Chemical Tagging of Solar Neighborhood
Kinematic Streams

Christopher Bayard Stringer

A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics & Astronomy.

Chapel Hill
2011

Approved by:

Bruce W. Carney
Gerald Cecil
Arthur E. Champagne
Fabian Heitsch
Sheila Kannappan
ABSTRACT

Christopher Bayard Stringer: Chemical Tagging of Solar Neighborhood Kinematic Streams
(Under the Direction of Bruce W. Carney)

Elemental abundance measurements for lanthanum, europium, and iron are presented for 504 stars in the solar neighborhood. The bulk of the data are planet search spectra taken with HIRES on the Keck I telescope at R=50,000, but a subset of 45 kinematically selected stars were observed on the Harlan J. Smith Telescope at McDonald Observatory at R=60,000 and S/N=100 at the 3988 Å lanthanum line and S/N=250 around 5240 Å near the iron lines. Statistical analyses of stellar kinematics in the solar neighborhood reveal much kinematic substructure in the disk, though it is not readily apparent whether this substructure is extragalactic or dynamical in origin. Much of the substructure can be quickly identified as well known moving groups of stars such as the Hercules, Sirius, and Hyades stellar streams. Additionally, the subset of kinematically selected stars observed at McDonald Observatory are members of a stellar stream putatively identified by Amina Helmi as part of a merger remnant. Taking advantage of a large data set and a homogeneous spectral analysis, a Kolmogorov-Smirnov hypothesis test is applied to investigate the possibility that these kinematic structures are chemically distinct from the Galactic Disk. In all cases, the kinematic streams have chemistries roughly consistent with the Galactic disk trends, although the statistical analyses suggest some subtle variations. The accretion hypothesis is not completely ruled out for Helmi’s stream, but the chemical variations are interpreted primarily in terms of dynamical effects.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>vi</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>x</td>
</tr>
</tbody>
</table>

Chapter

I. Introduction ...................................... 1
   1.1 The Kinematic Streams .......................... 2
      1.1.1 Helmi’s Stream ............................ 3
      1.1.2 The Hercules Stream ........................ 5
      1.1.3 The Hyades Stream ........................... 6
      1.1.4 The Sirius Stream ............................ 6
   1.2 Chemical Tagging ............................... 7
      1.2.1 Alpha Elements ............................. 8
      1.2.2 Iron Peak Elements .......................... 8
      1.2.3 Neutron Capture Elements ................... 9
   1.3 Chemical Trajectories .......................... 12
   1.4 Successes of Chemical Tagging ................. 13
   1.5 Goals ........................................... 16

II. Data ............................................... 17
   2.1 Equivalent width analysis ...................... 17
   2.2 Spectra and Data Reduction ..................... 19
   2.3 The Geneva-Copenhagen Survey of the Solar Neighborhood ........ 25
      2.3.1 Strömgren uvby-β photometry ............... 25
2.3.2 $T_{\text{eff}}$ ........................................ 26
2.3.3 Photometric [Fe/H] .................................. 26
2.3.4 Kinematics .......................................... 27
2.3.5 Stellar Masses ...................................... 27
2.4 Model Atmospheres .................................. 28
2.5 MOOG Synthetic Spectra ............................. 31

III. Analysis .............................................. 35
3.1 Population assignment ................................. 36
  3.1.1 Helmi's stream .................................... 36
  3.1.2 Classical streams, and the thin/thick disk .......... 36
3.2 Surface gravity ....................................... 43
3.3 The automated method ................................ 47
  3.3.1 The $\chi^2$ statistic ............................... 47
  3.3.2 Interpolation ..................................... 49
  3.3.3 Error detection .................................. 50
3.4 The Kolgomorov-Smirnov Test ......................... 51

IV. Results ................................................ 53
4.1 Consistency Checks ................................... 53
  4.1.1 Comparison with literature values : iron ........... 53
  4.1.2 Comparison with literature values : europium and lanthanum 56
  4.1.3 Line-to-line agreement ............................ 61
  4.1.4 Chemically homogeneous stellar groups ............ 64
  4.1.5 The outliers .................................... 69
  4.1.6 Rotational velocities ............................. 73
4.2 Elemental Abundance Results ......................... 75
  4.2.1 Iron ............................................. 75
  4.2.2 Thin and thick disk abundance trends ............. 77
  4.2.3 The classical kinematic streams ................... 82
  4.2.4 Helmi's stream .................................. 86
4.2.5 Cosmic scatter ........................................ 90

4.3 Statistical Results ........................................ 91
    4.3.1 Thin and Thick Disks ................................ 91
    4.3.2 Helmi’s stream: Group 1 ............................ 96
    4.3.3 Helmi’s stream: Group 2 and 3 ...................... 104
    4.3.4 Hercules stream ..................................... 106
    4.3.5 Hyades stream ....................................... 108
    4.3.6 Sirius stream ....................................... 110

4.4 Conclusions ............................................. 112

4.5 Future work ............................................. 113

References ................................................... 115
LIST OF TABLES

3.1 Collected data for population assignment: Galactic components from Bensby et al. (2003) and classical streams from Famaey et al. (2005). 38

4.1 Atmospheric parameters, elemental abundance results, and photometric data for the chemically homogeneous groups. 65

4.2 Atmospheric parameters, elemental abundance results, and photometric data for the outliers. 70

4.3 Gaussian fit to the residuals about a linear trend line fit to the thin and thick disk results. 90
LIST OF FIGURES

1.1 Following the example of Sbordone et al. 2007, the red line illustrates the thick disk trend, while the blue line illustrates the thin disk trend (Reddy 2005). The solid circles show the Sgr dSph main body stars, and the open circle is Terzan 7, a globular cluster embedded in the Sgr dSph. The big star shows the globular cluster Palomar 12 which is kinematically associated but spatial separate, and the pentagon is Ruprecht 106, another globular cluster with low [α/Fe] and a high radial velocity. .................................................. 15

2.1 A legendre polynomial is fit to the upper envelope of the spectra to define the continuum level. .......................... 23

2.2 Division by the fitted polynomial normalizes the flux scale. .............. 24

2.3 The line broadening in each object spectra is measured with a specialized set of synthetic spectra smoothed with a simple Gaussian kernel. The results for the narrowest lined stars illustrate the baseline broadening value. .................................................. 34

3.1 Toomre diagram of the thin disk stars in red circles, thick disk stars in blue triangles, and uncatagorized stars in open, black circles. ... 39

3.2 Toomre diagram of the classical streams with the Sirius stream in green circles, the Hyades stream in red circles, the Hercules stream in blue triangles, and the background stars in open, black circles. ....... 41

3.3 Kinematics of the classical streams with the Sirius stream in green circles, the Hyades stream in red circles, the Hercules stream in blue triangles, and the background stars in open, black circles. ....... 42

3.4 Calculated surface gravities compared to qualitative gravity estimates from the Yale-Yonsei isochrones. The stars are color coded according to their calculated gravities, and four isochrones are shown with ages 3, 6, 9, and 12 Gyr. All of the isochrones have [Fe/H] = −0.05, and the stars have metallicity in the range −0.10 < [Fe/H] ≤ 0.00. The horizontal lines are of constant gravity, coinciding with the gravity bin boundaries at log(g) = 4.4, 4.2, 4.0, and 3.8. .................................................. 44

3.5 The same as Figure 3.4, except for a different metallicity range. Here, all the isochrones have [Fe/H] = −0.15 and the stars are in the range −0.20 < [Fe/H] ≤ −0.10 .................................................. 45
3.6 The same as Figure 3.4, except for a different metallicity range. Here, all the isochrones have $[\text{Fe/H}] = -0.25$ and the stars are in the range $-0.30 < [\text{Fe/H}] \leq -0.20$. 

3.7 An example diagnostic plot from an $[\text{Eu/Fe}]$ measurement of HD 70. On the vertical axis is the $\chi^2$ values, and on the horizontal axis is the $[\text{Eu/Fe}]$ enhancement. Minimizing the fitted polynomial gives the result.

4.1 Spectroscopic $[\text{Fe/H}]$ versus photometric $[\text{Fe/H}]$ from GCS.

4.2 Comparison of spectroscopic $[\text{Fe/H}]$ results with literature values.

4.3 Comparison of $[\text{Eu/Fe}]$ results with literature values.

4.4 Comparison of $[\text{La/Fe}]$ results with literature values.

4.5 Self-consistency of the europium results.

4.6 Self-consistency of the lanthanum results.

4.7 $[\text{La/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with chemically homogeneous stellar groups marked.

4.8 $[\text{Eu/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with chemically homogeneous stellar groups marked.

4.9 $[\text{Eu/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with chemically homogeneous stellar groups marked.

4.10 Overplot of the three lanthanum rich outliers and the solar spectrum. HD22309 is shown in red. HD5072 is shown in green, and HD88446 is shown in blue. The solar spectrum is shown in black, and the 3988 Å lanthanum line has been marked. The S/N of the outliers in this order is $\approx 100$, and the Solar spectrum is much greater.

4.11 Yale-Yonsei isochrones are used to estimate the ages of the outliers. The $[\text{Fe/H}] = -0.4$ isochrones are colored in blue, and the $[\text{Fe/H}] = -0.3$ isochrones are colored in red.

4.12 Rotational velocity comparison with GCS values.

4.13 Metallicity histogram for the entire sample.

4.14 $[\text{La/Fe}]$ vs. $[\text{Fe/H}]$ for stars with distinct Thin/Thick disk kinematics.

4.15 $[\text{Eu/Fe}]$ vs. $[\text{Fe/H}]$ for stars with distinct Thin/Thick disk kinematics.

4.16 $[\text{Eu/Fe}]$ vs. $[\text{Fe/H}]$ for stars with distinct Thin/Thick disk kinematics.

4.17 $[\text{La/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with classical stellar streams marked.

4.18 $[\text{Eu/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with classical stellar streams marked.
4.19 [Eu/La] vs. [Fe/H] for the full sample, with classical stellar streams marked.  85
4.20 [La/Fe] vs. [Fe/H] for the full sample, with Helmi’s stream marked.  87
4.21 [Eu/Fe] vs. [Fe/H] for the full sample, with Helmi’s stream marked.  88
4.22 [Eu/La] vs. [Fe/H] for the full sample, with Helmi’s stream marked.  89
4.23 KS test result of [Eu/Fe] for the thin and thick disks.  92
4.24 KS test result of [La/Fe] for the thin and thick disks.  93
4.25 KS test result of [Eu/La] for the thin and thick disks.  94
4.26 KS test result of [Eu/La] for the thin and thick disks, including a
metallicity cut at [Fe/H] = 0.1 dex.  95
4.27 KS test result of [Eu/La] for Helmi stream group 1.  98
4.28 KS test result of [Eu/Fe] for Helmi stream group 1.  99
4.29 KS test result of [La/Fe] for Helmi stream group 1.  100
4.30 KS test result of [Eu/La] for Helmi stream group 1 with the thick
disk. HD214059 has been removed from group 1 because it is also
classified as a thick disk member.  101
4.31 KS test result of [Eu/Fe] for Helmi stream group 1 with the thick
disk. HD214059 has been removed from group 1 because it is also
classified as a thick disk member.  102
4.32 KS test result of [La/Fe] for Helmi stream group 1 with the thick
disk. HD214059 has been removed from group 1 because it is also
classified as a thick disk member.  103
4.33 KS test result for Helmi stream group 2.  105
4.34 KS test result for the Hercules stream.  107
4.35 KS test result for the Hyades stream.  109
4.36 KS test result for the Sirius stream.  111
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS</td>
<td>2 Micron All-sky Survey</td>
</tr>
<tr>
<td>AGB</td>
<td>Asymptotic giant branch</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative distribution function</td>
</tr>
<tr>
<td>CDM</td>
<td>Cold, dark matter</td>
</tr>
<tr>
<td>CMD</td>
<td>Color-magnitude diagram</td>
</tr>
<tr>
<td>COG</td>
<td>Curve of growth</td>
</tr>
<tr>
<td>CPM</td>
<td>Common proper motion</td>
</tr>
<tr>
<td>dSph</td>
<td>Dwarf spheroidal galaxy</td>
</tr>
<tr>
<td>EW</td>
<td>Equivalent width</td>
</tr>
<tr>
<td>GCS</td>
<td>Geneva-Copenhagen Survey</td>
</tr>
<tr>
<td>IMF</td>
<td>Initial mass function</td>
</tr>
<tr>
<td>ISM</td>
<td>Interstellar medium</td>
</tr>
<tr>
<td>KS</td>
<td>Kolmogorov-Smirnov</td>
</tr>
<tr>
<td>LSR</td>
<td>Local standard of rest</td>
</tr>
<tr>
<td>LTE</td>
<td>Local thermodynamic equilibrium</td>
</tr>
<tr>
<td>ODF</td>
<td>Opacity distribution function</td>
</tr>
<tr>
<td>mas</td>
<td>Milliarcsecond</td>
</tr>
<tr>
<td>MW</td>
<td>Milky Way</td>
</tr>
<tr>
<td>MLT</td>
<td>Mixing length theory</td>
</tr>
<tr>
<td>SDSS</td>
<td>Sloan Digital Sky Survey</td>
</tr>
<tr>
<td>SFR</td>
<td>Star formation rate</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>SNe</td>
<td>Supernova</td>
</tr>
<tr>
<td>UMa</td>
<td>Ursa Major</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The successful Λ-CDM model of cosmology predicts a hierarchical formation mechanism of galaxies, with smaller units accreting to construct larger ones. The detection of merger events in external galaxies is well known, and the detection and analysis of merger remnants in the Milky Way is a key component in piecing together the history of our home galaxy. The low density of the halo aids the survival of streams from disrupted merger events, with the Sagittarius dwarf spheroidal galaxy being one of the best examples (Ibata et al. 1994; Majewski et al. 2003). The stellar streams through the galactic halo, reminiscent of jet contrails, are suggestive to the eye of past merger events where smaller galaxies have been stretched and torn by tidal effects as they are absorbed into the Milky Way. The canonical example of these streams is perhaps the so-called “Field of Streams” presented in Belokurov et al. (2006).

While a haven for stellar streams, the halo is only a trace component of the Galaxy; the Galactic disk is the dominant repository of the stellar component and contains the record of our Galaxy’s history. However, it is challenging to identify merger events in the disk because spiral arms and molecular clouds disperse streams relatively quickly. Nonetheless, evidence for significant mergers exist. The Sloan Digital Sky Survey (SDSS) has detected a number of stellar streams in the outer disk, including the Monocerous Ring (Yanny et al. 2003). The extensive 2MASS database has also led to the identification of the Canis Major galaxy (Martin et al. 2004; Bellazzini et al. 2004; Martínez-Delgado et al. 2005). Radial velocities of the photometrically identified streams have confirmed the existence of unique streams (Peñarrubia & Benson 2005; Conn et al. 2005).
The disk is the major stellar component of the Milky Way, and if hierarchical formation of galaxies is the proper metaphor, then we should see signs of such merger events even in the solar neighborhood. Searches for such structures is very daunting, however. Dissolved large clusters may masquerade as streams; dynamical interactions within the disk can produce kinematic streams that pass through the solar neighborhood. Indeed, the existence of kinematically related “moving groups” of stars have been known for nearly a century, but the wealth of kinematic structure has only recently become apparent with success of the Hipparcos mission and 2MASS, combined with CORAVEL radial velocities and additional analysis in the GCS. In this work, the classical kinematic streams are revisited along with a more recently discovered stream with attractive properties as a putative merger remnant.

