



astronomy

An outsider's view on the metallicity and α -abundance distribution of the Milky Way



Figure 1: Metallicity and α -abundance distributions of the Milky Way as viewed from outside.

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1.1 Background

In the first seconds after the Big Bang the first elements were created. Most of the particles, ~ 92%, are in the form of hydrogen and approximately 8% is in the form of helium. Except for a small amount of lithium, no other metals were created. As the Universe expanded and cooled down, the first stars and galaxies started to form. In the very centre of a star hydrogen is burned into helium. At the end of a star's lifetime, helium is burned into heavier elements. The mass of the heaviest element that a star can produce becomes larger for more massive stars. This continues until iron is reached. Most metals are synthesized by combining multiple helium nuclei, like ²⁰Ne, ³²S and ³⁶Ar, the so-called α -elements. Other elements can be produced by atoms catching free neutrons and by radioactive decay.

As stars evolve, there can be episodes in which the outer layer of the stars mixes with inner layers. At the end of a star's lifetime, these outer layers are expelled and a star 'dies'. The most massive stars end their life with a violent explosion. The gas that originally made up the star has been 'enriched' by heavier elements and is returned to the interstellar medium. The stars that form from the enriched interstellar medium will have a higher metal abundance compared with their ancestors. The more frequent the recycling process occurs, the higher the metal abundances will become.

The light from stars is examined in two different ways: by photometry and by spectroscopy. From photometry one can determine how bright a star is and what its colours are. It is even possible to determine the effective temperature and the rough chemical composition. These stellar parameters can be derived better from spectroscopy. This is done by comparing the observed spectra with synthetic spectra. A synthetic spectrum is made from a model star for a set of stellar parameters: this includes not only the chemical composition, but also the gravitational acceleration at the surface and the effective temperature of the star.

1.2 Goal of the project

There are many studies tracing the abundances of many elements in our own Milky Way and there are also many studies looking at the abundances of other galaxies. In this report we make the translation from the abundance values for our Milky Way as observed from inside the disk to how it would look like if one would observe it from outside. The difference from the two observer positions is that an observer inside the disk only looks at individual stars while the distant outsider can only see the total light from stars and not individual stars. The observer in the disk will look most of the time at low-luminosity stars, which is the largest group of stars. For the outsider however, most of the starlight he or she looks at comes from high-luminosity stars.

Our Galaxy has four components: the bulge, the thin and thick disk and the halo. Although the halo is the largest and the most massive component, since the number of stars and the surface brightness is very low and it would be almost impossible to determine its



Figure 1.1: The Milky Way in the infrared. One can see the bulge in the middle, and the disk. In the middle of the disk it has a red/yellow colour due to the combination of light from stars and dust and is called the thin disk. Above and below the yellow coloured thin disk one can see a white band due to starlight only, the thick disk. The halo is almost invisible in this image. The image is made with the COBE satellite.

metallicity from outside.

The number of thin disk stars is much larger than the number of thick disk stars as one can also see from Figure 1.1. Therefore, we ignore the thick disk stars to avoid too much contamination from the thick disk. This leaves us with the two most visually striking parts of the Milky Way: the thin disk and the bulge. It is virtually impossible to observe the entire thin disk due to the large amount of gas and dust. In addition, abundances can vary at different places in the disk. Hence, we determine the metallicity and α -abundance in the Solar neighbourhood and extrapolate it over the entire disk.

A successful translation from the disk observer to the outside observer can hopefully enable one to compare the metallicity and abundance distribution of the Milky Way with other galaxies. We will therefore compare our metallicity and α -abundance with those of other galaxies like our Milky Way.

1.3 Metallicity and α -abundance

Metallicity is defined as the abundance of iron atoms and with α -abundance we mean the average abundance of α -elements. Abundances can be given in two ways, by number fractions and by mass fractions. Because number fractions are what one observes, the metallicity is defined as:

$$[Fe/H] \equiv \log_{10} \left(\frac{N_{Fe}}{N_{H}}\right)_{*} - \log_{10} \left(\frac{N_{Fe}}{N_{H}}\right)_{\odot}$$
(1.1)

where the subscript * denotes the star of our interest and \odot the solar value. Similarly, the α -abundance of a star is defined by:

$$\left[\alpha/\mathrm{Fe}\right] \equiv \log_{10} \left(\frac{N_{\alpha}}{N_{\mathrm{Fe}}}\right)_{*} - \log_{10} \left(\frac{N_{\alpha}}{N_{\mathrm{Fe}}}\right)_{\odot}$$
(1.2)

A positive value indicates that the metallicity or the α -abundance is higher in the star than in the Sun and vice versa. It is common in astronomy to assign the unit dex to a log-value, so we will use the same convention.

In most papers $[\alpha/\text{Fe}]$ is defined as the mean abundance of some α -elements, mostly including Mg, Si, Ca, Ti and sometimes Al. A weighted mean has been used in this report and is explained in the first part of chapter §3.

One may be surprised that oxygen and carbon are not mentioned as possible elements included in the $[\alpha/\text{Fe}]$ -definition as their abundance can be several orders of magnitudes larger than e.g. Ti. The reason behind it is that their abundance can be altered during the CNO cycle in contrast to other α -elements. On top of this, oxygen is hard to observe in stars and virtually impossible to observe in the starlight of other galaxies.

1.4 Methods

We select only stars with spectroscopically determined abundances, since these are more accurate than those derived from photometry. This will cause no problems for the disk, but for the bulge the number of stars with photometrically derived abundances is much larger than those with spectroscopic abundances.

In chapter 2 we will use two large spectroscopic surveys to determine the metallicity and abundance in the Solar environment. Only stars in the Solar neighbourhood are selected, and not from the entire disk, since the metallicity and abundance can vary at different places in the disk. We make a velocity selection to select thin disk stars near the Sun. As neither survey provides space velocities, we determine these ourselves using a method called isochrone fitting: matching a star with observed parameters to a model star with the same parameters and in addition absolute magnitudes. The absolute magnitudes are used in calculating the distances and space velocities by combining the distances with radial velocities and proper motions.

Since the number of bulge stars with spectroscopically determined metallicity and α abundance is low, chapter 3 has been divided into two parts: bulge field stars and stars inside globular clusters.

The extrapolation of the mean values for the Solar neighbourhood to the entire to the entire disk is described in chapter 4. We then continue with transforming the observer's position inside the disk to outside the galaxy. The absolute magnitudes obtained from isochrone fitting have been used to make the translation to outside the Milky Way by calculating a weighted [Fe/H] and $[\alpha/Fe]$. We then redetermine the metallicity and α -abundance for the disk using the luminosity function of stars in the solar neighbourhood. In chapter 6 we will compare our average [Fe/H] and $[\alpha/Fe]$ with those of other galaxies.

