# The nature of stars with a common origin: clues from metallicity, elemental abundances, and kinematics

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Thesis for the degree of Doctor of Philosophy


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LUND
UNIVERSITY

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Abstract

Most of field stars originate from dissolved star clusters. If the gas cloud is well mixed the stars in the cluster are expected to be chemically homogenous. Although the original kinematical information of a star may be lost under the Galactic dynamic evolution, the chemical signatures are preserved in the form of elemental abundances in individual low-mass stars. The present-day distribution of its stars therefore provides a strong constrain on the formation and evolution of the Galactic disks.
The aim of this thesis is to search for the origins of group of stars with similar kinematics making use of their chemical signatures. To efficiently and accurately measure stellar parameters and elemental abundances from high-resolution spectra of dwarfs and subgiants, an improved methodology is developed. A modified chemical tagging method suited to our special case is used to group stars which could share the same birthplace. We firstly employ this method to look for the lost siblings of the Sun. Star HIP 40317 that has very similar abundance pattern to the Sun is likely a solar sibling. However, it is not directly supported by our dynamical arguments. Then, we also explore the possible origins of a newly discovered stellar stream. We exclude a dissolved star cluster as the progenitor of the KFR08 steam based on the results of chemical tagging experiment. The old and $\alpha$-enhanced members of the stream have relatively hot kinematics. This suggests that the KFR08 stream originated from the thick disk population, which was perturbed by a massive merger in the early Universe.
NGC 6528 is the most metal-rich globular cluster in bulge. It is an ideal local template that can be used to infer the properties of old and metal-rich populations. We develop a new method to accurately measure physical parameters and metallicity for a large sample of red giant brach stars. Radial velocity of the stars is used to select the cluster members. The metallicity distribution and elemental abundance analysis of NGC 6528 members suggest that the cluster experienced chemical enrichment dominated by SNe II, while having smaller contributions from both SNe Ia and intermediate-mass AGB stars.

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# The nature of stars with a common origin: clues from metallicity, elemental abundances, and kinematics

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**Cover: The star cluster NGC 3293 would have been just a cloud of gas and dust itself about ten million years ago. Clusters like this are celestial laboratories that allow astronomers to learn more about how stars evolve.**
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# List of publications

This thesis is based on the following publications:

1 **Quest for the lost siblings of the Sun**

**C. Liu**, G. Ruchti, S. Feltzing, C. A. Martínez-Barbosa, T. Bensby, A. G. A. Brown, and S. F. Portegies Zwart
Astronomy & Astrophysics, vol. 575, A51 (2015)

2 **The nature of the KFR08 stellar stream**

**C. Liu**, S. Feltzing, and G. Ruchti
Astronomy & Astrophysics, vol. 580, A111 (2015)

3 **A methodology to determine stellar parameters and metallicities for metal-rich red giant branch stars. An application to NGC 6528**

**C. Liu**, G. Ruchti, S. Feltzing, and F. Primas
Astronomy & Astrophysics, submitted

4 **Elemental abundances in NGC 6528 – one of the most metal-rich globular clusters**

G. Ruchti, **C. Liu**, S. Feltzing, and F. Primas
Astronomy & Astrophysics, manuscript in prep.

# Popular summary

## Popular summary in English

A star is a ball of hot glowing gas. Stars vary enormously in mass, size, temperature and brightness and they are the main ingredients of a galaxy. Stars can be divided into high-mass, intermediate-mass, and low-mass stars. The evolution of a typical low-mass star, such as the Sun, goes through the main sequence, subgiant, red giant branch, and asymptotic giant branch, and the final stage is a white dwarf. Generally speaking the chemical compositions in the outer atmosphere of low-mass stars, such as F, G, K dwarfs and giants, do not change over the time of their evolution. Therefore, they will preserve the initial chemical information of their birthplaces. As most of the low-mass stars can survive as long as the age of our Galaxy, they act like fossils that keep key information of the formation and evolution of the Milky Way.

Star clusters are groups of stars. Two types of star clusters can be distinguished: open clusters and globular clusters. Globular clusters are tight groups of more than ten thousands of very old stars. An open cluster, however, contains hundreds or a few thousand stars that were formed from the same giant molecular cloud. They are loosely bound and can easily be disrupted by close encounters with other clusters and clouds of gas as they orbit the Galaxy. The loss of cluster members contribute to the Galactic disk. Typical open clusters can survive for a few million years, while the globular clusters can survive much longer. Most globular clusters have an age older than 10 Gyr.

It is commonly accepted that most stars were born in embedded clusters. As cluster members were born in the same cloud at the same time, assuming that the progenitor cloud was well mixed, the star cluster is chemically homogeneous. Although the original kinematical information of the dispersed cluster members may be lost under the long dynamical evolution of our Galaxy, their unique chemical signatures in form of elemental abundances can be used to separate them out from the field stars. The chemical tagging technique can then be used to reconstruct the dissolved open clusters. The tagged coeval stars that share the same formation site potentially enable us to trace the whole history of the Galactic disks.

The aim of this thesis is to search for the origins of groups stars with similar kinematics making use of their chemical information. Based on measured elemental abundances from high-resolution spectra, a modified chemical tagging method is used to identify the potential cluster members in two cases. In first case, we employ this method to quest for the lost siblings of the Sun. We find that HIP 40317 is likely a solar sibling. However, it is not directly supported by our dynamical arguments. In the second case, we explore the possible origins of a new kinematically discovered stellar stream. A star cluster can be excluded as the progenitor of the KFR08 steam based on the results of our chemical tagging experiments. We conclude that the stream could have a dynamical origin due to a strong perturbation from a massive merger event in the early epoch of the formation of the Milky Way.

We are also interested in one globular cluster: NGC 6528. It is the most metal-rich globular cluster in the Galactic bugle. We derive accurate physical parameters (effective temperature, surface gravity, and metallicity) and elemental abundances for a larger group of red giant branch stars. This study shows that NGC 6528 has solar metallicity. Elemental abundance analysis of NGC 6528 members suggest that the cluster was enriched by Type II supernovae in short period. There are small contributions from the yields of both Type Ia supernovae and intermediate-mass asymptotic giant branch stars.

# Populärvetenskaplig sammanfattning på svenska

En stjärna är ett klot av glödande gas. Stjärnor varierar enormt i massa, storlek, temperatur och ljusstyrka och de är den viktigaste beståndsdelen i en galax. Stjärnor kan delas in i tunga, medeltunga och lätta stjärnor beroende på deras massa. Utvecklingen av en typisk medeltung stjärna, som vår sol, går genom flera faser: huvudserien, underjätte, röda jättegrenen och asymptotiska jättegrenen, för att slutligen bli en vit dvärg. Hos lätta stjärnor som F, G, K-dvärgar och K-jättar förblir den kemiska sammansättningen av den yttre atmosfären i stort sett oförändrad under deras utveckling. De bevarar därför den ursprungliga kemiska informationen om de platser där stjärnorna bildades. Eftersom lätta stjärnor finnas kvar mycket länge i galaxen, utgör de fossil med information om Vintergatans uppkomst och utveckling.

Stjärhopar är grupper av stjärnor. Det finns två slags stjärnhopar: öppna stjärnhopar och klotformiga stjärnhopar. Klotformiga stjärnhopar är tätt sammanhållna grupper av mer än tiotusen mycket gamla stjärnor. En öppen stjärnhop däremot innehåller hundratals eller några tusen stjärnor som bildades ur ett enda jättemolekylmoln. De är löst ihophållna och kan lätt skingras om en annan stjärnhop eller ett gasmoln passerar nära hopen under deras banor i vår galax. Skingrade hopmedlemmar fyller på med stjärnor i Vintergatans skiva. Öppna stjärnhopar överlever oftast inte längre än några miljoner år, medan klotformiga stjärnhopar kan överleva mycket längre. De flesta klotformiga stjärnhopar är äldre än 10 miljarder år.

Det är allmänt accepterat att de flesta stjärnor föds i stjärnhopar inuti gasmoln. Eftersom alla medlemmarna i stjärnhopen föddes samtidigt, och man kan anta att gasmolnet var väl blandat, blir stjärnhopen kemiskt homogen. Även om de skingrade hopmedlemmarnas ursprungliga kinematiska information går förlorad under Vintergatans långa dynamiska utveckling, kan deras unika kemiska signatur i form av grundämneshalter användas för att skilja ut dem från övriga stjärnor. Denna teknik med “kemisk märkning” kan därför användas för att rekonstruera upplösta öppna stjärnhopar. De märkta stjärnorna har samma ålder och bildades på samma ställe, vilket eventuellt gör det möjligt att spåra utvecklingen av Vintergatans skiva.