1.1 The Kinematic Streams

It is difficult to discuss kinematic streams without first referring to the work of Olin Eggen. In a series of papers (Eggen 1958a,b,c), he defined what are referred to here as the Hercules, Hyades, and Sirius streams, among others. Eggen’s method is not so different from modern methods. In essence, Eggen sought to identify conglomerations of kinematically related stars, but in an effort to better understand the errors involved, and, indeed, in an effort to sidestep the errors in the parallax measurement in particular, Eggen adopted a “convergent point” method based on the observed proper motions and a spectroscopically derived radial velocity. The method is summarized in Eggen (1958a):

Although the tangential components of velocity cannot be found without knowledge of the parallax, the ratio of the two tangential velocities, in right ascension and in declination, is equal to the ratio of the proper motions which can, of course, be found independently of the star’s distance. This ratio gives $\theta_o$, the position angle of the star’s apparent motion from $\tan \theta_x = 15 \mu_\alpha \cos \delta / \mu_\delta$, which may be compared with $\theta_c$, the position angle of the group motion projected on to the tangential plane. The agreement between $\theta_o$ and $\theta_c$, together with the agreement between the observed radial velocity and that computed from the radial component of the group motion, provide
two criteria by which a star’s membership in the group can be judged.

The group motion is typically defined in terms of the motion of a well known star or cluster. For example, the Hyades cluster defines the group motion in Eggen’s membership criteria for the Hyades moving group, and the bright star Sirius defines the group motion for the Sirius moving group. Over the years, the accepted membership criteria have been refined, and in this work, the definitions in Famaey et al. (2005) are used. It is interesting to note that the star Sirius is no longer considered a member of the Sirius moving group, though the stream still bears its name. Unsurprisingly, the terminology used to refer to these groups of stars has evolved along with our understanding of them. Eggen’s origin hypothesis is that these moving groups, sometimes also referred to as super clusters, are evaporated members of slowly dissolving populations of stars, and the escaped members have retained the kinematic profile of their parent population. Indeed, many such related populations are well known (López-Santiago et al. 2006), but these are typically young, newly formed groups of stars, and they do not contribute to the kinematic structure in the solar neighborhood as prominently as Eggen’s groups. Additionally, this formation/dissolution mechanism is not restricted to clusters, as kinematically and chemically related pairs of stars are also observed, termed common proper motion pairs. With the addition of the accretion and dynamical resonance hypotheses for kinematic structure in the disk, it is simpler to refer to them as kinematic streams and dispense with the historically used terms of moving groups and super clusters, as these terms are steeped in the cluster origin hypothesis.

1.1.1 Helmi’s Stream

Helmi et al. (2006) have undertaken a careful analysis of the Geneva-Copenhagen survey (GCS) of the solar neighborhood (Nordström et al. 2004; Holmberg et al. 2007, 2009) to statistically quantify local kinematic substructure, and she identifies three kinematically related groups of stars as part of a putative merger remnant.
Observationally, the velocity vector of a star in the Solar neighborhood is determined by the combination of proper motion, radial velocity, and parallax measurements. The $UVW$ velocity components form a standard system for expressing the kinematics. The $UVW$ components are defined in terms of a right-handed coordinate system with basis vectors, $U$, pointing toward the Galactic center, $V$, in the direction of rotation, and $W$, pointing toward the north Galactic pole. Usually, $U$ points away from the Galactic center, but in the GCS it is defined inwardly. The calculation of $UVW$ velocity components in terms of observables is an exercise in spherical geometry, and it includes such details as the Sun’s distance from the Galactic center, the Sun’s peculiar motion, and the Sun’s circular motion about the Galactic center. The $UVW$ system is used in the GCS, but a first step in Helmi’s analysis is to transform the $UVW$ velocities into a set of quasi-conserved quantities. This is the APL space, referring to apo-galacticon, peri-galacticon, and $L_z$, the angular momentum. Using position and $UVW$ velocities as initial conditions, orbits are calculated about the Galactic center by adopting a form of the Galactic potential, and then computationally solving the Newtonian equations of motion. The APL system parameterizes these orbits. Since momentum is, in general, better conserved than velocity, the expectation is that the APL system is a better choice for detecting accretion events, as it should be better at resisting loss of information to dissipative processes. As the next step, a model of a “smooth” distribution of a galaxy is made by a Monte Carlo method. Specifically, the empirical APL quantities are randomized with a Gaussian kernel such that the statistical nature of the sample is conserved. In other words, the mean $UVW$ space velocities and the velocity ellipsoids $\sigma_u$, $\sigma_v$, and $\sigma_w$ are the same. Next, a statistical analysis is performed to identify overdense portions of APL space. As the argument goes, these overdense regions cannot be explained in terms of random, statistical overdensities. Indeed, a visual comparison of the “humpiness” of the real data versus the smoothed galaxy is enough to see that the solar neighborhood contains a wealth of kinematic structure, with the Hyades, Hercules, and Sirius streams as the most prominent structures.
Focusing on the substructure, Helmi draws attention to a particular overdense region of APL space. The distribution of the overdensity is compared to patterns made by accreted objects in computer simulations, and some similarity is noted. Further, it is shown that the CMD of the stars in this region of APL space display a main sequence turn off and a giant branch, whereas the CMD of stars with only slightly different orbits are much less distinct. Finally, she notes that the metallicity histogram for these stars is trimodal, very strange indeed. These three peaks in the metallicity histogram is the origin of the three Helmi groups: a metal rich group with $-0.45 \leq [\text{Fe/H}] < -0.2$, an intermediate group with $-0.60 \leq [\text{Fe/H}] < -0.45$, and a metal poor group with $-0.80 \leq [\text{Fe/H}] < -0.60$. Isochrone fitting suggests that the first group contains two populations with ages $\approx 8$ Gyr and $\approx 12$ Gyr. The second group contains three populations with ages $\approx 8$ Gyr, $\approx 12$ Gyr, and $\approx 16$ Gyr, and the third group contains a single population with an age $\approx 14$ Gyr. The kinematic, photometric, and chemical evidences argue in favor of an unusual population of stars residing in this portion of APL space. It is called a putative merger remnant, but more definitive proof is needed to make a strong claim.

1.1.2 The Hercules Stream

The Hercules stream was first described in Eggen (1958b) as those stars sharing a convergent point with $\beta$ Hydi and $\xi$ Herculis, but the membership criteria used here is the characterization of Famaey et al. (2005). In the same paper, Famaey et al. find that the Hercules stream accounts for approximately 6% of the stars in the solar neighbourhood. Similar to the thick disk, they lag the LSR by $\approx 50$ km/s, but they have a net radial drift of $\approx 40$ km/s directed away from the galactic center (Soubiran et al. 2003; Famaey et al. 2005). A analysis by Bensby et al. (2007a) measures chemical abundances, ages, and metallicities within the Hercules stream, and they find a bimodal distribution at higher metallicities corresponding to a mixture of thin and thick disk stars, and at lower metallicities the distribution follows the thick disk distribution. Additionally, computer simulations by Dehnen (2000) suggest
that a dynamical stream passing through the solar neighborhood with the observed characteristics of the Hercules stream could be induced by an interaction with the outer Lindblad resonance of the galactic bar. These evidences argue in favor of a dynamical origin for the Hercules stream.

1.1.3 The Hyades Stream

The Hyades stream has long been supposed as evaporated members of a formerly larger Hyades cluster. Indeed, Eggen’s original membership criteria was based on the kinematics of the Hyades cluster (Eggen 1958a). Recent studies seek to compare stellar ages and compositions of the Hyades cluster with the stars of the stream because, in Eggen’s scenario, the vast majority of the stream stars ought to share the same age and composition of the cluster. Clearly, this is not the case because the metallicity distribution for the stream spans too wide a range to be composed solely of evaporated cluster members. Nevertheless, Pompéia et al. (2011) suggest that the stream might well contain some evaporated members, but in this scenario, it is simply a coincidence that the cluster was caught on the same resonance orbit as the rest of the stars that compose the stream, and observed difference in mean metallicity between the stream and bulk solar neighborhood disk stars are explained in terms of the particular orbit of the Hyades stream tracing the metallicity of the inner disk.

1.1.4 The Sirius Stream

The Sirius stream is named, unsurprisingly, after the bright star Sirius in Canis Major. This is because the movement of Sirius was used by Eggen (1958a) to define the group movement for the purpose of the convergent point calculation. Compared to the Hercules and Hyades streams, the Sirius stream is sparse and less defined in kinematic space (Antoja et al. 2008), and it has a velocity very similar to the LSR (Famaey et al. 2005). Even before Eggen, a stream of stars were known to exist in Ursa Major (UMa), and there was a search for the Ursa Major nucleus cluster. The
UMa nucleus cluster has since been identified, and a list of 60 nearly assured members are identified by King et al. (2003), and as expected, many of these are young, bright stars. For those who desire clarity in astronomical naming schemes, it might have been preferable to retain UMa as the name of the stream, because with an age of $\approx 250$ Myr, Sirius A is too young to belong to the $\approx 500$ Myr old UMa cluster (King et al. 2003; Liebert et al. 2005). Nevertheless, the stream still bears Sirius’ name, and as is the case with the Hyades Stream, stars of the Sirius stream span a range of metallicity similar to the galactic disk.

1.2 Chemical Tagging

Chemical tagging, as defined by Freeman & Bland-Hawthorn (2002), is a useful technique to match stars with shared histories, even when evidences such as phase space information have been lost to dissipative processes. The essence of the technique is simple: stars born in the same protocloud of gas will inherit the chemical composition of the cloud, and that chemical pattern will remain present in the stellar atmosphere until some process changes it. So long as the pattern persists, it can be used to associate stars according to their formation sites, even if the kinematic and spatial information are diffused. An example of a process that will change a star’s chemical signature is “dredge up” during the AGB phase of stellar evolution where hydrogen fusion and/or CNO cycle products are transported to the photosphere by convection. Long lived, G and F dwarfs lack these deep convection zones, and so they are suitable targets for chemical tagging studies. However, an underlying assumption in this picture is that the protocloud is well mixed, such that the newly formed stars will have zero dispersion for elements of interest.

An ambitious end goal of such studies is to build a library of unique chemical patterns along with times and places of formation, in spite of the limitations imposed by dissipative processes on kinematic information. Of course, measuring the time of formation for any given star can be a daunting problem in itself. Whether by
nucleocosmochronology or isochrone fitting, stellar age dating is notoriously difficult, although chemical tagging may be able to assist if the age of a subset of a chemically related stars can be reliably measured. Another daunting problem is uniqueness. On considering the staggering number of formation sites since the formation of the disk, $10^8$ is the estimate given in Freeman & Bland-Hawthorn (2002), it is clear that in order to give a unique signature, many elements should be measured. However, it is not a matter of measuring just any elements; a judicious user will choose to measure elements that tend to be decoupled from a nucleosynthetic perspective, as these are the elements that will most likely show variation among stellar populations with different histories.

1.2.1 Alpha Elements

One good example of elements that are coupled nucleosynthetically are the alpha elements. These are carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, argon, calcium, and titanium. They are produced in the alpha process by successive captures of helium nuclei, and so their observed abundances tend to be correlated. However, to the extent that they participate in other nucleosynthetic pathways, variation is observed. Carbon, nitrogen, and oxygen, for example, participate in the CNO cycle, and so they are not considered as “pure” examples of alpha elements. Silicon and calcium are good examples of pure alpha elements. Low-mass stars do not produce many alpha elements, but massive stars, about $10 \, M_\odot$ or more, will pass through a brief silicon-burning phase near the end of their lifetimes when significant alpha products are produced. Because of this, alpha elements are associated with SNe II.

1.2.2 Iron Peak Elements

Another set of nucleosynthetically coupled elements are the iron-peak elements: vanadium, chromium, manganese, iron, cobalt, and nickel. These elements represent the end of fusion reactions that yield energy to support hydrostatic equilibrium. They
are “peak” elements in the sense that they have the greatest binding energy per nucleon of all the elements. As with the alpha elements, these are also produced during the silicon-burning phase in massive stars, but they are also produced abundantly in type Ia supernova. In this picture, a white dwarf accretes matter from a giant companion, slowly increasing its mass closer to the Chandrasekhar limit. Although the details are not well understood, as the mass of the star approaches the Chandrasekhar limit, it will begin to contract, and the increased temperature will ignite a sequence of carbon and oxygen burning. While a thermally-supported star would expand and cool, a white dwarf is supported by degeneracy pressure, independent of temperature, and the energy released from the runaway nuclear process unbinds the star. As a result, many of the iron-peak elements are produced, as evidenced by type Ia supernova spectra.

1.2.3 Neutron Capture Elements

Elements beyond the iron peak are not synthesized in standard fusion reactions. The reactions to produce yet heavier species become endothermic as the Coulomb barrier to charged particle interaction increases and the binding energy per nucleon decreases. Instead, these elements are produced by neutron capture in high neutron flux environments where the interaction probabilities become appreciable. Here, nuclei take paths through the table of nuclides by a succession of neutron-capture events and $\beta^-$ decay. The particular path taken depends strongly on how the neutron capture time scale compares with the $\beta^-$ decay time scale. If the capture rate is slow, then each capture event will be followed by a decay event, and the net effect is that the path through the table of nuclides will follow the valley of beta stability. The elements produced by this sort of process are referred to as s-process elements. If the neutron capture rate is rapid, then many capture events can occur in succession, pushing the nuclei toward the neutron drip line. Once the high neutron flux is removed, for example, in the aftermath of a core collapse supernova, then the nuclei quickly decay toward stability, but the decay products here include nuclides unreachable by the s-
process. In general, a nuclide is excluded from s-process production if it has an lighter isotope that is $\beta^-$ unstable, and a nuclide is excluded from r-process production if there is a stable nuclide with the same mass number, $A$, but greater $N$. That is because any r-process $\beta^-$ decay path terminates at the first stable nuclide. Clearly, there is overlap in the final products of the s and r processes, and the details depend on the quantum mechanical properties of the many nuclides. Some nuclides are excluded from the s or r-process pathways; for example, $^{134}$Xe is a pure r-process nuclide because $^{133}$Xe is $\beta^-$ unstable, and $^{134}$Ba is a pure s-process nuclide because it is shielded from the r-process by $^{134}$Xe. For the purposes of chemical tagging, those exceptional elements that are nearly pure are of special interest. Examples of pure r-process elements include europium (97%), thorium (100%), and uranium (100%). Examples of pure s-process elements include strontium (89%), barium (85%), and lanthanum (75%) (Burris et al. 2000).