There are several studies which look at the metallicity in the Solar neighbourhood, for instance the Geneva-Copenhagen survey (Nordström et al., 2004). The problem with most of these studies is that only a particular group of stars is considered: in the case of the Geneva-Copenhagen survey they only observed F and G-type dwarf stars. While F and G-type stars dominate the number of stars, their contribution to the total starlight is only ~ 50%. The other ~ 50% comes from giants, which were not observed in this survey.

For the disk there are two interesting surveys that contain both dwarfs and giants: the Sloan Extension for Galactic Understanding and Exploration (SEGUE) and the RAdial Velocity Experiment (RAVE). The SEGUE-survey is a spectroscopic survey of the sky "with the goal of studying the kinematics and populations of our Galaxy and its halo" (Yanny et al., 2009). RAVE is "an ambitious spectroscopic survey to measure radial velocities and stellar atmosphere parameters (temperature, metallicity, surface gravity, and rotational velocity) of up to one million stars" (Zwitter et al., 2008).

Both surveys have a selection criterion depending on magnitude, although for SEGUE survey they have additional selection criteria such that mainly stars at large distances are selected and RAVE mainly looks at stars outside the disk. Although magnitude selection is not the best criteria for our purpose, there are no other surveys meeting our intention better.

Both survey are magnitude-limited to avoid faint stars with a large signal-to-noise ratio: $14 < m_g < 20$ for SEGUE and $9 < m_I < 12$ for RAVE. For a solar-type star $M_{g,\odot} = 5.45$ (Blanton et al., 2003), the distance range is 0.8 kpc < d < 8 kpc for SDSS. For a giant star with $M_g = 1.0$ the distance range is larger: 6.3 kpc < d < 63 kpc. As SEGUE observes in the optical, dust extinction will limit the visibility of stars.

The distance range is 96 pc < d < 384 pc for $M_{I,\odot} = 4.08$ (Binney and Merrifield, 1998) and for giant stars with $M_I = 1.0$ the distance range is 0.4 kpc < d < 1.6 kpc for RAVE.

The RAVE and SEGUE catalogues look at the thin disk, the thick disk and the halo. Because the average abundance/metallicity can differ at different places in the disk a method was developed to select only disk stars in the Solar environment since the halo has a minor contribution to the light of a galaxy. Because most stars in the disk are only thin disk stars, stars from the thick disk were excluded to avoid having too many thick disk stars in our data. The criterion for the selection of thin disk stars in the Solar environment are:

- 1. The galactic latitude b is constrained to be $-10^{\circ} \le b \le 10^{\circ}$. Galactic latitude is defined such that b = 0 corresponds to the (thin) disk. Therefore stars with large |b| are not likely to be members of the thin disk.
- 2. The star's space velocity is constrained by v < 50 km/s with respect to the *Local Standard of Rest* (LSR). The LSR is the reference system in which the average velocity in the Solar environment is zero. A large velocity with respect to the LSR could indicate a star that is part of the halo or the thick disk.

There are only radial velocities given in the RAVE and SEGUE catalogues and no velocities but proper motions in right ascension and declination. We must therefore calculate the distance first in order to obtain the space velocities. The following section describes how the distances and velocities are calculated. In section §2.2 and §2.3 the data analysis for the SEGUE and RAVE catalogues respectively is described.

2.1 Space velocity calculation

The space velocities can be determined by combining distance and proper motions. Neither catalogues provide distances, but they can be derived from the other parameters by using isochrones. The method we describe here has been done earlier for the RAVE dataset (Breddels et al., 2010), but we use two other sets of isochrones because they also provide colours in the SDSS or *ugriz* photometric system.

An isochrone is a line in the Hertzsprung-Russell diagram connecting stars with the same age and the same chemical composition but different masses. The input parameters for an isochrone are [Fe/H], $[\alpha/Fe]$ and the age, while the output parameters are mass, absolute magnitudes (in different bands) and luminosity, effective temperature T_{eff} and the gravitational acceleration at the surface of the star log g.

The isochrones used in this report are the Dartmouth isochrones (Dotter et al., 2008) and the BASTI isochrones (Pietrinferni et al., 2004, 2006). We have used the complete set of the Dartmouth isochrones with an age range of 0.25 - 15 Gyr, [Fe/H] ranging from -2.5 to -0.5with a stepsize of 0.5 for negative [Fe/H] and also 0.0, 0.15, 0.3 and 0.5. [α /Fe] ranges from -0.2 to 0.2 for [Fe/H] > 0.0 with a stepsize of 0.2 and goes up to 0.8 for negative [Fe/H] in the case of solar helium abundance. For enhanced helium, no positive [Fe/H] isochrones are available and [α /Fe] can only take the values 0.0 and 0.4.

For the BASTI isochrones, canonical solar-scaled ($[\alpha/\text{Fe}] = 0.0$) and alpha-enhanced ($[\alpha/\text{Fe}] = 0.4$) isochrones were used for all metallicities, -2.62 < [Fe/H] < 0.40 where the boundaries depend on the $[\alpha/\text{Fe}]$ -value. Age ranges from 30 Myr to 16 Gyr and the mass-loss efficiency parameter was set to $\eta = 0.4$. Both groups provide these isochrones on a grid of [Fe/H], $[\alpha/\text{Fe}]$ and age.

To determine which grid points matches best with a star's parameters, a χ^2 -analysis has been employed. This means that for each star the χ^2 has been calculated by the equation

$$\chi^{2} = \frac{(\log g_{*} - \log g_{model})^{2}}{\sigma_{\log g_{*}}^{2}} + \frac{(T_{\text{eff},*} - T_{\text{eff},model})^{2}}{\sigma_{T_{\text{eff},*}}^{2}} + \sum_{\text{colours}} \frac{C_{*} - C_{model}^{2}}{\sigma_{C_{*}}^{2}}$$
(2.1)

and the grid point that leads to the smallest χ^2 -value is chosen to be the best fit. Due to the large spacing in [Fe/H] and [α /Fe] in the isochrones, these were not added to minimizing the χ^2 but were added as constraints:

$$[Fe/H]_* - \sigma_{[Fe/H]_*} < [Fe/H]_{model} < [Fe/H]_* + \sigma_{[Fe/H]_*}$$

$$(2.2)$$

$$[\alpha/\mathrm{Fe}]_* - \sigma_{[\alpha/\mathrm{Fe}]_*} < [\alpha/\mathrm{Fe}]_{model} < [\alpha/\mathrm{Fe}]_* + \sigma_{[\alpha/\mathrm{Fe}]_*}$$
(2.3)

This differs from Breddels et al. (2010) since they included [Fe/H] in their χ^2 -fitting.

