01	-0.03
160819	4822	3.23	-0.03	1.12	0.993	-0.01	-0.02	0.02	0.14	-0.06	0.08	0.16	-0.03	0.11	0.11	-0.08	0.16	0.33	0.14	0.01
161814	4911	2.71	0.08	1.46	0.992	0.52	0.02	0.24	0.22	0.11	0.31	0.11	0.05	-0.05	0.23	0.11	0.08	0.59	0.24	0.08
163652	5014	2.73	-0.36	1.54	0.995	-0.18	-0.25	-0.21	-0.23	-0.27	-0.30	-0.25	-0.26	-0.29	-0.27	-0.33	-0.20	-0.48	-0.29	-0.37
165135	4860	2.74	-0.20	1.38	0.993	0.12	-0.09	-0.07	-0.07	-0.12	-0.08	-0.15	-0.13	-0.20	-0.06	-0.17	-0.12	-0.21	-0.09	-0.22
165634	5062	2.58	-0.01	1.63	0.994	0.42	0.02	0.14	0.05	0.06	0.16	0.08	0.12	-0.06	0.17	0.06	-0.05	0.19	0.13	-0.03
166063	4996	2.32	-0.07	1.85	0.993	0.23	-0.13	0.01	0.04	-0.01	-0.05	-0.05	-0.04	-0.15	0.01	-0.02	0.17	0.14	-0.04	-0.10
166599	5052	2.94	0.00	1.39	0.993	0.24	-0.07	0.03	0.07	0.02	-0.01	0.01	-0.02	-0.07	0.03	0.01	0.01	0.35	-0.11	-0.03
166949	5130	3.26	-0.06	1.22	0.994	-0.06	-0.06	-0.01	-0.01	-0.01	-0.02	-0.04	-0.01	-0.09	0.02	-0.02	9.99	-0.11	-0.14	-0.10
168838	4930	2.79	0.09	1.43	0.992	0.32	0.02	0.15	0.19	0.10	0.21	0.09	0.07	-0.01	0.20	0.11	0.57	0.19	0.08	0.08
169767	4801	2.78	-0.19	1.28	0.993	-0.09	-0.09	-0.03	-0.06	-0.10	-0.02	-0.12	-0.14	-0.17	0.01	-0.16	-0.17	-0.14	-0.03	-0.20
169836	4934	2.75	-0.05	1.48	0.993	0.05	-0.02	0.01	0.05	-0.02	0.01	-0.06	-0.03	-0.08	0.04	-0.03	-0.02	-0.05	-0.08	-0.17
169916	4778	2.59	-0.11	1.35	0.993	0.13	-0.05	0.05	-0.02	-0.04	0.12	-0.14	-0.03	-0.19	0.12	-0.05	-0.17	0.23	0.01	-0.14
172211	5082	2.94	0.18	1.47	0.992	0.52	0.17	0.20	0.24	0.18	0.25	0.18	0.14	0.07	0.27	0.19	0.19	0.63	0.23	0.13
172875	5026	2.99	0.11	1.38	0.992	0.35	0.05	0.20	0.20	0.17	0.30	0.13	0.12	-0.03	0.27	0.14	0.22	0.23	0.10	0.10
173378	4994	3.17	-0.20	1.17	0.994	-0.09	-0.11	-0.08	-0.11	-0.12	-0.09	-0.11	-0.10	-0.15	-0.02	-0.16	-0.19	-0.18	-0.11	-0.20
173540	5591	3.48	-0.15	1.86	0.995	0.09	-0.13	-0.05	-0.09	-0.10	0.02	-0.04	0.03	-0.11	0.04	-0.07	0.06	-0.09	-0.07	-0.17
174295	4960	2.61	-0.20	1.46	0.994	-0.13	-0.08	-0.05	-0.11	-0.10	-0.11	-0.19	-0.10	-0.28	-0.08	-0.15	-0.24	-0.24	-0.12	-0.24
175145	5348	3.44	0.01	1.33	0.994	0.17	0.05	0.11	0.04	0.09	0.14	0.11	0.08	-0.03	0.19	0.03	0.51	0.00	0.06	0.00
175219	4888	2.64	-0.30	1.52	0.994	-0.19	-0.16	-0.15	-0.16	-0.20	-0.17	-0.17	-0.20	-0.26	-0.15	-0.27	-0.26	-0.19	-0.18	-0.29
175401	5042	2.79	0.12	1.55	0.992	0.37	0.10	0.19	0.23	0.15	0.20	0.08	0.11	0.00	0.22	0.15	0.16	0.56	0.19	0.09