The contribution of the s-process to the solar system neutron capture element abundance pattern is well understood (Kappeler et al. 1989), and our understanding of the r-process contribution intimately depends on being able to model the s-process yields. The s-process problem is solved by adopting what is called the classical s-process model. This approach assumes a pre-existing distribution of iron peak seed nuclei, a constant neutron irradiation rate, and a fixed temperature. The problem is further simplified by identifying those nuclides where the $\beta^-$ decay time is comparable to the neutron capture time, so-called “branching” points along the s-process path. Under these assumptions, a system of coupled differential equations are formed where the primary unknowns are the nuclear cross sections for the participating nuclides. Since the s-process path traces the valley of beta stability, the nuclear cross sections of these nuclides are accessible to laboratory testing. The equations are solved numerically, and the resulting match is very good with the s-process pure nuclides in the solar system. However, there is one important caveat. Due to the branch points in the s-process path, the calculated abundance pattern is sensitive to the neutron flux and the temperature, as these quantities are especially important if the decay time is
comparable to the capture time. The best match with the solar system abundances is attained by adopting a three component s-process, corresponding to three different sets of physical conditions. For this reason, it is said that there are three varieties of the s-process to explain the s-process chemical pattern (Sneden et al. 2008). The first is referred to as the “main” s-process that explains the s-process abundance pattern for the majority of elements, especially those with \( A > 90 \), and accounting for the bulk of the s-process distribution in the solar system. The production site is low to intermediate-mass stars \((1 - 5M_\odot)\) as they pass through their AGB phase. The second, lower neutron flux environment, is the “weak” component, needed to account for an excess of s-process products with \( A < 90 \). These are produced during helium-core fusion in massive stars, and finally, there is a “strong” component that accounts for an excess of lead in the solar system that is unexplainable in terms of the main s-process. Due to the production site of the main s-process, enrichment of the ISM in these elements proceeds at a pace regulated by the lifetimes of low and intermediate-mass stars, and the balance can be shifted further to the low-mass stars if study is restricted to the heavy s-process elements.

Excluding the \( \beta^- \) decayed end products of the r-process, the nuclides involved in the r-process exist far from stability, near the neutron drip line. Accordingly, the experimental and theoretical determination of the nuclear physics of these extreme states has been elusive, but progress has been made on this front in recent years (Kratz et al. 2007). Historically, however, the understanding of the r-process has proceeded phenomenologically. For example, the solar system r-process abundance pattern is measured by subtracting the better understood s-process distribution from the total neutron capture abundances and equating the r-process contribution with the residuals. Encouragingly, comparison of the empirically measured r-process abundance pattern for the solar system matches well with that observed in ultra metal-poor, neutron capture enriched stars, at least for elements heavier than barium (Westin et al. 2000). Since Big Bang nucleosynthesis only produces helium and light elements, ultra metal-poor stars represent the starting point of Galactic chemical evolution, and
they are likely ancient. The discrepancy for the light r-process elements observed in these stars suggests that there may be multiple r-process sites. In the seminal paper of Burbidge et al. (1957), a r-process site is hypothesized as type II, core collapse supernova, and in this respect it is not surprising to find ultra metal poor stars enriched in r-process elements. Certainly, the short lifetimes of the massive stars that end in SNe II are consistent with an early r-process enrichment of the ISM, but without a detailed theoretical understanding of the physics of SNe II, it is difficult to know whether the light r-process discrepancy is due to observational limitations or if there is, for example, a mass dependence on the SNe II abundance yields. Further confusing the matter is whether exotic production sites, such as neutron star mergers, have contributed significantly to the solar r-process pattern (Argast et al. 2004). With these caveats, it is still encouraging that the heavy r-process abundance pattern matches very well with a scaled solar pattern. For these elements, at least, there appears to be a universal r-process site that operates on a timescale consistent with SNe II.

1.3 Chemical Trajectories

In the earlier section on chemical tagging, the focus was on how stars born in the same star-formation episode, out of the same protocloud, retain their chemical signatures, and how this aids in tracing them back to their origins. However, the utility of this technique does not need to be restricted to homogeneous populations such as stellar clusters. By introducing the concept of chemical trajectories, it is possible to identify larger stellar populations that consist of stars spanning multiple star formation episodes. In this context, it is educational to think in terms of the closed box model. Although it fails to fit observations in all but a few contexts such as dwarf galaxies (Pagel 1997), the assumptions of the closed box model provide a simplified scenario where it is easy to understand how the abundances of the elements evolve over the course of time. In this context, one imagines a parcel of gas with a given initial composition, and by making some simplifying assumptions like flow into
our out of the parcel, it is possible to calculate how the composition of the ISM evolves with time. The details of the chemical evolution depend intimately on conditions such as the form of the initial mass function (IMF), but of special interest here is the importance of the star formation rate (SFR). As a first test case, consider a parcel of gas that experiences an early period of rapid, but brief, star formation. In this case, we will expect an enhancement of alpha and r-process elements at low metallicities that will persist until type Ia SNe begin to enrich the ISM. This is because the form of an IMF is typically weighted toward lower mass stars, and so a rapid SFR is required to drive the prevalence of alpha and r-process elements to higher abundances. However, another assumption of the closed box model is that all of the gas is converted into stars, and so the mean metallicity is related to the yield in the model. A population of stars that experiences an early cessation of star formation is then expected to have a low mean metallicity. A relative enhancement of alpha and r-process abundances and a low overall metallicity are both observed in the Galactic halo. As a second case, consider a parcel of gas that experiences a slow, long, and constant star formation epoch. SNe II will still dominate the enrichment process at the lowest metallicities, but the lower overall SFR means that type Ia SNe and AGB stars will begin to contribute at lower metallicities. This scenario would produce a population of stars similar to what is observed for the thin disk. The key point to take from this exercise is that abundance ratios such as \([\text{r-process/s-process}]\) or \([\alpha/\text{Fe}]\) at a given metallicity are expected to differ among stellar populations that have experienced different star formation rates because the production site for these classes of elements enrich the ISM on different time scales.

1.4 Successes of Chemical Tagging

Two primary successes of chemical tagging as a useful technique are the chemical differences between the thin and thick disks, and the chemical similarities of the Sgr dSph and the kinematically associated globular cluster Palomar 12 (Sbordone et al.
Figure 1.1 is a composite of several results in the literature that succinctly show these successes. The Sgr dSph, of course, is in the process of being accreted into the Milky Way (Ibata et al. 1997). Chemical analysis of Sgr dSph main body giants reveal a population of stars with $[\alpha/\text{Fe}]$ deficient relative to MW disk stars of comparable metallicity. This is consistent with the hypothesis that the unique environment of a dSph leads to a lower SFR (Lanfranchi & Matteucci 2003, 2004; Lanfranchi et al. 2006) compared to spiral galaxies such as the MW, thus we expect to see a lower $[\alpha/\text{Fe}]$ at a given metallicity. This is not a phenomenon unique to the Sgr dSph; analysis by Venn et al. (2004) demonstrates that the run of $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ is typically below MW values in other local group dSphs. Incidentally, this also shows that the MW is not built of the stars of accreted systems such as present day local group dSphs, though these systems may have survived because they are peculiar in some way, for example, their dark matter content. Palomar 12 is an interesting case because it is spatially separate from the Sgr dSph main body, but it has kinematic properties consistent with an origin in Sgr dSph (Dinescu et al. 2000). Following this suspicion, the chemical analysis of Palomar 12 shows the same exotic composition as the Sgr dSph. Along with the kinematic evidence, this argues strongly in favor of Palomar 12’s origin in the Sgr dSph. Another peculiar globular cluster is Ruprecht 106. It is a young globular cluster with an $[\alpha/\text{Fe}]$ reminiscent of the local group dSphs, although its metallicity precludes a direct comparison with Sgr dSph without further study to extend the dSph trend to lower metallicities. Lin & Richer (1992) suggest an origin in the Magellanic Clouds.
Figure 1.1 Following the example of Sbordone et al. 2007, the red line illustrates the thick disk trend, while the blue line illustrates the thin disk trend (Reddy 2005). The solid circles show the Sgr dSph main body stars, and the open circle is Terzan 7, a globular cluster embedded in the Sgr dSph. The big star shows the globular cluster Palomar 12 which is kinematically associated but spatial separate, and the pentagon is Ruprecht 106, another globular cluster with low $[\alpha/\text{Fe}]$ and a high radial velocity.
1.5 Goals

The primary goal of this study is to perform a chemical analysis of Helmi’s stream and the classical kinematic streams to determine if any of these constitute a unique stellar population. Helmi’s stream is of special interest as a putative merger remnant, and the classical streams are of interest because they form the most prominent kinematic structures in the solar neighborhood. The Hyades stream is investigated with the cluster evaporation scenario in mind, and the Hercules stream is considered with attention on the dynamical resonance hypothesis. The Sirius stream has been less studied overall, but the young UMa cluster nucleus is known, suggesting that the stream may contain some young, evaporated members. The analysis is performed in an automated, homogeneous fashion that yields results suitable for further statistical analyses. By use of the Kolmogorov-Smirnov (KS) test, it will be determined if the chemical signatures of these kinematic streams suggest histories dissimilar to solar neighborhood disk stars.
Chapter 2

Data

In this work, the spectral synthesis code MOOG is used to fit synthetic spectra to object spectra. For an analysis, MOOG requires a model atmosphere, an absorption line list, and the solar composition. In general, such an analysis begins with collecting known information about the targets; the model atmospheres must be computed first. For this, the Geneva-Copenhagen Survey of the Solar Neighborhood (GCS) has been invaluable as it incorporates many of the important atmospheric parameters in a convenient database. Not only does the GCS give the atmospheric parameters, but it also includes kinematics, age estimates, and mass estimates. An important atmospheric parameter that does not appear in the GCS is the surface gravity, and the calculation of this quantity is discussed in Chapter 3. Line broadening, an umbrella term that combines the effects of rotation, micro- and macroturbulence, is measured empirically. Equivalent width (EW) analysis is not used here, but lessons from EW analysis are used to guide the development of the software, and the accuracy of EW analysis is used as a benchmark for quality results.

2.1 Equivalent width analysis

The observed shape of an absorption line is modeled as a $\delta$ function, convolved with a set of functions that describe the broadening mechanisms (Gray 2008). On the smallest scale is the “natural” broadening due to the uncertainty principle. This effect has a Lorentzian profile, but in stellar spectroscopy the broadening from this source is small compared to the others. Another broadening mechanism is pressure broadening.
This is broadening due to collisional interactions, and the profile can be derived as a Lorentzian under the impact approximation. Types of collisional interactions include the Stark effect and the van der Walls effect. A third type of broadening mechanism is Doppler broadening due to velocity fields. This includes such effects as thermal motion, rotation, and convection. Under the assumption of local thermodynamic equilibrium (LTE), the thermal motions are isotropic, and the resulting broadening profile is a Gaussian. The other velocity fields are more complicated. The microturbulent velocity is isotropic, but macroturbulence and rotation are not. For this reason, the extra-thermal velocity fields are typically treated separately, although the microturbulent velocity can be included in the thermal broadening since both fields are isotropic. These extra-thermal velocity fields are discussed in detail in Section 2.5. A final broadening mechanism is due to the resolution of the spectrograph, referred to as the instrumental profile - also a Gaussian. Therefore, discounting the subtle effects of rotation and convection, the functional form of a stellar absorption line is a convolution of Gaussians and Lorentzians - a Voigt function.

Due to the many effects that influence the shape of the lines, the line strength is measured in terms of the equivalent width (EW), defined as the width of a rectangle that has a height equal to the continuum level and an area equal to that of the absorption line. The function that gives the EW as a function of the number of absorbers is called the curve of growth (COG). In a typical EW analysis, measured EWs are compared to COGs to derive both the atmospheric parameters and the elemental abundances. As a first step, a set of weak lines of a neutral species (usually iron) is used to fix the effective temperature. A neutral species is used because the derived abundance is insensitive to the surface gravity (i.e. - the electron pressure) as shown by the Saha equation. Weak lines are used because they are insensitive to the microturbulent velocity. The microturbulent velocity delays line saturation, and the further from saturation, the less sensitive the line is to the microturbulent velocity. With these two constraints in place, the set of lines also needs to span a range of excitation potential. Lines of differing excitation potential form at different depths in
the atmosphere, and insisting that each line gives the same abundance as a function of the excitation potential fixes the effective temperature. The next step in the EW analysis is to add some stronger lines to the list, and the microturbulence is adjusted to bring them into agreement with the weak lines. The third step is to add an ionized species of the same element to the list, and the surface gravity is adjusted to enforce ionization equilibrium between the neutral and ionized species. If iron has been used, as is usually the case, then the atmospheric parameters, including the metallicity are now known.

Equivalent width measurements typically have measurement errors from individual lines of about 0.05 dex in the best case scenario of unblended lines and quality atomic data. However, the known lines of neutron capture elements are few and often blended, especially in the blue end of the optical spectrum that contains the lanthanum and europium lines used in this work. Line blending, isotopic splitting, and hyperfine splitting are all situations where the line opacity is due to multiple components. There is no easy way to account for these difficulties in an EW analysis, and synthetic spectra fitting is superior in this regard because modeling the blends becomes a matter of identifying them and gathering atomic data to include them in the synthesis. Additionally, EW measurements are time-consuming, with the largest samples done by this method including at most a few hundred stars.

2.2 Spectra and Data Reduction

The stellar spectra come from two sources. The majority were originally observed as part of a planet search program with HIRES on the Keck I telescope at $R = 50,000$. This set of spectra includes all the data for the classical streams, the uncategorized, “background” stars, and some of the Helmi stream stars. I observed a subset of forty-five stars on the Harlan J. Smith telescope at McDonald Observatory, with an overlap of seventeen stars with the Keck spectra. The McDonald spectra are high resolution ($R = 60,000$), and the S/N is typically 100 near the bluest lines measured, the 3988
A lanthanum line, and S/N is typically 250 near the reddest lines, the 5240 Å order that contains the iron lines. All of the spectra are echelle spectra. In this case, the Keck spectra were inherited in a fully reduced state, but the McDonald spectra were reduced using IRAF.

Data reduction is the process of removing the instrumental signature from the raw data, and working them into a form amenable to visualization and further analysis. There are many methods to accomplish this goal, so the discussion here is shaped by my own experience. In general, the important aspect of the process is identification, modeling, and removal of the instrumental effects. In this work, the raw data are the output from a cross-dispersed echelle spectrograph, collected by a CCD chip. So, important topics include calibrating the CCD and converting a 2D image of many spectral orders into a set of 1D spectra as used in spectral analysis.

Commonly, the first set of calibration frames applied to the data are the bias frames. These are zero second exposures so that the output of the CCD is a measurement of the base level of electron counts across the chip when zero photons have been collected. Several frames are taken and averaged together, and this bias correction frame is then subtracted from every frame in the data set. This removes the bias pedestal due to the DC voltage applied to the instrument, and it also removes any minor pixel-to-pixel variations left after averaging out the stochastic electrical noise.

The next calibration is referred to as flat fielding. This is the calibration that accounts for pixel-to-pixel variation in the quantum efficiency of the many CCD elements across the chip. Such variation is expected due to imperfections in the manufacturing process, and the quantum efficiency is also likely to change as the device ages. Flat frames are taken by exposing the chip to a uniform light source. The calibration frame is calculated by finding the multiplicative factor, for each detector element, that normalizes the response across the chip. The flat field correction is then applied to all the object frames.

