Finding new atomic-diffusion stellar laboratories with Gaia and GALAH

UPPSALA UNIVERSITY

Bachelor degree project in astronomy

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SWEDISH ABSTRACT

Stellar atomic diffusion, where elements sink towards the core of the star, creates a deficiency of elements in the stellar atmosphere, altering the observable abundances in the spectra. The diffusion effects are expected to change as the star evolves, a red giant showing no such effects due to deep convective mixing. Therefore such effects can be studied by finding a turn-off point star and a red giant of common origin and comparing the observed abundance differences. In this project, this is done by searching for co-moving stellar pairs of common origin using kinematic data from Gaia Data Release 2 and selecting those of low metallicity ([Fe/H] < −2). The metallicity cut is done by cross-correlation with the ground-based spectroscopic GALAH survey. This cross-correlation left us with no interesting pairs below the metallicity limit. This study used the part of Gaia Data Release 2 that contains only stars with radial velocities determined, future studies should try using the complete catalogue.

This character means that the word following it is explained in appendix A. This is intended as an aid for non-astronomers.

We would like to thank Tomaz Zwitter on the GALAH team for providing the unreleased GALAH data used in the cross-correlation.

1. INTRODUCTION

While spectroscopy provides information about the chemical abundances in stellar atmospheres, it does not tell us anything about the abundances at layers beneath the surface. This is due to photons being absorbed and emitted many times on their way out of the stellar interior (Karttunen et al. 2017), leaving us with only the absorption lines (and possibly emission lines for hot stars) caused by the matter-light interaction taking in place in the stellar atmosphere.

Stellar atmospheres have long been assumed representative of the cloud of gas and dust, the progenitor cloud (PC), from which the star was once born (Witt 2001), it has therefore been assumed that we can infer knowledge about the interstellar medium (ISM) from spectra of stellar atmospheres. However, for more than a century, starting with a letter by Chapman (1917), it has been discussed whether or not atomic diffusion affects the chemical abundances of stellar atmospheres. In these diffusion processes heavy elements sink to deeper layers, creating a metal deficiency in the atmosphere. When assuming that the atmosphere of a star which has such a deficiency is representative of the PC one introduces biases. It is important to find the size of such biases in order to enable proper Galactic archaeology and chemical tagging (Dotter et al. 2017). In Galactic archaeology one wants to infer the ISM abundances in order to understand the early Galaxy. For chemical tagging one wants to find which stars may be of common origin by having precise enough abundance parameters. Two stars that have an identical chemical signature may have been born from the same PC. But this can only work if the biases introduced by atomic diffusion are already taken into account, so the size of these effects must be known.

A method for finding the size of these abundance biases is by comparing two stars of common origin (created from the same PC) where one is assumed to show diffusion effects and the other isn’t. Comparing the abundance differences tells us how much material has diffused to lower layers in the star affected by atomic diffusion. This can then be used to refine and calibrate models of atomic diffusion. These stars should preferably be old and metal poor because such stars show stronger diffusion, caused by thinner outer convection zones and longer evolution (see section 2.2). Korn et al. (2007) did such a study using metal-poor globular clusters, which are generally of the same progenitor material.
Another method, the one used in this project, is to find pairs of stars that are moving together, i.e. binary or wide binary (hereafter called co-moving), select those that have similarly low metallicity and then fit them to isochrones to ensure their common origin. Since globular clusters do not occur below $[Fe/H] < -2.5$, but field stars do, this method may be able to find more metal-poor atomic-diffusion laboratories. Finding co-moving pairs has previously been done by Oh et al. (2017) using Gaia Data Release 1 (GDR1). Due to the absence of radial velocities in GDR1 Oh et al. used a probabilistic approach. The more recent Gaia Data Release 2 (GDR2) contains radial velocities for 7 million stars (Gaia Collaboration et al. 2018), this enables a more direct method where positions and velocities are compared in order to build a list of co-moving candidates. GDR2 does not include metallicity estimates (required for finding metal-poor stars), hence the list of co-moving candidates would have to be cross-correlated with another survey such as GALAH, a survey focusing on acquiring high-precision metallicities (De Silva et al. 2015). As in the method used by Korn et al. (2007) stars that are predicted to show strong atomic diffusion or no diffusion are selected. A pair where one is a turn-off point (TOP) star and the other a red giant branch (RGB) star at the RGB bump would suffice. These are evolutionary stages further explained in section 2.1. The TOP star is expected to show strong diffusion due to its thin convection zone while the RGB bump star should show no diffusion due to deep convection that remixes it, this is further explained in section 2.2. Fitting the found pairs onto isochrones strengthens the case for common origin, this is explained further in section 2.3.

