Abstract

The Galactic disk is home of many billion stars, one of which is our Sun. The stellar population of which the Sun is a member resides in the vertically thin spiral structure of the disk. There is a second disk population, the so-called thick disk, that has somewhat different spatial, kinematic and chemical properties as compared to the thin disk. It may be systematically older than the thin disk (Bernkopf et al. 2001), with a star-formation hiatus separating the two. Observations of thick-disk subgiants allow us to probe the chemical properties of these stars. As the subgiant evolutionary phase is short, age-dating these stars is also possible. Are they in fact systematically older than the oldest thin-disk stars? This project will take first steps towards answering this question based on new target selections done on Data Release 1 of the Gaia mission.
Sammanfattning

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1 Introduction

Our galaxy, the Milky Way, can be described as having several different regions depending on their shape, kinematics or chemical properties. It can be described as having the following components (Figure 1):

- bulge - round structure in the middle of the galaxy formed of old stars, gas and dust roughly 10,000 light years across

- halo - an oblate spheroid containing individual old stars, clusters of old stars and dark matter and is roughly 130,000 light years across

- disk - a flattened rotating region surrounding the bulge formed mostly of young stars, gas, dust and some old stars. In the case of our galaxy this region is about 100,000 light years across and 1,000 light years thick and it contains the spiral arms.

The Milky Way’s disk is formed by two stellar populations. Young stars form the thin disk and old stars form the thick disk. The purpose of this study is to start exploring the issue of whether the two different populations of the disk are indeed systematically distinct. More exactly, the lower age limit of thick-disk stars is to be studied.

The Sun is a member of the thin disk due to it being a relatively young main sequence star. Since the subgiant branch is the next evolutionary stage for a Sun-like star and since it is a rather short stage in a star’s life, this type of star is an ideal target for the age-dating process. Ages determined in this study will help in better defining the hiatus in star formation or at least provide a better definition for the age of thick disk stars.
Making use of Data Release 1 from the Gaia mission, suitable targets can be selected for further observations and spectroscopic study. The Gaia database is used because the GAIA telescope provides the most accurate data about stellar distances and kinematics, thus the target selection will be as reliable as possible.

After the observations the data obtained will have to be reduced (the process will be described in another section) in order for one-dimensional spectra to be available. Once spectra are obtained spectral analysis can be performed.

Analyzing different regions of the spectra and comparing different observed absorption lines with computer models of line formation will provide the much needed data about a star’s chemical properties. These properties can then be used to locate the stars on isochrone maps (lines in the Hertzsprung-Russel diagram indicating stars of the same age).
Figure 2: The Hertzsprung-Russel diagram (HR diagram for short) - a representation of how the luminosity of stars depends on the effective temperature. The different stellar luminosity classes can also be observed in such a diagram. Source: Wikipedia
2 Background

Stellar populations are categories of stars that have a common origin and which undergo the same evolutionary process (Nissen 2013). For a better description of how the Milky Way was formed and how its evolution might continue it is therefore important to know if each region of the galaxy consists of one or several different stellar populations.

As mentioned in the study by Nissen (2013), each stellar population is described by common spatial, kinematic and chemical properties. Since the first two properties change with the evolution of the galaxy, the chemical composition of a star is assumed to be the one characteristic which can be best used to obtain information about the galaxy. In other words, studying the chemical properties of a star will provide information about the composition of the galaxy at the time and place for the formation of the star.

The main parameter of interest in the study of chemical composition of a star is the \([\text{Fe/H}]\) ratio. This is a logarithmic measure of the relation between the number of iron and hydrogen atoms in the star compared to the same ratio in the Sun. To obtain precise elemental abundances high-resolution spectra with high signal-to-noise ratio (S/N > 100) are needed. This leads to a better definition of the continuum, which is the hypothetical spectral energy distribution if all absorption and emission lines are removed. A well-defined continuum will prove to be very important when determining abundances with the help of weak spectral lines.

To determine elemental abundances one can use equivalent widths of spectra lines, as described in the Nissen study (2013), but in the case of this study another method is used.

Using observed spectra and then fitting spectral line profiles from modelled stellar atmospheres (different atmospheric temperatures result in different abundances, gravity etc.) abundances can be determined. For spectral lines showing a blend due to nearby lines, this represents a more reliable method for abundance determination than the use of equivalent widths. The process is therefore repeated for several line regions.
Figure 3: Example of observed spectrum (dotted line) and lines modelled for different [Fe/H] ratios, for TYC 3815-693-1. Blending is almost a rule when analyzing observed spectra.

In connection to the method mentioned above, accurate abundance ratios are determined only if the best stellar atmospheric parameters ($T_{\text{eff}}$ - surface temperature, $g$ - surface gravity and [Fe/H]) are derived.

For an even better definition of a stellar population the [$\alpha$/Fe] ratio can be determined. This is the ratio between the abundance of $\alpha$-elements (heavier elements which are products of Helium undergoing nuclear fusion in a star) and iron in a star. According to Nissen (2013) the [$\alpha$/Fe] ratio is the average of [Mg/Fe], [Si/Fe], [Ca/Fe] and [Ti/Fe], abundances being determined from weak absorption lines of the respective element using the method described above. Other studies, such as Bernkopf et al. (2001), use only the [Mg/Fe] ratio and a proxy for alpha enhancement the results being just as accurate.

A study performed by Gilmore and Reid (1983) suggested that the distribution of stars towards the Galactic South Pole can only be described when introducing a second disk population - the thin disk, with a scale height of 300 pc, and the thick disk, with a scale height of 1300 pc (height above the galactic disk at which the density of a particular constituent of the disk has declined by a factor $e$). Following the work of Gilmore and Reid, a discussion has developed around the two disk populations and what their connection
is regarding the different populations located in the bulge or halo. The fact that the thin disk and thick disk have a chemical separation is the first step in determining this and evidence was provided by several studies, among which the results of the Edvardsson et al. (1993) survey and the Fuhrmann (2004) study are of interest.