In addition to calculating the normalized flat field for the CCD, the flat field frames are also useful for defining the echelle orders because the echelle orders from the flat
field frames will have a width that encapsulates the orders from a stellar source. This is because the light from the uniform source fills the slit length while the stellar source does not. Therefore, as long as the observations are made with the star kept away from the top and bottom of the slit, the orders defined by the flat field frames will always encapsulate the object spectra. Thus, the flat field frames are used to define the echelle orders.

Before extracting the orders, there is one more calibration step. An inspection of the space between the orders reveals that light from outside the optical train reaches the detector despite the best efforts of engineers. This is the scattered light, and the interorder space is especially useful to remove it. With the orders defined in the previous step, the interorder light is fit with a 2D surface and subtracted off for each object frame.

With the orders extracted to 1D spectra, the final step is to apply the wavelength solution. This is the calibration that connects pixel numbers along the dispersion with a wavelength. To accomplish this, a source with a well-known emission spectrum is shined through the instrument; at McDonald observatory, I used a Th-Ar hollow-cathode lamp. The wavelength solution is calculated by identifying lines in the emission spectrum with an atlas. This is a time consuming process as each spectral order must be done individually, but so long as the instrument is not moved, a single wavelength solution is applicable for a full night of observing. A lucky observer will find that the same solution will work for several nights in a row. To verify that the wavelength solution is still applicable, the user checks for a match between the new calibration spectrum and the calibration spectrum from the earlier wavelength solution.

At this point, the shape of the spectra across any order is dominated by the blaze function of the diffraction grating, and the intensity scale is still in terms of the electron counts. For comparison with synthetic spectra, the upper envelope of the spectra, generally defined by the valleys between the absorption lines, is fit with a polynomial, and this function is used to convert the intensity scale into normalized
flux. An example of the continuum fitting and the resulting normalized spectra are shown in Figures 2.1 and 2.2. Although this method provides qualitatively acceptable fits with synthetic spectra, the flux has not been precisely calibrated. This method works best in spectra without dense line crowding, such as the warmer F dwarfs or in the red end ($\approx 6000$ Å) of the optical spectrum. In the blue end ($\approx 3900$ Å) of the spectra of cool ($\approx 5300$ K) G dwarfs, the continuum is very poorly defined by this method.

As a final step, the radial velocity shift must be removed. To accomplish this, the dvec package of IRAF was used. This package takes the wavelength dependence of the Doppler correction into account, as opposed to a simple subtractive approximation. In this work, it is important that the lines appear at the rest wavelength because the analysis software expects the lines to appear at the rest wavelength. To shift the stars to the rest wavelength, the wavelength of several prominent spectral features were measured in each object and in a solar spectrum, also obtained at McDonald. Three features were used - one near the lanthanum lines ($\approx 3988$ Å), one near the europium lines ($\approx 4205$ Å), and one near the iron lines ($\approx 5240$ Å). The radial velocity was measured from each feature, and a simple average gives the result. The three lines were typically within a few km/s of the mean value, and an added benefit of using three velocity measurements is that any misidentified line immediately appears as a spurious result, begging for a second look.
Figure 2.1 A legendre polynomial is fit to the upper envelope of the spectra to define the continuum level.
Figure 2.2 Division by the fitted polynomial normalizes the flux scale.
2.3 The Geneva-Copenhagen Survey of the Solar Neighborhood

The Geneva-Copenhagen Survey (GCS) is the source of many of the atmospheric parameters used in the spectral analysis. This database combines photometry, Hipparcos parallaxes, Tycho-2 proper motions, and CORAVEL radial velocities for $\approx 14,000$ stars in the solar neighborhood. The database is volume complete for F and G dwarfs out to 40 pc from the Sun. The original database is described in Nordström et al. (2004) with improved photometric calibrations in Holmberg et al. (2007) and improved distances, ages, and kinematics in Holmberg et al. (2009). Where there is ambiguity, the 2004 database is used in order to maintain consistency with Helmi et al. (2006), especially in regards to the kinematics and the photometric metallicity, as one of the primary goals is to follow up on her putative merger remnant, the Helmi stream.

2.3.1 Strömgren $uvby$ photometry

The GCS uses Strömgren $uvby$ photometry to derive many quantities of interest. This is an intermediate-band system well-suited to G and F dwarfs. The $u$ filter is centered at about 3500 Å, below the Balmer jump but before the atmospheric cutoff at about 3000 Å. The $v$ filter is at about 4100 Å, above the Balmer jump in a region where line blanketing is strong, including the Hδ line. The $b$ filter is at 4700 Å, and the $y$ filter is at 5500 Å. Both $b$ and $y$ are relatively clean of line blanketing so that $b - y$ is a measurement of color, useful for temperature and extinction measurements. The $\beta$ index is a difference of a wider and narrower filter near 4850 Å, designed to measure the strength of the Hβ line. This gives a extinction-independent temperature measurement, and so $b - y$ and $\beta$ are used together to determine interstellar reddening.

The $m_1$ index, defined as $m_1 = (v - b) - (b - y)$ is sensitive to the line blanketing and, hence, the metallicity. The $c_1$ index is defined as $c_1 = (u - v) - (v - b)$, and it is a measurement of the Balmer jump. For stars hotter than $\approx 10,000$ K, $c_1$ is sensitive to $T_{eff}$, but for coolers stars it is sensitive to the gravity for a given $T_{eff}$.
2.3.2 $T_{\text{eff}}$

The effective temperature of a star, $T_{\text{eff}}$, is the black body temperature that emits an equivalent amount of radiation. A relationship is derived between the bolometric luminosity and $T_{\text{eff}}$ as $L = 4\pi R^2 \sigma T_{\text{eff}}^4$, where $\sigma$ is the Steffan-Boltzman constant. This provides a rigorous definition, but bolometric luminosity and stellar radii are difficult to measure. The temperature calibration used in the GCS (Nordström et al. 2004) is that of Alonso et al. (1996), based on the infrared flux method. The standard deviation about the calibration fit is equivalent to 110 K, which serves as an estimate of the uncertainty. In the data, cuts are applied at 5200 K and 6200 K. The cut at 5200 K is made due a worrying failure to satisfy ionization equilibrium for iron in cool Hyades cluster dwarfs (Yong et al. 2004) and in cool, metal rich field stars in the solar neighborhood (Allende Prieto et al. 2004). Possible explanations include a failure to account for non-LTE effects, incomplete molecular opacities, inhomogeneities outside the scope of the 1D atmospheres, and magnetic effects. In any event, the problem appears to resolve itself above 5200 K. Additionally, for cool stars, in the blue part of the spectrum such as near the 3988 Å lanthanum line, lines are observed that are not present in the solar spectrum. Qualitatively, the fits appear poorer and the continuum placement in particular becomes increasingly difficult.

2.3.3 Photometric $[\text{Fe/H}]$

The metallicity calibration used in the GCS (Nordström et al. 2004) is that of Schuster & Nissen (1989). The calibration is based on spectroscopically determined $[\text{Fe/H}]$ from a variety of sources. The estimated uncertainty in $[\text{Fe/H}]$ for stars in this metallicity range is given as 0.14 dex by Schuster & Nissen (1989), but comparisons by Nordström et al. (2004) with spectroscopic $[\text{Fe/H}]$ in Edvardsson et al. (1993) and Chen et al. (2000) find dispersions about the mean difference of 0.08 and 0.11 dex, respectively. A further comparison with the spectroscopic $[\text{Fe/H}]$ from Taylor (2003) finds a dispersion of 0.12 dex. In this work, $[\text{Fe/H}]$ ranges from $\approx -0.80$. 

26
dex at the metal-poor end up to +0.20 dex at the metal-rich end. The metallicity range is a consequence of the target selection. Since we are looking at stars in the solar neighborhood, generally within 120 pc of the Sun, the sample is necessarily dominated by thin disk stars with a minor contribution of thick disk stars. Chen et al. (2001) gives 6.5%-13% as the local space number density normalization for the thick disk, and Siegel et al. (2002) gives a similar value of 6%-10%. This metallicity range is consistent with a mixture of those populations.

2.3.4 Kinematics

Nordström et al. (2004) calculates stellar kinematics based on the combination of Tycho-2 proper motions, CORAVEL radial velocities, and Hipparcos parallaxes. The kinematics are given in the standard $UVW$ velocity component system. It is a right handed coordinate system with $U$ pointing toward the Galactic center, $V$ pointing in the direction of Galactic rotation, and $W$ pointing toward the north Galactic pole. $U$ usually points away from the Galactic center, but that is not the case here. The error in the $UVW$ space velocities is dominated by the parallax error. The median parallax measurement is about 10 mas, corresponding to a distance of 100 parsecs with a relative error of 22% based on the Hipparcos measurement uncertainty of 1 mas (Perryman et al. 1997). Nordström et al. (2004) give 1.5 km/s as the average error in each velocity component.

2.3.5 Stellar Masses

Isochrone fitting is a technique that is useful in the measurement of difficult observables, such as age, mass, and helium mass fraction. In Nordström et al. (2004), it is used to measure ages and masses, and in this work the masses from the GCS are used in the surface gravity calculation outlined in Chapter 3. Generally, isochrone fitting is especially effective for clusters, but it can also be applied to field stars if the star has evolved off the main sequence. This is because the main sequence turn-off
marks the amount of time necessary for the star’s core to approach hydrogen depletion. Before depletion, the color-temperature relation changes very little with age, which contributes to the utility of the turn-off point as a fitting constraint, but this lack of observable evolution also means that isochrone fitting is generally inaccurate for stars still on the main sequence. In the case of age measurements, the most that can be generally said for an unevolved field star is that its age is less than the turn-off age. In Nordström et al. (2004), the fitting is done computationally by maximizing a probability function around the region in the color-magnitude diagram for a given star. Nordström et al. (2004) find that masses can be reliably measured even for stars where the age measurement is meaningless.

2.4 Model Atmospheres

With atmospheric parameters in hand, the next important set of data for the analysis are the model atmospheres. The most commonly used stellar atmosphere code over the past decade is ATLAS9 (Kurucz 2005), and this is what is used in this work. Other choices include ATLAS12 and CO5BOLD. Both ATLAS9 and ATLAS12 assume local thermodynamic equilibrium (LTE), time independence, and plane-parallel geometry for the model structure. Convection in these models is handled by mixing length theory (MLT). In this simplistic treatment of convection, a parcel of warm gas rises a characteristic distance, $l$, before mixing with the surroundings. A disadvantage of MLT is that it introduces a free parameter, $\alpha = l/H_P$, the ratio of the parcel’s mean free path and the pressure scale height. Essentially, $\alpha$ parameterizes the convection efficiency. In theoretical models that employ MLT, the choice of $\alpha$ affects the run of radius vs. temperature in regions where convection is important. Thus, $\alpha$ is calibrated by the measurement of stellar radii, especially the Sun’s, although clusters and RGB stars have also been used as calibrators (Vandenberg 1983; Abbett et al. 1997).

The primary difference between ATLAS9 and ATLAS12 is the treatment of the
line opacity. In both cases, the line opacity is modeled with opacity distribution functions (ODF), but in ATLAS9, the ODFs are pretabulated for a limited number of stellar compositions. In principle, the line opacity can be calculated directly using the full spectrum of over 100 million absorption lines, but to achieve this, the software must integrate the source function with a wavelength resolution small enough to resolve the individual lines (Kurucz 1970, 1974, 1996; Castelli 2005). This approach is infeasible because the computation times are too long. Instead, ODFs statistically model the mean opacity over larger wavelength domains, simplifying the opacity contribution from many lines into a single opacity coefficient. Because they are pretabulated, the ODFs used by ATLAS9 have necessarily assumed a composition, microturbulence, and mixing length parameter. So, if the user wants a specialized mix of those parameters, ATLAS9 is inadequate. ATLAS12, on the other hand, uses an opacity sampling technique that allows the program to calculate the ODF at run-time, for any composition of interest. No doubt, there is error associated with using an ODF that was calculated for a somewhat different composition than in the model atmosphere being calculated, but early testing in this work showed that the choice of ATLAS9 or ATLAS12 atmospheres had a negligible effect on the final result. Since there is a high computation time premium on the ATLAS12 atmospheres, the ATLAS9 atmospheres are used in this work.

The CO BOLD atmospheres mentioned earlier are one example of time dependent, 3D hydrodynamical model atmospheres. These models are more theoretically robust than the older 1D model atmospheres. In particular, convection is handled seamlessly, so there is no longer any need to parameterize it with mixing length theory. Not only do the 3D model atmospheres dispense with MLT, but the synthetic spectra produced with such model atmospheres also properly account for line shifts and line profile asymmetries due to convection in the photosphere (Asplund et al. 2000). In general, the synthetic spectra produced with 3D model atmospheres provide qualitatively better fits with observations, and accordingly, measurement uncertainty tends to be reduced. This is demonstrated in Asplund et al. (2005) where the solar
carbon abundance is measured from a varied set of lines, both atomic and molecular. These lines range widely in excitation potential, and molecular lines are noted for their strong temperature sensitivity. The carbon analysis is performed with a 3D model atmosphere and two varieties of 1D atmospheres, a theoretical MARCS model and a semi-empirical Holweger-Müller model. In the results, the 3D model achieves good agreement across all of the indicators, but the 1D atmospheres fail in this regard, giving differences as much as 0.2 dex between the high excitation CI lines and the CO vibration lines. This is taken as strong evidence in favor of the realism of the 3D models. However, the revised solar composition from 3D model atmospheres introduces some worrying discrepancies with results from helioseismology (Asplund et al. 2005, 2009). Although most of the elemental abundances are in agreement between the 1D and 3D models, the abundances of carbon, nitrogen, oxygen, and neon are all revised down in the 3D model results, and solar models constructed with these updated abundances predict sound speeds inconsistent with helioseismology. The resolution of this discrepancy is a matter of on-going debate. One possible answer is that the opacities are underestimated, but the required revision is about 10% in order to offset the effect of the reduced light metal abundances (Bahcall et al. 2005). This, of course, begs the question of where the missing opacity comes from. To date, the helioseismology discrepancy has yet to be resolved. Therefore, ATLAS9 continues to be the most widely used model atmosphere code in high resolution stellar spectroscopy, even though more sophisticated codes are available.

A grid of ATLAS9 model atmospheres was calculated using a bash shell script and the ATLAS9 Linux port described in Sbordone et al. (2004). The grid ranges from $T_{\text{eff}} = [5200, 6200]$ in steps of 100 K. It has metallicity grid points at $[\text{Fe/H}] = -1.0, -0.5, -0.3, -0.2, -0.1, 0.0, 0.1, \text{and} 0.2$ dex. The surface gravity has two values of $\log(g) = 4.0$ and 4.5. All together, this gives a grid with 176 points that encloses the set of atmospheric parameters for the full data set, with the exception of $\log(g)$. There is a subset of stars that were found to be subgiants with $\log(g) < 4.0$, so in these cases the surface gravity variable is extrapolated as far as $\log(g) = 3.8$. 