1.1. Problem definition and purpose

Can we use Gaia DR2 combined with GALAH (or another survey containing high-precision metallicities) to find co-moving pairs that have low metallicity, lie on the same isochrone where one star is a TOP star and the other is a RGB bump star?

If so, these stellar pairs can be used to verify models of stellar atomic diffusion by doing new observations that determines their metallicities to high precision and quantifying the difference. This is a potential follow-up project and outside the scope of this project.

2. THEORY

2.1. Evolution of solar mass stars up to the RGB bump

Here we give a short overview of the evolution of solar mass stars from the main sequence to a point called the RGB bump. The reason for only describing solar mass stars is that we require metallicity lower than $[Fe/H] = -2$, which only old ($> 10$ Gyr) low-mass stars have. The metallicity was lower in the early universe since the universe started with mostly hydrogen and helium and built up its metal content through successive generations of stars. Since stellar lifetimes get shorter the more massive the star and since the Sun is expected to have a main sequence lifetime of 10 Gyr, stars more massive than the Sun born 10 Gyr ago will already have died. As will be explained in the next sub-section on atomic diffusion, the TOP and the RGB bump are the points where we want to look for stars. This overview closely follows Böhm-Vitense (1992).

Stars live most of their lives on the main sequence where they burn hydrogen into helium in their core, but as the core hydrogen is depleted, the core contracts and the temperature increases enough for hydrogen to start burning in a shell around the helium core. The shell reaches a temperature high enough ($20 \times 10^6$ K) for the the CNO-cycle to dominate. This makes the radiation pressure higher than in the previous evolutionary stages and the star has to expand in order to reach a new equilibrium. As it grows it leaves the main sequence and starts evolving along the sub giant branch (SGB) and the subsequent RGB. The point at which it leaves the main sequence is called the turn-off point (TOP).

As the shell slowly burns its way out the star’s radius increases and two important things happen: the first dredge-up and the subsequent RGB bump phase follows. As the radius increases the effective temperature $T_{eff}$ decreases. Stars of solar mass or less have an outer convection zone, i.e. a zone of convection that starts at the surface and reaches into some deeper layer of star. The depth of the convection zone increases with decreasing $T_{eff}$ because ionization decreases with temperature. The ionization dependence is a result of photons being more prone to interact with less ionized matter, i.e. the matter becomes more opaque to radiation. The radiation has a hard time getting through it, this heats the matter until it is warm enough to start rising. So the convection zone deepens with decreasing $T_{eff}$, eventually making its lower boundary reach the burning shell. At this point processed nuclear matter is brought up to the surface (this makes those elements visible in the spectra, which is a good check for these models). This is the first dredge-up and it has the side-effect that it pulls up hydrogen-deficient material above the burning shell. When the shell later burns its way to the area to which the material was dredged, there is less hydrogen to burn and the evolution is temporarily halted. This makes stars bunch up at a evolutionary stage called the RGB bump.
The star then continues its way up the RGB branch, but the remaining evolution is of little interest to this project.

2.2. Stellar atomic diffusion

Diffusion is a process where material is slowly moved by molecular displacement, in a star it can cause atoms and molecules to sink or rise. There are several stellar properties that can be taken into account when studying diffusion such as: gravitational force, gas pressure, temperature gradient and radiation pressure. In this discussion we ignore the temperature gradient as it is only of importance at the bottom of very deep convection zones or out in the corona (Shine et al. 1975). Here we only give a simplified overview, for a review see Vauclair & Vauclair (1982).