One can then combine the observed apparent magnitude with the absolute magnitude from the isochrone to determine the distance d to the Sun according to

$$m - M = 5\log(d) - 5 \tag{2.4}$$

One can then easily calculate the velocity components with respect to the Sun in right ascension and declination by $v(\text{km/s}) = 4.74 \times d \times \mu$ with μ the proper motion in units of arcsec/yr. However, we need the space velocities, velocities with respect to the LSR, and this requires a velocity transformation.

The transformation from proper motions $\mu_{\alpha}(\text{mas})$ and $\mu_{\delta}(\text{mas})$ and the radial velocity $v_r(\text{km/s})$ to galactic space velocities is given by the following equation:

$$\begin{pmatrix} U_{\rm LSR} \\ V_{\rm LSR} \\ W_{\rm LSR} \end{pmatrix} = \begin{pmatrix} U_{\odot} \\ V_{\odot} \\ W_{\odot} \end{pmatrix} + \begin{pmatrix} -0.0548756 & -0.8734371 & -0.4838350 \\ +0.4941094 & -0.4448296 & +0.7469822 \\ -0.8676661 & -0.1980764 & +0.4559838 \end{pmatrix} \times$$

$$\begin{pmatrix} -\sin\alpha & -\cos\alpha \cdot \sin\delta & -\cos\alpha \cdot \cos\delta \\ \cos\alpha & \sin\alpha \cdot \sin\delta & \sin\alpha \cdot \cos\delta \\ 0 & \cos\delta & \sin\delta \end{pmatrix} \times \begin{pmatrix} 4.74047 \cdot r \cdot \mu_{\alpha} \\ 4.74047 \cdot r \cdot \mu_{\delta} \\ v_r \end{pmatrix}$$

$$(2.5)$$

where $(U_{\odot}, V_{\odot}, W_{\odot}) = (10.0, 5.25, 7.17)$ km/s are the velocities of the Sun with respect to the LSR, and α and δ are respectively the coordinates of the star in right ascension and declination (Bensby et al., 2003, app. A). The space velocity selection is carried out by considering stars with $|V_{\rm LSR}| < 50$ km/s and $\sqrt{U_{\rm LSR}^2 + W_{\rm LSR}^2} < 50$ km/s. This kinematical selection criterion for thin disk stars is taken from Bensby et al. (2003).

2.2 SEGUE

The SEGUE data set is obtained by using the SQL query form at SkyServer. The query, together with an explanation, is given in Appendix A. This SQL query returned 5,224 stars out of the possible 265,653 stars.



Figure 2.1: The Toomre diagram of the selected SDSS stars.

The velocity selection has been made with the SDSS colours u - g, g - r, r - i, i - z used in eq. (2.1). The isochrones used in this analysis are those for the ugriz photometric system. We have interpolated these isochrones so that [Fe/H]'s are separated by 0.01 dex, which is on the order of the errors in [Fe/H] for each star. The interpolation for the Dartmouth isochrones has been done by the interpolation routine provided by Dartmouth¹. For the BASTI isochrones we wrote our own interpolation routine which also interpolates the grid at

¹http://stellar.dartmouth.edu/~models/programs/iso_interp_feh.f



Figure 2.2: The difference between the observed i - z and the difference between the fitted and observed i - z.

the value of $[\alpha/\text{Fe}] = 0.2$. The velocity field of the stars selected from the query is displayed in Figure (2.1). All data points outside the solid line are not considered in our analysis.

There were a few strange data points that were probably due to giants, because the temperature and $\log(g)$ values for these stars are low and the Dartmouth isochrones do not go past the RGB-tip (Dotter et al., 2008) and the BASTI isochrones stop at the asymptotic giant branch. These are excluded if the difference between the observed i - z and best fitted i - z was larger then 0.5, see Figure (2.2). No data points have been excluded on the basis of their χ^2 -values.

This analysis has left us with 3,198 stars after the Dartmouth fitting and 3,196 after the BASTI fitting, which are most likely in the thin disk in the Solar neighbourhood. For the BASTI isochrones the median reduced $\chi^2 = 5.0$ and for the Dartmouth isochrones it is slightly lower with $\chi^2 = 5.8$, with the degrees of freedom equal to 6. A possible explanation for the large χ^2 values is an underestimation of the errors, e.g. the dataset contains some stars with $\sigma_{T_{\text{eff}}} = 0$.

The shapes of the iron and alpha distributions are shown in Figures (2.3a) and (2.3b). The average metallicity and α -abundance, together with the standard deviation, are $\langle [Fe/H] \rangle = -0.32 \pm 0.31$ and $\langle [\alpha/Fe] \rangle = 0.09 \pm 0.06$. All figures and averages are for stars with parameters



Figure 2.3: The [Fe/H] and $\left[\alpha/\text{Fe}\right]$ distribution of the selected stars in the thin disk (SEGUE).

from the Dartmouth isochrones since the values and figures do not differ significantly. This is also true for the RAVE dataset and the bulge data.

2.3 RAVE data

For this report the second data release of the RAVE catalogue has been obtained from VizieR, which contains 49,327 stars. The number of stars with spectroscopically determined parameters, including metallicity, is 21,121. For these stars $[\alpha/Fe]$ is given, but as described by Zwitter et al. (2008) they are not accurate enough for individual stars. Due to their poor accuracy they also can not be used for distributional analysis (M.A. Breddels 2010, priv. comm.). Another problem is that the catalogue does not contain [Fe/H] but [M/H]. [M/H] is the total metallicity and is defined in the same way as [Fe/H]. To relation between [M/H] and [Fe/H] is given by the following equation:

$$[M/H] = [Fe/H] + \log_{10} \left(0.694 \times 10^{[\alpha/Fe]} + 0.306 \right)$$
(2.6)

(Salaris and Cassisi, 2005). For the average SEGUE value of $[\alpha/\text{Fe}] = 0.09$, this translates into a shift of [M/H] - [Fe/H] = 0.06. The maximum value of $[\alpha/\text{Fe}] = 0.4$ leads to [M/H] - [Fe/H] = 0.31. As the deviations are not very large and since $[\alpha/\text{Fe}]$ is badly determined, we will assume [Fe/H] = [M/H].

The RAVE-experiment does not determine colours or magnitudes, so we used the infrared colours stars from the cross-identificated 2MASS sky survey. There are two colours in the 2MASS experiment: J-H and H-K. For the 2MASS colours we require that the photometric flags are set to "AAA" and there are no spectroscopic flags raised.



Figure 2.4: The Toomre diagram of the selected RAVE stars.