177222	4952	2.84	-0.08	1.34	0.993	0.01	-0.07	-0.01	-0.01	-0.02	0.05	-0.12	-0.02	-0.16	0.05	-0.03	-0.07	0.26	-0.09	-0.12
177389	5061	3.49	-0.05	1.05	0.994	-0.04	0.02	0.02	0.03	0.00	0.02	0.03	0.02	0.00	0.10	-0.02	0.06	0.02	0.07	-0.04
179433	5145	3.16	-0.04	1.39	0.993	0.08	-0.04	-0.09	0.03	0.00	-0.02	0.00	0.00	-0.01	0.03	0.01	0.15	-0.02	-0.07	-0.07
181517	4996	2.96	0.07	1.44	0.992	0.39	0.04	0.12	0.17	0.07	0.15	0.09	0.05	0.01	0.16	0.08	0.09	0.46	0.02	0.05

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Table C.5 – continued from previous page

star	teff	logg	feh	vturn	refl	NaI	MgI	AlI	SiI	CaI	ScI	Sc2	TiI	Ti2	VI	CrI	Cr2	MnI	CoI	NiI
182893	4994	3.09	0.12	1.36	0.992	0.32	0.12	0.17	0.24	0.15	0.30	0.15	0.12	0.06	0.27	0.13	0.20	0.21	0.28	0.15
185075	4749	2.55	-0.51	1.39	0.994	-0.36	-0.30	-0.28	-0.32	-0.41	-0.46	-0.37	-0.40	-0.41	-0.29	-0.50	-0.41	-0.42	-0.50	-0.49
189005	5203	2.88	-0.16	1.67	0.994	0.09	-0.17	-0.07	-0.05	-0.08	-0.11	-0.06	-0.09	-0.14	-0.11	-0.15	-0.15	-0.11	-0.17	-0.20
189080	4720	2.71	-0.15	1.34	0.993	-0.14	-0.08	-0.02	0.01	-0.12	0.04	-0.09	-0.13	-0.17	0.02	-0.14	-0.06	-0.07	0.01	-0.16
189195	4887	2.68	-0.14	1.47	0.993	-0.05	-0.06	-0.01	0.00	-0.08	-0.07	-0.09	-0.13	-0.16	-0.05	-0.10	-0.10	-0.19	-0.06	-0.16
195569	4909	2.83	-0.02	1.44	0.993	0.13	-0.04	0.04	0.09	-0.01	0.06	0.02	-0.04	-0.07	0.08	-0.01	0.03	0.37	0.02	-0.05
196171	4900	2.83	-0.07	1.43	0.993	0.05	0.01	0.01	0.07	0.04	0.01	0.00	-0.08	-0.07	0.05	-0.04	-0.01	-0.06	0.04	-0.09
198232	4898	2.37	-0.05	1.51	0.992	0.32	-0.08	0.06	0.04	0.02	0.05	-0.14	-0.03	-0.28	0.03	0.00	-0.12	-0.08	-0.02	-0.12
199951	5242	3.02	-0.02	1.52	0.994	0.20	-0.08	-0.05	0.02	0.05	0.06	-0.06	0.07	-0.02	0.12	0.03	0.25	0.11	-0.17	-0.06
201852	4999	3.05	-0.02	1.41	0.993	0.17	-0.03	0.04	0.09	0.00	0.05	0.07	-0.03	0.02	0.07	0.01	0.04	0.27	0.05	-0.03
207229	4887	2.71	-0.02	1.46	0.992	0.28	-0.01	0.06	0.11	0.00	0.07	-0.02	-0.06	-0.11	0.03	0.00	0.05	0.03	0.08	-0.04
207883	4911	2.75	-0.20	1.49	0.994	-0.07	-0.13	-0.02	-0.05	-0.11	-0.10	-0.09	-0.10	-0.14	-0.07	-0.17	-0.14	0.00	-0.05	-0.19
208285	4947	2.77	-0.44	1.60	0.994	-0.29	-0.06	-0.11	-0.17	-0.27	-0.25	-0.27	-0.16	-0.23	-0.19	-0.44	9.99	-0.71	-0.21	-0.39
208737	4968	2.68	0.03	1.59	0.992	0.40	0.03	0.11	0.13	0.07	0.09	0.06	0.04	-0.06	0.07	0.03	0.09	0.00	0.07	-0.01