On the timescales at which diffusion works, it would take longer than the lifetime of the star to diffuse elements to its center, but diffusion down to shallow layers below the atmosphere is possible. In the deep layers the gas pressure is high, collisions more common and the diffusion velocity is thus lowered. At shallow layers the pressure is lower and diffusion can happen at shorter timescales, such as $10^5$ years (Böhm-Vitense 1989a). As mentioned in the previous subsection, main sequence stars less massive than the Sun have an outer convection zone (the upper limit is roughly 1.3 Sun masses). Matter that is moved to the bottom of the convection zone can have momentum enough to overshoot the zone and end up below it. This matter is now in a non-convective zone where radiation pressure dominates, where momentum is transferred from photons to the atoms by absorption. For highly ionized matter or matter with high ionization energy, the radiation, working against gravitational forces, has a hard time pushing the matter back into the convection zone overhead. This is how ionized matter can sink to layers beneath the convection zone and thus be hidden away from the spectra, skewing the spectra towards showing a deficiency of especially heavier elements. The overshoot also introduces a slight mixing of the non-convection zone, which has to be taken into account in the models (Vauclair & Vauclair 1982; Freytag et al. 1996).

As explained in the previous subsection, the convection zone deepens as the star evolves along the RGB ($T_{\text{eff}}$ decreases), eventually reaching to depths where atomic diffusion becomes inefficient due to the high gas pressure. One could say that the convection zone “catches up” with the deepest possible point to which surface matter could have diffused. For RGB bump stars this depth of convection has already been reached and the diffused matter has been remixed into the upper layers of the star. It can thus be assumed that the RGB bump stars have spectral abundances similar to those of their PCs. This is why the comparison between the TOP star and RGB bump star abundances give the abundance bias introduced by atomic diffusion, given that we are certain that the stars share a common origin. The common origin is ensured by isochrone fitting, as will be explained in the following subsection.

2.3. Isochrones

If a large quantity of stars are born at the same time, from the same PC, but differ in mass, they will fall upon the same isochrone. Isochrones (meaning same (iso) time (chronos)) can be viewed as functions that output stellar parameters based on time since birth, metallicity and initial mass. Usually one specifies time since birth and metallicity and then varies the initial mass. This lets us see how stellar parameters vary for stars that are identical except for initial mass.

In Fig. 1 example isochrones of 10 Gyr stars are plotted, more precisely the Gaia G band absolute magnitude is plotted against the effective temperature, both values being outputs of the isochrone. The isochrones have been computed for five different metallicities (actually iron relative hydrogen abundance $[Fe/H]$, which is used as a reference to which all other elements are scaled). The further along each track one
travels, the higher the initial stellar mass, starting with 0.1 $M_\odot$ (0.1 Sun masses) in the lower-right corner. The main sequence stretches from the lower right up to the sharp turn. The sharp turn is the TOP where stars leave the main sequence. It is followed by the SGB and RGB. If the isochrones were calculated for even older stars, the TOP would move towards cooler temperatures, in accordance with more stars already having left the main sequence. See Dotter (2016) for a both physical and technical introduction on how isochrones work and are constructed.

Also in Fig. 1 one can see a slightly less smooth point near the top of the image for the $[Fe/H] = 0$ line, this is the RGB bump.

If two stars have similar position, similar space velocity and fall upon the same isochrone, one may assume that they were born together, from the same PC.

3. METHOD

3.1. Method overview

The general idea for finding the suitable stellar pairs is as follows: Compare the positions and spatial velocities of stars in GDR2. Keep those that have velocity difference less than 1 km/s and position difference less than 10 pc ($\Delta$ parsec). Cross-correlate the found stars with the GALAH survey to get metallicities and select those pairs with $[Fe/H] < -2$. Also, ensure that the pairs have metallicities that differ no more than 30% (leaving some room for the diffusion effects). Plot the remaining pairs on top of isochrones and visually inspect the image and choose such pairs where one is at the TOP and the other at the RGB bump. These final pairs are the resulting candidates of this project and need follow-up observations in order to investigate atomic diffusion effects. Next follows a more in-depth description of the method intertwined with what was actually done.