Syftet med denna avhandling är att söka ursprunget till grupper av stjärnor med liknande rörelser genom att utnyttja deras kemiska information. Baserat på grundämneshalter uppmätta i högupplösta spektra används en modifierad metod för kemisk märkning för att identifiera tänkbara hopmedlemmar i två fall. I det första fallet tillämpar vi metoden för att leta efter solens syskonstjärnor. Vi konstaterar att HIP 40317 kan vara en syskonstjärna. Detta stöds dock inte direkt av våra dynamiska överväganden. Vi utesluta att stjärnströmmen KFR08 har sitt ursprung i en stjärnhop. Baserat på kinematisk information drar vi slutsatsen att stjärnströmmen kan ha ett dynamiskt ursprung i form av en kraftig störning när ett ett tungt objekt slogs ihop med Vintergatan under dess tidiga utveckling.

Vi är också intresserade av den klotformiga stjärnhopen NGC 6528. Detta är den mest metallrika klotformiga stjärnhopen i Vintergatans inre del. Vi härleder noggranna fysiska parametrar (effektiv temperatur, ytgravitation och metallicitet) och grundämneshalter för en större grupp stjärnor på röda jättegrenen. Studien visar att NGC 6528 has samma metallicitet som solen. Grundämneshalterna tyder på att stjärnhopen under en kort tidsrymd berikades på vissa grundämnen genom supernovaexplosioner av typ II. Det finns små bidrag från både supernovor av typ Ia och från medeltunga stjärnor på den asymptotiska jättegrenen.

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# Chapter 1

# Introduction

Galaxy formation and evolution is one of the outstanding problems of contemporary astrophysics. In the current idea about the cosmogony of galaxies, they assembled through hierarchical merging. It implies that high-mass galaxies form by the merging of smaller ones. The Milky Way is a barred spiral galaxy in the Local Group of galaxies. Galactic Archaeology is a detailed approach to reveal the history of the Galaxy. This approach can give us insight about the processes that took place as the Galaxy formed by recovering the remnants of ancient building blocks of the disk, bulge, and halo.

## 1.1 The Milky Way

Figure 1.1 shows a schematic picture of the Milky Way. It contains three main components: the bulge, the disk and the halo. Halo stars tend to have low metallicities ([Fe/H] $\leq -1.0$) and eccentric orbits. There are two distinct stellar populations in the halo. Old, metal-rich and $\alpha$-enhanced stars which formed primarily in situ represent an inner population. The more metal-poor and $\alpha$-enhanced population within the outer halo are likely contributed from stars accreted from lower mass subgalactic systems (Tissera et al. 2014).

The bulge population has a large range of metallicities and is dominated by random motions. Two main scenarios, hierarchical merging of clumps and secular evolution of the disk, have been invoked for bulge formation. The bulge radial velocity assay (BRAVA) survey designed to observe red giants shows that the bulge exhibits cylindrical rotation, a characteristic of pseudo bulges. Dynamical secular evolution models have shown that the bulge is formed from a bar that has undergone buckling within a massive disk (Shen et al. 2010). However, the coexistence of two chemically and kinematically distinguish-

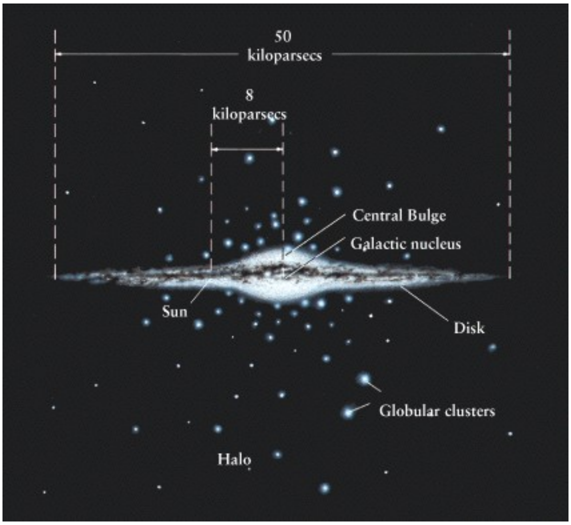


**Figure 1.1:** Edge-on sketch of the Milky Way. The major components present in the Galaxy are highlighted. The position of the Sun and the globular clusters are marked. The distance of the Sun to the Galactic center and diameter of the Galaxy are illustrated (Credit: Science Buddies).

able populations in different fields suggest a mixed formation scenario (Hill et al. 2011; Bensby et al. 2013).

The Galactic disk can be divided into two distinct stellar populations. The thick disk is characterized by mostly metal-poor, old, and $\alpha$-enhanced stars. They are also kinematically hot and show an asymmetric drift. Several scenarios for the formation of the thick disk are currently discussed; dynamically heating as a result of satellites merger (Robin et al. 1996) and accreting dwarf galaxies (Abadi et al. 2003), the collapse of accreted gas (Brook et al. 2004), and purely internal formation mechanisms, such as radial mixing (Schönrich & Binney 2009). The thin disk is the place in which star formation happens still today. Therefore, the thin disk mainly consists of young and metal-rich stars.

## 1.2 Abundance patterns in stellar populations

Since we live in the Milky Way, we can resolved the individual stars and perform spectroscopical analysis through elemental abundances in detail. This makes the Milky Way an ideal laboratory to examine the theory of the formation and evolution of spiral galaxies. Assuming that the chemical compositions in the outer atmospheres of low-mass stars do not change over the time of their evolution from the main sequence to the red giant branch, they will preserve the initial chemical signatures of their birth environments. As

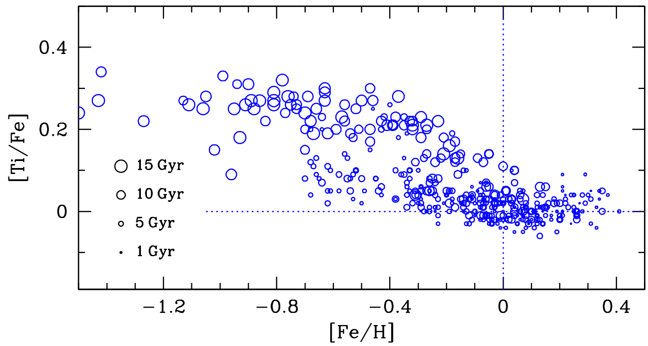


**Figure 1.2:** [Ti/Fe] versus [Fe/H] for the Milky Way disk stars. The sizes of the circles are scaled with the ages of the stars as indicated in the figure. Thick disk (high [Ti/Fe] ratios and old ages) and thin disk (low [Ti/Fe] ratios and young age) stars are significantly separated. Figure adopted from Bensby et al. (2014).

most low-mass stars survive as long as the Milky Way, they can be used to trace the history of our Galaxy. The different stellar populations could display distinct abundance patterns due to the different birthplaces and star formation history.

$\alpha$-elements, such as oxygen and magnesium, relative to iron are usually treated as a proxy for a cosmic clock. Those elements are produced in massive stars and expelled into the interstellar medium through Type II supernovae (SNe) explosions. Iron is mainly produced in the explosion of SN Ia. It has been shown that the halo stars keep $\alpha$-enhancement at a constant high level. This is interpreted as the result of an intense star formation. For the disk, a bimodality is usually revealed in a diagram of [$\alpha$/Fe] versus [Fe/H] (see Fig. 1.2). The enhanced $\alpha$ abundances of thick disk stars first have a flat trend. Then, abundance ratios decline from metallicity [Fe/H] $\sim$ –0.4 to the solar value. The "knee" represents the point where the SN Ia starts to enrich the interstellar medium. The thin disk, however, has a single slope in which the abundance ratios slowly decrease with increasing metallicity.

As open clusters vary in age from several Myr to over 10 Gyr (Dias et al. 2002), they make good probes in the study of the Galactic disk, providing chemical information in different locations for different times. Assuming all stars in a cluster show the same abundance patterns, then, open cluster can be used to trace the metallicity gradient along the disk. Like the open clusters, globular clusters are usually treated as a single stellar population, i.e. all cluster stars are believed to share the same age and chemical compositions. However, recent investigations using both photometric and spectroscopic observations (e.g. Carretta et al. 2009b; Milone et al. 2010) show that some globular clusters could harbour at least two different stellar generations. These different populations have different abundances in light elements (C, N, O, Na, Mg, Al) and maybe age. However, the metallicity is found to be extremely homogeneous for each cluster (Gratton et al. 2004). The discovery of Na-O and Mg-Al anticorrelations give further evidence of multiple populations within globular clusters. The theory put forth to explain the reasons behind this finding is that the first generation stars polluted the material from which second-generation stars formed.

## 1.3 Chemical tagging

Chemical tagging, first proposed by Freeman & Bland-Hawthorn (2002), is a relatively new technique designed to find unique stellar groups among Galactic field stars. Two assumptions should be satisfied for this technique to work fully. One is that the progenitor cloud is well mixed in chemical elements before the first stars are formed. The other is that the yields of the high-mass stars enrich the cloud fairly uniformly after assembling the cloud. The question of how star clusters become chemically well mixed has received much attention. Recent simulations show that the progenitor cloud was chemically well mixed (Feng & Krumholz 2014). Although the cloud is well mixed, the change in elemental abundances in the cluster stars could be measurable due to the ejection of the supernova. For clusters smaller than $10^4 M_\odot$, Bland-Hawthorn et al. (2010) concluded that almost all of the stars will form before the first supernova explosion. This implies that the clusters should essentially all be chemically homogeneous. From observations, several works on open clusters and moving groups have demonstrated that their members are chemically homogeneous (e.g. De Silva et al. 2007).