210056	4824	2.99	-0.10	1.25	0.993	-0.05	0.14	0.01	0.03	-0.07	0.07	0.00	-0.05	-0.05	0.07	-0.08	0.00	-0.02	0.08	-0.09
210622	4999	3.19	0.03	1.18	0.992	0.14	0.10	0.10	0.12	0.07	0.16	0.01	0.05	-0.05	0.24	0.07	0.02	0.21	0.17	0.02
212953	4893	2.63	-0.41	1.55	0.994	-0.26	-0.11	-0.11	-0.16	-0.26	-0.25	-0.29	-0.16	-0.25	-0.19	-0.41	9.99	-0.59	-0.22	-0.37
213009	5013	2.54	-0.23	2.39	0.992	0.32	-0.19	0.02	-0.04	-0.12	0.19	-0.27	-0.12	-0.32	0.07	-0.06	-0.05	-0.06	-0.09	-0.18
214462	4770	2.76	-0.09	1.30	0.993	0.02	-0.09	0.03	0.05	-0.04	0.04	-0.05	-0.06	-0.12	0.10	-0.08	-0.08	0.27	0.05	-0.10
215104	4882	2.70	-0.13	1.49	0.993	-0.04	-0.06	-0.03	-0.02	-0.09	-0.03	-0.06	-0.06	-0.14	0.01	-0.11	-0.09	-0.17	-0.01	-0.15
215682	4728	2.51	-0.15	1.50	0.993	-0.06	0.01	0.08	0.03	-0.09	0.08	-0.15	-0.06	-0.14	0.02	-0.13	-0.05	-0.15	0.07	-0.14
216210	5135	3.14	-0.03	1.30	0.994	0.23	-0.08	0.01	0.05	0.02	0.01	-0.03	-0.01	-0.08	0.07	0.02	0.02	0.01	0.00	-0.06
216742	4812	2.86	-0.18	1.31	0.993	-0.09	-0.10	-0.03	-0.05	-0.12	-0.01	-0.09	-0.13	-0.14	0.01	-0.18	-0.14	0.12	-0.03	-0.18
216763	4980	2.87	-0.14	1.47	0.994	-0.10	-0.16	-0.06	-0.06	-0.10	-0.09	-0.06	-0.12	-0.17	-0.06	-0.11	-0.09	-0.19	-0.09	-0.18
219507	4763	2.63	-0.14	1.50	0.993	0.03	0.11	0.12	0.04	-0.10	0.13	-0.03	-0.01	-0.09	0.10	-0.15	-0.10	-0.23	0.03	-0.14
219572	5087	2.91	-0.04	1.44	0.993	0.19	-0.05	-0.02	0.04	0.00	-0.05	0.00	-0.05	-0.09	0.00	-0.01	-0.03	0.19	-0.13	-0.09
220790	4902	2.75	-0.21	1.48	0.994	-0.11	-0.06	-0.03	-0.07	-0.12	-0.07	-0.11	-0.09	-0.13	-0.05	-0.18	-0.16	-0.02	-0.06	-0.20
221323	4842	2.63	-0.04	1.47	0.993	0.09	-0.02	0.08	0.11	0.01	0.08	0.00	-0.01	-0.11	0.06	-0.01	-0.01	0.31	0.08	-0.06
222433	4941	2.71	-0.14	1.44	0.994	-0.03	-0.13	-0.05	-0.02	-0.07	-0.07	-0.12	-0.12	-0.15	-0.05	-0.11	-0.11	0.07	-0.15	-0.17
223647	5017	2.77	-0.34	1.51	0.994	-0.22	-0.20	-0.19	-0.21	-0.24	-0.26	-0.23	-0.22	-0.28	-0.23	-0.31	0.21	-0.44	-0.26	-0.34
223700	5018	3.09	0.11	1.31	0.992	0.25	0.03	0.16	0.18	0.11	0.21	0.11	0.08	0.05	0.25	0.12	0.13	0.58	0.22	0.09
224362	4782	2.52	-0.07	1.51	0.992	0.16	0.16	0.11	0.06	-0.05	0.13	-0.07	-0.04	-0.19	0.10	-0.04	-0.04	0.40	0.12	-0.07

Table C.6: The table of the Galactic space velocity components and the probabilities to assign the stellar population to which each star belongs..