The former study mentioned above (Edvardsson et al. 1993) provides results showing that there is a scatter in [$\alpha$/Fe] for a certain metallicity for stars neighboring the Sun. This was explained as being due to the fact that stars located closer to the galactic center receive iron from type Ia supernovae at a higher [Fe/H] ratio than stars located close to our Sun.

Meanwhile, the study of Fuhrmann (2004) provides an even better separation between the thin- and thick-disk for stars with temperatures between $5300 < T_{\text{eff}} < 6600K$ and $3.7 < \log g < 4.6$. Through the use of Mg I, Fe I and Fe II lines, precise Mg and Fe were determined and with the help of these parameters stellar ages were calculated. The result lead to defining the upper age limit of thin-disk stars as being approximately 9 Gyr and the age of thick-disk stars being around 13 Gyr (Fuhrmann 2004).

This leads to believing that there was a hiatus of about 4 Gyr in star formation, a possible explanation being the interruption of a rapid star formation caused by the merging of a satellite galaxy with ours, which heated up the stars to thick-disk characteristics. The hiatus could have been caused by the accretion of metal-poor gas and a decrease in [$\alpha$/Fe] due to type Ia supernovae. The star formation process resumed afterwards and stars with lower metallicity and [$\alpha$/Fe] were formed, these being the thin-disk stars (Nissen 2013).

More precise studies, which include bigger samples of stars, regarding the chemical composition of thin- and thick-disk stars are therefore needed to better determine when and what could have caused the hiatus in star formation (see figure 4).
Figure 4: Example of separation between thick- and thin-disk stars when plotting abundance ratios with respect to Fe and Mg (Bernkopf et al. 2001)

3 Method

Determining the age of a star is not a straightforward process, several different methods can be employed in this kind of study. This section aims therefore to better explain the importance and nature of these methods.

3.1 Target selection

The first step towards the main goal of this study is selecting suitable targets which are to be observed with a telescope. Data from the Gaia mission, Gaia Data Release 1, is therefore necessary since distances and magnitudes are needed to select a suitable group of stars (this is also what the Gaia satellite is best known for). With help of the database, targets within certain parameters can be retrieved (see Table 1).
Table 1: The restricting parameters for star selection. Right ascension and declination are determined by the observing dates and the location of the NOT telescope at La Palma. The magnitude $m$ has a limit so that very faint objects can be excluded. Finally $\Delta \pi$ is the error of the parallax $\pi$.

<table>
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<th>$m$</th>
<th>RA</th>
<th>DEC</th>
<th>$\Delta \pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>45° to 285°</td>
<td>-20° to 90°</td>
<td>0.10</td>
</tr>
</tbody>
</table>

After applying these restrictions, a cross-reference with the TGAS and 2MASS catalogues is performed in order to limit the number of possible targets only to those which currently have measured distances and K-magnitudes. A table with information about each star with many different measured parameters can be generated. As the purpose of this step is to identify possible targets only the apparent magnitude, parallax, K magnitude and Tycho ID are of interest.

Plotting the G-K index versus the absolute magnitude of these stars will provide a HR-diagram-like image, which is used to retrieve targets found only in the sub-giant evolutionary branch. The absolute magnitude is a measure of luminosity (the apparent magnitude of an object if it is placed 10 parsecs away) while the G-K index, also known as a color index, is a temperature restricting parameter (G-K is the difference between the apparent magnitude registered by the Gaia telescope, G, and the infrared apparent magnitude registered by the 2Mass telescope, K).

3.2 Observations

When the target selection process is over stars can be observed with a telescope. For this study the observations were made at the Nordic Optical Telescope (NOT), La Palma, during the month of February 2017. Most objects are observed twice if possible, so that there is at least one spectrum which can be analyzed for each star. After the observations are done the data is handed over to the observer for further processing and analysis.

3.3 Data reduction

Modern telescopes use CCD (charged coupled device) cameras in order to get high-quality images of the sky. In order to get the spectrum of an object, a spectrograph has to be placed in front of the camera (a device
that spreads the light across a certain wavelength dimension). The downside is that spectroscopy cannot be done directly on these frames, as they do not provide a wavelength scale. What must be done, in order to have spectra to work with, is data reduction. This is the process of going from 2D CCD images to 1D spectra. Since the observations were done at the Nordic Optical Telescope, the special spectrograph known as FIES (FIber-fed Echelle Spectrograph) is used. An automated data reduction package name FIEStool is therefore used to create 1D spectra.

Data reduction involves several different procedures. In spectroscopy a CCD camera will not provide a picture of an object, but several types of so-called frames including the spectrum of the object and several calibration frames. The frame types needed for the data reduction are:

- **BIAS** - this represents the count level when no light hits the CCD for each pixel on the array, as there is some variation in how the camera reads data off the sensors. Pictures taken with a closed aperture and zero exposure time are necessary in order to account for this effect.

- **Dark** - each pixel reads the signal received differently be it due to finite temperature or other instrument induced signals. Taking several pictures with a closed aperture and a longer exposure time will provide information about the difference in signal read-out and its time dependence.

- **FLAT** - the light coming from the spectrograph is not evenly distributed over the sensor. FLAT frames register how an evenly illuminated surface should look like and they also compensate for dust present on the sensor. This is done by letting light from a simple light source (whose properties are known) pass through the spectrograph.

In order to obtain 1D spectra a special program is needed, as mentioned before. Since the FIES spectrograph is fixed, this means that once the format of the data obtained with the detector is determined one can use the automated package to finish the data reduction process, the reduction for all different exposures being more or less the same.

For this to be possible FIEStool has to first be calibrated. This is the part during which the master frames are created and the following steps are performed.

**Master BIAS**, the average of all BIAS frames having removed all pixel values exceeding 5-sigma from the average pixel value.
Master FLAT, the average of all FLAT frames.

