An investigation of a method to determine the metallicity distribution function in the thick Disk

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Abstract

The formation and evolution of the Milky Way is a subject under constant debate. Our understanding of the hierarchical structure formation of the Galaxy is limited and as it stands now, there are several different competeing models that aim to explain the observations.
The initial aim of this project was to study vertical metallicity gradients in the thick disk whilst applying a previously unused methodology to separate the two Galactic disks. Instead of separating the disk stars by looking at the stellar parameters we attempted to subtract a well determined metallicity distribution function (henceforth MDF) of the thin disk from the solar neigbourhood from a MDF of a field towards Draco. In doing so we found that the amount stars of solar and higher metallicity in our data from the field was much lower than we expected. This lead to a closer examination of the data where we first examined the metallicity scale of our different datasets and found no significant offset. This lead us to believe that there might be a selection bias in the data, due to limitations in time we could not make a thorough examination of what might be causing this, although we examined whether the cuts in magnitude could be responsible for the bias and found that this might be the case.

Populärvetenskaplig sammanfattning

En av de stora olösta problemen inom astronomi är hur galaxer bildas och utvecklas och i synnerhet hur våran egen Galax, Vintergatan, formades och utvecklades. Det är ett problem som astronomer har försökt lösa i åtskilliga årtionden, men först påsenare tid har instrumenten blivit såpass nogranna att vi har möjligheten lösa detta problemet. Med moderna observationer har vi idag en bra bild av hur Vintergatan ser ut, vi vet att Vintergatan är vad vi kallar en spiralgalax. Det som karaktäriserar denna typen av galaxer är deras struktur; majoriteten av galaxens stjärnor ligger i ett plan som har en spiralstruktur och i mitten av detta plan finns det oftast en bulb, det vill säga utbuckling. Utöver detta såomges spiralgalaxer oftast av en såkallad stjärnhalo. För att försöka förståhur dessa galaxer bildas får vi undersöka Vintergatan. När vi tar en närmre titt pådet Galaktiska planet i Vintergatan såser vi att den består av tvåunderliggande strukturer, en tunn som innehåller stoft, gas och till större del metallrika stjärnor som vi kallar den tunna disken. Samt en tjockare och glesare struktur som består nästan enbart av stjärnor som vi kallar den tjocka disken.

I detta projektet undersöker vi hur metallhalten hos stjärnorna i den tjocka disken är fördelad med avseende påhöjden över det Galaktiska planet. Detta är av intresse för vi vet inte varför det Galaktiska planet är uppdelat i tvådistinkta populationer och med hjälp att studera metallhaltsfördelning för dessa stjärnor såkan vi begränsa vart de befann sig vid sin födsel (detta eftersom när en massiv stjärna når slutet av sin livcykel såexploderar den och förorenar den runtomkringliggande gasen med metaller) och med hjälp av detta förståhur den tjocka disken kan ha bildats och således fåytterliggare insikt i hur Galaxen utvecklades.

Vi har försökt göra detta genom att hitta den metallhaltsfördelning för den tunna disken i solens närhet och sedan subtrahera denna från metallhaltsfördelningen för en observation gjord i ett helt fält med hjälp av diskernas respektive skalhöjder (hur mycket av disken du har kvar vid en viss höjd över det Galaktiska planet). I våran undersökning såfann vi att den metallrika tunna disken var väldigt underrepresenterad i våran data för det fulla fältet, vi började utreda vad detta kan ha berott påmen en fullständig utredning var inte inom projektets omfång såvi lyckades inte faställa vad det berodde på. Således presenteras inga slutsatser i rapporten.

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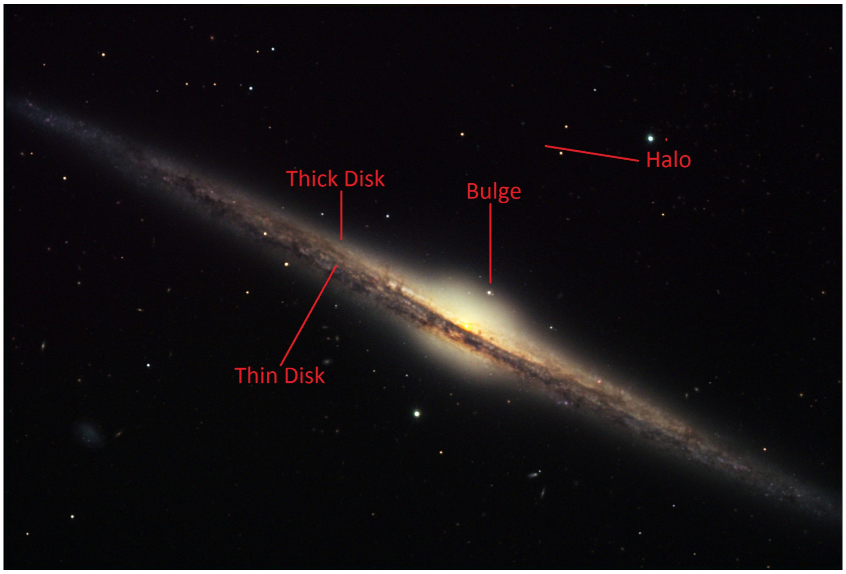

Figure 1: This picture shows the spiral galaxy NGC 4565. We see the galaxy with almost no inclination so its' components are clearly visible and are marked in the picture. (Image credit: Bruce Hugo and Leslie Gaul/Adam Block/NOAO/AURA/NSF)

1 Introduction

1.1 The Milky Way Galaxy

By studying our Galaxy we can see that it is made up of four major stellar components.

The bulge/bar is an overdensity of stars and gas in the central region of the Galaxy, it is believed to have been formed by a buckling of the stellar and gas disk due to instabilities within the Galaxy (so called secular evolution).

Stretching through and far above the Galactic plane there is a population of stars we call the halo. These stars are the oldest population in the Galaxy. It has not yet been determined with certainty where these stars came from, although the most probable origin of the Galactic halo is two fold; stars forming in the protogalactic cloud and stars accreted by the Galaxy from dwarf spheroidal galaxies (dSph) as they were merging with the Galaxy.