Stars that formed from the same material will retain their unique chemical signatures compared with other field stars. For a star cluster, we can determine accurate elemental abundances for a large number of elements. The cluster has a unique location in the elemental space ($\mathcal{C}$-space, Freeman & Bland-Hawthorn 2002) compared to other star clusters within that space. Using high resolution elemental abundances of old open clusters available from the literature, cluster to cluster comparisons show that different clusters have different abundance levels for a given element. Some decoupled elements, such as Na, Fe, Mn, Zr, Ba, and Eu, show large abundance dispersions and therefore play a significant role in the $\mathcal{C}$-space (De Silva et al. 2009). It has been estimated that at least nine independently varying elements are required to reveal the dissolved clusters from the field (Ting et al. 2012; Mitschang et al. 2013). The higher the dimensionality of $\mathcal{C}$-space, the more power of chemical tagging to identify the debris of disrupted systems.

There are at least two approaches to quantify differences in chemical abundance patterns that has been used in chemical tagging. A simple metric ($\delta_C$) for quantifying the chemical difference between any two stars across all available elements is defined by Mitschang et al. (2013, see also Paper I). Using high-resolution elemental abundances of open clusters, they analysed the relative contributions of $\delta_C$ for both intra- and intercluster pairs (Fig. 1.3) in order to estimate a probability function $P_{\delta_C}$. The probability describes the likelihood that a particular pair of stars share the same cluster environment. This method was tested by

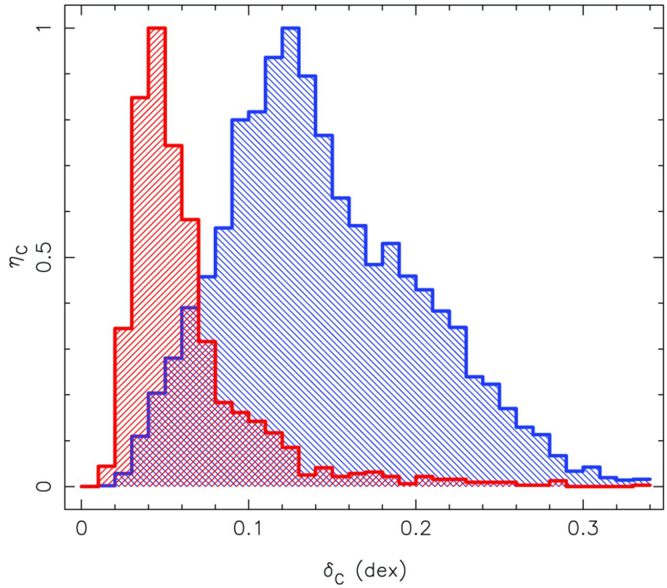


**Figure 1.3:** The binned probability density distributions of $\delta_C$ for intracluster (red; left) and intercluster (blue; right) populations. Figure adopted from Mitschang et al. (2013).

Mitschang et al. (2014) on a large sample of disk field stars with a number of high quality elemental abundances. They demonstrated that coeval groups of stars are linked to the chemically tagged field stars. We use a similar procedure adapted to our special cases (see Paper I and II for more details).

Principal component analysis (PCA) is another method to study stellar elemental abundances and their correlations. In brief, the PCA converts the abundances into a set of values of linearly uncorrelated variables (named components) applying an orthogonal transformation. The first two components are normally used to estimate the central locations in the PCA space for independent systems. Ting et al. (2012) has illustrated the power of this method by confirming the high yield ratio of $n$-capture elements and testing it on open clusters.

Although chemical tagging is a powerful technique to reconstruct dissolved star clusters, it is challenged by several limitations. It is still not quite clear what accuracy of the elemental abundances is needed to distinguish star formation sites. Blind chemical tagging experiments concluded that tagged groups could be contaminated by coeval stars or the stars with similar chemistry (Mitschang et al. 2014). If a higher accuracy is needed, differential abundance analyse and distinct chemical patterns of stars at different evolutionary stages should be especially considered (e.g. Gruyters et al. 2013). An increase of chemical dimensions can lead to improvements in the chemical tagging experiments, however, the difficulty in deriving abundances for some elements could introduce greater uncertainties and potential scatter.

## 1.4 Analysis of stellar spectra

In our work, Spectroscopy Made Easy (SME, Valenti & Piskunov 1996; Valenti & Fischer 2005) is used to determine the stellar parameters by comparing synthetic spectra with observed spectra. SME can also be used to determine atomic parameters ($\log gf$ and van der Waals damping) and elemental abundances for individual lines. SME performs an automatic parameter optimization using a chi-square minimization algorithm. SME requires line data, including element name, ionization state, wavelength, excitation energy of initial state, and $\log gf$, for all atomic transitions of interest. The atomic data can be obtained in different ways. In our work we have made heavy use of VALD (Kupka et al. 1999, 2000) and the line list developed for the Gaia-ESO Survey (see Heiter et al., in prep.). Further details can be found in the respective paper. Model stellar atmospheres are required to compute the synthetic spectra. In SME the model atmospheres are interpolated in the precomputed MARCS model atmosphere grid (Gustafsson et al. 2008), which have standard composition. In addition to the atmospheric models and line data, SME requires masks that contain the spectral segments, selected absorption lines, and the continuum regions. For each element, we measure its abundance ratio with respect to iron by fitting all selected lines in SME simultaneously (see Paper I and III for more details). To avoid systematic biases on determined elemental abundances, an unblended line list was selected and examined in the solar spectrum.

# Chapter 2

# The nature of stars with common kinematics

The kinematics of stars in the solar neighbourhood is an essential ingredient for the understanding of the structure and evolution of the Galaxy. It is well known that the stellar space velocity distribution has a complex small-scale structure. Stellar streams (or moving groups), which are groups of stars on very similar orbits in the Galactic potential, have been detected as over-densities in the velocity distribution of stars in the solar neighbourhood (Eggen 1996; Dehnen 1998; Arifyanto & Fuchs 2006). A stellar stream that is homogeneous in age and chemical composition is associated with a dissolved star cluster. But the stream could also originate from an accreted satellite galaxy or have a dynamical origin caused by resonances with the bar(s) or spiral arms in the Milky Way (Dehnen 2000). It is also possible to create streams in velocity space because of the result of a massive merger (Minchev et al. 2009).

## 2.1 Stellar sample

To constrain the origin of a stream, clean memberships of the candidates are needed. As the stream stars have similar kinematics, they can be detected by searching over-density regions within their phase space distributions, such as in angular momentum, eccentricity, and space velocity. Almost all discovered streams have been found or confirmed using the Hipparcos Catalogue (van Leeuwen 2007), as it offers high quality astrometry data on the positions, proper motions, and parallaxes, all essential for determining the space velocity of stars (once complemented with radial velocity).

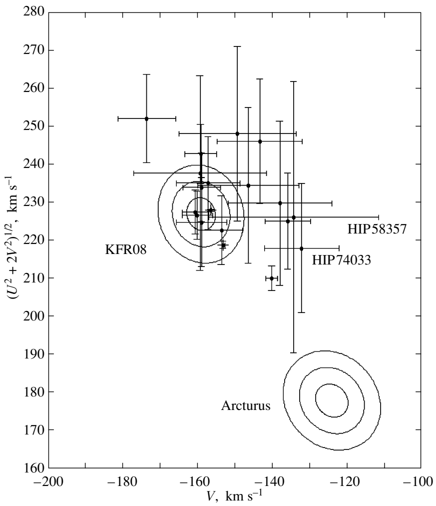


**Figure 2.1:** Positions of KFR08 stream members in the $V$ and $(U^2+2V^2)^{1/2}$ plane. Three contours corresponding to probabilities of $1\sigma$, $2\sigma$, and $3\sigma$ are given for the KFR08 and Arcturus streams. Figure adopted from Bobylev et al. (2010).

### 2.1.1 KFR08 stream members

As discussed in Arifyanto & Fuchs (2006), tidal streams show a typical "banana"-shaped distribution in $U$ and $V$ and a symmetric distribution in $U$ and $W$. On the other hand, dynamical streams show a more clump-like structure in $U$ and $V$ space. The velocities $U$, $V$, and $W$, relative to the local standard of rest, represent components toward the Galactic center, along the Galactic rotation, toward the Galactic north pole. Stars with a common progenitor are expected to cluster around regions of roughly constant eccentricity (Helmi et al. 2006). For a flat rotation curve of the Galaxy under an axisymmetric potential, eccentricity $e$ is given by (Arifyanto & Fuchs 2006):

$$e = \sqrt{\frac{U^2 + 2V^2}{2V_{LSR}^2}}. \tag{2.1}$$

Here $V_{LSR}$ denotes the circular velocity of the local standard of rest. As the velocity $V$ is related to the angular momentum $L_z$, which defines the guiding-center of the orbits of the stars, the stream stars should form a clump in the projection of velocity space ($V$, $(U^2 + 2V^2)^{1/2}$). A new candidate stream, called the KFR08 stream, was recently discovered by Klement et al. (2008) using this method. It is centered at $V \sim -160$ km s$^{-1}$ and $(U^2 + 2V^2)^{1/2} \sim 220$ km s$^{-1}$ (see Fig. 2.1).