Spectral order localization is done interactively with the IRAF routine (Image Reduction and Analysis Facility - Linux based program which can be used to reduce CCD spectra to 1D spectra) using a FLAT frame. This implies identification and ordering of apertures within the FLAT frame.

Renormalizing the master FLAT is the step during which scattered light is removed from the master FLAT. Invoking the IRAF task ‘apnormalize’ will create a two dimensional model of the order shapes and then divide the master FLAT by it. The renormalized master FLAT is obtained as well as the blaze shape, the latter representing the shape of the blaze function determined from the two dimensional model of the order shapes.

The wavelength solution is the final calibration step. Identifying lines across the whole CCD array and assigning them tabulated wavelengths will provide data so that a two dimensional dispersion function can be computed.

Once the calibration procedure is finished the actual data reduction can begin by using the obtained calibration frames and the observation frames. The first step is preprocessing of the observed frame. This implies the removal of overscan regions, rotating the frame and checking that the FITS header is correct.

Next, the master BIAS is subtracted. The 1D spectrum is then extracted and the blaze shape removed. Assigning the wavelength solution to the extracted orders makes it possible to merge all orders into a single spectrum. The overlapping regions will have an increased signal-to-noise ratio. This is the final step in the data reduction process and spectra should now be ready for the next major step of this study, the spectral analysis.
3.4 Spectral analysis

During this part a more detailed explanation will be provided about how the stellar spectra are analyzed and what information can be retrieved from them.

For this part an IDL-based program called Spectral Investigation Utility (SIU for short) is used in order to be able to process the spectra and compare them to modelled ones.

Once a spectrum has been reduced it can be loaded into SIU. Before starting to determine stellar parameters the continuum level has to be indicated. The continuum is the level in flux that defines the border between emission and absorbtion lines. In this case it is done interactively by looking for points in the spectrum which are not affected by absorption lines. Selecting one or more such points will create a slope and it is used to normalize the spectrum accordingly (this level represents a flux of 1.0). Looking at the whole spectrum corresponding to a star will not provide a very reliable definition of the continuum because the spectrum is curved due to the data reduction step. First loading a specific region of the spectrum (a wavelength range of interest) and then selecting the Continuum rectification option in SIU will provide a spectrum for which the continuum level can be indicated.

To be able to indicate a star’s age several parameters have to be determined, as mentioned before. The parameters of interest are:

- the atmospheric temperature $T_{\text{eff}}$ [K]
- metallicity, specifically the [Fe/H] and [Mg/Fe] ratios
- surface gravity $\log g$ [cm/s$^2$]
- microturbulence $\xi$ [km/s]
Figure 5: SIU window showing which parameters can be modified as to obtain a different model atmospheres

All of this can be retrieved from comparing the observed spectrum with synthetic (modelled) spectra. The model atmospheres used for this project are computed under the assumption of local thermodynamic equilibrium (LTE). In other words, the atmosphere is supposed to be in thermal equilibrium locally, as a function of depth. The number of atoms spread across different excitation states is determined by the Boltzmann equation and the number of atoms across different ionization states is computed with help of Saha’s equation.

Surface effective temperature is the main parameter when computing model atmospheres as this indicates the flux of energy, which is constant. As soon as the assumed effective temperature is changed so are all other param-
eters, such as metallicity and surface gravity. This means the temperature must be determined first.

Certain absorption lines, corresponding to different chemical elements, are known to show a higher or lower sensitivity to changes in different parameters. Specific spectral line regions are therefore to be used when deriving a parameter such as the metallicity for example. Ideally, an absorption line should only show changes when the parameter of interest is modified.

The $H_\alpha$ spectral line (6562.8 Å) is such a case, as it is ideal when deriving surface temperatures for stars similar to the Sun. The changes it shows when modifying any other parameters than $T_{\text{eff}}$ being quite insignificant (see figure 6).

An aspect that is worth mentioning is that all the lines used in this study were first tested on the solar spectrum, this being a way to verify that the method gives accurate results and also to remove any absorption lines which might prove to be too difficult to model.

**Figure 6:** Observed $H_\alpha$ line and lines modelled for different temperatures for the star TYC 3815-693-1. The temperature difference between the artificial lines is 100 Kelvin. The error is determined when the gap between the modelled lines is minimal.

After determining what the surface temperature should be and what the error is (done by loading atmospheric models for different temperatures
and looking for any deviation between them) the next step is to decide the overall metallicity of the star. This is represented by the [Fe/H] ratio (when changing this ratio all other elemental abundances will change accordingly), so varying this parameter and comparing the theoretical spectrum with the observed one will give the abundance for the star in question. In order to get a reliable [Fe/H] ratio the lines used are weak Fe\textsc{i} lines, weak meaning their equivalent width is lower than 50 m\(\text{Å}\) (equivalent width - the area of an absorption line in a flux versus wavelength plot). The lines used in this study were chosen from the Korn et. al study (2001).

After deriving the metallicity the next step is to vary the [Mg/Fe] ratio while analyzing weak magnesium absorption lines (in this case the Mg \textsc{i} line used is 4730.029 \(\text{Å}\)). This needs to be done since magnesium is a neutral element and weak lines are therefore relatively insensitive to changes in surface gravity (see figure 7). A strong line (equivalent width over 100 m\(\text{Å}\)) of the same element is afterwards used to obtain a reliable surface gravity value, since this type of lines show pressure broadening which scales with log \(g\) making sensitive to changes in surface gravity. The strong magnesium line used for this study is the line found at 5172.695 \(\text{Å}\). These lines were selected from the Rhodin study (2016).