The Dartmouth isochrones for the colours in the Bessel/2MASS-system have been interpolated in [Fe/H] with step size 0.1 dex and not with 0.01 dex, because the errors in RAVE are larger than in SEGUE. The χ^2 -analysis gives a median reduced $\chi^2 = 1.2$ for the BASTI isochrones and $\chi^2 = 0.8$ for the Dartmouth isochrones. The conservative error estimations from Zwitter et al. (2008) are used, which are $\sigma_{T_{\text{eff}}} = 400$ K and $\sigma_{\log g} = 0.5$ dex.

After selecting thin disk stars using the same velocity selection method as above, we are left with 1,017 stars in the case of BASTI and 1,051 for the Dartmouth isochrones. Just like for the SEGUE dataset, there seems to be no significant difference between the two isochrone sets. Therefore only the values and plots resulting from the Dartmouth isochrones are plotted.

The distribution of [Fe/H] seems similar to the distribution obtained from the SEGUE data (Figure 2.5). The mean metallicity and the standard deviation is $\langle [Fe/H] \rangle = -0.04 \pm 0.39$. This value is higher than for SEGUE with 0.24, but falls within the standard deviation. If we would have used eq. (2.6) to translate [M/H] to [Fe/H] we would get $\langle [Fe/H] \rangle = -0.13 \pm 0.39$. In Chapter 5 we discuss the difference in the [Fe/H] value in more detail.



Figure 2.5: The [Fe/H] distribution of the selected stars in the thin disk (RAVE).

The bulge is the most difficult part of the Milky Way to observe due to the distance and the large amount of dust. There are a few 'windows' in which stars can be seen without obscuration being a large problem. Even though these windows exist, there are just a few papers with α -abundances obtained from spectroscopic observations, with each containing data from at most tens of stars. Combining these data sets will give systematic errors, because the papers use different kinds of model grids of synthetic spectra to determine the abundances and also use different oscillator strengths for the spectral lines. Due to the uncertainties in the solar values, there is also a difference between the solar values used to scale the abundances.

To tackle these uncertainties one needs to re-examine the spectra with one set of synthetic spectra and oscillator strengths. Even then uncertainties will remain since the spectra were obtained at different resolutions. Analysing the spectra by ourselves would require a lot of time, so the only thing we have done is recalculated the abundances using one particular set of solar abundance values, namely Asplund et al. (2009). This is also done for the stars in the SEGUE and RAVE catalogues.

Another systematic difference one can treat is that different authors often use different definitions for $[\alpha/\text{Fe}]$. For the SEGUE catalogue, (Lee et al., 2010) gives the following weighted definition of $[\alpha/\text{Fe}]$ with corresponding error:

$$[\alpha/\text{Fe}] = 0.5 \times [\text{Mg/Fe}] + 0.3 \times [\text{Ti/Fe}] + 0.1 \times [\text{Ca/Fe}] + 0.1 \times [\text{Si/Fe}]$$
(3.1a)

$$\sigma_{[\alpha/\text{Fe}]}^2 = 0.5 \times ([\text{Mg/Fe}] - [\alpha/\text{Fe}])^2 + 0.3 \times ([\text{Ti/Fe}] - [\alpha/\text{Fe}])^2 + 0.1 \times ([\text{Ca/Fe}] - [\alpha/\text{Fe}])^2 + 0.1 \times ([\text{Si/Fe}] - [\alpha/\text{Fe}])^2$$
(3.1b)

Since there are no individual abundances given in the SEGUE-catalogue, we can not adopt another definition for $[\alpha/\text{Fe}]$. For the sake of consistency, $[\alpha/\text{Fe}]$ for all bulge stars is defined in the same way as in the SEGUE stellar parameter pipeline.

As sometimes [Ti I/Fe] and [Ti II/Fe] are given instead of [Ti/Fe], and similarly for [Fe/H], we need to combine them. This is done by averaging the abundances of the two different excitation states:

$$[Fe/H] = \frac{[Fe I/H] + [Fe II/H]}{2}$$
 $[Ti/Fe] = \frac{[Ti I/H] + [Ti II/H]}{2}$ (3.2)

We have split the bulge data sets into two parts: the bulge field stars and the bulge stars inside globular clusters. This has been done due to the small amount of bulge field stars that are available. The isochrone fitting developed in the previous chapter will also be applied to the bulge stars so that we can derive absolute magnitudes. The same isochrone set as for RAVE are used, although for BASTI we added the AGB extended isochrones since most observed stars are giants. Another difference is that we dropped the $[\alpha/Fe]$ -constraint, eq. (2.3), as the error in $[\alpha/Fe]$ is small due to the above definition. Since there are stars with metallicity or α -abundance outside the isochrone range, we forced these stars to fit with the isochrones on the metallicity or α -abundance boundary of the grid.

3.1 Bulge field stars

In Table (3.1) all the papers concerning bulge field stars are listed. All the stars in each paper have reported $\log(g)$ and T_{eff} .

Paper	No. of Stars
Rich and Origlia (2005)	14
Fulbright et al. (2006, 2007)	27
Lecureur et al. (2007)	53
Rich et al. (2007)	17
Meléndez et al. (2008)	19
Zoccali et al. (2008)	521
Bensby et al. (2010)	13
Alves-Brito et al. (2010)	25

Table 3.1: F	Papers	containing	abundances	of	bulge	field	stars
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The stars from Rich and Origlia (2005) are observed in Baade's window. The only difference between Rich and Origlia (2005) and Rich et al. (2007) is that the last one looks at another window; both papers look at M-type giants. Fulbright et al. (2006, 2007) have observed K giants in Baade's window. From the 53 stars from Lecureur et al. (2007), 40 are red giant branch stars and 13 are stars that are burning helium in their core. Since the abundances for some α -elements are not given, no [α /Fe] could be calculated for these stars. The same holds for the stars described by Meléndez et al. (2008). Zoccali et al. (2008) have determined [Fe/H] for a large number of bulge field stars. Unfortunately there are no [α /Fe] given for these stars. Bensby et al. (2010) observed dwarf stars through gravitational microlensing. Alves-Brito et al. (2010) has looked at giants in Baade's window.

The isochrone analysis resulted in the metallicity distribution function and α -distribution function as shown in Figures (3.1a) and (3.1b). The scatterplot of [Fe/H] against [α /Fe] is shown in Figure (3.2). For the field stars we obtain the average metallicity is \langle [Fe/H] $\rangle = -0.20 \pm 0.40$ and for the α -abundance we find \langle [α /Fe] $\rangle = 0.23 \pm 0.10$.



Figure 3.1: The [Fe/H] and $[\alpha/\text{Fe}]$ histograms of the bulge field stars.



Figure 3.2: [Fe/H] vs. $[\alpha/Fe]$ for the bulge field stars.