Based on the Hipparcos Catalogue and Geneva-Copenhagen Survey of F and G dwarfs (Nordström et al. 2004), Bobylev et al. (2010) identified statistically significant signals of the main inhomogeneities in the velocity distribution using the wavelet transform technique. They found 19 stars shown in Fig. 2.1 around (–160, 225) km s$^{-1}$ in the $V$ and $(U^2 + 2V^2)^{1/2}$ plane which are possible members of the KFR08 stream. A study of the origin of KFR08 members is the subject of Paper II and is further discussed in Sect. 2.4.2.

### 2.1.2 Solar sibling candidates

The Sun is the closest star to Earth, but its birthplace is unknown. Stars that were born within an open cluster together with the Sun are called solar siblings. As the solar siblings are expected to remain near the Sun's orbital trajectory, the predicted proper motion versus parallax phase space can be used as a first selection of solar sibling candidates for further studies. Assuming that solar siblings have almost the same orbit as the Sun, their proper motion will at large distances converge to a value of about 5–6 mas yr$^{-1}$. At small distances (large parallaxes), simulations indicate that there is a group of siblings at low proper motion ($<$ 6 mas yr$^{-1}$, Brown et al. 2010). As suggested by Brown et al. (2010), we therefore selected a sample of Hipparcos stars using the following selection criteria:

$$\varpi \geq 10 \text{ mas} \wedge \sigma_{\varpi}/\varpi \leq 0.1 \wedge \mu \leq 6.5 \text{ mas yr}^{-1}, \tag{2.2}$$

where $\varpi$ and $\mu$ are the parallax and proper motion of the stars, respectively, and $\sigma_{\varpi}$ is the precision of the parallax. This equation makes use of the observationally established value of $(V_{LSR} + V_{\odot})/R_{\odot}$ in order to avoid introducing biases related to inadequacies in the simulated phase-space distribution of solar siblings (Brown et al. 2010). Inspection of stellar isochrones shows that for solar metallicity, a star with a colour of $B - V \leq 0.4$ is too young to be a solar sibling. Such stars are therefore not included as solar siblings. A study to hunt for solar siblings is the subject of Paper I and the results are discussed in Sect. 2.4.1

## 2.2 Methodology to determine stellar parameters

For the two studies described above, we obtained spectra of about 50 stars. They were analysed using the same methodology to determine stellar parameters ($T_{\text{eff}}$, $\log g$, and [Fe/H]) and elemental abundances. Briefly, we use spectrum synthesis for this. The exact method is fully described in Paper I. As the precision of the parallaxes for our sample stars is better than 15%, we utilized this to determine not only the stellar parameters but also the stellar ages (see Paper I for details).

Analysing solar sibling candidates, we found that some stars with $\log g > 4.2$ appear to fall in regions not occupied by the isochrones (Fig. 2.2). A comparison of stellar parameters

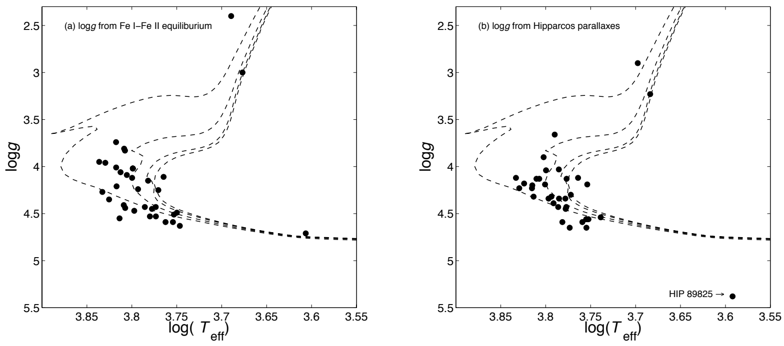


**Figure 2.2:** HR diagram for the solar sibling candidate sample a) when $\log g$ is based on FeI-FeII ionization equilibrium and b) when $\log g$ is based on Hipparcos parallaxes. Four isochrones at solar metallicity and four different ages (1, 3, 5, and 6 Gyr) according to the Yonsei-Yale models (Demarque et al. 2004) are also shown. Figure from paper I.

using parallax rather than ionizational equilibrium to derive $\log g$ shows improvements in each star's location in the HR diagram (Fig. 2.2) when we used $\log g$ derived from the parallax. This is in part because we used the isochrones to derive parallax gravities. Even though the isochrones have their own associated uncertainties (corresponding to uncertainties in stellar evolution theory), the systematic effect on the derived parallax gravities is expected to be less than 0.15 dex. Thus, the stellar parameters derived using the parallax method are in general recommended for further elemental abundances analysis (see also Bensby et al. 2014).

## 2.3 Stellar ages

The age of an individual star cannot be directly measured. It can only be estimated through model-dependent methods, such as decline in lithium, isochrone fitting, and asteroseismology. The use of isochrone fitting is possibly the only one that can be applied on a large scale to the full range of stellar ages. For a given set of stellar parameters, the age can be determined from an isochrone age probability distribution (APD), as described in Bensby et al. (2011). The most probable age is determined from the peak of the age probability distribution. $1\sigma$ lower and upper age limits are obtained from the shape of the distribution served as an error estimate. For very old (or young) stars, both the peak and the upper (or lower) error bar of the APD are not well defined, because the parameters may fall outside of the region covered by the isochrones. It should be noted that the accuracy of the age determinations are limited significantly by errors in $T_{\rm eff}$ and the systematic biases mainly caused by sampling the isochrone data points (Nordström et al. 2004).

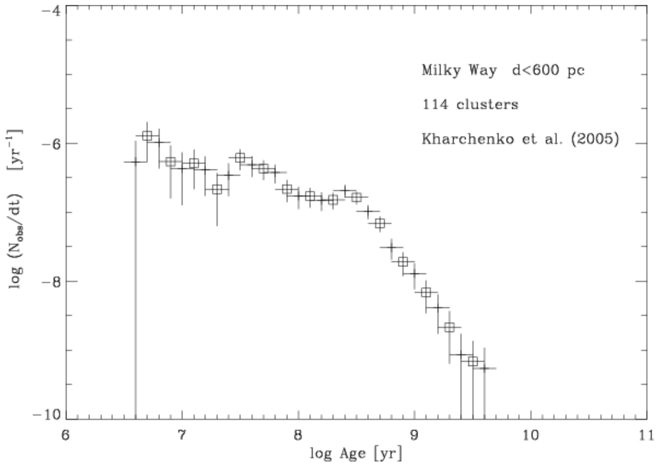


**Figure 2.3:** Age distribution of open clusters. The figure shows the age histogram in units of number per year, in logarithmic age-bins of 0.2 dex, of 114 open clusters within 600 pc from Kharchenko et al. (2005). The distributions are plotted for two sets of bins, shifted by 0.1 dex, and indicated with and without squares respectively. The error bars indicate the $1\sigma$ statistical uncertainty. Figure adopted from Lamers et al. (2005).

## 2.4 Birthplaces of the stars

### 2.4.1 The solar siblings – born in a star cluster

It was suggested by Lada & Lada (2003) that 70–90% of stars form in embedded clusters within giant molecular clouds. The age distribution of open clusters is shown in Fig. 2.3. It suggests that the majority of embedded clusters do not survive longer than 10 Myr (Lamers et al. 2005) and then dissolve and contribute to the Galactic field population. Some of them remain bound and evolve to open clusters. Janes et al. (1988) suggested that a typical lifetime of an open cluster in the disc is 100 Myr. The stellar components of the open cluster dissipate through dynamical interactions.

The Sun is likely to have been born in an open cluster consisting of a few thousand stars (Portegies Zwart 2009; Adams 2010). According to simulations of the parent cluster orbiting our Galaxy, Portegies Zwart (2009) concluded that about 10–60 of the Sun's siblings remain within 100 pc from the present-day position of the Sun. Since the cluster stars have metallicity, elemental abundances, stellar age, and kinematics in common, those parameters can be used to identify the solar siblings.