**Figure 7:** Observed Mg \textsc{i} absorption line along with two different lines modelled for different log \(g\) values - 3.65 and 3.95
**Table 2:** List of weak Fe I lines used to determine the [Fe/H] ratio and strong Fe I lines used to determine the microturbulence parameter $\xi$

<table>
<thead>
<tr>
<th>Fe I [Å] (weak)</th>
<th>Fe I [Å] (strong)</th>
</tr>
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<tbody>
<tr>
<td>5054.650</td>
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<tr>
<td>5197.939</td>
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Microturbulence is a help parameter simulating turbulence in the stellar atmosphere. It is the result of not properly modelling the hydrodynamics of convection and it thus has no true physical meaning. By making use of both weak and strong Fe I lines to determine the $[Fe/H]$ ratio and then plotting the obtained results against the line strength (equivalent width), one can derive the microturbulence parameter $\xi$. The process is repeated while changing the value of $\xi$ and fitting a regression line to the results. To obtain the best microturbulence parameter the slope of the regression line has to be as close to zero as possible.

3.5 Dating process

When all the atmospheric parameters have been derived the dating process can start. This is done with the help of isochrones, which are curves in the Hertzsprung-Russell diagram representing the location of stars of a certain age. Two different ways of dating a star are used in this study.

The first one is plotting isochrones in a log $T_{\text{eff}}$ versus log $g$ diagram. There are several databases which provide isochrones where the necessary parameters can be retrieved. For this project the Dartmouth database was used. Since the surface temperature and gravity have been derived for the analyzed star, all that remains is to plot the star itself on the isochrones and simply read the age and its uncertainty.

The second method is to plot a log $T_{\text{eff}}$ versus $M_{\text{bol}}$ diagram (bolometric magnitude - the absolute magnitude of an object across the whole electromagnetic spectrum). To be able to create such a plot we use the same database as above to determine the bolometric magnitude for stars corresponding to the ages of interest. That is done with help of the following equation:

\[
M_{\text{bol},*} = M_{\text{bol},\odot} - 2.5 \cdot \log_{10} \left( \frac{L_*}{L_{\odot}} \right)
\]

where $M_{\text{bol},*}$ is the bolometric magnitude for the star and $M_{\text{bol},\odot}$ is the bolometric magnitude of the Sun. $L_*$ is the luminosity of the star and $L_{\odot}$ is the luminosity of the Sun.

Determining the bolometric magnitude of the analyzed star is not as straightforward. Its mass must first be derived. This is done by retrieving data about evolutionary tracks for stars of a certain mass. In other words, a log $T_{\text{eff}}$ versus log $g$ diagram is plotted, but this time the tracks show where stars of the same mass can be found in the HR diagram. After plotting
the star in this diagram its mass can be determined and with the help of an IDL routine the bolometric magnitude can then be derived. Interstellar extinction is very important when computing the bolometric magnitude of a star. This represents the amount of electromagnetic radiation (measured in magnitudes) that is absorbed or scattered by interstellar dust. In order to find out what the extinction is in the direction of a certain star the NASA/IPAC Extragalactic Database is used.

Having calculated the bolometric magnitude, the log $T_{\text{eff}}$ versus $M_{\text{bol}}$ diagram can be used to read the star’s age by plotting the specific values for the star in question.

4 Results

As mentioned before, the first step of this study is to select suitable stars which are to be analyzed later on. After retrieving the necessary information from the Gaia database about the stars which meet the restricting parameters, a Matlab code is used to plot them in a G-K versus absolute magnitude diagram (see figure 8).

Figure 8: The result of the Matlab routine. The orange objects represent the possible subgiant stars which can be selected for observations.
Table 3: The final selection of targets which were observed at the NOT observatory. The \textit{TYC} acronym means these identifiers are used to find objects in the Tycho reference catalogue. Using the Simbad database these identifiers can be used to find any other names these objects have been given in other catalogues.

<table>
<thead>
<tr>
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After the observations, the 2D CCD spectra are retrieved and processed. In other words, the CCD spectra are used to create the master frames needed to correct for any atmospheric or instrumental effects (data reduction). At the end of the data reduction process 1D spectra are obtained, meaning the spectral analysis step can begin.
Before thoroughly investigating a star’s properties, a quick analysis of each object is performed in order to find the objects which are most probable to be thick-disk inhabitants. This is done by looking at the $H_\alpha$ spectral line and fitting atmospheric models until the atmospheric temperature ($T_{\text{eff}}$) and a guess for the metallicity [Fe/H] are determined. During this step the assumed atmospheric gravity is $\log g = 3.5$, this being a somewhat typical value for subgiants. The microturbulence is assumed to be equal to 1 $km/s$. The metallicity is determined by trying to fit several weak metal lines found close to the $H_\alpha$ absorption line.

The most promising object proved to be TYC 3815-693-1, with a $T_{\text{eff}}$ of 5350 K and a metallicity of -0.4. The following results are therefore connected only to this star.

After determining the temperature and its error - $T_{\text{eff}} = 5350 \pm 75$ K, weak Fe I lines are selected as to determine a more reliable [Fe/H] ratio. The lines used can be found in the table above.
Table 4: List of weak Fe I lines and the corresponding [Fe/H] ratios derived for spectrum one and two

<table>
<thead>
<tr>
<th>Fe I [Å] (weak)</th>
<th>[Fe/H] spectrum one</th>
<th>[Fe/H] spectrum two</th>
</tr>
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<tbody>
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<td>5054.650</td>
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<tr>
<td>5856.080</td>
<td>-0.60</td>
<td>-0.60</td>
</tr>
<tr>
<td>5927.800</td>
<td>-0.75</td>
<td>-0.80</td>
</tr>
<tr>
<td>6079.020</td>
<td>-0.70</td>
<td>-0.75</td>
</tr>
<tr>
<td>6096.690</td>
<td>-0.75</td>
<td>-0.65</td>
</tr>
<tr>
<td>6229.230</td>
<td>-0.65</td>
<td>-0.60</td>
</tr>
<tr>
<td>6315.815</td>
<td>-0.65</td>
<td>-0.70</td>
</tr>
<tr>
<td>6498.945</td>
<td>-0.55</td>
<td>-0.60</td>
</tr>
<tr>
<td>6703.570</td>
<td>-0.55</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

The mean value of these results represents the [Fe/H] ratio. Therefore the ratios obtained from the spectra are approximately -0.66 ± 0.06 for spectrum one and -0.65 ± 0.06 for spectrum two. These values are now used together with the atmospheric temperature to determine the magnesium abundance. The absorption line utilized for this purpose is the weak Mg I line found at 4730.030 Å. The ratio displayed by SIU is -0.3, but if the [Fe/H] abundance drops below -0.59 the program includes a so-called $\alpha$-enhancement and the [Mg/Fe] ratio is set to +0.4. The correct [Mg/Fe] ratio is therefore +0.1.