The Galactic plane consists of two components, the thin disk and the thick disk (the density of halo stars in the plane is orders of magnitude less than

the disk stars). It is impossible to distinguish the two populations by simply looking at the plane since they coexist within it; instead they are distinguished by kinematics and properties of the stars, such as age and metallicity. By investigating these properties we can try to figure out what might have occured to cause this dual population in the plane (some of the possibilities are orbital migration, heating of pre-existing disk, accretion).
We know all this because with recent advances in observational astronomy the outer (and inner) parts of the Galaxy can be probed to a much larger extent and with higher accuracy than ever before. We find the oldest stars within the Galaxy, these stars are approximately the same age as the most distant galaxies seen in the Hubble Deep Field, i.e. 10 Gyrs and older (Freeman & Hawthorn 2002) and by looking at them we have been able to gain insight in one of the biggest problems for cosmology; how do galaxies form and evolve? This means that, to put in the words of the aforementioned authors, "The old Galactic stars and the distant galaxies provide a record of conditions at early times in cosmic history, and both harbour clues to the sequence of events that led to the formation of galaxies like the Milky Way".

1.2 History of the Milky Way Galaxy

When astronomers first started investigating the history and the large scale structure of the Galaxy the observations lead them to a model where the Galaxy was formed in a single collapse of a cloud of protogalactic gas (Eggen, Lynden-Bell & Sandage 1962). The most noteworthy evidence being the discovery of the metal-poor halo and the discovery of a galactocentric metallicity gradient for globular clusters[1]. However, recent findings have excluded the possibility of a single collapse creating the entire Galaxy. These include the discovery of streams in the Galactic halo, which are basically tracks left by smaller galaxies and globular clusters as they were accreated to the Galaxy (eg. Palomar 5). These findings suggest that part of the halo of the Galaxy might have been formed by smaller galaxies accreating over a long time.

If the galactic plane was formed by a single uninterrupted collapse we would not expect to find a dual population within it. The aim of this project is to

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[1] The protogalactic cloud would contain almost no metals, the halo was believed to be the stars formed in the beginning of the collapse from unpolluted gas. As the cloud collpased (Gyr timescale) stars formed and died and polluted the gas, the expected result was a galactocentric metallicity gradient within the first generation of stars. Because globular clusters are gravitationally bound they represent the first generation of stars.

investigate and put constraints on what might have caused this dual population and to do this we need to look at the old Galactic stars mentioned in the previous section. The lifetime of a star, τ, is proportional to its' mass, m, ($\tau \propto m^{-2}$), so to find the old stars in which we are interested we have to look for low mass stars. Finding these stars is not a problem since most stars have low mass. We know this from the initial mass function, i.e. the distribution of stellar masses on the zero age main sequence, which states that the mass, is approximately distributed over N stars according to

$$\frac{dN}{dm} \propto m^{-2.5} \tag{1}$$

However, it is not easy to determine the stellar parameters for any type of low mass star, so the stars used in this project consists primarily of low mass F and G-class dwarfs. By looking at the atmosphere of these stars (which remains pretty much unchanged whilst the star is on the main sequence and it's on the main sequence for a long time) we can determine the chemical composition of the gas from which the star was created. Of particular interest for this project is the metallicity (which refers explicitly to iron abundance $[Fe/H]$ in this paper) and the MDF of the thick disk. By finding the MDF of the thick disk at different heights above the galactic plane we will be able to derive a metallicity gradient for the thick disk, and in doing so be able to put constraints on its' formation since different models predict different results. For example, if the thick disk was created by accretion then we don't expect to find a vertical metallicity gradient as shown by Abadi et al. (2003), whereas if the disk was created by radial migration we can expect to find a vertical metallicity gradient depending on how the parameters (such as star formation history) are chosen.

1.3 The galactic disks

The fact that the Galactic plane is made up of two different disks was first discovered by Gilmore & Reid (1983). They studied the vertical metallicity distribution in the direction of the South Galactic Pole and found that the distribution was a mix of three underlying distributions with different scale heights, the thin disk, the thick disk and the halo. A scale height, h, is defined as the height over the Galactic plane at wich the number density drops by a factor e, i.e.:

$$N = N_0 \times exp(-h/z) \tag{2}$$

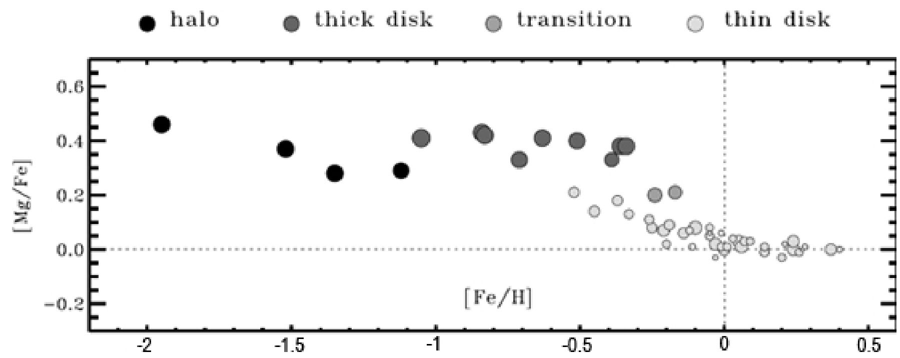

Figure 2: Shown is the abundance ratio of magnesium (α-element) to iron for nearby F- and G-stars. Circle diameter is proportional to age, and the different greyscale colors represent different stellar populations, as shown in the legend. Besides the elemental abundance shown here, kinematics and age determinations are also used to distinguish the populations. (Fuhrmann 1999)

Where N is the amount of stars found at a distance z above the galactic plane and N_0 the amount of local stars for the distribution in question. The major differences between the disks is that h is about 3 times larger for the thick disk and N_0 is 5-20 times larger (depending on the direction you look in) for the thin disk. This is shown in Fig. 3.

Simply looking at the metallicity distribution and finding that it can be fitted with several distributions does not mean that there actually is more than one population. However, by looking for specific characteristics in the supposedly different populations we can find other ways of inferring the existence of more than one population. One way of doing so is to look at the chemical abundances, specifically the α-elements. This can be seen in Fig. 2 above.