In our study of solar siblings (Paper I), elemental abundances were determined for 33 sibling candidates. Using the Na, Mg, Al, Si, Ca, Ti, Cr, Fe and Ni abundances, we performed chemical tagging experiments to identify members of the dissolved parent cluster. This resulted in a high probability (> 90%) that four sibling candidates (HIP 21158, HIP 24232, HIP 40317, and HIP 73600) share the same origin as the Sun. The abundance patterns of the four tagged stars are compared with that of the Sun in Fig. 2.4. Given further constraints on metallicity and stellar age, we found that only HIP 40317 is consistent with the properties of the Sun. However, HIP 40317 has a relatively high barycentric radial velocity (34 km s$^-$1). Simulations of the Sun's birth cluster in a non-axisymmetric model of the Galaxy were performed in order to assess the probability to detect such high radial velocity solar siblings. This results in that most of the radial velocities of the solar siblings lie in the range $-10 \leq V_r \leq 10$ km s$^{-1}$, which is lower than the radial velocity of HIP 40317. The probability that a solar sibling in the solar neighborhood has such a large radial velocity is at most $\sim$ 2.5%. Thus, although the abundance and age data favour sibling status for the identified star, it is not directly supported by the dynamical arguments.

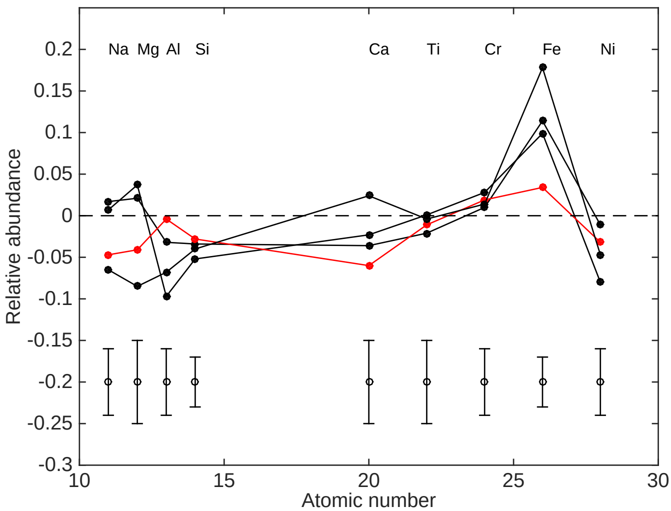


**Figure 2.4:** Relative elemental abundance ratios with respect to the Sun ([X/Fe]) as a function of atomic number for the four sibling candidates that were tagged (see Paper I). When the element is Fe, the relative elemental abundance is [Fe/H]. The abundance ratios of HIP 40317 are highlighted in red filled circles connected with red lines. The dashed line indicates the solar abundance. The circles with error bars represent the estimated errors of elemental abundances.

One interesting question is: Where has the Sun been formed in our Galaxy? The determination of the birth radius of the Sun is interest in the context of radial migration. It is possible that the Sun has migrated from its birthplace to its current position. Wielen et al. (1996) found that the Sun has travelled outwards by about 2 kpc from the birthplace over

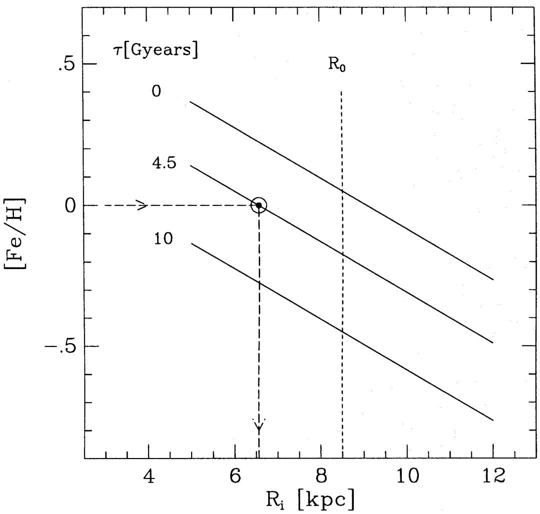


**Figure 2.5:** Schematic explanation for the determination of the birth-place of the Sun. The metallicity is shown as a function of the galactocentric distance $R_i$ of a star at birth for various ages $\tau$. $R_0$ is the present distance of the Sun from the Galactic center. Using [Fe/H] = 0 and $\tau_\odot$ = 4.5 Gyr as input data, a galactocentric distance $R_{i,\odot}$ = 6.6 kpc is found. Figure adopted from Wielen et al. (1996).

the past 4.6 billion years. Adopting the presence of a radial galactic gradient in metallicity (see Fig. 2.5), their conclusion is derived from an observation that the Sun has a metallicity +0.17 dex higher than the average metallicity of nearby F and G dwarfs of solar age. Comparing the cosmic abundance standard that was obtained by measuring early B-type stars in solar neighbourhood with the solar standard, Nieva & Przybilla (2012) also claim that the Sun has migrated outwards from its birthplace in the inner disk at 5–6 kpc Galactic distance over its lifetime to the current position. However, Martínez-Barbosa et al. (2015) carried out orbit integrations backward in time using an analytical model of the Galactic potential which includes the contribution of spiral arms and a central bar. They found that in most of their simulations the Sun has not migrated from its birth place to its current position. This is consistent with the recent studies of the Geneva-Copenhagen Survey data (Casagrande et al. 2011) that the metallicity of the Sun is not unusual with respect to the surrounding stars of the same age.

There are several indications that the solar system was formed in a bound cluster, including the excitation of the Kuiper Belt (Morbidelli & Levison 2004), the extreme orbital elements of Sedna (Brown et al. 2004), and the presence of short-lived radioisotopes in meteorites (Wadhwa & Russell 2000). Although the solar system was formed in a relatively dense star cluster, the cluster dissolved 4.3 Gyr ago (Portegies Zwart 2009; Adams

2010). Recent work based on high-resolution spectra of evolved and solar-type stars in M67, indicate that they have almost the same chemical compositions as the Sun (Friel et al. 2010; Önehag et al. 2014). The very similar metallicities, ages, and distance from the Galactic center of the Sun and M67 (see e.g. Önehag et al. 2011), suggest that the Sun and M67 might have a common birthplace within a giant molecular cloud. Based on Monte Carlo numerical simulations, however, Pichardo et al. (2012) show a very low probability ($< 10^{-7}$) that the Sun was ejected from M67 in an encounter with a giant molecular cloud, as the relative velocity between the Sun and M67 is larger than 20 km $s^{-1}$. It should noted that the giant molecular clouds could heat the disk stars and the orbits of stellar clusters (see Gustafsson et al., submitted). Assuming that M67 and the Sun were not born on their current orbit, although present-day position of M67 is about 400 pc above the plane, there is still a chance that the Sun comes from M67 (private communication with Ross Church).

## 2.4.2 KFR08 stellar streams

As mentioned at the beginning of this Chapter, there are at least three different mechanisms to form a stellar stream. Assuming that a progenitor is a chemically homogeneous cluster, the stars in the stream should have the same elemental abundances. Based on an analysis of high-resolution spectra, we determine stellar parameters, stellar ages, and detailed elemental abundances for 16 KFR08 stream members. To find out whether the KFR08 stream originates from a dissolved star cluster, we perform a chemical tagging experiment. We here use the abundances of 14 elements (Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Fe, Ni, Zn, Y, Ba, and Eu) to identify members with similar abundances. Given a confidence limit of $P_{\rm lim}$ = 68%, three stars with similar abundances could belong to one group (see Fig. 2.6). However, no star is tagged as a member of a group of stars when tested with a higher threshold ($P_{\rm lim}$ = 85%). This result is consistent with the prediction that half of the tagged members are interlopers when we use a low threshold (Mitschang et al. 2013). We further examine the kinematics of the three stars. It turns out that the star-to-star scatter of radial velocity with respect to the Sun is larger than 50 km $s^{-1}$. This is one order of magnitude higher than the velocity dispersion of cluster stars. One of the three stars (HIP 74033) has a relatively low probability ($\sim$ 65%) of belonging to the KFR08 stream (Bobylev et al. 2010). It is also a potential member of the Arcturus stream as discussed in Arifyanto & Fuchs (2006). All of this suggests that the stream does not originate from a star cluster.