Taking this result over to the strong Mg I line (5172Å) the log $g$ value can be derived. For both spectra the obtained surface gravity was log $g =$
The remaining step in the spectral analysis process is to determine the microturbulence parameter. After using the method described earlier the diagrams in Figure 10 and Figure 11 were plotted with Matlab.

**Figure 10:** Spectrum 1 - Top: [Fe/H] ratio versus excitation energy. Bottom: [Fe/H] ratio versus line strength (equivalent width). The lines represent regression lines fitted to each set of data (the derived [Fe/H] ratios for the weak Fe I absorption lines) corresponding to different $\xi$ values.

The bottom diagrams in figures 10 and 11 are of interest ([Fe/H] versus line strength) for this step, but it is worth mentioning that the top diagrams ([Fe/H] versus excitation energy) are a temperature indicator. More exactly, deriving the same abundance ratio from lines with low and high excitation energies will determine the effective temperature (the regression lines should have no slope in this case). It is expected to get a result as the one obtained in these figures, the $H_\alpha$ absorption line being therefore the best indicator for surface temperatures.

The microturbulence derived (done by fitting regression lines to the datapoints in the [Fe/H] versus line strength diagram and trying to get the slopes as close to zero as possible) was $\xi = 0.85$ km/s. For the second spectrum the obtained value was $\xi = 0.83$ km/s.
The final step of this project is to determine the age of the observed stars. After the retrieval of isochrones from the Dartmouth database (for stars with metallicity equal to -0.65 and a [\(\alpha/Fe\)] ratio of +0.2) and their plotting with Matlab, the atmospheric temperature and gravitation derived for TYC 3815-693-1 were used to plot the star itself on the diagram (see Figure 12). Since the log \(g\) value turned out to give a star as old as 18-19 Gyr (gigayears), older than the universe itself, another method was used to correct this error.

The method in question is using weak Fe II lines (chosen from the Korn et al. study - The ionization equilibrium of selected reference stars, 2003) in order to derive a more reliable log \(g\) value. This is done by first determining the [Fe/H] ratio again, this time with the help of Fe II absorption lines. The new [Fe/H] ratio is compared with the one obtained from the Fe I lines. The difference between them is multiplied by 3 and added or subtracted to the log \(g\) value. This is the expected effect for log \(g\), an approximate rule of thumb derived from line-formation theory, the following formula describing exactly how the new value is derived.

\[
\log(g_{\text{new}}) = \log(g_{\text{old}}) - 3 \cdot ([Fe/H]_{\text{old}} - [Fe/H]_{\text{new}})
\]

The process is repeated until the Fe II derived [Fe/H] ratio is the same.
as the Fe I derived [Fe/H] ratio. Thus, the new logarithmic values for the atmospheric gravitation are 3.78 for the first spectrum and 3.70 for the second spectrum. These parameters are now taken and used to plot the star again in the isochrone diagram. The result is seen in Figure 12:

**Figure 12:** Isochrone diagram - log $g$ versus log $T_{\text{eff}}$. Data 1 and data 2 represent the different spectra, while the bars represent the error in atmospheric temperature and gravity. The resulting ages are about 8 Gyr ± 5 Gyr from the first spectrum and 11.5 Gyr ± 5 Gyr from the second spectrum.

The mass of the star is determined with help of evolutionary tracks taken from the MIST database (selected metallicity of -0.65 and rotation selected as Initial $v/v_{\text{crit}} = 0$). After obtaining a value (see Figure 13) the bolometric magnitude of the analyzed star can be computed.

This is done with the help of an IDL routine and by making use of the derived mass (about 0.85 solar masses), surface temperature and surface gravity. The bolometric magnitude is calculated to be 3.78 for the first spectrum and 3.69 for the second one (see Figure 13).

As it can be seen in Figure 14 the error in age is not as significant as when using surface gravity, the age of the star determined with this method being 8 Gyr ± 2 Gyr (first spectrum) and 13 Gyr ± 2 Gyr (second spectrum). The derived age and chemical properties are typical for a thick-disk star, indicating that TYC 3815-693-1 might be an inhabitant of the thick-disk.
Figure 13: log $g$ versus log $T_{\text{eff}}$ diagram

![Figure 13](image1.png)

Figure 14: Bolometric magnitude versus log $T_{\text{eff}}$ diagram.

![Figure 14](image2.png)

To see if the determined age is accurate, the bolometric magnitude is determined again (with the same IDL routine) this time using astrometric
data. The distance, apparent magnitude, bolometric correction and interstellar extinction towards the observed object (obtained using the NED database) are therefore needed. The result can be seen in Figure 15.

**Figure 15:** Bolometric magnitude versus log \( T_{\text{eff}} \) diagram. The data point in the figure represents the age obtained using astrometric data.

Gaia gives an age of about 4.5 Gyr. The error is computed as the root of the sum of squared residuals (the error in distance, bolometric correction and apparent magnitude are taken into account here). Because the error in apparent magnitude is about ± 0.001 and the parallax error is much smaller, the dominant factor is the bolometric correction (BC) with a deviation of about ± 0.1, giving the end result a higher accuracy. The astrometric analysis gives \( M_{\text{bol}} = 2.42 \pm 0.17 \), hence an error in age of just 0.5 Gyr.