3.2 Bulge globular clusters

Paper	Globular cluster	No. of Stars
Origlia and Rich (2004)	Terzan $4/5$	4/6
Zoccali et al. (2004)	NGC 6528	3
Origlia et al. (2005)	NGC 6539/UKS 1	6/4
Barbuy et al. (2006)	HP-1	2
Gratton et al. (2006)	NGC 6441	5
Alves-Brito et al. (2006)	NGC 6553	4
Carretta et al. (2007)	NGC 6338	7
Barbuy et al. (2007)	NGC 6558	5
Origlia et al. (2008)	NGC 6440/6441	10/8
Barbuy et al. (2009)	NGC 6522	8

Due to the low number of bulge field stars, globular cluster stars have been added to the sample. The data for the bulge globular cluster are obtained from the Table (3.1).

Table 3.2: Papers with observed abundances in bulge globular cluster

There are four stars observed from blue horizontal branch globular cluster Terzan 4 and six stars in the metal-rich globular cluster in Terzan 5. From the five observed stars described in Zoccali et al. (2004), only for three stars the abundances are determined. The two other stars are binary systems. Origlia et al. (2005) have observed intermediate-metallicity globular clusters while Barbuy et al. (2006) have observed metal-poor globular clusters. The stars observed in NGC 6338/6441 are mainly RGB-stars while NGC 6441 is a blue-horizontal branch cluster. NGC 6553 is a metal-rich globular cluster while NGC 6552 is metal-poor.

The metallicity and abundance distribution for the globular cluster is given in Figures

(3.3a) and (3.3b). The plot of [Fe/H] vs. $[\alpha/\text{Fe}]$ is shown in Figure (3.4). For the cluster stars we obtain the average metallicity $\langle [\text{Fe}/\text{H}] \rangle = -0.64 \pm 0.36$ and for the α -abundance we have $\langle [\alpha/\text{Fe}] \rangle = 0.25 \pm 0.12$.



Figure 3.3: The [Fe/H] and $[\alpha/Fe]$ histograms of the globular cluster stars.



Figure 3.4: [Fe/H] vs. $[\alpha/Fe]$ for the globular cluster stars.

3.3 Combining field stars and globular clusters

Now that both the bulge field stars and the stars in the globular cluster have been analysed, we can put them together. Although the histograms seem to behave quite normal, as can be seen in Figures (3.1a) and (3.1b), the plot of [Fe/H] vs. $[\alpha/Fe]$ in Figure (3.2) shows there is a problem. The spread in [Fe/H] for the field stars is much larger than for the stars in the globular clusters. The mean metallicity of all bulge stars is $\langle [Fe/H] \rangle = -0.27 \pm 0.31$ and the mean α -abundance is $\langle [\alpha/Fe] \rangle = 0.28 \pm 0.09$.



Figure 3.5: The [Fe/H] and [α /Fe] histograms of all bulge stars.



Figure 3.6: [Fe/H] vs. $[\alpha/Fe]$ for all bulge stars. The + and x represent the field stars while the filled triangles are the bulge stars inside globular clusters.

For a galaxy, it is the starlight from which one determines the metallicity and not every star generates the same amount of light. The light is observed in a particular band, e.g. one of the bands in the ugriz or UBVRIJHK photometric system. Therefore we calculate a weighted metallicity and abundance in the Solar neighbourhood. The calculation of the weighted means is done by the following equation

$$[Fe/H]_{SNBD} = \log_{10} \left[\frac{\sum_{i}^{n} w_{i} \times 10^{[Fe/H]_{i}}}{\sum_{i}^{n} w_{i}} \right]$$
$$[\alpha/Fe]_{SNBD} = \log_{10} \left[\frac{\sum_{i}^{n} w_{i} \times 10^{[\alpha/Fe]_{i}}}{\sum_{i}^{n} w_{i}} \right]$$
(4.1)

where w_i can be the bolometric luminosity or the luminosity in different bands. As the isochrones provide absolute magnitude, we translate these into luminosities using

$$\frac{L_*}{L_{\odot}} = 10^{\frac{M_{\odot} - M_*}{2.5}} \tag{4.2}$$

where the solar value for the absolute magnitude in each different band has been obtained from Binney and Merrifield (1998, Table 2.1). Since the isochrones also provide masses for each star, one can also use mass as the weight function.

Since the SEGUE catalogue gives other magnitude bands than RAVE and the bulge papers, we first transform the ugriz colours to the UBVRIJHK-system. This is done by the transformation equations given in Appendix B. The resulting weighted averages for the metallicity and abundance are given in table (4.1). The standard deviation has been calculated from the equation

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left([\text{Fe/H}] - [\text{Fe/H}]_{\text{SNBD}} \right)^2}$$
(4.3)

and similarly for $[\alpha/\text{Fe}]$. This standard deviation is much larger than the weighted errors which are not given here.

Since we only selected thin disk stars in the Solar environment, a model is needed to estimate the metallicity and α -abundance distribution of the total disk. The first assumption that we make is that the disk is cylindrically symmetric. As our interest is in the global metallicity of the disk, local variations can be neglected.

Furthermore we use the observation that there appears to be a radial chemical gradient in the disk. The gradients used in this paper are taken from Cescutti et al. (2007) who give the metallicity gradient for [Fe/H] and also for the α -elements. The numbers are summarized in Table (4.2). The gradient in $[\alpha/\text{Fe}]$ is calculated by substituting the gradients for the abundances in the definition of $[\alpha/\text{Fe}]$, eq. (3.1a):

$$\nabla_{[\alpha/\text{Fe}]} = 0.5 \times \nabla_{[\text{Mg/Fe}]} + 0.3 \times \nabla_{[\text{Ti/Fe}]} + 0.1 \times \nabla_{[\text{Ca/Fe}]} + 0.1 \times \nabla_{[\text{Si/Fe}]}$$
(4.4)

Weight	[Fe/H]	$[\alpha/\mathrm{Fe}]$
-	-0.32 ± 0.36	0.09 ± 0.06
L_U	$+0.09\pm0.44$	0.13 ± 0.06
L_B	$+0.07\pm0.42$	0.12 ± 0.06
L_V	$+0.03\pm0.36$	0.12 ± 0.06
L_R	-0.00 ± 0.34	0.12 ± 0.07
L_I	-0.02 ± 0.29	0.12 ± 0.07
L_J	-0.04 ± 0.23	0.12 ± 0.07
L_H	-0.05 ± 0.20	0.12 ± 0.07
L_K	-0.05 ± 0.20	0.12 ± 0.07
$L_{\rm bol}$	-0.01 ± 0.34	0.12 ± 0.07
mass	-0.09 ± 0.39	0.11 ± 0.06

Table 4.1: The weighted [Fe/H] and $[\alpha/Fe]$ for the Solar environment. The value for [Fe/H] is obtained by taking the average value of the selected thin disk stars in the SEGUE and RAVE catalogue and the $[\alpha/Fe]$ -value is the average of the thin disk stars in the SEGUE survey.