Does the KFR08 stream originate from an accreted galaxy? That it is part of the tidal debris from a satellite was suggested by Klement et al. (2008), because of the high $W$ velocities of the stream stars. However, the mean $W$ and $U$ velocities of our sample are $W = -7 \pm 65$ km $s^{-1}$ and $U = -12 \pm 86$ km $s^{-1}$. The low velocities might be inconsistent with the hypothesis that the KFR08 stream was accreted from a dwarf satellite galaxy. Chemically, the stream members have a mean metallicity of [Fe/H] = –0.75 and are $\alpha$-enhanced. This

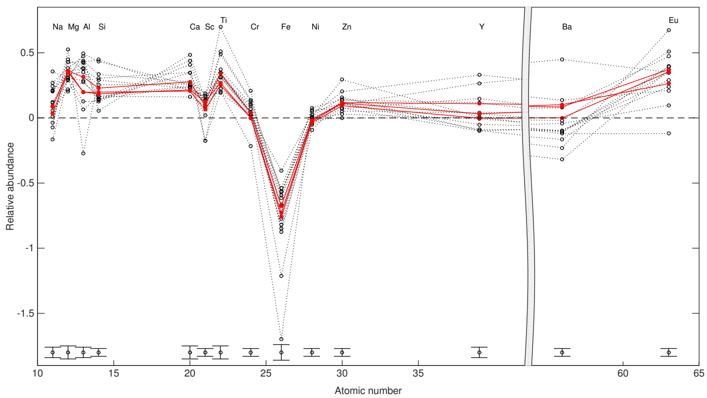


**Figure 2.6:** Relative elemental abundance ratios with respect to the Sun ([X/Fe]) as a function of atomic number for the KFR08 stream members. When the element is Fe, the relative elemental abundance is [Fe/H]. The red dots with red lines represent the abundance patterns of the three stars tagged as cluster stars according to our chemical tagging technique, while circles with dotted lines represent the abundance patters of the other stars in our sample. The dashed line indicates the solar abundance. The grey break in the x-axis is due to the cut between Y and Ba elements. Figure adopted from Paper II.

speaks against the accretion debris origin of the stream if we expect its progenitor to be similar to present-day dSph galaxies, as observations show that surviving dwarf satellite galaxies have low [$\alpha$/Fe] ratios (Tolstoy et al. 2009). But it should be noted that a high-mass dwarf galaxy has a higher rate of star formation than the low-mass satellites, and that their metallicity can be enriched to [Fe/H] = –0.6 (Tamura et al. 2001). We therefore cannot rule out a satellite progenitor of the stream, with a substantial mass similar to that of the LMC or Sgr dwarf galaxy.

We find that the abundance patterns of stream stars match the thick-disc population well. For our sample, the mean [Eu/Mg] = –0.02 $\pm$ 0.20 dex is consistent with the trends found for the thick-disc stars rather than the halo stars (Mashonkina et al. 2003). In term of their kinetic energy, the kinematics of the stream is intermediate between the thick disc and halo populations. They might have once belonged to the thick disc and gained hot kinematics as a result of a satellite merger. According to the stellar age estimation, most of the stream members have very old age ($>$ 11 Gyr). All of this suggests that the members of the KFR08 stream have a dynamical origin due to a strong perturbation from a merger event in the early Universe.

# Chapter 3

# Spectral analysis of a metal-rich globular cluster

It has long been known that the Galactic globular cluster system contains at least two distinct groups: a metal-poor ([Fe/H] $\leq$ –0.8) system and a metal-rich ([Fe/H] $>$ –0.8) system (Zinn 1985). The metal-poor globular clusters generally are associated with the Galactic halo population, while most of the metal-rich systems have the properties of a bulge population. There is a group of the metal-rich globular cluster projected within the Galactic center and about 60 globular clusters have galactocentric distances $R_{\mathrm{GC}} < 4$ kpc (Barbuy et al. 1999). These highly concentrated globular cluster could be associated with the Galactic bulge (Bica et al. 2006).

## 3.1 Phenomena of the globular clusters

Globular clusters have been considered good examples of single stellar populations. A single stellar population can be described by a single isochrone in the colour-magnitude diagram (CMD). The structure of the CMD includes the horizontal branches (HB), the red giant branch (RGB) stars, and the main-sequence turn-off (MSTO). The TO region can not be clearly identified in the CMD for the cluster in the bulge, because they are distant to us and subjected to strong contamination. For the metal-rich globular clusters, the luminosity of the RGB bump is fainter than the red HB (see Fig. 3.1). The RGB, the TO and the HB of the bulge field and globular cluster will also appear at the same magnitudes and colours making correct identification hard. One example, for the metal-rich globular cluster NGC 6528 and surrounding bulge stars is shown in Fig. 3.1. As can

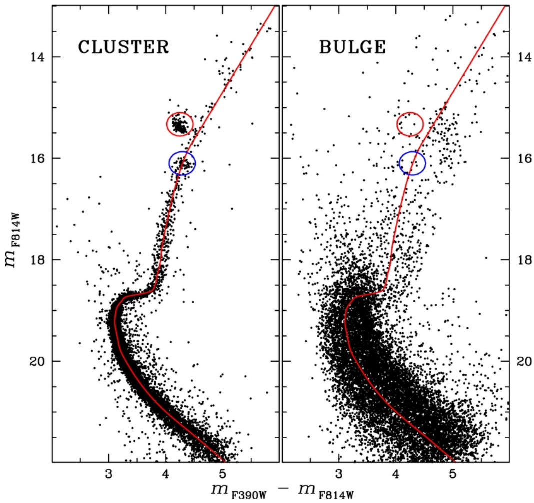


**Figure 3.1:** Left panel: CMD of cluster NGC 6528 members. The red solid line shows the ridge line of NGC 6528, while the red and the blue ellipses mark the position of red HB stars and of RGB bump stars. Right panel: same as the left, but for bulge stars. The line and the symbols are the same of the left panel. Figure adopted from Lagioia et al. (2014).

been seen, the bulge cluster projected onto the bulge will have a strongly contaminated CMD. Then, it is important to get clean cluster members before questing the properties of one bulge cluster.

The best cluster membership is to obtain proper motion (PM) and radial velocities (RVs) for the stars. Some clusters have PM very distinct from that of the field (Zoccali et al. 2001, e.g. NGC 6553), whilst other have an RV that is very distinct from that found in the field (e.g. NGC 6528). PMs can be obtained by comparing the position of stars measured at two different epochs. In an ideal scenario, the globular cluster has a distinguishable motion in relation to the field stars. Two different motions will form two distinct distributions in the proper motion diagram. In practice, the candidate cluster members cluster together, while the field stars are distributed over a broad range of PMs, because the field stars have a larger velocity dispersion than that of the cluster stars. The PM approach is limited to a small sample of globular clusters which have deep image from $HST$ (Bellini et al. 2014).

Radial velocity measurement is another useful (and much used) method to pick out the cluster members from the field stars. As the globular cluster is a strongly gravitationally bound stellar system, the cluster stars should have similar radial velocity. The velocity dispersion in globular clusters have been measured by Pryor & Meylan (1993). They found that the typical velocity dispersion is less than 10 km s$^{-1}$. Therefore the cluster members can be confidently separated from the field stars if the radial velocity of the cluster is significantly different from the mean radial velocity of the surrounding stars.

## 3.2 Membership for NGC 6528

According to Harris (1996), the heliocentric radial velocity $v_r$ of NGC 6528 is 184.9±3.8 km s$^{-1}$, while the average radial velocity of the field stars is less than 50 km/s in the bulge (Zoccali et al. 2014). For our case, the RV is thus a good criterion to select the member of NGC 6528. We derive a mean velocity for NGC 6528 of 212.11 km s$^{-1}$ with $\sigma$ = 4.28 km s$^{-1}$ for 26 cluster members. Further details on member selection can be found in Paper III.

## 3.3 Methodology to determine stellar parameters and metallicity

It is problematic to analyze the spectra of metal-rich red giant branch stars in the bulge. This could be caused by (1) reddening and crowding that hamper accurate observations toward the Galactic bulge; (2) line blending; and (3) the ambiguous location of the continuum in the stellar spectra due to the atomic line crowding and molecular bands.

To determine stellar parameters and metallicity for the metal-rich giants, different methods that combine the measurement of H$\alpha$, Ca, and iron lines were explored. As iron lines are the most common ion in terms of lines in an observed spectrum, the standard approach is to impose excitation equilibrium for Fe I lines and impose ionization equilibrium for Fe I and Fe II lines simultaneously. The hydrogen lines are sensitive to the temperature and do not depend on the gravity. It is common to determine $T_{\rm eff}$ by fitting the H$\alpha$ wings. Wide metal lines, such as Ca lines at 612.2, 616.2, and 643.9 nm, show strongly pressure-broadened wings in the spectra of cool stars. As [Fe/H] can be easily estimated from iron lines, the combination of the only H$\alpha$ and Ca lines with the Fe I or Fe II lines was used to determine the stellar parameters. In paper III we explored different ways of combining these measurements to a suitable method.

To test which method is the best to determine the parameters accurately, we adopted ten benchmark stars from a set of reference stars (Heiter et al. 2015). Ten red giants in the list of the Gaia benchmark stars, which have [Fe/H] greater than –0.55 dex, were selected. For these benchmark stars, $T_{\rm eff}$ and $\log g$ are well determined independently of spectroscopy, and the metallicity of each benchmark star has been carefully derived through spectroscopic analysis (Jofré et al. 2014).