2 Statistical and Observational Methods

2.1 Examining the free parameters

Having well-determined free parameters in a model is very useful as it forces you to work within strict constraints. However, if the parameters have large

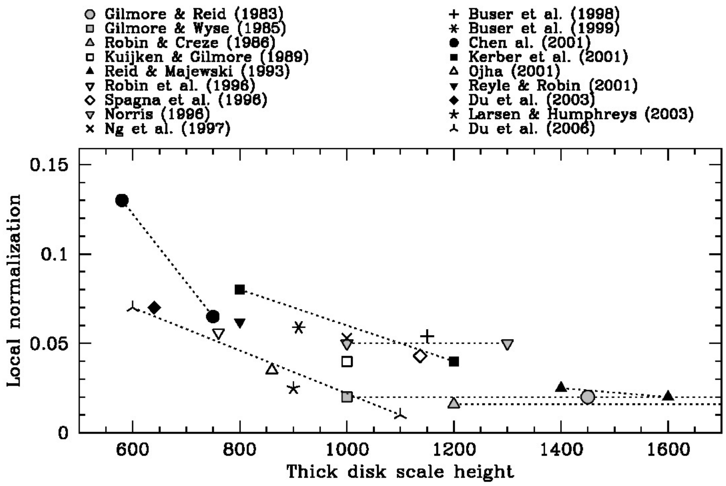

Figure 3: Local normalisation plotted against scale height as derived in different studies looking in different directions. Plot taken from Árnadóttir PhD thesis, see that article for references as indicated in the legend.

margins of error the constraints imposed are much looser, which makes drawing conclusions from the data much harder. The error in the free parameters in this paper(the scale heights of the thin and thick disk and their local normalization, N_{thick}/N_{thin}) are very large, having relative errors up to 50%, shown in Árnadóttir PhD thesis, Paper 3, Table 4 .
As mentioned previously, these parameters are used to determine what fraction of thin and thick disk stars there are at a certain height above the galactic plane. The problem is not simply that the margins of error are large, the problem lies in the fact that different configurations of the parameters can yield very similar fractions, i.e. there exists a degeneracy.

The graphs in Fig. 4 are plots of the function

$$F = \frac{f * e^{-z/h_{TKD}}}{f * e^{-z/h_{TKD}} + e^{-z/h_{TND}}} \tag{3}$$

where f is the local normalization fraction, z the height above the plane and h_{TKD} and h_{TND} the scale heights for the thick and the thin disk, respectively. The variables in Fig. 4 are chosen as to explicitly demonstrate the degeneracy in the problem, other configurations can yield completely different results. The reason we can get widely different results is because

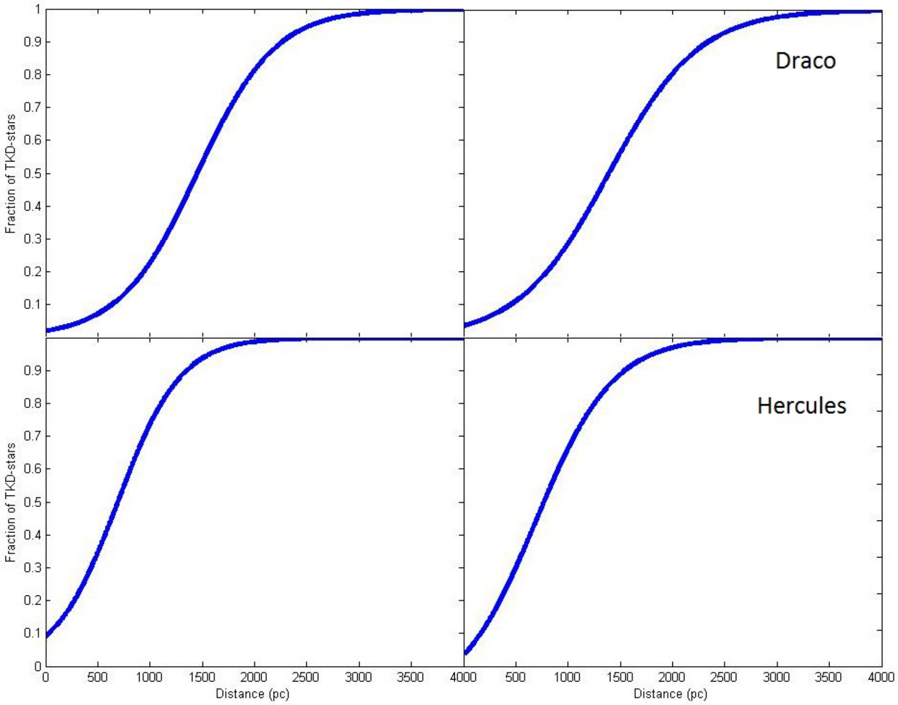

Figure 4: Fraction of thick disk-stars as a function of height above the galactic plane. The top panels are with values in direction of Draco and were calculated using the values $h_{z,TND} = 292pc$,$h_{z,TKD} = 1365pc$, $n_{TKD}/n_{TND} = 0.02$ (left) and $h_{z,TND} = 308pc$, $h_{z,TKD} = 1079pc$, $n_{TKD}/n_{TND} = 0.04$ (Right) The bottom panels are in direction of Hercules and are $h_{z,TND} = 224pc$, $h_{z,TKD} = 878pc$,$n_{TKD}/n_{TND} = 0.10$ (left) and $h_{z,TND} = 250pc$, $h_{z,TKD} = 783pc$, $n_{TKD}/n_{TND} = 0.15$ (right). All the values are within the estimated errors

we have large margins of error in every parameter. By simply looking at Eq. 3 it is obvious that a change in one of these parameters, for example h_{TKD} which has a relative error of 45% in the direction of Draco, will have a signfiicant effect on the derived fraction. The parameters seem to also vary depending on which direction you look in (As shown in Fig. 3).

2.2 Error weighted distribution functions

Working with histograms introduces two new free parameters, the binwidth and where the edges of the bins are located. For a small dataset the appearance of the histogram can be very dependant on these parameters. If the starting value and bin size are chosen 'incorrectly' it can make it look like the data is distributed in a certain way, for example bimodal, whilst a small change in the binning could make it look completely different, for example a continuous distribution.