star	U	V	W	B03			group	R03			group
				P_{thick}	P_{thin}	P_{halo}		P_{thick}	P_{thin}	P_{halo}	
HD163652	-74	31	15	0.15	0.85	0	thin	0.03	0.97	0	thin
HD208285	-62	-20	53	0.72	0.28	0	thick	0.5	0.5	0	transition thick/thin
HD189005	-40	15	18	0.03	0.97	0	thin	0.01	0.99	0	thin
HD60574	39	55	11	0.25	0.75	0	thin	0.03	0.97	0	thin
HD174295	-46	-4	-1	0.02	0.98	0	thin	0.01	0.99	0	thin
HD169916	-29	-14	7	0.01	0.99	0	thin	0.01	0.99	0	thin
HD179433	-32	7	-1	0.01	0.99	0	thin	0.01	0.99	0	thin
HD155276	-23	4	-15	0.02	0.98	0	thin	0.01	0.99	0	thin
HD169767	-35	-6	-22	0.03	0.97	0	thin	0.02	0.98	0	thin
HD73898	39	31	-23	0.08	0.92	0	thin	0.02	0.98	0	thin
HD146686	-27	0	21	0.02	0.98	0	thin	0.02	0.98	0	thin
HD172875	-21	-2	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD182893	-27	-5	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD143009	-24	1	11	0.01	0.99	0	thin	0.01	0.99	0	thin
HD73468	-47	22	11	0.04	0.96	0	thin	0.01	0.99	0	thin
HD166063	-20	-6	12	0.01	0.99	0	thin	0.01	0.99	0	thin
HD140861	-47	-41	34	0.26	0.74	0	thin	0.13	0.87	0	thin
HD129462	-38	-6	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD139521	-9	19	-3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD175219	-8	-2	20	0.02	0.98	0	thin	0.01	0.99	0	thin
HD129893	-15	9	-20	0.02	0.98	0	thin	0.01	0.99	0	thin
HD175401	-22	2	5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD173540	-12	9	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD62412	29	23	0	0.02	0.98	0	thin	0.01	0.99	0	thin
HD215682	-38	4	1	0.01	0.99	0	thin	0.01	0.99	0	thin
HD141832	-24	-38	12	0.04	0.96	0	thin	0.02	0.98	0	thin
HD123569	-30	-8	-6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD139980	-12	2	10	0.01	0.99	0	thin	0.01	0.99	0	thin
HD11977	-25	18	11	0.02	0.98	0	thin	0.01	0.99	0	thin
HD198232	0	-1	14	0.01	0.99	0	thin	0.01	0.99	0	thin
HD67977	9	27	11	0.02	0.98	0	thin	0.01	0.99	0	thin
HD55151	12	24	17	0.03	0.97	0	thin	0.01	0.99	0	thin
HD74006	27	22	3	0.02	0.98	0	thin	0.01	0.99	0	thin
HD69879	24	21	25	0.04	0.96	0	thin	0.02	0.98	0	thin
HD216763	2	17	16	0.02	0.98	0	thin	0.01	0.99	0	thin
HD33285	-2	24	7	0.02	0.98	0	thin	0.01	0.99	0	thin
HD220790	-21	35	-6	0.04	0.96	0	thin	0.01	0.99	0	thin
HD172211	-13	0	0	0.01	0.99	0	thin	0.01	0.99	0	thin
HD17504	8	15	19	0.02	0.98	0	thin	0.01	0.99	0	thin
HD111295	-45	-33	-24	0.08	0.92	0	thin	0.04	0.96	0	thin
HD103462	13	43	30	0.2	0.8	0	thin	0.04	0.96	0	thin
HD91437	10	19	-10	0.02	0.98	0	thin	0.01	0.99	0	thin
HD134505	-10	0	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD177389	-9	20	-13	0.02	0.98	0	thin	0.01	0.99	0	thin
HD16815	-2	-7	29	0.03	0.97	0	thin	0.03	0.97	0	thin
HD496	1	-30	23	0.04	0.96	0	thin	0.03	0.97	0	thin
HD208737	-16	8	-2	0.01	0.99	0	thin	0.01	0.99	0	thin