As mentioned before, the H$\alpha$ line can give us a good estimate of $T_{\rm eff}$ (see Fig. 3.2). It should be noted, however, that its wings suffer strong contamination from blend in the spectra for cooler metal-rich giants ($T_{\rm eff}$ < 4400 K), potentially resulting in a serious problem for the normalization of the continuum around the lines (see Fig. 3.3). We

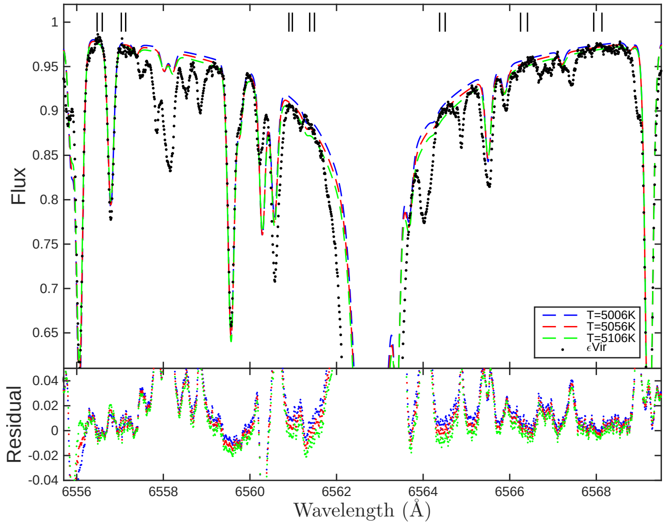


**Figure 3.2:** Comparison of synthetic spectra with the wings of H$\alpha$ for the Gaia benchmark stars $\epsilon$Vir ($T_{\rm eff}$ = 4983 K, $\log g$ = 2.77 cm s$^{-2}$, [Fe/H] = 0.15). The middle synthetic spectrum (in red colour) is the best fit to the H$\alpha$ wings, and the other two synthetic spectra indicate the shape of the wings when $T_{\rm eff}$ is changed according to our estimated uncertainty. Short, vertical lines at the top indicate the regions which were used to evaluate the goodness of the fit. The residuals of the comparison are shown in the bottom of plot. Figure adopted from Paper III.

further found that the wings of the H$\alpha$ line almost vanish for these stars. Therefore, a better option might be to derive $T_{\rm eff}$ using Fe I lines (exitational equilibrium) rather than the wings of the H$\alpha$ line for these stars. We thus split the finally adopted method into two parts:

For the warm giants with $T_{\rm eff} \geq 4400$ K, the following steps are used:

1. Take the parameters obtained from the standard method (excitation and ionization equilibrium) as initial input;
2. Fit the wings of H$\alpha$ to derive $T_{\rm eff}$ (Fig. 3.2), while the other parameters are kept fixed;
3. Fit the wings of the three strong Ca lines ($\lambda$ 612.22, 616.22, and 643.91 nm) to determine $\log g$. To break the degeneracy of $\log g$ and Ca abundance, several weak Ca lines are also fitted at the same time;
4. Derive [Fe/H] from the Fe I lines by setting both $v_{\rm mic}$ and $v_{\rm mac}$ free, while the other parameters are kept fixed at the values derived in the steps above;

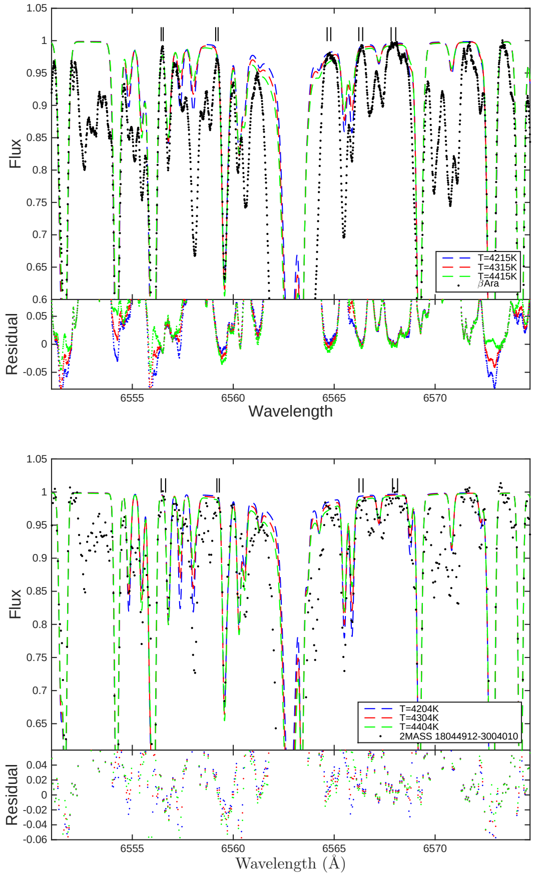


**Figure 3.3:** Comparison of synthetic spectra with the wings of H$\alpha$ for the Gaia benchmark star $\beta$Ara ($T_{\rm eff} = 4197$ K, $\log g = 1.05$ cm s$^{-2}$, [Fe/H] = –0.05) and a NGC 6528 star 2MASS 18044912-3004010 ($T_{\rm eff} = 4304$ K, $\log g = 1.52$ cm s$^{-2}$, [Fe/H] = 0.04). The dashed and vertical lines have the same meaning as in Fig. 3.2.

5. Repeat steps 2 to 4 with updated parameters ([Fe/H], $v_{\rm mic}$, and $v_{\rm mac}$) until all five parameters reach convergence.

For the cool giants with $T_{\rm eff} < 4400$ K, the following steps are used:

1. Take the parameters obtained from the standard method as initial input;
2. Fit the wings of the three strong Ca lines to determine $\log g$ and several weak Ca lines to break the degeneracy of $\log g$ and Ca abundance simultaneously;

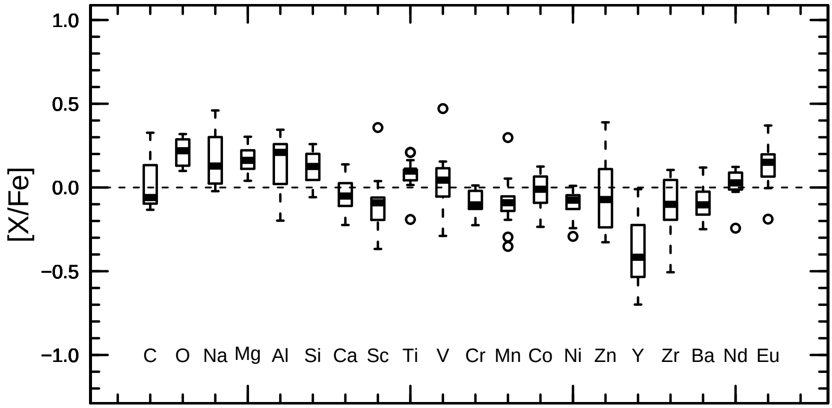


**Figure 3.4:** Boxplots for each element are plotted for NGC 6528 members with S/N > 35. The lower and upper extent of each box represents the 1st and 3rd quartile of the [X/Fe] values, respectively. The black bar inside each box represents the median (2nd quartile) [X/Fe] value. The whiskers extending beyond each box represent the variability beyond the upper and lower quartiles. Points lying outside of these whiskers represent those values of [X/Fe] which are considered outliers. Figure adopted from Paper IV.

3. Setting both $v_{\mathrm{mic}}$ and $v_{\mathrm{mac}}$ free while keeping $\log g$ fixed, $T_{\mathrm{eff}}$ and [Fe/H] are determined by only fitting Fe I lines at the same time;

4. Repeat steps 2 to 3 with updated parameters until all five parameters converge.

## 3.4 Elemental abundances in NGC 6528

For our sample, the stellar parameter and the metallicity were determined by making use of the method described in Sect. 3.3. The metallicity ([Fe/H]) distribution of NGC 6528 members can be fitted by a single Gaussian. We thus obtain a main peak at [Fe/H] = 0.0 with a dispersion of $\sigma$ = 0.11 dex. Limiting the members of NGC 6528 with high S/N (> 35) spectra, the mean metallicity is [Fe/H] = –0.03±0.08 dex. The small star-to-star scatter of NGC 6528 suggests that the cluster is homogenous in the metallicity. This result is consistent with the observations that there is no variation in iron abundance in most globular clusters (Carretta et al. 2009a). The comparison of our results and the metallicities derived from other studies suggests that our determination of [Fe/H] is consistent with previous studies based on high-resolution spectra of smaller samples (Carretta et al. 2001; Zoccali et al. 2004). As NGC 6528 is located in Baade's window, it is interesting to compare the cluster stars and the field stars. We find that NGC 6528 has almost the same metallicity as the mean metallicity of the surrounding field stars.

In the Paper IV, abundance ratio of 18 elements, including $\alpha$-elements, iron peak elements, odd-Z elements, s- and r-process elements, are measured. The results show that the majority of $\alpha$-elements are typically enhanced with a exception of Ca. It suggests that the cluster stars were likely enriched by SNe II at early epochs. The under-abundance of Mn suggest that the stars in our sample have undergone little enrichment from SNe Ia. NGC 6528 has probably undergone little pollution from intermediate-mass AGB stars. This is consistent with our observations that the element Eu are moderately enriched while the stars are deficient in s-process (e.g. Y, Zr, and Ba, see Fig. 3.4).