2.5 MOOG Synthetic Spectra

The grid of synthetic spectra are calculated with a slightly modified version of the spectral synthesis code MOOG; the input routine is modified so that it can be controlled in batch mode by a bash shell script. To produce synthetic spectra, MOOG solves the radiative transfer equation following the formulation of Edmonds (1969). The grid of ATLAS9 model atmospheres and a list of atomic absorption lines are given as input, and for each grid point in the grid of model atmospheres, the enhancement of an element of interest is varied from $[\text{X/Fe}] = -0.5$ to $+0.5$ with step sizes of 0.1 dex.

However, before proceeding with the abundance analysis, the line broadening must be determined. While the thermal broadening is determined from the effective temperature of the input model atmosphere, the line broadening due to the instrumental resolution and the velocity fields other than the thermal broadening must be specified by the user. Extra-thermal velocity fields include rotation, micro-, and macroturbulence. The micro- and macroturbulence have little to do with aerodynamic turbulence, but the term originates from speculation by Rosseland (1928) that the granulation observed on the Solar surface is due to turbulent eddies. The difference between the micro and macro version is whether the parcel size involved in the velocity field is greater or less than the mean free path of a photon. Although the obvious physical cause for such bulk movement of the atmosphere is convection, turbulence is also needed to model the spectra of hot stars with the time-independent, 1D atmospheres. This is counter intuitive because they have radiative atmospheres, and so poorly understood magnetic effects are suspected. In any case, the turbulence model is another example of a time-independent treatment of hydrodynamical processes. Whereas the MLT simplified the energy transport due to convective flows, the turbulence model accounts for the effect of the extra-thermal velocity fields on the emergent stellar spectrum. In the 3D hydrodynamical model atmospheres, the turbulence model is rendered obsolete along with MLT, and in fact, the match of line asymmetries and shifts due to convective
granulation are two of the triumphs of the 3D, hydrodynamic models (Asplund et al. 2000).

In the language of Doppler line broadening from the velocity fields, it is common to convert wavelength shifts to a corresponding velocity differential by $\Delta \nu / c = \Delta \lambda / \lambda$. This has the advantage of specifying a broadening value without reference to the wavelength. Values for the microturbulence are typically small, in the range of 1 to 2 km/s for dwarfs and increasing to as high as 5 km/s in supergiants (Gray 2008). Macroturbulence and rotation, on the other hand, can range to higher values, and the effects are comparable in F and G dwarfs. In principle, the rotation and macroturbulence can be disentangled, but the subtle differences in how the two effects shape the lines are impossible to distinguish without very high resolution spectra. The microturbulent velocity field is isotropic and therefore properly modeled as a Gaussian, and it is included in the thermal broadening calculation. Conversely, rotation and macroturbulence are not isotropic, although they are modeled as such in MOOG. Precise determinations of macroturbulence and rotation are beyond the scope of this work, and since all three effects are modeled as Gaussians, it is preferable to refer simply to line broadening with the understanding that it is an umbrella term.

For the purposes of measuring the line broadening, the synthetic spectra are smoothed using a Gaussian with a width corresponding to 1 through 12 km/s, and the results are shown in Figure 2.3. An inspection of the plot suggests the lowest values are about 1 km/s, and 2 km/s is the value that was adopted as a baseline for the microturbulence. Any broadening greater than 2 km/s is taken as a combination of macroturbulence and rotation. The Solar value for the microturbulence is usually given as 2 km/s, and the ODFs used by ATLAS9 were calculated at 2 km/s. The grid of synthetic spectra used in the analysis has a microturbulence of 2 km/s at every grid point, and the line broadening varies from 1 km/s to 12 km/s with steps of 1 km/s. There is a negligible difference between spectra smoothed with a 1 km/s versus a 2 km/s Gaussian, but by 3 or 4 km/s, the difference is apparent to the eye at the resolving power of the data. Recall, the Keck spectra have a resolving power $R= 50,000,$
and the McDonald spectra have a resolving power $R=60,000$. These correspond to velocity-equivalent broadenings of 6 and 5 km/s, respectively. So, after accounting for line broadening and the enhancement range, the final grid of synthetic spectra has 23,232 points.
Figure 2.3 The line broadening in each object spectra is measured with a specialized set of synthetic spectra smoothed with a simple Gaussian kernel. The results for the narrowest lined stars illustrate the baseline broadening value.
Chapter 3

Analysis

At the outset, one of the primary goals was to design a method to analyze stellar spectra in an automated fashion. We want to devise a method that produces elemental abundance results with an accuracy comparable to traditional equivalent width measurements, and yet it should be scalable to much larger data sets. With a modular design philosophy, I have written a library of utility programs in C++ and Perl that can be run “by hand” or controlled by a bash shell script to do the spectral analysis. Using a desktop computer with a Pentium 4 processor, results for the full data set of 640 stars, deriving abundances from ten absorption lines for each star, can be reproduced in about four days. A few more days are necessary to complete the error checking to ensure quality results, but this is clearly much faster than a manual analysis, as a dedicated worker would take months to finish the same task. The script also has the advantage of being easy to correct if a problem with the analysis is found, and the famous advantage of computers in general is that they do not get weary of repetitive tasks.

In addition to the spectral analysis, it is necessary to calculate the membership probabilities for the stellar populations, using examples from the literature as a guide. Also, the surface gravities must be calculated because they do not appear in the GCS. Finally, at the end of this chapter is a discussion of the Kolmogorov-Smirnov hypothesis test, eminently useful with a large, homogeneously analyzed data set.
3.1 Population assignment

3.1.1 Helmi’s stream

The selection criteria given in Helmi et al. (2006) is that the stream has $0.3 \leq e < 0.5$ and $[\text{Fe/H}] < -0.2$ dex, where $e$ is the orbital eccentricity defined as,

$$e = \frac{R_{apo} - R_{peri}}{R_{apo} + R_{peri}} \quad (3.1)$$

$R_{apo}$ is the apogalacticon, and $R_{peri}$ is the perigalacticon. Then, the stars are further divided into three groups according to metallicity. To apply the eccentricity criteria, orbits are calculated using an Newtonian orbit integrator by David Gilden and Luis Aguilar. This software takes the position and velocity of each star and integrates several orbits around a galactic potential. Several potentials were tested and no significant difference was noted, and the potential finally used is that of Bahcall et al. (1982, 1983). The software characterizes each star’s orbit with $R_{apo}$, $R_{peri}$, and $L_z$, among other things. From these results, Helmi’s stream is extracted according to the eccentricity, and then these are divided into three groups according to metallicity. Group 1 has $-0.45 \leq [\text{Fe/H}] < -0.20$. Group 2 has $-0.70 \leq [\text{Fe/H}] < -0.45$, and group 3 has $-1.5 \leq [\text{Fe/H}] < -0.70$.

3.1.2 Classical streams, and the thin/thick disk

Population assignment for the classical streams and the thin and thick disk stars is applied according to their $UVW$ velocities by a Bayesian statistical technique. Following the example of Bensby et al. (2003), the prior distribution for each population is defined in terms of the motion relative to the local standard of rest (LSR) and the velocity ellipsoids $\sigma_U$, $\sigma_V$, and $\sigma_W$. Assuming Gaussian distributions, the membership probability is given by,
\[ f(U, V, W) = Xk \exp \left( -\frac{(U_{LSR} - U)^2}{2\sigma_U^2} - \frac{(V_{LSR} - V)^2}{2\sigma_V^2} - \frac{(W_{LSR} - W)^2}{2\sigma_W^2} \right) \] (3.2)

where

\[ k = \frac{1}{(2\pi)^{3/2}\sigma_U\sigma_V\sigma_W} \] (3.3)

is a normalization factor and \( X \) gives the local number density of the population. Then, the relative probability of a star, \( i \), belonging to either the thin disk population, \( D \), the thick disk, \( TD \), or halo, \( H \), is given by,

\[ P_i = \frac{f_i}{f_D + f_{TD} + f_H} \] (3.4)

where

\[ i = D, TD, \text{or} H \] (3.5)

This is done three times for each star, once to test each galactic component, and the membership threshold is set at \( P = 0.80 \). Table 3.1 summarizes the literature data for the calculations, and a Toomre diagram showing the results of the thin/thick disk population assignment is shown in Figure 3.1.
<table>
<thead>
<tr>
<th>Population</th>
<th>X</th>
<th>$U_{LSR}$ (km/s)</th>
<th>$V_{LSR}$ (km/s)</th>
<th>$W_{LSR}$ (km/s)</th>
<th>$\sigma_U$ (km/s)</th>
<th>$\sigma_V$ (km/s)</th>
<th>$\sigma_W$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Disk</td>
<td>0.90</td>
<td>0</td>
<td>-15</td>
<td>0</td>
<td>35</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Thick Disk</td>
<td>0.10</td>
<td>0</td>
<td>-46</td>
<td>0</td>
<td>67</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>Halo</td>
<td>0.0015</td>
<td>0</td>
<td>-220</td>
<td>0</td>
<td>160</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Hyades</td>
<td>0.07</td>
<td>-30</td>
<td>-20</td>
<td>-5</td>
<td>12</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Hercules</td>
<td>0.09</td>
<td>-42</td>
<td>-52</td>
<td>-8</td>
<td>28</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>Sirius</td>
<td>0.04</td>
<td>7</td>
<td>4</td>
<td>-6</td>
<td>14</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Background</td>
<td>0.67</td>
<td>-3</td>
<td>-15</td>
<td>-8</td>
<td>33</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.1 Collected data for population assignment: Galactic components from Bensby et al. (2003) and classical streams from Famaey et al. (2005).
Figure 3.1 Toomre diagram of the thin disk stars in red circles, thick disk stars in blue triangles, and uncatagorized stars in open, black circles.
For the classical streams, the membership probability relative to the background is calculated by,

\[ P_i = \frac{f_i}{f_{Bak}} \quad (3.6) \]

Again, this is done three times for each star, once for the Hyades, Hercules, and Sirius stream. The membership threshold is set at \( P_i = 1 \), indicating an equal probability of belonging to the stream or to the background. The results of the population assignment for the stream are shown in Figures 3.2 and 3.3.
Figure 3.2 Toomre diagram of the classical streams with the Sirius stream in green circles, the Hyades stream in red circles, the Hercules stream in blue triangles, and the background stars in open, black circles.
Figure 3.3 Kinematics of the classical streams with the Sirius stream in green circles, the Hyades stream in red circles, the Hercules stream in blue triangles, and the background stars in open, black circles.
3.2 Surface gravity

The surface gravity does not appear in the GCS, but the information needed to calculate it does. Starting with the fundamental relations,

\[ g = \frac{GM}{r^2} \]  
\[ L = 4\pi R^2 \sigma T_{eff}^4 \]

\[ M_{bol} - M_{bol,\odot} = -2.5 \log \frac{L}{L_\odot} \]

one can derive,

\[ \log \frac{g}{g_\odot} = \log \frac{M}{M_\odot} + 4 \log \frac{T_{eff}}{T_{eff,\odot}} + 0.4(M_{bol} - M_{bol,\odot}) \]

In the preceding equations, \( g \) is the surface gravity, \( M \) is the stellar mass, \( T_{eff} \) is the effective temperature, and \( M_{bol} \) is the bolometric absolute magnitude. \( M_{bol} \) is calculated with the standard equation,

\[ M_{bol} = V + 5(\log \pi + 1) + BC \]

where \( V \) is the apparent visual magnitude, \( \pi \) is the trigonometric parallax, and \( BC \) is the bolometric correction, taken from Gray (2008). The Solar parameters are \( \log g_\odot = 4.44, \) \( T_{eff,\odot} = 5777 \) K, \( M_{bol,\odot} = 4.75, \) and \( M_\odot = 1. \) To test the gravity calculations, each star is placed on a color-magnitude diagram and qualitatively compared with the isochrones by Yi et al. (2001), known as the Yale-Yonsei or \( Y^2 \) isochrones. The agreement is very good, and three examples of the comparisons are shown in Figures 3.4, 3.5, and 3.6.
Figure 3.4 Calculated surface gravities compared to qualitative gravity estimates from the Yale-Yonsei isochrones. The stars are color coded according to their calculated gravities, and four isochrones are shown with ages 3, 6, 9, and 12 Gyr. All of the isochrones have [Fe/H] = −0.05, and the stars have metallicity in the range −0.10 < [Fe/H] ≤ 0.00. The horizontal lines are of constant gravity, coinciding with the gravity bin boundaries at log(g) = 4.4, 4.2, 4.0, and 3.8.
Figure 3.5 The same as Figure 3.4, except for a different metallicity range. Here, all the isochrones have [Fe/H] = −0.15 and the stars are in the range $-0.20 < [\text{Fe/H}] \leq -0.10$. 

$-0.20 < [\text{Fe/H}] \leq -0.10$
Figure 3.6 The same as Figure 3.4, except for a different metallicity range. Here, all the isochrones have $\text{[Fe/H]} = -0.25$ and the stars are in the range $-0.30 < \text{[Fe/H]} \leq -0.20$. 
3.3 The automated method

The software that carries out the spectral analysis is a bash shell script that controls a library of utility programs designed to carry out specific tasks. I have found that such a modular design helps with debugging because the script’s progress with a star’s analysis is transparent at each step. In fact, the analysis can be performed “by hand” using the utility programs, and the bash script simply handles the repetitiveness of typing the commands with the help of some small perl programs that do the bookkeeping - modifying input files for the next calculation, and ensuring that the correct grid points are used for the star in question. Additionally, the software generates many diagnostic files and diagrams, including $\chi^2$ minimization curves and the synthetic spectra fits.

3.3.1 The $\chi^2$ statistic

At the core of the software is an unnormalized $\chi^2$ statistic. The method used here is known as Pearson’s $\chi^2$ test; it is a convenient pattern matching technique. The form of the calculation for comparing the observed spectra to the synthesis is given by,

$$\chi^2 = \sum_{i=1}^{n} \frac{(Observed_i - Synthesis_i)^2}{Synthesis_i}$$  \hspace{1cm} (3.12)

where $n$ spans the wavelength window of the line being measured. The width of the window is tunable by modifying the variable in the source code for the $\chi^2$ calculator, and each measured line has a somewhat different width, so the number of terms in the sum are different in each case. In this sense, the statistic is unnormalized, and no claim is made for an absolute “goodness” of any individual fit based on the $\chi^2$ value. Instead, the statistic is computed as a quantity of interest is varied to find the best relative fit. Generally, the varied quantity is an elemental abundance enhancement, but the nature of the software is that any quantity that affects the line shape can be
used. For example, the line broadening is measured by the script with a specially made grid of synthetic spectra, and the results of that endeavor are shown in Figure 2.3.

As the script varies a quantity of interest, the resulting $\chi^2$ values are recorded, and *Gnuplot* is used to fit a polynomial and produce a diagnostic plot. An example is shown in Figure 3.7. A utility program is used to minimize the polynomial, and the results are recorded to an output file. For each star, this is done eight times to enclose the star in parameter space; the calculation is done at the nearest two grid points in the three dimensions of $T_{\text{eff}}$, [Fe/H], and log(g). The next step is to interpolate to the correct atmospheric parameters.