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Table C.6 – continued from previous page

star	U	V	W	B03				R03			
				P_{thick}	P_{thin}	P_{halo}	group	P_{thick}	P_{thin}	P_{halo}	group
HD114474	-23	-5	1	0.01	0.99	0	thin	0.01	0.99	0	thin
HD37811	33	15	-2	0.02	0.98	0	thin	0.01	0.99	0	thin
HD6793	-15	-6	19	0.02	0.98	0	thin	0.01	0.99	0	thin
HD81136	-4	20	18	0.02	0.98	0	thin	0.01	0.99	0	thin
HD9362	-32	20	7	0.02	0.98	0	thin	0.01	0.99	0	thin
HD14832	-36	8	20	0.03	0.97	0	thin	0.02	0.98	0	thin
HD166599	2	0	20	0.02	0.98	0	thin	0.01	0.99	0	thin
HD3488	-31	-13	11	0.02	0.98	0	thin	0.01	0.99	0	thin
HD160720	2	15	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD60666	-21	37	5	0.04	0.96	0	thin	0.01	0.99	0	thin
HD168838	5	16	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD156854	7	19	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD121853	18	22	-6	0.02	0.98	0	thin	0.01	0.99	0	thin
HD341720	8	17	7	0.01	0.99	0	thin	0.01	0.99	0	thin
HD165634	5	5	-11	0.01	0.99	0	thin	0.01	0.99	0	thin
HD29291	20	22	-2	0.02	0.98	0	thin	0.01	0.99	0	thin
HD207229	7	-3	18	0.01	0.99	0	thin	0.01	0.99	0	thin
HD17715	23	14	9	0.02	0.98	0	thin	0.01	0.99	0	thin
HD120457	11	14	1	0.01	0.99	0	thin	0.01	0.99	0	thin
HD219572	-7	13	-3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD70982	19	19	-3	0.02	0.98	0	thin	0.01	0.99	0	thin
HD23719	16	14	9	0.01	0.99	0	thin	0.01	0.99	0	thin
HD83380	25	14	11	0.02	0.98	0	thin	0.01	0.99	0	thin
HD21011	17	6	14	0.01	0.99	0	thin	0.01	0.99	0	thin
HD96566	-10	6	4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD74772	2	15	5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD6245	9	16	7	0.01	0.99	0	thin	0.01	0.99	0	thin
HD196171	7	22	3	0.02	0.98	0	thin	0.01	0.99	0	thin
HD63744	19	20	-35	0.09	0.91	0	thin	0.04	0.96	0	thin
HD100708	-50	-1	42	0.23	0.77	0	thin	0.13	0.87	0	thin
HD169836	1	14	-19	0.02	0.98	0	thin	0.01	0.99	0	thin
HD143546	17	23	1	0.02	0.98	0	thin	0.01	0.99	0	thin
HD94890	46	11	-13	0.02	0.98	0	thin	0.01	0.99	0	thin
HD146690	11	15	-5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD88836	-2	8	-9	0.01	0.99	0	thin	0.01	0.99	0	thin
HD88323	-27	0	4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD201852	-1	14	-6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD28732	11	16	2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD39640	39	7	5	0.02	0.98	0	thin	0.01	0.99	0	thin
HD113778	32	21	0	0.02	0.98	0	thin	0.01	0.99	0	thin
HD24160	31	12	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD214462	38	13	18	0.03	0.97	0	thin	0.01	0.99	0	thin
HD55865	-7	2	15	0.01	0.99	0	thin	0.01	0.99	0	thin
HD23670	48	-19	21	0.04	0.96	0	thin	0.03	0.97	0	thin
HD216210	18	8	5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD30185	-3	26	-12	0.02	0.98	0	thin	0.01	0.99	0	thin