The error weighted distribution (henceforth EWD) is an alternative to histograms that circumvents the problems that using histograms might cause, whilst also enabling new methods of data analysis. The concept behind the EWD is really simple, all you do is that you create a Gaussian for each data point. The mean is the value of the data point and the standard deviation is the error in each data point, once you have done this you simply add them together as shown in Eq. 4 and the result is an EWD. This is illustrated in Fig. 5.

$$EWD(x) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{\sigma_i\sqrt{2\pi}}exp(-\frac{(x-\mu_i)^2}{2\sigma_i^2}) \tag{4}$$

Since each Gaussian will have an area of 1, the area of the EWD will be N, so to normalize it we simply divide by N, giving each EWD unit area. The most useful property of the EWD, at least for the purpose of this project, is its' linearity. This means that we can freely add or subtract EWD's from each other. We will investigate this property of the EWD to get the metallicity distribution of the thick disk by subtracting the thin disk from a complete sample in section 4.

2.3 Strömgren Photometry

The data for the study was taken from Árnadóttir PhD Thesis, Paper 2. The data is based on observations taken using the Wide Field Camera on the Isaac Newton Telescope and the stellar parameters were derived using the photometric system introduced by Bengt Strömgren (Strömgren 1963).

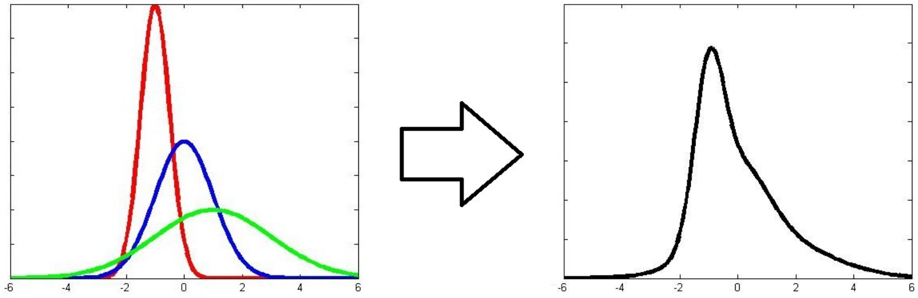

Figure 5: This figure illustrates how three distributions might be added together to create an EWD. As mentioned in Eq. 4 each Gaussian has unit area

The advantage of Strömgren photometry is that we can get accurate estimates of stellar parameters, reliably identify the evolutionary stage of the star and in doing so derive the distance to the star without having parallaxes. The system does this by using 4 different filters u, v, b and y centred at 370, 410, 470 and 550 nm with respective half-widths of 38, 20, 10 and 20 nm. These are combined to the indices:

1. $(b - y)$
2. $m_1 = (v - b) - (b - y)$
3. $c_1 = (u - v) - (v - b)$

The $(b - y)$ index has almost no line blanketing[1] and therefore gives a good estimate of the surface temperature. Contrary to this, the m_1 index is designed to measure the amount of blanketing around 410 nm. This makes it very good for determining the metallicity of the star, to quote Strömgren (1963) ”a colour difference that is a measure of the total intensity of the metals in the v-band”. The c_1 index is designed to measure the Balmer discontinuity (Strömgren 1963). This means that for early type stars, A and B, this index functions as a measure of temperature. For later types than A it is a measure of surface gravity, which means that by using this index

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[1] Line blanketing means that there are so many absorption lines in the spectra that they cannot be distinguished, this makes getting an accurate black body profile impossible, which in turn makes it impossible to determine the temperature. This effect is most prominent in cold stars since their atmospheres' contain a lot of molecules.

you can identify in what evolutionary stage the star is.
When observing with a CCD something to keep in mind is that for a single observation, only a certain magnitude interval can be probed. I.e., a longer exposure time will allow you to detect fainter stars, but at the same time the brighter stars will saturate your CCD and thus no information about them can be derived. The data in this study is in the magnitude interval $15 < V_0 < 18.5$ and was taken in several $34' \times 34'$ fields towards dSph galaxies within the Local Group. For a detailed description of the data see Árnadóttir PhD thesis Paper 2.

3 Constructing the metallicity distribution functions

Getting accurate data becomes increasingly difficult the further away we look and to study the gradient of the thick disk we need to look at stars of the order of kpc's away from the Galactic plane. In the solar neighbourhood the separation of thin and thick disk stars can be done by looking at their kinematics, recently (Fuhrmann et al. 1995) a new method of separation was suggested, in which the different populations can be separated by looking at their $[\alpha/Fe]$ values. For the first method there will always be a statistical overlap between the samples, as the kinematic distribution of the two disks to some extent overlap. What we instead attempt to do is to use the property of EWDs that allows for subtraction of distributions to get a MDF of the thick disk directly from the MDF of the complete sample. The idea is to get an accurate MDF of the thin disk (which does not vary significantly with $|z|$) in the solar neighbourhood and then by using the scale heights weight the thin disk and subtract this from the full field and be left with a sample that represents the thick disk.

3.1 Thin Disk MDF

The data chosen to represent the thin disk came from Fuhrmann (priv. conv.). We chose this data because it is the most accurate study done of the thin disk in the solar neighbourhood. Figure 6 shows the EWD of the thin disk constructed from this data.

Before proceeding we must make sure that this EWD has a real spread and is not dominated by measurement errors. From the Central limit theorem we know that a summation of random measurement errors will result

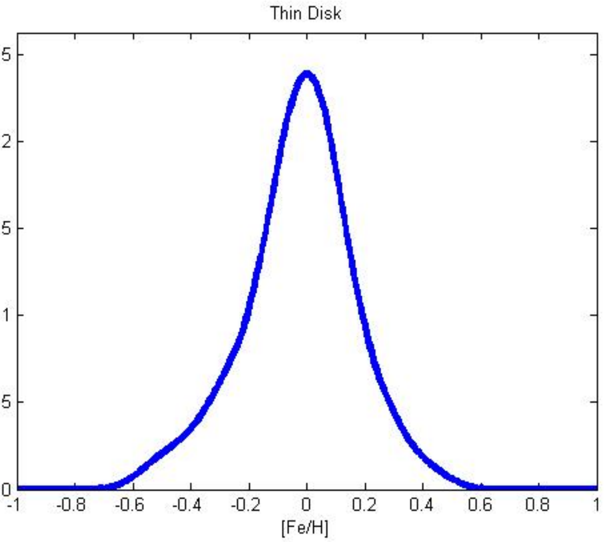

Figure 6: The EWD of our data for the thin disk as described in section 3.1. Where the mean, $\mu = -0.03$ the standard deviation, $\sigma = 0.16$ and the mean error $\langle\epsilon\rangle = 0.07$

in a Gaussian distribution. To test our distribution we created a Gaussian with the same values as the ones shown in Fig. 6 and then did a KS-test to compare the two. We found that the probability of getting our distribution from that Gaussian was vanishingly small and could thus conclude that the the distribution for the thin disk represents an astrophysical dispersion and is not dominated by measurement error.