# Chapter 4

# Future work

The European Space Agency Gaia mission will survey the full sky and derive unparalleled high-precision 3D space motions and distances of stars far beyond the solar neighborhood. As a complement to Gaia, the follow-up ground-based spectroscopic surveys will deliver high-resolution spectra for more than a hundred thousand stars, such as Gaia-ESO (Gilmore et al. 2012), and millions of stars from WEAVE (Dalton et al. 2012), and 4MOST (de Jong et al. 2014). Then, a large sample of disk field stars with a number of high quality elemental abundances can be obtained from the spectra. Based on chemical tagging method mentioned in Sect. 1.3, we would be able to search for the solar siblings from those ground-based datasets. The dynamical analysis based on more realistic Galactic model will further constrain these chemically identified solar sibling candidates. Additionally, by exploring large sample stellar chemistry, we will be able to identify coeval stars that are the members of dissolved star clusters by using the chemical tagging technical. These stars likely move throughout the Galactic disk via radial migration, which transports a star from a circular orbit to another at a different radial distance in the disk. The present-day distribution of these stars provides a strong constraint on the rate of radial diffusion or migration in the Galactic disk (Bland-Hawthorn et al. 2010).

The bulge has a rich population of globular clusters. NGC 6553 is another metal-rich globular located in a low extinction region called Baade's Window. This cluster is another good template for metal-rich populations and distant galaxies. As it has been observed in optical and infrared wavelength for red giant branch stars within different programs and surveys, we would like to collect their high-resolution spectra from archives and use the methodology described in Sect. 3.3 to derive their metallicity and the abundance ratios of elements, especially [$\alpha$/Fe]. In addition to our results of NGC 6528 (see Paper III and IV), it allows us to better understand the formation and evolution of the globular clusters.

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# Author contributions

The next page summarizes the individual papers and my contribution to each of them.

# Paper I: Quest for the lost siblings of the Sun

**C. Liu**, G. Ruchti, S. Feltzing, C. A. Martínez-Barbosa, T. Bensby, A. G. A. Brown, and S. F. Portegies Zwart
Astronomy & Astrophysics, vol. 575, A51 (2015)

The aim of this paper is to find lost siblings of the Sun by analyzing high resolution spectra. Finding solar siblings will enable us to constrain the parameters of the parental cluster and the birth place of the Sun in the Galaxy. The solar siblings can be identified by accurate measurements of metallicity, stellar age and elemental abundances for solar neighbourhood stars. The solar siblings candidates were kinematically selected based on their proper motions, parallaxes and colours. Stellar parameters were determined through a purely spectroscopic approach and partly physical method, respectively. Comparing synthetic with observed spectra, elemental abundances were computed based on the stellar parameters obtained using a partly physical method. A chemical tagging technique was used to identify the solar siblings. We present stellar parameters, stellar ages, and detailed elemental abundances for Na, Mg, Al, Si, Ca, Ti, Cr, Fe, and Ni for 32 solar sibling candidates. Our abundances analysis shows that four stars are chemically homogenous together with the Sun. Technique of chemical tagging gives us a high probability that they might be from the same open cluster. Only one candidate –HIP 40317– which has solar metallicity and age could be a solar sibling. We performed simulations of the Sun's birth cluster in analytical Galactic model and found that most of the radial velocities of the solar siblings lie in the range $-10 \leq V_r \leq 10$ km s$^{-1}$, which is smaller than the radial velocity of HIP 40317 ($V_r = 34.2$ km s$^{-1}$), under different Galactic parameters and different initial conditions of the Sun's birth cluster. The sibling status for HIP 40317 is not directly supported by our dynamical analysis.

*My contribution:*
In this project, I reduced the FIES spectra using the FIEStool pipeline and collected other reduced spectra from the ESO archive. I led an improvement of a methodology to efficiently and accurately measure the physical parameters (e. g. effective temperature, surface gravity, and metallicity). I compiled the linelist and measured elemental abundances by comparing synthetic with observed spectra. With the help of Thomas Bensby, stellar ages were also calculated from isochrones. Based on elemental abundances, I led chemical tagging experiment and found that four stars might be from the same star cluster. To assess what are the probabilities to detect a high radial velocity solar siblings ($> 30$ km s$^{-1}$), the state-of-the-art simulations of the Sun's birth cluster in a non-axisymmetric model of the Galaxy were performed by Carmen A. Martínez-Barbosa. The discussion and interpretation of the results were mainly done together with Sofia Feltzing and Gregory Ruchti. Except for the text of Section 7.2 (contributed by Carmen A. Martínez-Barbosa), the text

was written by me with corrections and suggestions from other collaborators.

## Paper II: The nature of the KFR08 stellar stream

**C. Liu**, S. Feltzing, and G. Ruchti
Astronomy & Astrophysics, vol. 580, A111 (2015)

The origin of the new kinematically identified metal-poor stellar stream, the KFR08 stream, has not been established to date. We present stellar parameters, stellar ages, and detailed elemental abundances for Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Ni, Zn, Sr, Y, Zr, Ba, La, and Eu for 16 KFR08 stream members based on an analysis of high-resolution spectra. Based on the abundance ratios of 14 elements, we use the chemical tagging method to identify the stars with the same chemical composition that therefore might have a common birthplace, such as a cluster. Although three stars were tagged with similar elemental abundances ratios, we find that, statistically, it is not certain that they originate from a dissolved star cluster. This conclusion is consistent with the large dispersion of [Fe/H] ($\sigma_{[Fe/H]}$ = 0.29) among the 16 stream members. We find that our stars are $\alpha$-enhanced and that the abundance patterns of the stream members match the thick-disc population well. In addition, most of the stream stars have estimated stellar ages greater than 11 Gyr. These results, together with the hot kinematics of the stream stars, suggest that the KFR08 stream originated from the thick-disc population, which was perturbed by a massive merger in the early Universe.

*My contribution*
I reduced the FIES spectra using the FIEStool pipeline and collected other reduced spectra from the ESO archive. Based on the previous developed methodology, I measured stellar parameters and elemental abundances for the stream stars. I led chemical tagging experiments and excluded a dissolved cluster as the origin of the KFR08 stream. To further constrain the origin of the stellar stream, I calculated angular momentum and kinetic energy of stream members. The discussions and interpretation of the results were done together with with Sofia Feltzing and Gregory Ruchti. The text was written by me with corrections and suggestions from co-authors.

## Paper III: A methodology to determine stellar parameters and metallicities for metal-rich red giant branch stars. An application to NGC 6528

**C. Liu**, G. Ruchti, S. Feltzing, and F. Primas
Astronomy & Astrophysics, submitted

Temperature, surface gravity, and metallicity are basic atmospheric parameters necessary to characterize a star, as well as to determine elemental abundances. As the standard methods are problematic to determine stellar parameters for the metal-rich giants, a new method that combines the measurement of H$\alpha$, Ca, and iron lines is developed. Testing on benchmark stars, our determined parameters are well agreement with the recommended values within uncertainties. We measure heliocentric radial velocity from high-resolution spectra for 34 sample stars and find that 26 radial velocity members of NGC 6528 cluster at 212.11 km $s^{-1}$ with a dispersion $\sigma = 4.28$ km $s^{-1}$. Based on our developed methodology, the present determination of stellar parameters provides a metallicity [Fe/H] = –0.03$\pm$0.08 dex which is consistent with the mean metallicity of surrounding field stars.

*My contribution*
All the raw data from our observations and collected from ESO archive were reduced making use of the different pipelines by me. I confirmed NGC 6528 members by measuring heliocentric radial velocity of the sample stars. I led a development of methodology which was tested on a set of benchmark stars to accurately measure the stellar parameters for the metal-rich red giant brach stars. The development of the method was done in discussion with Gregory Ruchti, while I carried out all the tests and developed the pipelines. The discussion of the metallicity distribution were done with Sofia Feltzing. The text was written by me with corrections and suggestions from co-authors.

## Paper IV: Elemental abundances in NGC 6528 – one of the most metal-rich globular clusters

G. Ruchti, **C. Liu**, S. Feltzing, and F. Primas
Astronomy & Astrophysics, manuscript in prep.

Here we study the elemental abundances in one of the most meta-rich globular clusters known, NGC6528. This cluster is important as it often is used as a calibrator for studies of photometry or integrated light from clusters in extra-galactic studies. If the stars in the cluster are alpha-enhanced then this need to be taken into account in the modeling of the population properties. To date there is a range of answers to the question if this cluster is indeed enhanced in the alpha-elements or not. In a previous paper we have studied the metallicity of this cluster in some detail and developed a method to determine stellar parameters in a consistent and well tested manner from high resolution (but sometimes poor S/N) spectra of evolved red giant stars. We now use these parameters and spectra to investigate the further properties of this cluster based on a large radial velocity selected sample of members.

*My contribution*
I reduced all the raw spectra of NGC 6528 collected from the ESO archive by making use of the different pipelines. I measured the heliocentric radial velocity of the sample stars and excluded the non-members of NGC 6528 by training $3\sigma$-clipping. Based on the developed methodology in Paper III, I measured the stellar parameters for all the stars. I participated the discussion of the results with Sofia Feltzing and Gregory Ruchti. I have written the text of the section on the stellar parameters and given suggestions to the paper.