Figure 3.7 An example diagnostic plot from an [Eu/Fe] measurement of HD 70. On the vertical axis is the $\chi^2$ values, and on the horizontal axis is the [Eu/Fe] enhancement. Minimizing the fitted polynomial gives the result.
3.3.2 Interpolation

The $\chi^2$ minimization can be visualized as occurring at the corners of a box enclosing the star in parameter space, and a trilinear interpolation calculator is used to find the value inside the box - the final result. Trilinear interpolation is understood as the generalization of one dimensional, linear interpolation to higher dimensions. To begin, interpolate to eliminate the first dimension, $x$,

$$C_{0,0} = \frac{x_0 - x}{x_0 - x_1} C_{1,0,0} + \frac{x - x_1}{x_0 - x_1} C_{0,0,0} \quad (3.13)$$

$$C_{1,0} = \frac{x_0 - x}{x_0 - x_1} C_{1,1,0} + \frac{x - x_1}{x_0 - x_1} C_{0,1,0} \quad (3.14)$$

$$C_{0,1} = \frac{x_0 - x}{x_0 - x_1} C_{0,0,1} + \frac{x - x_1}{x_0 - x_1} C_{1,0,1} \quad (3.15)$$

$$C_{1,1} = \frac{x_0 - x}{x_0 - x_1} C_{0,1,1} + \frac{x - x_1}{x_0 - x_1} C_{1,1,1} \quad (3.16)$$

Use these results and interpolate in the next dimension, $y$,

$$C_0 = \frac{y_0 - y}{y_0 - y_1} C_{0,0} + \frac{y - y_1}{y_0 - y_1} C_{1,0} \quad (3.17)$$

$$C_1 = \frac{y_0 - y}{y_0 - y_1} C_{0,1} + \frac{y - y_1}{y_0 - y_1} C_{1,1} \quad (3.18)$$

Now, interpolate in the final dimension, $z$,

$$C = \frac{z_0 - z}{z_0 - z_1} C_0 + \frac{z - z_1}{z_0 - z_1} C_1 \quad (3.19)$$

Substitution gives an analytical solution for $C$ that is independent of the order of interpolation.
3.3.3 Error detection

While the script is very good at quickly fitting synthetic spectra and calculating the results, it is not very good at deciding whether or not the fits are meaningful. Because of this, it is perilous to completely dispense with a visual inspection. Among the many diagnostic plots generated by the script are the fits themselves, and each of these has been given a minimum of a quick, qualitative inspection. Although this is a time consuming process, it is still much faster than doing the fits by hand, and many of the problems detected here can also be detected by quicker methods. The most useful of these is the line-to-line comparison - verifying that each line of the same element gives the same result to within a tolerance level. To make it into the final results, a star must have both lanthanum and both europium lines in agreement within 0.15 dex of each other. This requirement accounts for the majority of problematic stars, including errors such as bad pixels ruining the line and stars with qualitatively poor fits. There is also a small subset of stars with reasonable fits that are eliminated by this method, and it is difficult to explain why the lines do not agree. One speculative possibility that would explain these stars is an unusual isotopic ratio. Although lanthanum only has one abundant, naturally occurring isotope, $^{139}$La, europium has two abundant isotopes, $^{151}$Eu and $^{153}$Eu, with equal contributions to the solar system abundance pattern (Lodders 2003). The solar system isotopic ratio is assumed in the computation of the synthetic spectra. This is expected to be a good assumption based on a universal r-process argued for in Section 1.2.3, but an unusual isotopic ratio could produce a well-fit spectrum with poor line-to-line agreement.

Stars with log(g) < 4.0 are eliminated from the final results to avoid the need to extrapolate outside of the grid of synthetic spectra, and stars with $v_{broad} > 6$ km/s are eliminated because above this value the shape of the line becomes increasingly dependent on the broadening rather than the abundance. Recall, 6 km/s is the resolving power of the Keck data. While stars with broadenings up to 8 km/s may still have useful results, I have chosen a more conservative rejection criteria because the extra-
thermal velocity fields are not robustly modeled by MOOG. The difference between rejecting at 8 km/s rather than 6 km/s is 28 stars. Other reasons for rejection include incomplete spectra due to problems in the data reductions and being marked as a poor fit; there is a subset of stars with tolerable line-to-line agreement that nevertheless have qualitatively poor fits. After all these rejections, the original set of 640 stars are whittled down to 504.

3.4 The Kolgomorov-Smirnov Test

With a large, homogeneously analyzed set of results, we can now apply statistical analysis in an attempt to detect significant chemical differences among the stellar populations we have identified. The two-sample Kolgomorov-Smirnov (KS) test is a standard statistical technique for hypothesis testing. It is nonparametric and distribution free, and so it lends itself well to applications where the user prefers not to make any assumptions about the underlying distribution. Intuitively, the result of a KS test is the probability that the two given distributions could have been randomly drawn from the same parent distribution.

To apply the test, the two data sets are ordered from least to greatest along a parameter of interest. In this work, [Eu/La] is a good choice because of its sensitivity to the star formation rate. Once the data are ordered, the empirical cumulative distribution functions (CDF) can be calculated. A CDF describes, as a function of the ordered variable $x$, what proportion of the population has a value less than $x$. The next step is to calculate the $D$ statistic. Formally, given two CDFs, $F_1$ and $F_2$,

$$D_{1,2} = \sup_x |F_1(x) - F_2(x)|$$

Graphically, this can be represented as the maximum separation between the CDFs.

The final step of the test is the calculation of the p-value. The question is whether or not the $D$ statistic can be explained in terms of a Wiener process whereby the CDFs have been drawn from the same parent distribution; that is, any apparent differences are due solely to the randomness inherent in the drawing process. To quantify this,
statisticians use the Brownian Bridge, a mathematical model of a Wiener process anchored on either end at 0 and 1. In other words, the Brownian Bridge has fixed end points and white noise in between. The Kolmogorov distribution is defined as,

\[ K = \sup_{t \in [0,1]} |B(t)| \]  

(3.21)

where \( B(t) \) is a Brownian Bridge. Kolmogorov (1933) derives the CDF for this distribution as,

\[ P(x) = 1 - 2 \sum_{i=1}^{\infty} (-1)^{i-1} e^{-2i^2x^2} \]  

(3.22)

which gives the probability that the test statistic exceeds \( x \). The test statistic for two populations of sizes \( n_1 \) and \( n_2 \) is given by,

\[ \sqrt{\frac{n_1n_2}{n_1 + n_2}} D_{n_1,n_2} \]  

(3.23)

and the p-value is calculated from Kolmogorov’s distribution.

The null hypothesis is rejected at the level given by the p-value. In practice, the null hypothesis is commonly rejected at \( P = 0.05 \), or the 95% confidence level, and that is what is adopted in this work. The difficulty is in evaluating Kolmogorov’s distribution; this work uses the formulation given in Marsaglia et al. (2003).
Chapter 4

Results

4.1 Consistency Checks

4.1.1 Comparison with literature values: iron

An important consistency check to ensure that the analysis software is working correctly is to cross-reference the results with comparable literature values. A first check is to compare our spectroscopic iron results with the photometric iron results from the GCS. Recall that the GCS is the source of the atmospheric parameters used in the analysis. The comparison is shown in Figure 4.1. Note that the spectroscopic results are about 0.10 dex higher than the GCS values. On the other hand, the Hyades cluster stars are about 0.05 dex higher than the typical values found in the literature. For example, \([\text{Fe/H}] = 0.17\) dex versus about 0.12 dex in Allende Prieto et al. (2005). However, given that the input metallicities for the Hyades cluster from the GCS are around \([\text{Fe/H}] = 0.00\), it is a satisfying result that the spectroscopically determined Hyades cluster metallicities turn out to be closer to the literature value. Furthermore, the scatter about the mean for the Hyades cluster is very tight at \(\sigma = 0.03\) dex. This argues in favor of reliable results because the Hyades cluster stars sample a range of \(T_{\text{eff}}\), and the fact that they all return the same metallicity confirms that the iron lines are free of temperature dependent errors such as unmodeled blends in the synthesis and poor atomic data for the lines.

An offset between the results is not particularly worrisome because it is typical to find these sort of systematic differences when comparing results between various authors in the literature, and in fact, this serves as a good example of why it is perilous
to simply compile spectroscopic results from several authors. The most obvious reason why such differences are observed is differences in the atomic data. In particular, differences in the oscillator strengths, the gf values, can produce exactly this sort of temperature and metallicity independent shift in the results. In a typical analysis, oscillator strengths are taken from standard sources as a first step in making a list of absorption lines, and it is common practice to tune them to a personally observed solar spectrum. Besides differences in oscillator strengths, the continuum fitting step in the data reduction procedure can influence the final results in this manner as well. Especially in cool, metal-rich stars, the continuum level is poorly defined on a visual inspection. Thus, different authors will inevitably set their continuum level somewhat differently than others. Although any given continuum level is dependent upon temperature, metallicity, and the observed wavelength, overall biases of different authors to set it a bit higher or lower can lead to systematic differences in the results. Yet another source of systematic differences among authors is the resolving power. With lower resolution spectra, the continuum is more difficult to define and line blending issues are more difficult to detect.

Figure 4.1 also shows the internal agreement for the iron results. For each star, [Fe/H] is derived from an average of five Fe I lines. The standard deviation about this mean is then a measure of the internal consistency of the results. In Figure 4.1, all the stars with line-to-line agreement better than 0.05 dex are marked with solid circles, and stars with line-to-line agreement greater than 0.05 are shown as open circles. The mean standard deviation for the line-to-line agreement in iron for the whole sample is \( <\sigma> = 0.07 \text{ dex} \). The general “rule-of-thumb” for quality results by traditional, fine analysis in high resolution spectroscopy is about 0.05 dex, so this is an acceptable result for the automated analysis.
Figure 4.1 Spectroscopic [Fe/H] versus photometric [Fe/H] from GCS.
4.1.2 Comparison with literature values: europium and lanthanum

The next check is to compare the spectroscopically derived iron, europium, and lanthanum results to literature spectroscopic results. Three similar studies have been identified: Reddy et al. (2003), Bensby et al. (2005), and Brewer & Carney (2006). These three comparisons are shown in Figures 4.2, 4.3, and 4.4. Once again, the results from this analysis tend to be a bit more than 0.05 dex higher than literature values across the other three studies. For iron, the offsets range from $-0.08$ dex for Reddy et al. (2003) to $-0.05$ dex for Brewer & Carney (2006). Accounting for the offset, the agreement is superb with a scatter about the mean difference of $\sigma = 0.03$ dex across all three studies.

The worst agreement is found in the comparison for europium with Reddy et al. (2003). In this case, an offset of $[\text{Eu/H}] = -0.09$ is observed with a scatter about the mean difference of 0.11 dex. However, note that among the three studies used for comparison, this is the most difficult comparison to satisfy. In this case, Reddy et al. (2003) measures the europium line at 6645 Å while the result from this work is taken as the mean value measured from the europium lines at 4129 Å and 4205 Å. Naturally, when the same lines are measured, the agreement tends to be better. In the europium comparison with Bensby et al. (2005) the 4129 Å line is measured in both cases, and in the comparison with Brewer & Carney (2006) both the 4129 and 4205 Å lines are used, plus two others. In these two cases, the scatter about the mean difference is small at $\sigma = 0.06$ dex, good agreement considering the difficulties in comparing among the results of different authors.

In Figure 4.4, note that there are only comparison values from Brewer & Carney (2006). Lanthanum has not been widely studied, so comparison values are difficult to come by for this element. Lanthanum has many lines in the optical that are good candidates for observation, but barium is often preferred to lanthanum because it is a purer s-process element. The barium lines in the optical are, however, very strong in F and G dwarfs, and so the analysis of those lines are more vulnerable to non-LTE
effects. So, although barium is a purer s-process element, the measurement errors are smaller for lanthanum because there are more lines to measure and the lines are weaker. Brewer & Carney (2006) provides nine stars in common for comparison. The Brewer and Carney results are an average of nine lanthanum lines, including the two measured in this study, the lines at 3988 Å and 3995 Å. Once again, an offset of $-0.06$ dex is observed, but the scatter about this offset is very small at $\sigma = 0.03$ dex.
Figure 4.2 Comparison of spectroscopic [Fe/H] results with literature values.

\[ \text{[Fe/H], this work} \]

\[ \text{[Fe/H], literature} \]

- Reddy (2003): \( <\Delta> = -0.08, \sigma = 0.03 \)
- Bensby (2005): \( <\Delta> = -0.05, \sigma = 0.03 \)
- Brewer & Carney (2006): \( <\Delta> = -0.07, \sigma = 0.03 \)
Figure 4.3 Comparison of [Eu/H] results with literature values.
Figure 4.4 Comparison of [La/H] results with literature values.

\[ \langle \Delta \rangle = -0.06 \]

\[ \sigma = 0.03 \]
4.1.3 Line-to-line agreement

A test of the internal consistency of the results is made by checking the agreement among the lines. For both europium and lanthanum, two lines have been measured. It is known a priori that the lines formed by the same element ought to give the same result. Moreover, the abundance agreement between the lines as a function of temperature is sensitive to errors in the analysis such as line blends, temperature scale, and the model atmospheres. Blends can become a source of error especially in cool, metal-rich stars because there are lines observed in their spectra that are not present in the solar spectrum. If one of these unidentified lines encroaches on one of the lines of interest, it can introduce an error in the result. If the temperature scale is wrong, then lines will not agree due to the dependence of the result on the excitation potential of the lines. The model atmospheres give the T-τ relation, describing how the temperature varies as a function of optical depth. If the model atmosphere is incorrect, then the derived abundances will diverge because the synthesized lines are forming at the wrong depths and temperatures. All of these aspects of the analysis must be correct if the lines are to agree over a range of effective temperature.

The comparisons are shown in Figures 4.5 and 4.6. In both cases, there is no appreciable trend with effective temperature, the offsets are small at −0.03 dex, and the scatter is small at $\sigma = 0.05$ dex for europium and $\sigma = 0.03$ dex for lanthanum. The horizontal, dotted lines indicate the 0.05 dex rule-of-thumb level for quality results. The good agreement between the lines in both cases argue strongly in favor of reliable results.
Figure 4.5 Self-consistency of the europium results.
Figure 4.6 Self-consistency of the lanthanum results.
4.1.4 Chemically homogeneous stellar groups

A final test of the reliability of the results is made by noting the measured elemental abundance scatter among chemically homogeneous stellar groups. In Figures 4.7, 4.8, and 4.9 the Hyades cluster and two sets of common proper motion (CPM) pairs have been identified. These constitute three spatially and kinematically associated groups, and it is expected that all the stars in each group formed out of the same protocloud. Hence, it is also expected that they are chemically homogeneous. The scatter among these chemically homogeneous groups gives an empirical measurement of the degree of uncertainty in the final results.

The results and the atmospheric parameters are summarized in Table 4.1. Overall, the agreement is quite good. For the Hyades cluster in particular, the standard deviations about the mean value for [La/Fe], [Eu/Fe], and [Eu/La] are 0.03, 0.05, and 0.04 dex, respectively. Although there are only two lines each measured for lanthanum and europium, nearly the same level of internal agreement is observed here as compared to the result for iron of \( \sigma = 0.03 \) dex, where five lines are used. The approximate error bars shown for \( \sigma_y \) in 4.9 is shown as a conservative estimate of 0.07 dex, and this is based on the simple assumption of errors adding in quadrature for the europium and lanthanum measurement. [Eu/La], of course, is a derived quantity from [Eu/Fe] and [La/Fe]. However, note that since the europium and lanthanum measurements both use lines formed by ionized species, the measurement errors due to the atmospheric parameters tend to cancel out in forming the ratio [Eu/La].