3.2 Thick Disk MDF

As discussed previously, the idea is to subtract the MDF of the thin disk from the complete sample in order to get the MDF of the thick disk.
To be able to subtract the thin disk from the complete data we need to construct an EWD. Since we will use the fractions derived from the scale heights to weight the thin disk while subtracting we need to bin the data-points according to their height above the Galactic plane ($|z|$).
The primary consideration when binning the data was to have a statistically significant number of stars in each bin, but at the same time we have to take into consideration that to derive the gradient the mean $|z|$ of the bins must

be sufficiently spread. However, we found that when the data was binned in such a manner to get statistical significance in each bin, the spread in $|z|$ was also taken care of. Originally we intended to do the study in two directions, towards Draco and Hercules as they had the smallest margins of error, we started with Draco because we had the better margins of error in that dataset. However when analysing the data we discovered that there appeared to be stars missing in the samples, in particular stars of solar and higher metallicities. Since this bias appeared in both directions we decided to focus our investigation on the Draco sample and attempt to understand why there was an apparent shortage of stars.
Towards Draco we had 379 datapoints, so we decided to put these into 3 bins. The bins in $|z|$ were 0-650pc 650-1300pc and 1300-4000pc, each containing 124, 130 and 125 datapoints and with a mean $|z|$ of 332pc, 876pc and 1859pc respectively.

4 Investigations

As shown in Eq. 4 the EWDs are already normalized when they are created, so even though the datasets we use contain a different number of stars the subtraction is still straight forward. The subtraction looks like:

$$EWD_{TKD} = EWD_{Field} - (1 - F) \times EWD_{TND} \tag{5}$$

Where F is the derived fraction from the scale heights shown in Eq. 3

Figure 7 shows the first attempt at subtraction of EWDs. By simply looking at the plots you can see that the subtraction yields negative values on the y-axis, this would mean that there is a negative fraction of stars at a certain metallicity, which makes no physical sense. So we need to investigate what might have gone wrong.

Our data for the thin and the thick disk came from separate observations so an offset in the metallicity calibration might have been the reason for the subtraction not working as it should. Since we had no common stars with Fuhrmann we had to check the calibration by proxy. The metallicity of the stars in our catalogue had also been derived using a different calibration by Casagrande et al. (2009). This is on the same scale used by Bensby et al. (2003, 2005) who in turn had stars in common with Fuhrmann. The first comparison can be seen in Fig. 8.

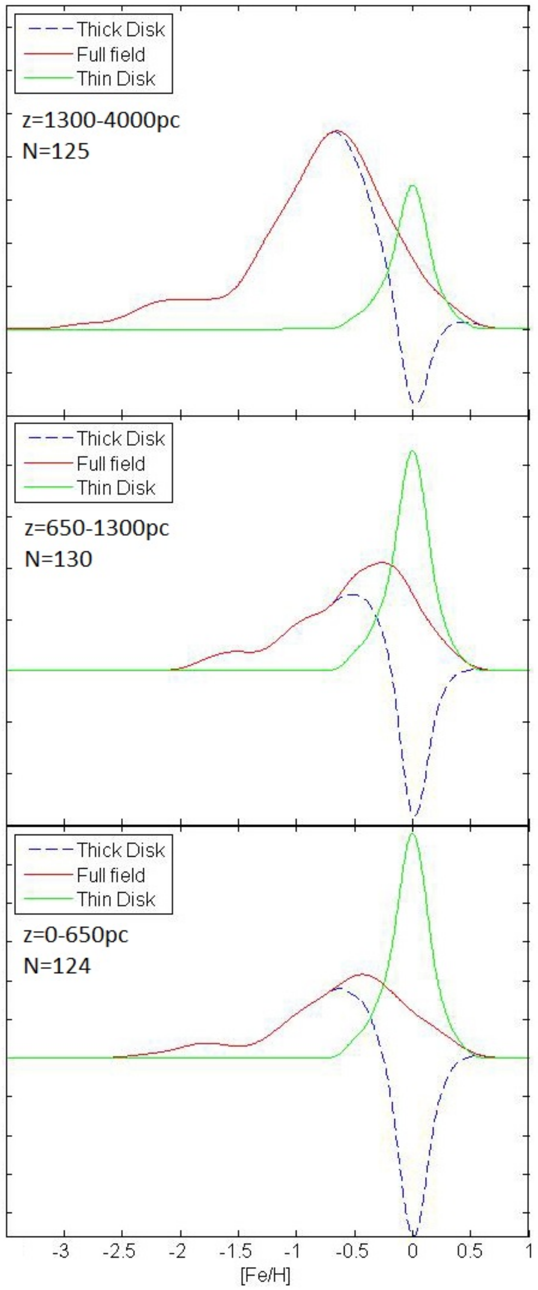

Figure 7: First attempt at subtracting the thin disk from the thick. The panels show the subtraction done in each of our bins, the scale on the Y-axis is arbitrary and only has to do with the normalization of the EWDs, what is of interest is the relative sizes of the green and red plots.

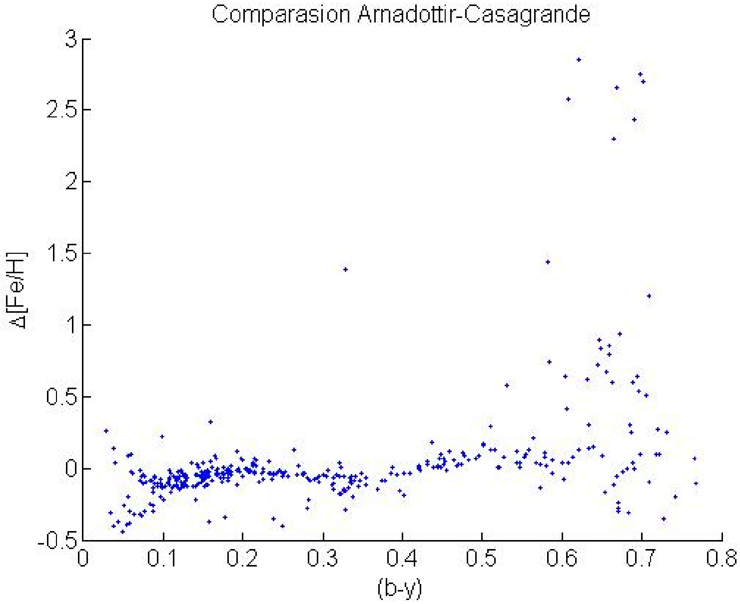

Figure 8: The figure shows the difference in metallicity, where Casagrande's values have been subtracted from Árnadóttir's and plotted against $(b - y)$