Since the paper gives [El/H] instead of [El/Fe], we transformed this by the equation

$$\nabla_{\rm [El/Fe]} = \nabla_{\rm [El/H]} - \nabla_{\rm [Fe/H]} \tag{4.5}$$

The equations for the metallicity and abundance gradients are

$$[Fe/H](r) = [Fe/H]_{SNBD} + (r-8) \cdot \nabla_{[Fe/H]}$$

$$(4.6)$$

$$[\alpha/\text{Fe}](r) = [\alpha/\text{Fe}]_{\text{SNBD}} + (r-8) \cdot \nabla_{[\alpha/\text{Fe}]}$$
(4.7)

where we assume that the Sun is at a distance of 8 kpc from the centre of our galaxy and the subscript SNBD stands for *Solar NeighBourhooD*.

Now that we know how the metallicity and abundance in the total disk behaves, we need to specify the surface brightness profile of the entire disk, as the inner part of our galaxy produces more light than the outer parts. Therefore we presume an exponentially decaying surface brightness profile for the Milky Way:

$$\Sigma(r) = \Sigma_0 e^{-r/r_s} \tag{4.8}$$

where Σ_0 is the central brightness and r_s is a scale length. This brightness profile together with $r_s = 3$ kpc is adopted from Kent et al. (1991).

Combining the radially dependent metallicity and abundances with the surface brightness profile of our Milky Way results in the following equations for the light-weighted average for

$\nabla_{\rm [Fe/H]}$	$ abla_{\mathrm{[Mg/H]}}$	$ abla_{\mathrm{[Ti/H]}}$	$ abla_{ m [Ca/H]} $	$ abla_{ m [Si/H]} $	$ abla_{[lpha/{ m Fe}]}$
-0.036	-0.031	-0.032	-0.034	-0.033	0.0038

Table 4.2: The abundance gradients for the disk, defined for 4 < r(kpc) < 22

the entire disk:

$$\langle [Fe/H] \rangle = \frac{\int_{r_{in}}^{r_{out}} 2\pi r dr \ [Fe/H](r) \times \Sigma(r)}{\int_{r_{in}}^{r_{out}} 2\pi r dr \ \Sigma(r)} \\ \langle [\alpha/Fe] \rangle = \frac{\int_{r_{in}}^{r_{out}} 2\pi r dr \ [\alpha/Fe](r) \times \Sigma(r)}{\int_{r_{in}}^{r_{out}} 2\pi r dr \ \Sigma(r)}$$
(4.9a)

with the standard deviation given by

$$\sigma_{\langle [Fe/H] \rangle}^{2} = \frac{\int_{r_{in}}^{r_{out}} 2\pi r dr \ ([Fe/H](r) - \langle [Fe/H] \rangle)^{2} \times \Sigma(r)}{\int_{r_{in}}^{r_{out}} 2\pi r dr \ \Sigma(r)}$$
$$\sigma_{\langle [\alpha/Fe] \rangle}^{2} = \frac{\int_{r_{in}}^{r_{out}} 2\pi r dr \ ([\alpha/Fe](r) - \langle [\alpha/Fe] \rangle)^{2} \times \Sigma(r)}{\int_{r_{in}}^{r_{out}} 2\pi r dr \ \Sigma(r)}$$
(4.9b)

The lower and upper boundaries of the integral are 4 kpc and 22 kpc, respectively. These are also the boundaries for which the metallicity and abundance gradient were determined. As one can see by looking at equations (4.8) and (4.9), Σ_0 drops out of the equations.

Weight	$[\mathrm{Fe}/\mathrm{H}]_{\mathrm{disk}}$	$[\alpha/\mathrm{Fe}]_{\mathrm{disk}}$	$[\mathrm{Fe}/\mathrm{H}]_{\mathrm{bulge}}$	$[\alpha/\mathrm{Fe}]_{\mathrm{bulge}}$
-	-0.32 ± 0.04	0.09 ± 0.004	-0.27 ± 0.31	0.28 ± 0.09
L_U/L_{\odot}	$+0.08\pm0.04$	0.13 ± 0.004	-0.39 ± 0.47	0.26 ± 0.11
L_B/L_{\odot}	$+0.06\pm0.04$	0.12 ± 0.004	-0.60 ± 0.59	0.27 ± 0.11
L_V/L_{\odot}	$+0.03\pm0.04$	0.12 ± 0.004	-0.67 ± 0.67	0.28 ± 0.11
L_R/L_{\odot}	-0.01 ± 0.04	0.12 ± 0.004	-0.60 ± 0.68	0.28 ± 0.11
L_I/L_{\odot}	-0.03 ± 0.04	0.12 ± 0.004	-0.40 ± 0.57	0.28 ± 0.10
L_J/L_{\odot}	-0.05 ± 0.04	0.12 ± 0.004	-0.08 ± 0.38	0.28 ± 0.09
L_H/L_{\odot}	-0.05 ± 0.04	0.12 ± 0.004	-0.07 ± 0.36	0.28 ± 0.09
L_K/L_{\odot}	-0.06 ± 0.04	0.12 ± 0.004	-0.06 ± 0.35	0.28 ± 0.09
$L_{\rm bol}/L_{\odot}$	-0.02 ± 0.04	0.12 ± 0.004	-0.12 ± 0.40	0.28 ± 0.10
mass	-0.09 ± 0.04	0.11 ± 0.004	-0.08 ± 0.38	0.24 ± 0.11

Table 4.3: The weighted [Fe/H] and $[\alpha/Fe]$ for the disk and the bulge.

After numerically integrating eq. (4.9) one obtains the values as given in Table (4.3). In this table we also give the value of the bulge, which are obtained directly from eq. 4.1 since we are looking at the entire bulge.

A closer look at Table (4.3) reveals two opposite trends. Where for the disk the weighted luminosity goes down as we move to the infrared, it goes up for the bulge. This could indicate that the metal-rich stars in the disk are mainly bright dwarf stars while for the bulge the giants are metal-rich. It is surprising to see that $[\alpha/\text{Fe}]$ does not change significantly when looking in a particular band.

4.1 Luminosity function

The selection criteria for the disk stars in the SEGUE and RAVE survey were based on magnitudes and not on stars within some volume. This could lead to a possible bias for our thin disk stars as giant stars are brighter than dwarf stars leading to an overabundance of giant stars in our sample. We therefore calculate the abundances using a luminosity function. A luminosity function gives the amount of luminosity that is generated within some magnitude range. We use the luminosity function as published by Binney and Merrifield (1998) in Table 3.16. They binned the luminosity function, which ranges from $-6.5 < M_V < 19.5$ in bins of 1 mag. They provide the fraction of the total luminosity $\delta L/L_{\odot}$ contributed by the stars in each magnitude bin.