3.2. Method details and procedures

Initially it was discussed whether we should use the complete GDR2 catalogue or GDR2RV, which only contains those stars in GDR2 that have measured radial velocity. Having radial velocity makes it possible to do simple, full 3D velocity comparisons, so the decision to use the RV catalogue was made. GDR2RV contains roughly 0.5% of the stars found in GDR2, meaning that GDR2RV contains 7.2 million stars (Gaia Collaboration et al. 2018). The GDR2RV catalogue was downloaded, all work with the catalogue was done on a local computer. There was also the possibility to use the online ADQL interface, avoiding the download, but comparing velocities and distances is easier to do in Python code than using the ADQL query language. Fig. 2 shows how stars of different Gaia $G$ apparent magnitudes are distributed in the GDR2RV catalogue.

A Python script was written that goes through all stars in GDR2RV and for each star it looks at nearby stars, comparing the position and velocity. This took some work as the catalogue had to be split into a 3D grid in order to make the queries fast enough. Using such a grid the script only has to compare stars in the same or nearby grid cells. The grid was initially created using spherical coordinates, but this proved complicated, so we later changed it to being a set of Cartesian 3D "boxes" where each box has the size 60x60x60 pc. The Cartesian positions and velocities had to be computed from whatever Gaia supplies. It gives us positions on the sky as equatorial coordinates, meaning two angles: $ra$ (right ascension) and $dec$ (declination). $ra$ is the angle along the equator and $dec$ is the angle from the equator. Gaia also supplies the parallax $p$, from which the distance $r$ can be inferred. $ra$, $dec$ and $p$ thus makes it possible to specify a set of spherical coordinates, which can be converted into Cartesian coordinates by:

\[
\begin{align*}
x &= r \cos(ra) \cos(dec) \\
y &= r \sin(ra) \cos(dec) \\
z &= r \sin(dec)
\end{align*}
\]

These formulas are identical to the ones for converting spherical to Cartesian with the change that $dec$ (the vertical angle) is measured from the equator instead of the north pole. The distance $r$ is given by:

\[
 r = \frac{1}{p}
\]

where $r$ is the distance in pc and $p$ is the parallax in arc seconds. This formula can only be safely used at distances less than about 3 kpc. At greater distances...
errors grow large and Bayesian methods have to be used to estimate the distance from the parallax, see Bailer-Jones (2015); Bailer-Jones et al. (2018). In this project only distances of up to 2-3 kpc were of interest because the resolution of follow-up measurements would be too low for greater distances, so Eq. 2 was used and stars with distances larger the 3 kpc were removed. Judging from Fig. 3, which shows a distance histogram of all objects, the cut isn’t large, but not negligible either.

The velocity in Cartesian coordinates is found by differentiating Eq. 1 w.r.t. time. The time derivatives of \( ra \) and \( dec \) are known as the proper motion of the star and the time derivative of \( r \) is the radial velocity. These values are all given by GDR2RV. The proper motion components in the \( ra \) and \( dec \) directions are denoted \( pmra \) and \( pmdec \), the radial velocity is denoted \( rv \).

With the grid in place the comparison of positions and velocities between stars could get started. The rules used to find co-moving stars were

\[
\begin{align*}
\| \vec{p}_2 - \vec{p}_1 \| &< 10 \text{ pc} + 3 \sigma \| \vec{p}_2 - \vec{p}_1 \| \\
\| \vec{v}_2 - \vec{v}_1 \| &< 1 \text{ km s}^{-1} + 3 \sigma \| \vec{v}_2 - \vec{v}_1 \|
\end{align*}
\]

(3)

where \( \vec{p}_{1/2} \) is a position vector of a star and \( \vec{v}_{1/2} \) is a velocity vector of a star. The \( \sigma \) denotes the errors and had to be found by error propagation. This might at first seem simple, but as Gaia gives errors for \( ra, \) \( dec \) and \( r \) (and \( pmra, pmdec \) and \( rv \) for velocities), the propagation can get quite involved. This is especially true for the velocity differences, Eq. 1 first had to be differentiated w.r.t. time and then the difference between two such velocity vectors had to be computed and then the magnitude had to be found. This process was greatly simplified by first error propagating the error to Cartesian coordinates and then doing a second propagation to \( \| \vec{v}_2 - \vec{v}_1 \| \).