5 Discussion and future prospects

Data from the Gaia database was used to determine the most reliable value for the bolometric magnitude and hence the most accurate age for the star. As it turns out, the analysis performed during this project is quite inaccurate. The actual age of the star should be about 4.5 Gyr ± 0.5 Gyr,
typical for thin-disk stars, placing the result obtained in this study (8±2 Gyr or 13±2 Gyr) well outside the error margin.

This begs the question: why such a big difference between the astrometric and spectroscopic ages? The method used in this project to derive the age of the stars has been used before by other scientists and it produced successful results.

There are several reasons why the age error could be so significant. The continuum level of the spectrum indicated during the analysis might be wrong, but this could only produce an error in surface gravity as big as 10%, indicating that it is highly unlikely that this is the main source of the error. This leads to believing that either the absorption lines used to derive the log g value are not suitable (might have an unusual blend) or that there is something peculiar about the star itself, meaning that it could actually be a binary system. In this case more complicated computations would be necessary to determine the correct atmospheric properties and age.

The absorption line used to determine the log g value showed no significant blend, but on the other hand the line used to derive the magnesium abundance (Mg I - 4730Å) was affected by blending already when looking at the Sun. This means that in the case of TYC 3815-693-1 the error in [Mg/Fe] has a significant effect on the log g value, hence a big effect on age determination.

Using the same IDL routine that was used to determine the bolometric magnitude of the analyzed star, another combination of parameters was derived so that the same age as the one determined with help of the Gaia database would be obtained. The result led to some significant changes. TYC 3815-693-1 should have a mass of 1.2 solar masses and a logarithmic surface gravity of approximately 3.44. The effective temperature was not modified during this step since the obtained value was deemed accurate enough.

Nevertheless, one star is not enough to prove that the method is wrong. The search for more suitable objects continues, as well as the analysis of the already observed stars. Should the error repeat itself for several objects, then it means that there certainly is something wrong within the procedure. Otherwise, it means that TYC 3815-693-1 is a star worthy of a more in depth and lengthy analysis.
6 References


Fuhrmann, K. 2004, AN, 325, 3

IRAF webpage - http://iraf.noao.edu/
Dartmouth database - http://stellar.dartmouth.edu/models/isolf_new.html
MIST database - http://waps.cfa.harvard.edu/MIST/interp_tracks.html
Gaia database - http://gea.esac.esa.int/archive/
NED database - https://ned.ipac.caltech.edu/forms/byname.html
2MASS - https://arxiv.org/abs/1311.5246
Simbad database - http://simbad.u-strasbg.fr/simbad/sim-fid
7 Appendix

Code used for target selection

```matlab
1 clear
2 clc
3 load('par.mat'); %load a table with parameters of interest
4 \text{M} = \text{phot\_g\_mean\_mag} + 5 + 5 \times \log_{10}(\text{parallax}/1000); %formula used to compute the absolute magnitude
5 \text{G}_K = \text{phot\_g\_mean\_mag} - \text{ks\_m}; %formula used to compute the G-K index
6 %
7 plot(\text{G}_K, \text{M}, 'x') %plot the stars in an absolute magnitude versus G-K index diagram
8 xlim([0 3])
9 ylim([0 4])
10 xlabel('G-K')
11 ylabel('Absolute magnitude')
12 set(gca,'Ydir','reverse')
13 %
14 \text{A} = \text{table(tycho2\_id, parallax, G}_K, \text{M};}
15 \text{TS} = \text{A(A.G}_K\geq1.5 \& A.G}_K\leq1.75 \& A.M\geq2 \& A.M\leq3.8, :) %list the stars with absolute magnitudes and G-K index which meet the restrictions
16 %
17 hold on
18 plot(\text{TS.G}_K, \text{TS.M}, 'x') %plot the stars listed above in the same diagram in order to obtain a box indicating possible targets
19 xlim([0 3])
20 ylim([0 4])
21 xlabel('G-K')
22 ylabel('Absolute magnitude')
23 set(gca,'Ydir','reverse')
```