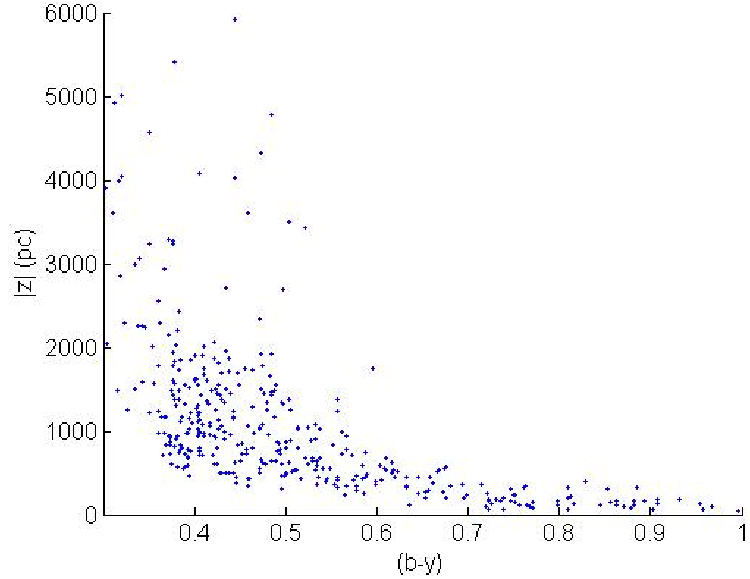

Figure 9: $|z|$ as a function of $(b-y)$ in the direction of Draco

Looking at Fig. 8 we see that overall the agreement is good for a large range of $(b-y)$, however the offset in metallicity becomes very large for $(b-y) > 0.5$. This is most likely due to that the metallicity calibrations for photometry are not very good for the coolest stars as typically the calibrating datasets for these stars are very small. All the stars with $(b-y) > 0.5$ were thus removed from our dataset. In the figure you can also see a lot of stars with low $(b-y)$, these are not part of our dataset, they are part of Árnadóttir's raw data but they were later removed because they were identified as HB-stars. The bluest star in our dataset of dwarf stars has $(b-y) = 0.30$. Doing the same comparison between Bensby and Fuhrmann in the same $(b-y)$-range we found no significant offset. We can thus conclude that there is no offset between the metallicty scales of Fuhrmann and Casagrande. This can then not be the reason for the negative values in Fig. 7.

Figure 9 shows that by doing the colour-cut at $(b-y) = 0.5$ we primarily lose nearby stars. This means that we lose a higher fraction of stars from the thin disk than we do from the thick disk. As expected Fig. 10 shows that only using the stars within the $(b-y)$-range does not change the resulting negative MDF. Although the fact that we primarily lose nearby stars means that by doing the colour-cut we're not only improving the accuracy in metallicity but we're also removing an underlying bias in our dataset, which can clearly be seen by looking at Fig. 9. Having eliminated the possibility of an offset in metallicity the only remaining error in the subtraction itself was the fact that the mean error in the data for the thin disk is significantly smaller than the mean error in the data for the full field ($\langle\epsilon_{TND}\rangle = 0.07$ dex and $\langle\epsilon_{field}\rangle = 0.16$ dex). To explore this we attempted the subtraction one more time but this time we increased the errors in the thin disk data to match the errors in rest of the data. However in doing so we found that it made the results even worse, because this way we always got negative values in the EWD of the thick disk no matter how we weighted the subtraction. Having eliminated all the errors in our methodology that we could think of we came to the conclusion that the explanation must lie in the construction of our datasets. We feel confident that the thin disk MDF be the best possible as determined from stars in the solar neighbourhood. The question then becomes: is the field data actually giving a fair representation of the total MDF in the combined stellar disks. If it is not, then clearly we will not be able to obtain good results until we understand the selection effect that goes in to this sample.

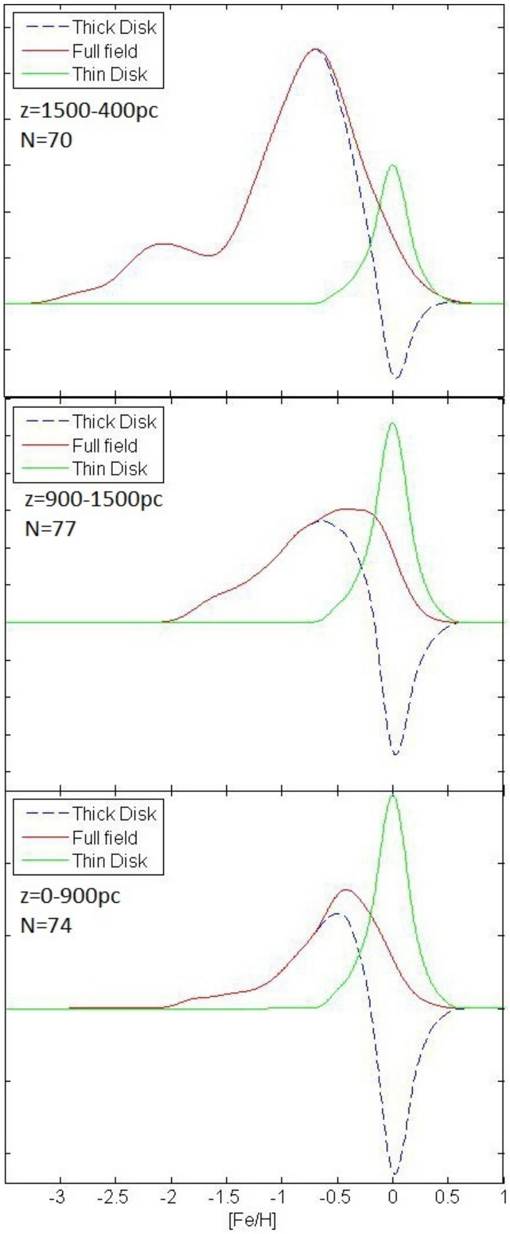

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Figure 10: Subtraction after we cut in colour, the bins are now 0-900pc, 900-1500pc and 1500-4000pc and contain 74, 77 and 70 stars respectively.