Note that the velocity difference limit of \( 1 \text{ km s}^{-1} \) in Eq. 3 is very conservatively chosen. Two stars that have this relative speed will move much further than 10 pc apart over 10 Gyr. However, we rather get more false positives that we can remove after the GALAH cross-correlation than miss potential positives.

The script for finding co-moving candidates was then run across the GDR2RV catalogue. During one of the early runs it successfully found the Pleiades cluster, see Fig. 4. Note that Pleiades is of no interest to us, but the scripts’ ability to find it means that it is able to find groups of co-moving stars.

With the script finding co-moving candidates we wanted to cross-correlate the result with the GALAH survey in order to get metallicities. For this we cut away everything that GALAH can’t see (the observatory is located in Australia). Only stars with \( dec < +35^\circ \) were kept and the result was sent to GALAH team member Tomaz Zwitter for cross-correlation. We used the unreleased GALAH Data Release 3, so we had to get the data manually in this fashion. Getting data back from the GALAH team took much longer than expected (over a month). In the meantime I did a literature study. I read Böhm-Vitense’s three introductory books on stellar astrophysics (Böhm-Vitense 1989a,b, 1992), a review on atomic diffusion by (Vauclair & Vauclair 1982) and some papers such as Dotter (2016) about isochrones. From these I started working on this report, writing the Theory section.
As we got the data back from GALAH it was evident that we had only gotten three matches with \([\text{Fe/H}] < -2\) between our co-moving candidates and their catalogue. These were not three pairs of common metallicity, but just three separate stars. Despite this, these stars and the co-moving groups to which they belong to were investigated. This is the topic of the next section.

4. CANDIDATE INVESTIGATION AND RESULTS

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Shows the result of cross-correlating co-moving pair candidates from GDR2RV with GALAH survey. Black dots are \([\text{Fe/H}] < -2\), green are \([\text{Fe/H}] < -1\), grey are stars with higher metallicities. Blue line is an isochrone for 10 Gyr old stars with metallicity \([\text{Fe/H}] = -2\).

In Fig. 5 we see three black dots. These are the three stars with \([\text{Fe/H}] < -2\) that turned up after cross-correlating our co-moving candidates with GALAH. None of these are a pair of stars, i.e. there is not even a single pair where both stars have \([\text{Fe/H}] < -2\). Despite this, we can inspect them and see if any of them have a co-moving companion that lies on the same isochrone.

In Tables 1, 2 and 3 we see the co-moving groups that each of the black dots in Fig. 5 are part of. These tables include stars that were not in GALAH but still part of a co-moving group for which GALAH found at least a single star with \([\text{Fe/H}] < -2\).

In Table 1 we see two stars with metallicity specified, both have different GALAH IDs but the same Gaia ID. These two stars are in fact a single star observed at different nights because one of the nights produced erroneous results. We see this because the GALAH ID is identical except for the fourth-to-last digit. A 2 in this position is used by GALAH to indicate that it is from an observation night where the average was marked as bad, therefore, whenever we see a 1 or a 2 in this position, the star with a 1 should be used. This leaves us with a \([\text{Fe/H}] = 0.182(204)\) star, which is of no interest to us.

In Table 2 there are two stars, both available in GALAH. However, they have very different metallicities and are therefore of no interest to us because they cannot be born from the same PC.

In Table 3 there are three stars, one of them has \([\text{Fe/H}] = -2.03\) specified. In Fig. 6 we plot these along with a 10 Gyr isochrone of metallicity \(-2.03\). The TOP is the sharp turn at magnitude 4. We have previously stated that we need a TOP star and a star at the RGB bump. As none of these are at the TOP, we find this group uninteresting. We also note that the stars are slightly below the isochrone, possibly because Gaia is lacking > extinction for them.

This leaves us with no candidates to go forward with, this negative result is discussed in the next section.

All Python scripts written can be found at: https://github.com/karl-zylinski/bachelor-project.

5. DISCUSSION

Here follows general criticism of the method used and also suggestions for possible future investigations.