Code used to determine the mass of the stars

```matlab
1 clear
2 clc
3 %
4 load Mass06 %load tables containing the log T_{eff} and log g values for stars with a mass equivalent to 0.6 solar masses
5 load Mass07
6 load Mass08
7 load Mass09
8 load Mass1
9 load Mass11
10 load Mass12
11 %
12 \text{x} = \log_{10}(5350); %compute the log value of the effective temperature of the analyzed star
13 \text{y} = 3.68; %input the log g values for both spectra - y,z
14 \text{z} = 3.78;
15 %
16 figure %plot the evolutionary tracks for stars with the same mass
17 plot(Mass06.logTeff, Mass06.logg)
18 hold on
19 plot(Mass07.logTeff, Mass07.logg)
20 hold on
21 plot(Mass08.logTeff, Mass08.logg)
22 hold on
23 plot(Mass09.logTeff, Mass09.logg)
```
Code used to compute the microtubulence for spectrum one

```matlab
clear
clc
lambda = [5054.650 5079.223 5197.939 5216.274 5242.491 5253.469 5321.112 5436.300 ... 5436.590 5464.290 5483.110 5487.160 5522.460 5584.770 5635.850 5662.516 5705.480 ... 5852.190 5856.080 5927.800 6003.030 6065.482 6079.020 6096.690 6229.230 6252.555 ... 6302.493 6315.815 6421.350 6498.945 6703.570]; %list of wavelengths of the spectral absorption lines used
FHs1.Xi11 = [-0.55 -0.65 -0.75 -0.70 -0.90 -0.95 -0.65 -0.75 -0.65 -0.65 -0.70 ... -0.65 -0.65 -0.60 -0.65 -0.75 -0.70 -0.70 -0.70 -0.70 -0.70 -0.70 ... -0.65 -0.70 -1.15 -0.65 -0.75 -0.55 -0.55]; %metallicity obtained for each line corresponding to a certain microturbulence parameter value
FHs1.Xi1 = [-0.55 -0.65 -0.75 -0.65 -0.80 -0.90 -0.65 -0.75 -0.65 -0.65 -0.70 ... -0.65 -0.65 -0.60 -0.75 -0.75 -0.65 -0.75 -0.70 -0.70 -0.70 ... -0.65 -0.70 -1.15 -0.65 -0.75 -0.55 -0.55];
FHs1.Xi105 = [-0.55 -0.65 -0.75 -0.70 -0.90 -0.95 -0.65 -0.75 -0.70 -0.70 -0.70 ... -0.65 -0.65 -0.60 -0.65 -0.75 -0.75 -0.65 -0.65 -0.65 -0.65 -0.65 ... -0.65 -0.60 -1.15 -0.65 -0.75 -0.55 -0.55];
FHs1.Xi102 = [-0.55 -0.65 -0.65 -0.65 -0.65 -0.65 -0.65 -0.75 -0.65 -0.65 -0.65 ... -0.65 -0.65 -0.65 -0.75 -0.75 -0.65 -0.75 -0.70 -0.70 -0.70 ... -0.65 -0.70 -1.15 -0.65 -0.75 -0.55 -0.55];
FHs1.Xi10 = [-0.50 -0.60 -0.75 -0.85 -0.90 -0.95 -0.65 -0.75 -0.65 -0.65 -0.70 ... -0.65 -0.65 -0.60 -0.60 -0.65 -0.75 -0.75 -0.65 -0.65 -0.65 ... -0.65 -0.60 -1.10 -0.60 -0.65 -0.55 -0.55];
FHs1.Xi03 = [-0.50 -0.55 -0.75 -0.55 -0.80 -0.85 -0.85 -0.85 -0.85 -0.85 -0.85 ... -0.65 -0.55 -0.70 -0.75 -0.75 -0.75 -0.75 -0.75 -0.75 -0.75 ... -0.65 -0.65 -1.15 -0.65 -0.65 -0.55 -0.55];
```
%equivalent width (line strength) for each absorption line
figure
subplot (2,1,1) %plot the metallicity versus excitation energy
p1 = plot(E, FHX11, '*')
xlabel('Energy (eV)')
ylabel('\[Fe/H\]')
set(gca, 'FontSize', 25)
lsline %fit a regression line to the \[Fe/H\] values obtained for a microturbulence of ...
mdl = fitlm (E, FHX11, 'linear'); %display its slope (estimate value for xi)
hold on
p2 = plot(E, FHX11, 'o')
mdl = fitlm (E, FHX11, 'linear'); %display its slope

mdl = fitlm (E, FHX11, 'linear'); %display its slope

mdl = fitlm (E, FHX11, 'linear'); %display its slope

p3 = plot(E, FHX11, '>')
mdl = fitlm (E, FHX11, 'linear'); %display its slope
p4 = plot(E, FHX11, '<')
mdl = fitlm (E, FHX11, 'linear'); %display its slope

p5 = plot(WL1, FHX11, '*')
xlabel('W_{\lambda}')
ylabel('\[Fe/H\]')
set(gca, 'FontSize', 25)
lsline %fit a regression line to the \[Fe/H\] values obtained for a microturbulence of ...
mdl = fitlm (WL1, FHX11, 'linear') %display its slope
hold on
p6 = plot(WL1, FHX11, 'o')
mdl = fitlm (WL1, FHX11, 'linear') %display its slope
p7 = plot(WL1, FHX11, '>')
mdl = fitlm (WL1, FHX11, 'linear') %display its slope
p8 = plot(WL1, FHX11, '<')
mdl = fitlm (WL1, FHX11, 'linear') % display its slope
hold off
legend([p1 p2 p3 p4], '\[\xi = 1.1 \text{ km/s}\]', '\[\xi = 1.0 \text{ km/s}\]', '\[\xi = 0.9 \text{ km/s}\]', '\[\xi = 0.85 \text{ km/s}\]')
mdl = fitlm (WL1, FHX11, 'linear'); %compute the mean value of the metallicity for the best ...

m = mean(FHX11) %compute the mean value of the metallicity for the best ...
%microturbulence value
STD = std(FHs1Xi085) %compute the deviation of the metallicity for the best ... microturbulence value

Code used to compute the microturbulence for spectrum two

```matlab
1 clear
2 clc
3 lambda = [5054.65 5079.22 5197.93 5216.27 5242.49 5253.47 5321.11 5436.3 5436.59 5464.29 5483.11 5487.16 5522.49 5584.77 5635.85 5662.52 5705.48 ...]; %list of wavelengths of the spectral absorption lines used
5 WLs2 = [28.520 99.162 19.813 133.988 72.558 60.496 27.339 23.946 39.500 26.673 ...]; %equivalent width (line strength) for each absorption line
6 FHs2Xi102 = [-0.60 -0.65 -0.70 -0.75 -0.85 -0.90 -0.55 -0.60 -0.60 -0.60 ...]; %metallicity obtained for each line corresponding to a certain microturbulence parameter value
7 FHs2Xi1 = [-0.65 -0.65 -0.70 -0.75 -0.80 -0.90 -0.55 -0.60 -0.60 -0.60 ...];
8 FHs2Xi085 = [-0.60 -0.55 -0.70 -0.75 -0.80 -0.90 -0.55 -0.60 -0.60 -0.60 ...];
9 FHs2Xi082 = [-0.60 -0.55 -0.70 -0.75 -0.80 -0.90 -0.55 -0.60 -0.60 -0.60 ...];

figure
subplot (2,1,1) %plot the metallicity versus excitation energy
p1 = plot(E, FHs2Xi102, '*')
xlabel('Energy (eV)')
ylabel('[Fe/H]')
set(gca, 'FontSize', 25)
lsline
mdl = fitlm(E, FHs2Xi102, 'linear'); %fit a regression line to the [Fe/H] values obtained for a microturbulence of 1.02 km/s and display its slope (estimate value for x1)
hold on
p2 = plot(E, FHs2Xi11, 'o')
lsline
mdl = fitlm(E, FHs2Xi1, 'linear'); %fit a regression line to the [Fe/H] values obtained for a microturbulence of 1.0 km/s and display its slope (estimate value for x1)
p3 = plot(E, FHs2Xi105, '>')
lsline
mdl = fitlm(E, FHs2Xi105, 'linear'); %fit a regression line to the [Fe/H] values obtained for a microturbulence of 0.85 km/s and display its slope (estimate value for x1)
p4 = plot(E, FHs2Xi1082, 'r')
lsline
mdl = fitlm(E, FHs2Xi1082, 'linear'); %fit a regression line to the [Fe/H] values obtained for a microturbulence of 0.82 km/s and display its slope (estimate value for x1)
```