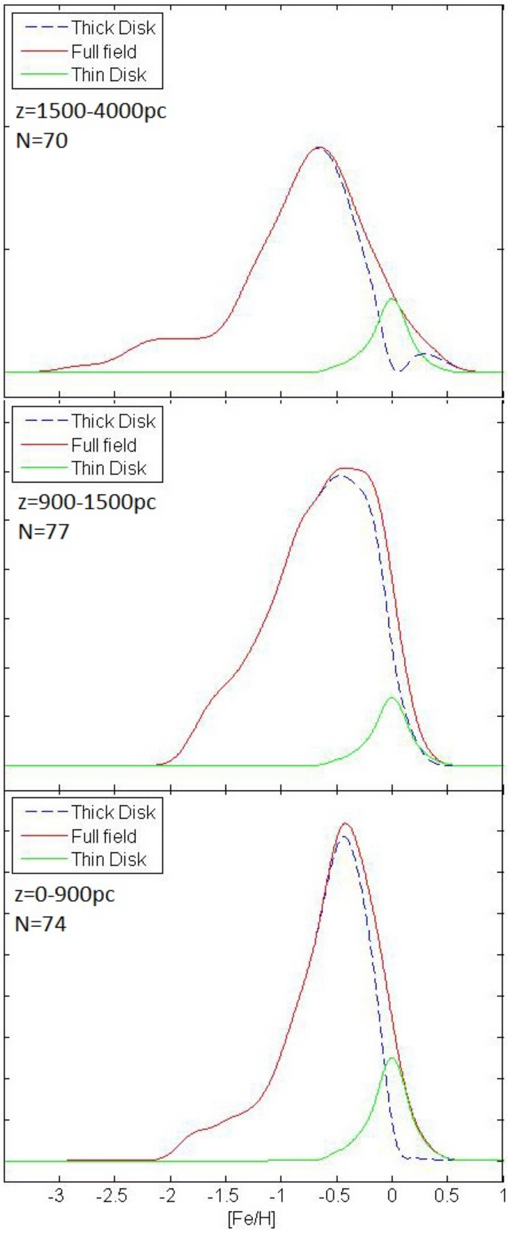

Figure 11: The panels above show how much thin disk it is possible to have in each bin without getting negative values. This was calculated by doing the subtraction and if it gave a negative result the subtraction was done again with F reduced by 0.01, this was iterated until the subtraction gave positive results. At the mean height of each bin there is supposed to be 83, 58 and 18% thin disk respectively. Which would mean that the area under the green curve should be those percentages of the area under the red curve, which it clearly isn't.

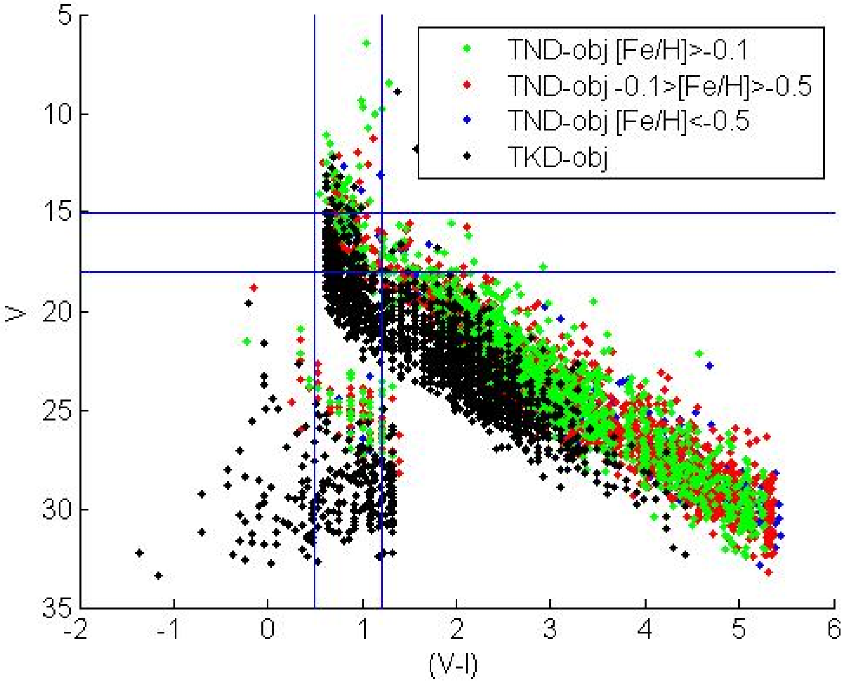

Figure 12: The figure shows the colour magnitude diagram towards Draco (excluding Halo stars) as seen in the Besançon model. The quadratic area that is created with the intersections of the lines represents what part of the colour magnitude diagram we can see with the restrictions in colour and magnitude we have used. It is important to note that the markers in the graph are layered in the same way that the legend is.

For some reason we are losing stars from the thin disk in our observations, this is illustrated in Fig. 11 where the maximal possible thin disk that does not give any negative values is shown. In this figure we see that the fraction of thin disk stars is much lower than expected and the amount of thin disk stars we have in each bin seems to be independent of $|z|$. This lead us to investigate whether or not the cuts in magnitude and colour in any way affected which stars we picked up on our CCD. To do this we ordered a Besançon sample in the direction of Draco and then applied the same cuts in magnitude and colour. The Besançon model uses $(V - I)$ as a measure for colour instead of $(b - y)$. We converted our $(b - y)$-values using the calibrations in Alonso et al. 1995. What we found is shown in Fig. 12. Since it is very hard to draw any conclusions by just looking at the plot some fractions were calculated. We checked what fraction of the stars from each set (black/green/red/blue) that were inside our colour-range, $0.6 < (V - I) < 1.2$, also were inside the observed magnitude-range, $15 < V < 18.5$. What we found was (note that the white dwarfs were excluded from this calculation):