Early in the project it was decided to use the GDR2RV catalogue, which is a subset of GDR2 containing only those stars that have radial velocities. This was done in order to make the search straight-forward. GDR2RV contains only 0.5% of the stars in GDR2. Also, the

<table>
<thead>
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<th>Gaia ID</th>
<th>GALAH ID</th>
<th>G</th>
<th>[Fe/H]</th>
</tr>
</thead>
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<td>1501120025001152</td>
<td>12.8</td>
<td>0.182(204)</td>
</tr>
<tr>
<td>487754984859960696</td>
<td>150112002502152</td>
<td>12.8</td>
<td>-2.61(13)</td>
</tr>
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<tbody>
<tr>
<td>3038316185100360320</td>
<td>160130003101013</td>
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<tr>
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<table>
<thead>
<tr>
<th>Gaia ID</th>
<th>GALAH ID</th>
<th>G</th>
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</thead>
<tbody>
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<td>160419005101051</td>
<td>12.3</td>
<td>-2.03(26)</td>
</tr>
<tr>
<td>5921751408511009024</td>
<td>-</td>
<td>12.3</td>
<td>-</td>
</tr>
<tr>
<td>5921376578117781760</td>
<td>-</td>
<td>10.7</td>
<td>-</td>
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GDR2RV stars are in the brighter end of what GDR2 provides. Looking at Fig. 2, one sees that there are few sources dimmer than 14 mag. The complete GDR2 has sources as dim as 21 mag with a so-called 5-parameter solution (Gaia Collaboration et al. 2018). 5-parameter means that these sources have 5 astrometric parameters, including positions and proper motions, but they may lack the radial velocity. Looking at Fig. 7 we see that our sample (red curve) is consistently below GALAH DR3 (black). At the peak of the red curve we have a factor of 10 (the vertical axis is logarithmic) fewer stars than in GALAH DR 3. We also see that the red curve cuts off sharply at around 14 mag, while the black does continue after 14 mag, albeit at lower stars per bin. We also see that the overlap between the two (blue) is relatively small, the list of co-moving candidates sent to GALAH contained 89477 sources, the cross-correlation gave us only 5653 sources back. In order to increase the overlap, a search in the complete GDR2 catalogue should be done (with some magnitude cuts, it is not easy to follow up stars fainter than 17). In order to compensate for missing radial velocities, one can compare only proper motion and position. This will give more both false and true co-moving pairs. However, GALAH supplies radial velocities for their sources, so a second pass where we use radial velocities and metallicities supplied by GALAH would increase our chances of finding candidates to go forward with.

Instead of computing distances using Eq. 2 we could have used the Bayesian methods that give better estimates of the errors described by (Bailer-Jones 2015; Bailer-Jones et al. 2018). We wouldn’t necessarily have to do the computation since Bailer-Jones et al. supplies tables of pre-computed distances and errors using their method.

Some additional cross-correlations of our co-moving candidates with surveys far smaller than GALAH were done. These surveys were the BPS surveys described by Beers et al. (1985) (and subsequent papers in the series) as well as the catalogue of 10,000 very metal poor stars in LAMOST DR3 (Li et al. 2018). They all turned out negative.

### 6. FUTURE OUTLOOK

We are looking into doing a second attempt at this by using the full GDR2 catalogue as described in the discussion. Also, the GALAH Data Release 3 is due for release within a year and having the data locally instead of having to ask for the data would make our turn-around times much faster. However, a second attempt may be done before this.

Also, Gaia Data Release 3, available in 2020/2021 will include metallicities, which would make similar investigations simpler. It remains to be seen how good the resolution of Gaia’s metallicities are relative those of GALAH.

### 7. CONCLUSION

Using the Gaia DR2 Radial Velocity catalogue we looked for pairs of stars that share a common position and space velocity. This gave a list of stars that we cross-correlated with GALAH DR3, resulting in three stars with $[Fe/H] < 2$. None of these stars were part of a co-moving group that had one star at the turn-off point and the other at the red giant bump, giving us a negative result. Issues with the method were discussed.
and we may do a second attempt using the complete Gaia Data Release 2 catalogue.