34
Code used to determine the age of the stars

```matlab
clear
clc
load('D4.mat') %load tables containing information for stars of the same age
load('D5.mat')
load('D6.mat')
load('D7.mat')
load('D8.mat')
load('D9.mat')
load('D10.mat')
load('D11.mat')
load('D12.mat')
load('D13.mat')
load('D14.mat')
load('D15.mat')

T_sun = 5780; %compute the log value of the effective temperature of the analyzed star
Mbol_sun = 4.74;
x = log10(5350); %compute the log g values for both spectra - y,z
y = 3.68;
```
```matlab
z = 3.5;

figure %plot the isochrones
plot(D4.logTeff, D4.logg)
hold on
plot(D5.logTeff, D5.logg)
hold on
plot(D6.logTeff, D6.logg)
hold on
plot(D7.logTeff, D7.logg)
hold on
plot(D8.logTeff, D8.logg)
hold on
plot(D9.logTeff, D9.logg)
hold on
plot(D10.logTeff, D10.logg)
hold on
plot(D11.logTeff, D11.logg)
hold on
plot(D12.logTeff, D12.logg)
hold on
plot(D13.logTeff, D13.logg)
hold on
plot(D14.logTeff, D14.logg)
hold on
plot(D15.logTeff, D15.logg)
hold on
plot(x,y, '*') %plot the analyzed star in the isochrone diagram
hold on
plot(x,z, '*') %plot the analyzed star in this diagram to obtain its mass

xlim([3.65 3.85])
ylim([3.25 4.3])
set(gca,'Xdir','reverse', 'FontSize', 20)
set(gca,'Ydir','reverse')
xlabel('log T_{eff}')
ylabel('log g')
legend('4Gyr', '5 Gyr', '6 Gyr', '7 Gyr', '8 Gyr', '9 Gyr', '10 Gyr', '11 Gyr', '12 ... Gyr', '13 Gyr', '14 Gyr', '15 Gyr')

zneg = (-0.18); %plot bars showing the error in the obtained values, hence the error ... when determining the age
zpos = (0.18);
yneg = (-0.18);
ypos = (0.18);
xneg = (-0.0040);
xpos = (0.0040);
e1 = errorbar(x,y,yneg,ypos,xneg,xpos,'o');
e2 = errorbar(x,z,zneg,zpos,xneg,xpos,'o');

Mbol_4 = Mbol_sun - 2.5*D4.logLLS; %formula used to compute the bolometric ... magnitude for stars of the same age
Mbol_5 = Mbol_sun - 2.5*D5.logLLS;
Mbol_6 = Mbol_sun - 2.5*D6.logLLS;
Mbol_7 = Mbol_sun - 2.5*D7.logLLS;
Mbol_8 = Mbol_sun - 2.5*D8.logLLS;
Mbol_9 = Mbol_sun - 2.5*D9.logLLS;
Mbol_10 = Mbol_sun - 2.5*D10.logLLS;
Mbol_11 = Mbol_sun - 2.5*D11.logLLS;
Mbol_12 = Mbol_sun - 2.5*D12.logLLS;
Mbol_13 = Mbol_sun - 2.5*D13.logLLS;
Mbol_14 = Mbol_sun - 2.5*D14.logLLS;
Mbol_15 = Mbol_sun - 2.5*D15.logLLS;

w = 3.67; %bolometric magnitude obtained for the analyzed star (using and IDL routine)
```
e = 2.42; %bolometric magnitude obtained from the astrometric data (Gaia satellite)
figure %plot the isochrones in a log T_{eff} versus bolometric magnitude diagram
plot(D4.logTeff, Mbol4)
hold on
plot(D5.logTeff, Mbol5)
hold on
plot(D6.logTeff, Mbol6)
hold on
plot(D7.logTeff, Mbol7)
hold on
plot(D8.logTeff, Mbol8)
hold on
plot(D9.logTeff, Mbol9)
hold on
plot(D10.logTeff, Mbol10)
hold on
plot(D11.logTeff, Mbol11)
hold on
plot(D12.logTeff, Mbol12)
hold on
plot(D13.logTeff, Mbol13)
hold on
plot(D14.logTeff, Mbol14)
hold on
plot(D15.logTeff, Mbol15)
hold on
plot(x, z, '*') %plot the analyzed star in this diagram
hold on
plot(x, e, 'o') %plot the analyzed star in this diagram
xlim([3.65 3.85])
ylim([2 3.5])
eneg = (-0.17); %plot bars showing the error in the obtained values, hence the error ...
when determining the age
epos = (0.17);
wneg = (-0.17);
wpos = (0.17);
xneg = (-0.0040);
xpos = (0.0040);
errorbar(x, w, wneg, wpos, xneg, xpos, 'o')
errorbar(x, e, eneg, epos, xneg, xpos, 'o')
set(gca, 'Xdir', 'reverse', 'FontSize', 20)
set(gca, 'Ydir', 'reverse')
xlabel('log T_{eff}')
ylabel('M_{bol}')
legend('4 Gyr', '5 Gyr', '6 Gyr', '7 Gyr', '8 Gyr', '9 Gyr', '10 Gyr', '11 Gyr', '12 ... Gyr', '13 Gyr', '14 Gyr', '15 Gyr')