HD87816	-21	2	-5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD213009	4	8	-3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD5457	17	-1	13	0.01	0.99	0	thin	0.01	0.99	0	thin

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star	U	V	W	B03			group	R03			group
				P_{thick}	P_{thin}	P_{halo}		P_{thick}	P_{thin}	P_{halo}	
HD47001	-25	21	-14	0.02	0.98	0	thin	0.01	0.99	0	thin
HD118338	-8	-13	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD32453	-7	16	3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD85250	-14	2	-5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD110829	32	17	-3	0.02	0.98	0	thin	0.01	0.99	0	thin
HD59219	3	6	3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD221323	-3	-7	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD94510	21	7	17	0.02	0.98	0	thin	0.01	0.99	0	thin
HD195569	14	0	-2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD79846	-30	0	3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD46116	-65	-10	4	0.03	0.97	0	thin	0.02	0.98	0	thin
HD148890	15	10	-17	0.02	0.98	0	thin	0.01	0.99	0	thin
HD85154	-3	0	-12	0.01	0.99	0	thin	0.01	0.99	0	thin
HD36189	-10	9	-5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD22676	27	7	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD81169	-20	3	-11	0.01	0.99	0	thin	0.01	0.99	0	thin
HD85396	40	12	8	0.02	0.98	0	thin	0.01	0.99	0	thin
HD212953	17	-56	-3	0.11	0.89	0	thin	0.04	0.96	0	thin
HD9525	15	3	-2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD19940	18	19	-13	0.02	0.98	0	thin	0.01	0.99	0	thin
HD136014	-5	-72	-31	0.76	0.24	0	thick	0.34	0.66	0	transition thick/thin
HD4737	13	23	-8	0.02	0.98	0	thin	0.01	0.99	0	thin
HD12055	-19	-14	5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD116243	26	8	-3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD115310	33	2	-3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD6192	6	11	-9	0.01	0.99	0	thin	0.01	0.99	0	thin
HD34266	-5	3	8	0.01	0.99	0	thin	0.01	0.99	0	thin
HD130650	43	11	21	0.03	0.97	0	thin	0.02	0.98	0	thin
HD13940	27	5	-6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD18650	34	-18	-7	0.02	0.98	0	thin	0.01	0.99	0	thin
HD44956	1	10	-17	0.02	0.98	0	thin	0.01	0.99	0	thin
HD185075	4	14	-38	0.09	0.91	0	thin	0.05	0.95	0	thin
HD222433	58	8	5	0.03	0.97	0	thin	0.01	0.99	0	thin
HD636	26	2	6	0.01	0.99	0	thin	0.01	0.99	0	thin
HD223647	36	5	9	0.02	0.98	0	thin	0.01	0.99	0	thin
HD21430	-24	25	0	0.02	0.98	0	thin	0.01	0.99	0	thin
HD49947	77	14	0	0.06	0.94	0	thin	0.02	0.98	0	thin
HD17652	-36	19	0	0.02	0.98	0	thin	0.01	0.99	0	thin
HD16975	-6	2	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD161814	21	-2	-2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD77580	-24	-1	5	0.01	0.99	0	thin	0.01	0.99	0	thin
HD199951	25	15	-4	0.01	0.99	0	thin	0.01	0.99	0	thin