Coming back to the problem defined earlier: "Can we use Gaia Data Release 2 combined with GALAH (or another survey containing high-precision metallicities) to find co-moving pairs that have low metallicity, lie on the same isochrone where one star is a TOP star and the other is a RGB bump star?", the answer is inconclusive, but we now know that a search in the small subset provided by the Gaia DR2 Radial Velocity catalogue is insufficient.

REFERENCES

APPENDIX

A. DICTIONARY FOR NON-ASTRONOMERS

Some entries have references at the end such as (K267). These are references to pages in Karttunen et al. (2017).

CNO-cycle. A fusion process where hydrogen is converted into helium that requires temperatures of at least $15 \times 10^6$ K. It is a process that uses carbon as a catalyst and thus requires its presence. The CNO-cycle is highly temperature dependent and becomes the dominant energy producer at $20 \times 10^6$ K (K255-256).

Effective temperature. Usually denoted $T_{\text{eff}}$. This is the same temperature that a black body would have it shone with the same flux density as the star. Stars are approximated as black bodies (K114).

Equilibrium in stars. On short timescales (non-variable) stars are stable in brightness, radius and average surface temperature. This equilibrium is caused by the pressure from within balancing the inward force of gravity.

Extinction. The decrease in magnitude of a star caused by dust between the star and the telescope. Makes the star look dimmer and redder (K97).

Field star. A star not connected to any astronomical object other than the Galaxy.

Gaia. An ESA satellite measuring the position and velocities of stars with high precision from 2013 to 2021. The current data release 2 contains 1.7 billion stars. It gives us the largest, most precise 3D map of the sky ever created.

Magnitude. A measure of the brightness of a star. It is measured relative to another star. A common zero point is the star Vega, letting Vega have magnitude 0. Magnitudes below 0 are brighter than Vega and magnitudes above 0 are dimmer than Vega. Since the scale is "reversed" one often uses the words brighter or dimmer in order to not make mistakes. Magnitudes come in apparent and absolute flavors. Apparent magnitudes are as they appear just outside Earth’s atmosphere. Absolute magnitudes measure how bright the star would be at a distance of 10 pc. There are many systems for measuring magnitudes which involve different wavelengths of light and different optical filters. The magnitude scale used in this project is the one used by the Gaia project, Gaia $G$ magnitude (K93-97).

Main sequence. For most of their lives stars burn hydrogen in their cores. This is a state where the brightness and temperature only changes slowly, it is a stable state relative to the later evolutionary stages. When the star runs out of hydrogen in the core it leaves the main sequence. The Sun is currently a main sequence star of age $\sim 4.5$ Gyr, it will leave the main sequence and become a red giant at $\sim 10$ Gyr (K267)

Metallicity and $[Fe/H]$. The abundance of iron relative hydrogen in a star compared to that of the Sun. Usually defined as $[Fe/H] = log_{10}(N_{Fe}/N_{H})_{\text{star}} - log_{10}(N_{Fe}/N_{H})_{\text{sun}}$. $[Fe/H]$ is often used as a proxy for overall metallicity, even though it only specifies the abundance of iron.

Metal. Astronomers label all elements other than hydrogen and helium as "metals".

Parallax. Describes how something far away shifts in position with respect to a static background as the observer changes perspective. Stellar parallaxes are calculated by using the Sun-Earth distance as baseline and noting how much the stars shift with respect to very distant background objects. $\frac{1}{\text{parallax}}$ gives an estimate of the distance to a star in pc.

Parsec (pc). A measure of distance used by astronomers. 1 pc = $3.086 \cdot 10^{16}$ m or 1 pc = 3.262 light years. Makes calculating distances from parallaxes simple because 1 pc = $\frac{1}{AU}$ where AU is the Sun-Earth distance and ” is the angle in arc seconds.

Sub giant branch, red giant branch. At the end of the main sequence the star runs out of hydrogen in the core. The core then contracts. A shell around the core becomes hot enough to burn hydrogen (it is only depleted in the core). The star grows toward the red giant branch. For low-mass stars there is an initial sub giant branch before climbing the red giant branch. For more massive stars there is a much faster "jump" to the red giant branch (K269).

Survey. A catalogue of observed objects. Often made with a specific science case in mind or to fill a specific gap in our observational data.