The agreement among the CPM pairs is not as compelling as the Hyades cluster case, but these stars still represent an important test of the reliability of the results. The CPM pair HD86133AB appears to be a best case scenario with elemental abundance difference between the stars of 0.02, 0.02, and 0.04 dex for [La/Fe], [Eu/Fe], and [Eu/La], respectively. HD114060AB, on the other hand, appears to be a worst case scenario with elemental differences of 0.19, 0.15, and 0.05 dex for [La/Fe], [Eu/Fe], and [Eu/La]. However, note that, to first order, much of the disagreement can be at-
tributed to differences in the metallicities. For example, in the case of HD114060AB, if the more metal poor star of the pair is revised up to \([\text{Fe/H}] = -0.06\) dex, then the elemental differences would be reduced to 0.06, 0.03, and 0.04 dex. This serves to illustrate the importance of accurate atmospheric parameters and also the complex way in which the errors are correlated.

| Group  | Name     | \(T_{\text{eff}}\) | \([\text{Fe/H}]\) | \(\log(g)\) | \([\text{Eu/Fe}]\) | \([\text{La/Fe}]\) | \([\text{Eu/La}]\) |
|--------|----------|---------------------|-------------------|-------------|----------------|----------------|----------------|----------------|
| CPM 1  | HD 86133A| 5902                | -0.20             | 4.31        | 0.06           | -0.04          | 0.10           |
|        | HD 86133B| 5534                | -0.17             | 4.45        | 0.08           | -0.06          | 0.14           |
| CPM 2  | HD 114060A| 5572               | -0.18             | 4.52        | 0.24           | 0.09           | 0.14           |
|        | HD 114060B| 5370               | -0.06             | 4.54        | 0.09           | -0.10          | 0.19           |
| Hyades | HD 27859 | 5888                | 0.18              | 4.30        | -0.05          | -0.15          | 0.09           |
| Cluster| HD 27732 | 5433                | 0.17              | 4.44        | -0.06          | -0.15          | 0.09           |
|        | HD 25825 | 5957                | 0.20              | 4.40        | 0.02           | -0.16          | 0.17           |
|        | HD 26767 | 5768                | 0.19              | 4.44        | 0.01           | -0.08          | 0.09           |
|        | HD 30589 | 5984                | 0.17              | 4.31        | -0.04          | -0.14          | 0.10           |
|        | HD 29461 | 5768                | 0.17              | 4.37        | -0.08          | -0.14          | 0.06           |
|        | HD 28344 | 5848                | 0.14              | 4.34        | -0.03          | -0.11          | 0.08           |
|        | HD 28099 | 5728                | 0.11              | 4.39        | -0.04          | -0.11          | 0.07           |
|        | HD 28237 | 6067                | 0.19              | 4.29        | -0.15          | -0.17          | 0.02           |

Table 4.1 Atmospheric parameters, elemental abundance results, and photometric data for the chemically homogeneous groups.
Figure 4.7 [La/Fe] vs. [Fe/H] for the full sample, with chemically homogeneous stellar groups marked.
Figure 4.8 [Eu/Fe] vs. [Fe/H] for the full sample, with chemically homogeneous stellar groups marked.
Figure 4.9 [Eu/La] vs. [Fe/H] for the full sample, with chemically homogeneous stellar groups marked.
4.1.5 The outliers

In the analysis of such figures, the eye is naturally drawn to the outliers. Indeed, for the purposes of finding errors, a fruitful search often begins by closely scrutinizing the deviant data points. In the course of this analysis, some outliers have been eliminated by noting poorly fit lines or, more often, a discrepancy in the result from the two absorption lines. In the final analysis, four notable outliers still remain, and these four stars have been given extra attention to confirm the accuracy of their results. These are the four stars in the lower left quadrant of Figure 4.9, and their atmospheric parameters and abundance results are given in Table 4.2. With the exception of HD36667, the fact that these stars are outliers can be attributed to an unusually high lanthanum abundance. For HD36667, the low \([\text{Eu}/\text{La}]\) ratio is a combination of a somewhat low europium abundance and a somewhat high lanthanum abundance. For comparison, Figure 4.10 overplots the three Lanthanum enriched stars with the solar spectrum. All three of these stars are both warmer and more metal poor than the Sun, and these two effects would tend to make the lines appears weaker. This is the case for the majority of lines shown. Nevertheless, the lanthanum lines in these stars are much stronger than in the solar spectrum. Accepting that such oddball stars exist in the galactic disk, how do they fit into the narrative of the evolution of the disk? HD88446 is part of the Helmi stream, while HD22309 is a thick disk star. HD5072 and HD36667 do not fall into any kinematic classification explored here. Given that they deviate significantly from the general trend, it is tempting to suppose that something unusual has happened them. For example, is it possible that these stars have experienced enrichment by mass transfer? In this picture, the more massive companion in a binary system evolves into the AGB phase where s-process elements are synthesized. The s-enriched material is transfered to the low-mass companion, and the high-mass member eventually evolves into a white dwarf. This is the possible explanation offered in Bensby et al. (2005) to explain the s-process enhanced outliers. If this is the case, then the lifetime of AGB stars provides a lower limit to the ages of
s-process enhanced mass-transfer companions. Figure 4.11 shows a color-magnitude plot of the outliers along with a set of Yale-Yonsei isochrones. This shows that these fours stars are not uniformly old, but HD88446 and HD36667 are certainly subgiants with ages between 6 and 9 Gyr, so the mass transfer hypothesis seems especially plausible for this pair.

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{eff}$</th>
<th>[Fe/H]</th>
<th>log(g)</th>
<th>[Eu/Fe]</th>
<th>[La/Fe]</th>
<th>[Eu/La]</th>
<th>V-H</th>
<th>$M_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD88446</td>
<td>5957</td>
<td>-0.49</td>
<td>4.09</td>
<td>0.13</td>
<td>0.42</td>
<td>-0.29</td>
<td>1.390</td>
<td>3.77</td>
</tr>
<tr>
<td>HD36667</td>
<td>5848</td>
<td>-0.28</td>
<td>3.90</td>
<td>-0.01</td>
<td>0.25</td>
<td>-0.27</td>
<td>1.396</td>
<td>3.34</td>
</tr>
<tr>
<td>HD5072</td>
<td>5916</td>
<td>-0.43</td>
<td>4.28</td>
<td>0.22</td>
<td>0.46</td>
<td>-0.24</td>
<td>1.291</td>
<td>4.35</td>
</tr>
<tr>
<td>HD22309</td>
<td>5888</td>
<td>-0.26</td>
<td>4.34</td>
<td>0.25</td>
<td>0.49</td>
<td>-0.24</td>
<td>1.370</td>
<td>4.39</td>
</tr>
</tbody>
</table>

Table 4.2 Atmospheric parameters, elemental abundance results, and photometric data for the outliers.
Figure 4.10 Overplot of the three lanthanum rich outliers and the solar spectrum. HD22309 is shown in red. HD5072 is shown in green, and HD88446 is shown in blue. The solar spectrum is shown in black, and the 3988 Å lanthanum line has been marked. The S/N of the outliers in this order is \( \approx 100 \), and the Solar spectrum is much greater.
Figure 4.11 Yale-Yonsei isochrones are used to estimate the ages of the outliers. The $[\text{Fe/H}] = -0.4$ isochrones are colored in blue, and the $[\text{Fe/H}] = -0.3$ isochrones are colored in red.
4.1.6 Rotational velocities

Measurement of the line broadening is a necessary first step in the spectroscopic analysis, and this measurement has uncovered a subset of stars that are rotationally broadened. The GCS also includes a rough estimate of the rotational velocities as a side result of their radial velocity measurements. Whereas the results from the analysis in this thesis come from the measurement of line broadenings in six iron lines, the GCS rotational velocities are calculated from the width of a cross-correlation profile of an observed and a template spectrum. The comparison of results is shown in Figure 4.12. The agreement is quite good beyond the 6 km/s resolving power limit, especially considering that rotational velocity measurement was not a goal at the outset. Note that 12 km/s is the highest rotational velocity in the grid of synthetic spectra, which explains the three data points with high $v_{rot}$ in the figure where the GCS gives values greater than twelve.
Figure 4.12 Rotational velocity comparison with GCS values.
4.2 Elemental Abundance Results

4.2.1 Iron

Figure 4.13 shows the metallicity distribution for the entire sample. The primary result here is that this distribution is consistent with a sample primarily composed to thin disk stars, with the shoulder appearing at $[\text{Fe/H}] \approx -0.25$ due to a small mixture of thick disk stars. The thick disk has a mean metallicity of $[\text{Fe/H}] = -0.70$ dex with an upper bound of at least $[\text{Fe/H}] = 0.00$ dex (Bensby et al. 2007b).
Figure 4.13 Metallicity histogram for the entire sample.
4.2.2 Thin and thick disk abundance trends

Figures 4.14, 4.15, and 4.16 show the chemical abundance trends for the thin and thick disk stars. These two populations of stars have well-studied chemical abundance patterns available in the literature (Brewer & Carney 2006). In general, a clear chemical distinction between these two populations is observed for metallicities less than about -0.20 dex. For example, in Bensby et al. (2005), a clear separation is observed for oxygen, magnesium, aluminum, and silicon where the thick disk is clearly enhanced in alpha elements relative to the thin disk.

With the exception of a couple notable outliers in Figure 4.14, these results are consistent with previous literature results that the thin and thick disks become chemically distinct at sub-solar metallicities, especially in terms of r-process enrichment. Finding conclusive evidence of s-process element differences is less compelling, mainly due to the existence of certain highly-enriched outliers that appear not only in this work, but can also be seen in, for example, Bensby et al. (2005) and Reddy et al. (2006). However, discounting the two outliers, we confirm that relative to the thin disk, the thick disk is deficient in s-process elements at subsolar metallicities.

An inspection of Figure 4.16 reveals the utility of the chemical tagging technique. With the exception of the two lanthanum enhanced outliers, the thick disk stars display a clearly different chemical abundance pattern, and the natural conclusion is that during epochs of star formation, the thick disk has experienced a greater mean star formation rate relative to the thin disk. While it is exciting to draw conclusions about the history of the disk, it is necessary to impose more observational constraints to guide speculations. Bensby et al. (2004, 2005, 2007a) attempt to combine ages and elemental abundance patterns to refine the interpretation. In Bensby et al. (2004), an age-metallicity relation in the thick disk spanning ≈ 5 Gyr is presented as evidence that star formation proceeded for at least this long. In order to produce an age-metallicity relation, the ISM must be well-mixed, and this is further supported by a tight trend observed for [$\alpha$/Fe] vs. [Fe/H]. Bensby et al. (2007a) traces the thick disk
trend to solar metallicities, and his age measurements show that the thick disk stars comprise an older population of stars relative to the thin disk. The youngest, most metal-rich members of the thick disk are shown to be about 8-9 Gyr, considerably older than the 5 Gyr typical of the oldest thin disk stars. Moreover, it is shown that there is no age-metallicity relation in the thin disk. In other words, the oldest, metal-rich stars of the thin disk are about 5 Gyr old, the same as the oldest of the metal-poor thin disk stars. They appear to have formed at the same time! The interpretation is that the thick disk underwent an early enrichment period that ended 8-9 Gyr ago, and there has been little star formation in the thick disk since. The thin disk, on the other hand, is proposed to have experienced an epoch of enhanced star formation starting about 5 Gyr ago, initiated by a gas inflow including the poorly mixed remains of old, metal-rich stars. This picture has the advantage of helping to explain why no age-metallicity relationship is observed among thin disk stars, and it explains the relative age differences between the two populations in spite of the significant overlap in metallicity. In any event, it is impossible to explain the chemical differences between the thin and thick disks in terms of the closed box model, which argues strongly in favor of the interpretation that the thin and thick disk serve as a compelling example of two stellar populations with distinct histories, whatever those histories may be.
Figure 4.14 [La/Fe] vs. [Fe/H] for stars with distinct Thin/Thick disk kinematics.
Figure 4.15 [Eu/Fe] vs. [Fe/H] for stars with distinct Thin/Thick disk kinematics.
Figure 4.16 $[\text{Eu}/\text{La}]$ vs. $[\text{Fe}/\text{H}]$ for stars with distinct Thin/Thick disk kinematics.
4.2.3 The classical kinematic streams

The chemical abundance results for the Hercules, Hyades, and Sirius streams are shown in Figures 4.17, 4.18, and 4.19. It is difficult to draw clear conclusions from these figures alone because the trends coincide roughly with the disk. Certainly, this rules out the extreme case of accretion material from an object quite different from the MW, such as the Sagittarius dwarf. Indeed, any accreted objects present in this sample would necessarily have experienced a similar chemical history as the MW in order for the trends to agree so well. The more likely scenario from an analysis of these figures is that the classical kinematic streams shown here are the result of dynamical interactions within the disk. In this case, some subtle chemical differences may be observed by closely comparing the kinematic streams to background disk stars. Chemical differences may be explainable in terms of the stream preferentially sampling a distinctive part of the disk, for example, the inner disk.
Figure 4.17 $[\text{La/Fe}]$ vs. $[\text{Fe/H}]$ for the full sample, with classical stellar streams marked.
Figure 4.18 [Eu/Fe] vs. [Fe/H] for the full sample, with classical stellar streams marked.
Figure 4.19 [Eu/La] vs. [Fe/H] for the full sample, with classical stellar streams marked.
4.2.4 Helmi’s stream

Figures 4.20, 4.21, and 4.22 show the chemical abundance results for the three metallicity bins of Helmi’s stream. Qualitatively, Helmi’s stream appears reminiscent of the thick disk results, especially in regard to lanthanum (compare 4.20 with 4.14). Europium is less impressive as [Eu/Fe] spans roughly the same range in both Helmi’s stream and in the disk stars. In Figure 4.22, the metal-rich group of Helmi’s stream displays a hint of enhancement in [Eu/La] relative to the disk, though it is difficult to say for sure. The putative enhancement appears dependent upon the lack of Helmi group 1 stars in the lower envelope of the disk star trend. Clearly, this situation begs for a statistical analysis to quantify the significance of this putative enhancement.
Figure 4.20 [La/Fe] vs. [Fe/H] for the full sample, with Helmi’s stream marked.
Figure 4.21 [Eu/Fe] vs. [Fe/H] for the full sample, with Helmi’s stream marked.
Figure 4.22 [Eu/La] vs. [Fe/H] for the full sample, with Helmi’s stream marked.
4.2.5 Cosmic scatter

A minor point of discussion within the context of galactic disk spectroscopic surveys is how much of the scatter, at a given metallicity, is attributable to measurement error and how much of it is real, i.e. - cosmic scatter. Reddy et al. (2006) and Reddy et al. (2003) compute linear fits to the thin and think disk trends and then fit a Gaussian to the residuals. This is then compared to the measurement error to determine if the scatter is dominated by measurement error. The same technique has been applied here, and the results are shown in Table 4.3. Note, however, that the fits to the [La/Fe] results excludes the two lanthanum enhanced stars in the thick disk. Leaving these two stars in gives a result of $\sigma = 0.15$ dex instead. The results shown in Table 4.3 are very similar compared with Reddy et al. (2006) who get $\sigma = 0.08$ dex in both the thin and thick disk for [Eu/Fe]. However, their measurement uncertainty is also higher at $\sigma = 0.11$ dex. Given the measurement uncertainty in [Eu/La] of $\sigma = 0.05$ dex in this work, as evidenced by the scatter in the Hyades cluster stars shown in Figure 4.15, we find weak evidence that not all of the scatter in the thin disk abundance trends can be explained in terms of measurement error. The scatter in the thick disk is consistent with the previous measurement uncertainty estimates.