HD73887	19	-4	-7	0.01	0.99	0	thin	0.01	0.99	0	thin
HD1737	17	-25	-14	0.02	0.98	0	thin	0.02	0.98	0	thin
HD29085	49	-13	-29	0.07	0.93	0	thin	0.04	0.96	0	thin
HD34642	47	-32	-2	0.04	0.96	0	thin	0.02	0.98	0	thin
HD165135	33	-13	0	0.01	0.99	0	thin	0.01	0.99	0	thin
HD189195	26	14	-13	0.02	0.98	0	thin	0.01	0.99	0	thin
HD210056	40	-11	16	0.02	0.98	0	thin	0.02	0.98	0	thin

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star	U	V	W	B03				R03			
				P_{thick}	P_{thin}	P_{halo}	group	P_{thick}	P_{thin}	P_{halo}	group
HD12438	72	2	-27	0.12	0.88	0	thin	0.05	0.95	0	thin
HD219507	21	5	-15	0.01	0.99	0	thin	0.01	0.99	0	thin
HD136672	62	37	-27	0.28	0.72	0	thin	0.05	0.95	0	thin
HD40409	-59	-20	8	0.03	0.97	0	thin	0.02	0.98	0	thin
HD106572	-119	-129	-109	0.4	0	0.6	transition thick/halo	0.49	0	0.51	transition thick/halo
HD61642	26	-19	2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD60060	-22	-10	1	0.01	0.99	0	thin	0.01	0.99	0	thin
HD89015	-2	-15	10	0.01	0.99	0	thin	0.01	0.99	0	thin
HD14247	-63	-32	5	0.06	0.94	0	thin	0.03	0.97	0	thin
HD12296	54	-13	-13	0.03	0.97	0	thin	0.02	0.98	0	thin
HD69123	-10	-9	-2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD47973	-7	-11	2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD224362	35	-8	3	0.01	0.99	0	thin	0.01	0.99	0	thin
HD32436	12	-35	9	0.03	0.97	0	thin	0.02	0.98	0	thin
HD10142	52	-35	-12	0.06	0.94	0	thin	0.03	0.97	0	thin
HD119250	9	-32	5	0.02	0.98	0	thin	0.01	0.99	0	thin
HD46727	12	-16	-7	0.01	0.99	0	thin	0.01	0.99	0	thin
HD13263	22	-13	-8	0.01	0.99	0	thin	0.01	0.99	0	thin
HD215104	30	-20	-15	0.02	0.98	0	thin	0.02	0.98	0	thin
HD79091	-32	-19	-7	0.02	0.98	0	thin	0.01	0.99	0	thin
HD22382	-40	-33	3	0.03	0.97	0	thin	0.02	0.98	0	thin
HD29399	23	4	-30	0.04	0.96	0	thin	0.03	0.97	0	thin
HD39720	11	-25	2	0.01	0.99	0	thin	0.01	0.99	0	thin
HD63948	-17	-13	-9	0.01	0.99	0	thin	0.01	0.99	0	thin
HD101162	-11	-33	-13	0.03	0.97	0	thin	0.02	0.98	0	thin
HD93410	-87	-32	-1	0.15	0.85	0	thin	0.05	0.95	0	thin
HD83465	-70	-31	1	0.07	0.93	0	thin	0.03	0.97	0	thin
HD123151	48	-7	21	0.03	0.97	0	thin	0.02	0.98	0	thin
HD132905	68	10	-13	0.05	0.95	0	thin	0.02	0.98	0	thin
HD28093	-93	-37	-15	0.32	0.68	0	transition thick/thin	0.09	0.91	0	thin
HD63295	23	-34	-4	0.02	0.98	0	thin	0.02	0.98	0	thin
HD81101	17	-37	-4	0.03	0.97	0	thin	0.02	0.98	0	thin
HD23940	57	-73	-34	0.92	0.08	0	thick	0.53	0.46	0	transition thick/thin
HD45145	-35	-22	-9	0.02	0.98	0	thin	0.01	0.99	0	thin
HD189080	86	-7	5	0.08	0.92	0	thin	0.03	0.97	0	thin
HD67762	-77	-47	-7	0.24	0.76	0	thin	0.07	0.93	0	thin
HD8651	17	-21	-60	0.76	0.24	0	thick	0.65	0.34	0	transition thick/thin
HD7082	70	-73	-34	0.95	0.05	0	thick	0.61	0.39	0.01	transition thick/thin

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