Thick disk (Black)	Thin disk (Green)	Thin disk (Red)	Thin disk (Blue)
0.48	0.45	0.66	0.66

Table 1: Table showing the calculated fractions described in the text above. The colours refer to the the legend in Fig. 12. Worth noting is that there were only 18 stars from the blue set within the colour-range and that makes it very hard to draw any conclusions from that particular derived fraction

As this investigation is done based on a model we cannot draw any conclusions simply based on the model, but we can learn from it. What we see is that the selection of where to cut in both colour and magnitude needs to be done with great care to ensure that the data is representative of the entire population. Since we do not know how the MDF of the thick disk looks, we cannot say if the cut in magnitude introduces any biases to which part of the thick disk population we sample. However, for the thin disk we have a good sample in the solar neighbourhood and we have no reason to believe that it should change in a major way as we go up in $|z|$, at least not as much as our data of the full field suggests. We expect more stars of higher metallicity in our datset, and the fractions derived for the red and green set of stars in the model affirms our belief that that there exists some form of selection bias in our data. However it does not offer any explanation as to why this might be the case. Due to the limitation in time, we could not investigate this matter much further although part of the explenation might be found by simply looking at a general isochrone. Which is shown in Fig 13

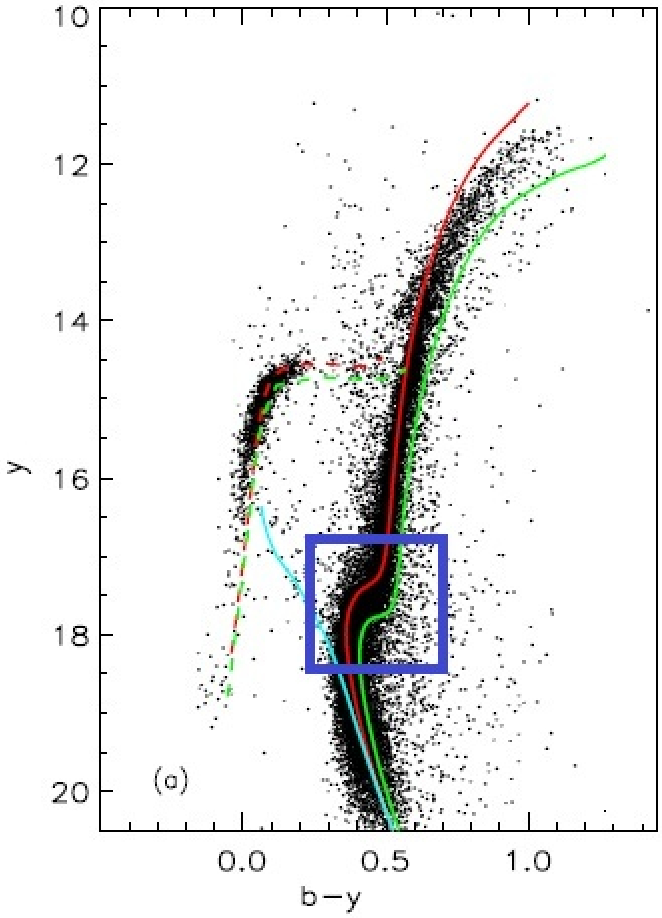

Figure 13: Figure taken from Calamida et al. (2009), depicting Strömgren colour magnitude diagram of ω Cen. In the figure there are 3 theoretical isochrones plotted on top of their data. We are only interested in the red and green isochrones as they are of equal age, 12 Gyr, whilst the turqoise one shows a population of 6 Gyrs. The area in the plot of particular interest is their turnoffs which are enclosed by the blue box. Note that the metallicities in Fig. 12 are not the same as the ones in the isochrones above, although $[Fe/H]_{green} > [Fe/H]_{red}$.

First it has to be pointed out that their y and $(b-y)$ values have no relevance for our data as they are looking at a globular cluster. However, by looking at the boxed region of the plot it is not hard to imagine that by having a cut in magnitude we might lose more from the metal rich part of the population than the metal poor. In fact, the same point can be made about a vertical cut in colour although we cannot say anything for certain without further investigations.

4.1 Further Investigations

There's not much more that can be done by just using our data. One thing that could be attempted is to add a completness-dependant factor in the EWD of the field. (i.e. in Eq. 4 weight the area of each Gaussian, which of course also would mean that the normalization would have to be done differently). There's more than one problem with this, to avoid negative values after the subtraction the weights would have to be very large. This is because there are so few stars of the same metallicity as the ones we are missing that can be weighted to compensate for the missing stars. Also, we cannot guarantee that the weighting will be on the high metallicity stars if we weight according to completeness. We could also weight according to metallicity using the Besançon model or some data from another observation, since our own dataset is rather small it might be better to simply use other data or gather some new high quality data.
What could be done in combination with the weighting is to add some form of error to the EWD, since the EWD only shows *the most probable* shape of the distribution, to see if the negative values end up being within some margin of error.

5 Conclusions

The method of subtracting error weighted distributions from each other seems to be a very useful way of separating joint distributions when some, but not all of them are known. It is unfortunate that we were not able to use this method to find the MDF of the thick disk and thus derive the gradient we were looking for. If that had been the case we would have been able to compare our result to work done in similar studies using different methodologies. As it stands we cannot say with certainty that the method used in this project actually can provide good results.

References

Abadi, M. G. et al. 2003, ApJ, 597, 214

Alonso, A. Arribas, S. Martinez-Roger, C. 1996, A&A, 313, 873

Árnadóttir, A. S. 2009, PhD thesis, ISBN 978-91-628-7922-8

Bensby, T. Feltzing, S. Lundström, I. 2003, A&A, 420, 527

Bensby, T. Feltzing, S. Lundström, I. Ilyin, I. 2005, A&A, 433, 185

Casagrande, L. et al. 2011, A&A, 530, A138

Eggen, O. J. Lynden-Bell, D. Sandage A. R. 1962, ApJ, 136, 748

Freeman, K. Bland-Hawthorn, J. 2002, ARA&A, 40, 487

Fuhrmann, K. Axer, M. Gehren, T. 1995, A&A, 301, 492

Fuhrmann, K. 1998, A&A, 338, 161

Gilmore, G. Reid, N. 1983, MNRAS, 202, 1025

Strömgren, B. 1963, QJRAS, 4, 8