Calculating the average metallicity and abundance in the SNBD can still be done by using eq. (4.1), but now $[Fe/H]_i$ represents the average [Fe/H] or $[\alpha/Fe]$ in each magnitude bin and the weight w_i becomes $w_i = \delta L/L_{\odot}$. Empty bins are not added in eq. (4.1). Note that the luminosity function is given in the V-band. This leads to the average $\langle [Fe/H] \rangle = -0.38 \pm 0.03$ and $\langle [\alpha/Fe] \rangle = 0.10 \pm 0.01$ for the Solar neighbourhood. Extrapolating these values with eq. (4.9) leads to the following mean abundances: $\langle [Fe/H] \rangle = -0.38 \pm 0.04$ and $\langle [\alpha/Fe] \rangle =$ 0.10 ± 0.004 . The distributions of [Fe/H] and $[\alpha/Fe]$ in our Milky Way as viewed from outside is plotted on the first page of this report.

If there would be a much larger number of bulge stars, we could also use a luminosity function for the bulge. Another problem for bulge stars is that the ratio of giants to dwarfs in our sample is not representative for the entire bulge. One of the important concerns in our whole analysis is the limited number of bulge stars and the large amount of papers. The description of the papers in Chapter 3 made also clear that the stars are in most cases selected of a particular class: some authors selected stars on basis of their spectral type or on their particular location in the colour-magnitude diagram. The globular clusters are sometimes described as metal-poor and sometimes as metal-rich. These selection criteria can cause the derived values to differ from the real value. Another concern is the discrepancy in the ([Fe/H], $[\alpha/Fe]$)-plot between the bulge field stars in the bulge stars inside globular clusters. This could indicate that the bulge globular clusters are not representative for the bulge stars in general.

A possible solution to the above problem is to re-examine the spectra from Zoccali et al. (2008) since they published more than 500 spectra online. Even then there will remain a bias towards high-luminous stars since they lack dwarf stars. Including a large number of dwarf stars from microlensing events is not an option while there remains no explanation for the significant correlation between maximum magnification and metallicity (Cohen et al., 2010). The only way in which this problem can be solved is to use metallicity and abundances derived from photometric methods.

Another problem for the bulge is that we have a few windows through which we can observe stars. We can determine the average metallicity and abundance in each window, but it is not clear if this is also the average [Fe/H] and $[\alpha/Fe]$ for the entire bulge.

Although SEGUE and RAVE are vey good catalogues, their main goal is to search for stars mainly at large distances (SEGUE) or away from the disk (RAVE). One can therefore question if there could be a bias for the thin disk stars in the Solar neighbourhood. Comparing our calculated unweighted mean metallicity in the disk, $\langle [Fe/H] \rangle = -0.32 \pm 0.36$, with that of the Geneva-Copenhagen survey, $\langle [Fe/H] \rangle = -0.19 \pm 0.20$, shows that the two values lie close to each other. We therefore presume that there is no bias in the SEGUE and RAVE catalogues.

One possible problem is that the RAVE dataset gives [M/H]. As we saw in section §2.3, the metallicity for the RAVE dataset, [M/H] = -0.04, differs from the average metallicity from the SEGUE dataset, $\langle [Fe/H] \rangle = -0.32$. If we would use the transformation equation (2.6) to obtain [Fe/H] from [M/H] and $[\alpha/Fe]$, then the average metallicity becomes $\langle [Fe/H] \rangle = -0.13$ which is closer to the value of the SEGUE dataset. The shape of the $[\alpha/Fe]$ -distribution for the RAVE stars, Figure (5.1), does not encourage one to use the transformation equation as it differs a lot from the $[\alpha/Fe]$ -distribution for SEGUE stars.

Another small concern remains: we could not find if and how the 2MASS magnitudes for the RAVE stars are dereddened. We do not think this is a major problem since the 2MASS magnitudes are obtained from infrared bands, where the problem of extinction is much smaller.

The magnitude selection that we used can cause a bias. Where the SEGUE stars are selected in the optical g band, the RAVE stars were selected in the infrared I band. Since giants have a relative larger portion of their luminosity in the infrared than dwarf stars there could be more giants in RAVE than in SDSS. Even within one sample there is a bias to nearby



Figure 5.1: The $\left[\alpha/\text{Fe}\right]$ distribution of the stars in the RAVE dataset.

faint stars and far bright stars as distant bright stars can be selected but nearby faint stars can not.

As one can see from Table 4.3 there is a large difference in [Fe/H] in the optical bands and the difference decreases when moving to the infrared bands. A possible explanation for the large difference is given by Monachesi et al. (2011). In Figure 15 of their paper we see that at low optical magnitudes, the luminosity is dominated by the low-metallicity stars.

Using a luminosity function instead of the individual luminosities of the star moves causes [Fe/H] to go down by 0.41 dex and $[\alpha/\text{Fe}]$ decreases by 0.02 dex. An explanation for the decrease in metallicity can be found in Figure (5.2a). The bright stars seem to have a higher metallicity than the other stars, causing to shift the average metallicity to higher values when one calculates the metallicity weighted by individual stars. This does not seem the case for $[\alpha/\text{Fe}]$, causing only a slight shift in the average α -abundance.



Figure 5.2: [Fe/H] and $[\alpha/\text{Fe}]$ vs. M_V .

Chapter 6 Conclusions

In chapter 2 we obtained the metallicity and α -abundance distribution for the Solar environment from the thin disk stars selected from the RAVE and SEGUE survey. The selection of the thin disk stars has been done by restricting the apparent magnitude, the galactic latitude and taking a velocity selection. The velocities were calculated by fitting isochrones to the stars. The average metallicity for the Solar neighbourhood is $\langle [Fe/H]_{SNBD} \rangle = -0.32 \pm 0.36$ and the average α -abundance $\langle [\alpha/Fe]_{SNBD} \rangle = 0.09 \pm 0.06$.

The bulge stars are separated into two parts: the field stars and the stars inside globular clusters. Although we obtain a distribution which behaves quite well, the distributions for the two parts individually do not. The average [Fe/H] and $[\alpha/\text{Fe}]$ for the bulge are $\langle [\text{Fe}/\text{H}] \rangle = -0.27 \pm 0.31$ and $\langle [\alpha/\text{Fe}] \rangle = 0.28 \pm 0.09$.

The mapping from the observer's position inside the galaxy to (far) outside is described in chapter 4. First, we calculate the [Fe/H] and [α /Fe] in the Solar neighbourhood which is weighted with a luminosity function. Next, we extrapolate the weighted metallicity and α abundance to the entire disk by assuming an exponential surface brightness profile for the disk together with a radial abundance gradient. For the bulge we assume that the observed [Fe/H] and [α /Fe] is representative for the entire bulge, even though the stars were observed through a few windows and are mainly giant stars. Here we use the luminosities of the individual stars to represent the weights for the mean metallicity and α -abundance. The values that we obtained in the V band for the disk are \langle [Fe/H]_{disk} $\rangle = -0.34 \pm 0.10$ and \langle [α /Fe]_{disk} $\rangle =$ 0.10 ± 0.01 . The average abundances in the bulge are given by \langle [Fe/H]_{bulge} $\rangle = -0.67 \pm 0.67$ and \langle [α /Fe]_{bulge} $\rangle = 0.28 \pm 0.11$.

Ganda et al. (2007) have published line strength indices for iron and magnesium for 18 late-type spiral galaxies, galaxies like our Milky Way. From the line strength indices we calculated [M/H] and $[\alpha/Fe]$, assuming that $[\alpha/Fe] = [Mg/Fe]$ for these galaxies, so that we can compare their abundances with our abundances for the Milky Way. We used eq. (2.6) to transform [M/H] to [Fe/H]. The galaxies are observed in a magnitude range that is comparable with the V-band. The average abundance for the late-type galaxies are $\langle [Fe/H]_{disk} \rangle = -0.55 \pm 0.31$ and $\langle [\alpha/Fe]_{disk} \rangle = 0.06 \pm 0.05$ for the disk and $\langle [Fe/H]_{bulge} \rangle = -0.51 \pm 0.32$ and $\langle [\alpha/Fe]_{bulge} \rangle = 0.05 \pm 0.06$ for the bulge. This would mean that our disk is slightly overabundant in [Fe/H] and in $[\alpha/Fe]$. In contrast, our bulge is underabundant in [Fe/H] but overabundant in $[\alpha/Fe]$.

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Using the SQL query form at SkyServer¹, stars were selected for which [Fe/H] and $[\alpha/Fe]$ are known. These have been subtracted from the Stellar Parameter Pipeline (Lee et al., 2010). The following SQL query has been used to retrieve data from SkyServer:

```
SELECT
```

```
sp.feha, sp.fehaerr, sp.alphafe, sp.alphafeerr, sp.logga, sp.loggaerr, sp.teffa,
sp.teffaerr, sp.umg0 + sp.g0, sp.g0, sp.g0 - sp.gmr0, sp.g0 - sp.gmr0 - sp.rmi0,
sp.g0 - sp.gmr0 - sp.rmi0 - sp.imz0, sp.uerr, sp.gerr, sp.rerr, sp.ierr,
sp.zerr, sp.ra, sp.dec, sp.targ_pmra, sp.targ_pmdec, sp.targ_pmraerr,
sp.targ_pmdecerr, sp.elodierv, sp.elodierverr
FROM sppLines AS sl
join sppParams as sp on sl.specobjid = sp.specobjid
WHERE
sp.b between -10 and 10 AND
(sp.fehan != 0 OR sp.alphafen != 0) AND
sp.alphafe != -9.999 AND
(sp.targ_pmra != 0 AND sp.targ_pmdec != 0)
```

In the SELECT part there are several parameters which we want to retrieve for each star. sp.feha is the average [Fe/H] with error sp.fehaerr and sp.alphafe corresponds to $[\alpha/Fe]$ with the error given by sp.alphaerr. sp.logga and sp.teffa are weighted means of respectively log g and the effective temperature T_{eff} . Their errors are given by sp.loggaerr and sp.teffaerr.

The apparent magnitudes in respectively the *u*-band, the *g*-band, the *r*-band, the *i*-band and the *z*-band are given by respectively sp.umg0 + sp.g0, sp.g0, sp.g0 - sp.gmr0, sp.g0 - sp.gmr0 - sp.rmi0 and sp.g0 - sp.gmr0 - sp.rmi0 - sp.imz0. These are the five SDSS magnitude bands in the *ugriz* photometric system. These apparent magnitudes are already dereddened. The errors in these bands are given by sp.uerr, sp.gerr, sp.rerr, sp.ierr, sp.zerr.

Right ascension and declination are selected by sp.ra and sp.dec and the proper motions in these directions by sp.targ_pmra and sp.targ_pmdec. The radial velocity and its error are selected by sp.elodierv and sp.elodierverr.

The first statement in the WHERE ensures that the selected stars are in the galactic latitude range $-10^{\circ} < b < 10^{\circ}$. The second and third statement must make sure that only stars with known stellar parameters are selected.

¹http://cas.sdss.org/dr7/en/tools/search/sql.asp

The stars from the SEGUE catalogue are observed within the SDSS photometric system with colours ugriz while the RAVE stars are observed in the JHK system and bulge stars are observed in the UBVRI system. From the isochrones it is possible to obtain the absolute magnitude in the whole range UBVRIJHK. Therefore, comparing RAVE and bulge stars in different bands will not be a problem.

To make a comparison between the SEGUE stars and the RAVE/bulge stars when using absolute magnitudes a set of equations to transform the absolute magnitudes from the ugriz photometric system to the UBVRIJHK photometric system were used. This is done by the following set of equations:

$$\begin{split} U_1 &= B + 0.52(u-g) + 0.53(g-r) - 0.82 \\ U_2 &= B + 0.79(u-g) - 0.93 \\ U &= (U_1 + U_2)/2 \\ B_1 &= g + 0.175(u-g) + 0.150 \\ B_2 &= g + 0.313(g-r) + 0.219 \\ B &= (B_1 + B_2)/2 \\ V_1 &= g - 0.565(g-r) - 0.016 \\ V_2 &= I + 0.675(g-i) + 0.364 & \text{if } g-i <= 2.1 \\ V_2 &= I + 1.11(g-i) - 0.52 & \text{if } g-i > 2.1 \\ V &= (V_1 + V_2)/2 \\ R_1 &= r - 0.153(r-i) - 0.117 \\ R_2 &= I + 0.930(r-i) + 0.259 \\ R &= (R_1 + R_2)/2 \\ I &= i - 0.386(i-z) - 0.397 \\ J &= g - 1.379(g-r) - 1.702(r-i) - 0.518 \\ H &= g - 1.849(g-r) - 1.536(r-i) - 0.666 \\ K &= g - 1.907(g-r) - 1.654(r-i) - 0.684 \end{split}$$

obtained from Jordi et al. (2006) for the UBVRI magnitudes and Bilir et al. (2008) for the JHK magnitudes. Since there are multiple equations given to calculate U, B, V and R, we take the average of the values to obtain the value in the magnitude band of our interest.