<table>
<thead>
<tr>
<th>[X/Fe]</th>
<th>Thin disk $\sigma$</th>
<th>Thick disk $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Eu/Fe]</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>[La/Fe]</td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 4.3 Gaussian fit to the residuals about a linear trend line fit to the thin and thick disk results.
4.3 Statistical Results

4.3.1 Thin and Thick Disks

Shown in Figures 4.23, 4.24, 4.25, and 4.26 are the results of a KS test for the thin and thick disk. This represents a test case that the KS test works as we expect, and indeed, the very low result of $P < 0.0001$, shown in Figure 4.23, gives the expected result that the thick disk is statistically enhanced in europium relative to the thin disk. Figure 4.24, however, gives an unexpected result. Referring back to Figure 4.14, we can see that the thick disk is deficient in lanthanum relative to the thick disk for $[\text{Fe/H}] < -0.20$. However, the KS test is inconclusive. Perhaps the two lanthanum enriched data points are spoiling the analysis? Perhaps the high metallicity, low $[\text{La/Fe}]$ end of the thin disk distribution is ruining the comparison because there are no thick disk stars with comparable metallicities? Figure 4.26 shows an attempt to account for these effects. In this figure, the two lanthanum enriched stars have been discarded, and a metallicity cut is applied to the thin disk stars at $[\text{Fe/H}] = 0.1$ dex. Even with these artificial restrictions, the result of the test is barely significant at $P = 0.04$. These difficulties serve to highlight the fact that the KS test is a non-membership test - a high $P$ value should not be interpreted as evidence of membership.
Figure 4.23 KS test result of [Eu/Fe] for the thin and thick disks.
Figure 4.24 KS test result of [La/Fe] for the thin and thick disks.
Figure 4.25 KS test result of [Eu/La] for the thin and thick disks.

D = 0.55
n1 = 228
n2 = 23
P < 0.0001

Thin Disk
Thick Disk
Figure 4.26 KS test result of [Eu/La] for the thin and thick disks, including a metallicity cut at [Fe/H] = 0.1 dex.
4.3.2 Helmi’s stream: Group 1

Shown in Figures 4.27, 4.28, and 4.29 are the results of KS tests on group 1 of Helmi’s stream. This is the metal rich group with $-0.45 < \text{[Fe/H]} < -0.2$. The low p-value of 0.01 in the \([\text{Eu/La}]\) test rejects the null hypothesis, and the clear separation between the CDFs reveal a \([\text{Eu/La}]\) enhanced population of stars. This result is perhaps surprising because Helmi’s stars were identified as a putative merger remnant, and present day dSphs show \([\alpha/\text{Fe}]\) ratios below MW values for a given \([\text{Fe/H}]\). Therefore, if one expects to find merger remnants of objects like present day dSphs, then one also expects to find \([\text{Eu/La}]\) depleted relative to MW disk stars, and that is the opposite of what is observed for Helmi Stream 1. The result here is more reminiscent of the chemical differences between the thin and thick disks, and in comparing Figures 4.20 and 4.14 it is observed that the lanthanum trends are remarkably similar. Indeed, the kinematics of Helmi’s stream are more similar to the thick disk than the thin disk; a few of Helmi’s stars are, in fact, classified here as thick disk members as well as Helmi stream members. In this regard, it is not surprising to find a thick disk chemical signature as part of Helmi’s stream.

Following this speculation, a further set of KS tests are performed on group 1 of the Helmi stream against the thick disk, and the results are shown in Figures 4.30, 4.31, and 4.32. There is one star in group 1 that is also classified as a thick disk star, and in the interest of removing contamination from known thick disk stars in group 1, it is counted as a thick disk star for the purposes of the KS test. In all three cases, the Helmi stream is indistinguishable from the thick disk at the 95% confidence level. This is a necessary but insufficient condition for the Helmi stream being composed of thick disk stars, with a couple of caveats. First, for the Helmi stream comparison with the background stars shown in Figures 4.27, 4.28, and 4.29, the metallicity range for the comparison group has been constrained to match that of the group 1 stars, but that restriction has not been applied in the thick disk test. Although this is not necessarily incorrect because we are specifically testing the thick disk stars in this case,
it would be preferable to constrain the metallicity range for the sake of consistency. The second caveat is that the number statistics in each group are barely sufficient for a meaningful test, and this is also the reason that the metallicity range has not be constrained. A more robust result would come from observing at least ten more members of each population.

So, is the accretion scenario still viable? The ages of the stars in the Helmi stream are of interest here. Isochrone fitting in Helmi et al. (2006) suggests that the Helmi 1 stream contains two populations of stars with ages 8 and 12 Gyr, and a similar method applied in Bensby et al. (2004) finds that the median age for the most metal-rich thick disk stars is $\approx 8$ Gyr, with a formation history stretching back about 5 Gyr. So, the Helmi stream seems to be of comparable age with the thick disk, but this is only weak evidence in favor of the accretion hypothesis. After all, it would make intuitive sense for stellar merger remnants to be old as well. In conclusion, it appears that more elements need to be measured in order to disentangle any merger remnant stars in the Helmi stream from the thick disk. One would want to choose an element with little scatter in the thick disk to improve sensitivity, and inspection of the trends in Bensby et al. (2005) suggest oxygen and magnesium as candidates.
Figure 4.27 KS test result of [Eu/La] for Helmi stream group 1.

Helmi Stream : Group 1

D = 0.40
n₁ = 13
n₂ = 101
P = 0.01

percentile

Helmi’s stream

Background stars

[Eu/La]

Figure 4.27 KS test result of [Eu/La] for Helmi stream group 1.
Figure 4.28 KS test result of [Eu/Fe] for Helmi stream group 1.

D = 0.26  
n1 = 13  
n2 = 101  
P = 0.21

Helmi's stream
Background stars
Figure 4.29 KS test result of [La/Fe] for Helmi stream group 1.

Helmi Stream : Group 1

D = 0.21
n_1 = 16
n_2 = 607
P = 0.02

Helmi's stream
Background stars

percentile

[La/Fe]
HD214059 has been removed from group 1 because it is also classified as a thick disk member.

Figure 4.30 KS test result of [Eu/La] for Helmi stream group 1 with the thick disk.
Figure 4.31 KS test result of [Eu/Fe] for Helmi stream group 1 with the thick disk. HD214059 has been removed from group 1 because it is also classified as a thick disk member.
Figure 4.32 KS test result of [La/Fe] for Helmi stream group 1 with the thick disk. HD214059 has been removed from group 1 because it is also classified as a thick disk member.
4.3.3 Helmi’s stream: Group 2 and 3

The result from the KS test for Helmi group 2 is shown in Figure 4.33. It is primarily shown for completeness as the number statistics for group 2 are quite poor. Helmi group 3 is no better. Testing with the KS calculator shows that, in general, a threshold of about fifteen stars in both the groups are needed to ensure a robust result, and twenty stars is better. Below this value, the test becomes insensitive to the D statistic, and by about $n = 10$ the test returns inconclusive results for any D.
Figure 4.33 KS test result for Helmi stream group 2.
4.3.4 Hercules stream

Shown in Figure 4.34 is the result of a KS test on the Hercules stream. The low p-value of 0.03 is a weak, statistically significant result, and the enhanced [Eu/La] should be interpreted in the context of the stream’s supposed origin as a dynamical resonance with the galactic bar. The chemical signature from this stream is possibly due to it sampling a different portion of the galactic disk than we are used to seeing among solar neighborhood stars. Daflon & Cunha (2004) demonstrate metallicity and abundance gradients in the Galactic disk for the alpha elements, with greater mean values observed at smaller galactic radii, and this is consistent with an enhanced signal for [Eu/La] if inner disk stars have been captured onto a resonance orbit. This result is complimentary to work by Dehnen (2000) that shows that a stream like Hercules could be induced by the Galactic bar, and it is also complimentary with the work by Bensby et al. (2007a) that shows that the metallicity distribution is bimodal at the metal-rich end.
Hercules Stream

D = 0.27
n_1 = 25
n_2 = 429
P = 0.03

Figure 4.34 KS test result for the Hercules stream.
4.3.5 Hyades stream

The Hyades stream is especially interesting because of its connection with the evaporated cluster hypothesis. Of the classical streams explored here, it appears the most likely to bear out Eggen’s original hypothesis. However, a simple inspection of the Hyades stream metallicity from the GCS demonstrates that there are many interlopers because the Hyades stream has a metallicity range similar to the thin disk. However, this does not rule out the possibility of the stream containing some evaporated members. As shown in Table 4.1, the Hyades cluster has a distinct chemical signature, so the search for evaporated members is a search for an over-representation of stars with these chemical abundances among the stream. Results in Famaey et al. (2007) and Pompéia et al. (2011) suggest that as much as 15% of the stream can be attributed to evaporation of the Hyades cluster. Additionally, Pompéia et al. (2011) measure a mean metallicity of the stream about 0.10 dex higher than the local thin disk population. Together, these results are reminiscent of the Hercules stream where metallicity differences are attributed to the stream sampling a different part of the disk. Does this mean that the Hyades stream is primary due to dynamical effects? Computer simulations by Quillen & Minchev (2005) suggest that the inner Lindblad resonance can split the velocity distribution into two orbital families as observed from the solar circle. One of these families is consistent with the Hyades stream, and the other is consistent with the Sirius stream.

Shown in Figure 4.35 is the result of a KS test on the Hyades stream. While the CDFs qualitatively coincide, the result is inconclusive due to poor number statistics. For future work, it may be fruitful to improve the statistics of this stream. Not only would it be interesting to complete the Hyades stream comparison as shown here, but it would also be interesting to test for similarities between the Sirius and Hyades streams.
Figure 4.35 KS test result for the Hyades stream.

$D = 0.19$

$n_1 = 11$

$n_2 = 429$

$P = 0.46$
4.3.6 Sirius stream

Shown in figure 4.35 is the result of a KS test on the Sirius stream. The good number statistics and low p-value of 0.03 argue for a chemically distinct population of stars, but the interpretation in terms of this population’s origins is unclear. Like Helmi’s stream, the signature is deficient in [Eu/La] relative to the disk, but in this case, the kinematics of the Sirius stream are very much like the thin disk. Quillen & Minchev (2005) suggest dynamical resonance origin for a stream with properties similar to the Sirius stream, but if this were the case then we would expect to see the chemical signature of inner disk stars. That is, we would expect to see stars enhanced in [Eu/La] relative to solar neighborhood thin disk stars as was the result for the Hercules stream stars. A speculative possibility is that the Sirius stream contains a statistically significant number of UMa evaporated members. Little chemical abundance information is known about UMa because the known members tend to be young, hots stars that are not appropriate for the sort of spectra analysis done here. Clearly, the Sirius stream is an interesting group that begs for further analysis.
Figure 4.36 KS test result for the Sirius stream.

D = 0.24  
n_1 = 33  
n_2 = 429  
P = 0.03

Figure 4.36 KS test result for the Sirius stream.
4.4 Conclusions

There is a trend in astronomy moving toward large data sets, and analysis tools must be developed to keep pace. In this work, stellar spectroscopy has been automated with a combination of well-used methods, such as spectral synthesis, and an application of computerized methods that are rather new to the field, such as the $\chi^2$ statistical pattern matching. The good line-to-line agreement for europium and lanthanum in Figures 4.5 and 4.6, and the good spectroscopic-to-photometric comparison for iron in Figure 4.1 all argue in favor of the software’s effectiveness. By these measures, the technical aspect of the project is a success.

The interpretations of the chemical abundance results are more nuanced. The well-known thin and thick disk abundance trends are reproduced, as shown in Figures 4.14, 4.15, and 4.16, but neither the Helmi stream nor the classical stellar streams display chemical abundance patterns as dramatically distinctive as observed in the Sgr dSph, outlined in Section 1.4. The highest hope for the detection of merger remnants is in the Helmi stream, but the simplest interpretation is that it is a kinematic statistical overdensity in the thick disk, composed of thick disk stars. The europium, lanthanum, and iron abundances, shown in Figures 4.20, 4.21, and 4.22, are all reminiscent of the thick disk, and the ages given in Helmi et al. (2006) for the putative merger remnants are comparable with the age of the thick disk. The best evidence arguing in favor of the accretion origin remains the suggestive color-magnitude diagrams in shown in Helmi’s work. However, this does not rule out the accretion hypothesis. The thick disk may have been formed by a major merger event with the generally younger thin disk forming from the infalling gas. In this scenario, the thick disk is a natural place to find merger remnants, but given the chemical similarities found here, more work is required, with special attention paid to distinguishing the Helmi stream from the thick disk.

The chemical signature for the Hercules stream shown in Figure 4.34 is consistent with the growing evidence that this stream is an intrusion from the inner disk, formed
by a dynamical resonance with the outer Lindblad resonance of the Galactic bar. Enhancements in [$\alpha$/Fe] generally track a corresponding enhancement in [r-process/Fe] since all these elements are associated with SNe II, so the observed enhancement of [Eu/La] is consistent with the known gradient of [$\alpha$/Fe] increasing toward smaller Galactic radii.

The statistical results for the Hyades stream are, unfortunately, inconclusive due to a lack of stars, but the work of Quillen & Minchev (2005) makes it tempting to associate this stream with the Sirius stream through the inner Lindblad resonance. The metallicity ranges for both of these streams are incompatible with Eggen’s dissolved cluster hypothesis, though they both contain clusters. It is still an intriguing question whether or not dissolved members can be found among the interlopers. Famaey et al. (2007) and Pompeia et al. (2011) claim to have found some, composing $\approx 15\%$ of the Hyades stream, but the Sirius stream has not been searched in this manner. The most interesting result for the Sirius stream in this work is the deficient [Eu/La] shown in Figure 4.36. If the Sirius stream is an inner disk intrusion caused by the inner Lindblad resonance, we expect to see an enhanced ratio consistent with the Galactic disk [$\alpha$/Fe] gradient. Since that is not what is observed, a better explanation might be found by a careful look at the UMa cluster. Although there is no significant age-metallicity relation in the thin disk, it is still tempting to associate the young age of the UMa cluster with the low [Eu/La], metal rich end of the thin disk abundance trend. It is an open question whether or not the Sirius stream contains a significant number of evaporated members, and little is known about the neutron capture elemental abundances of these stars.

4.5 Future work

The majority of my time spent on this project has been on developing the software, and there are still many possible improvements. Besides cleaning the source code and writing documentation toward the goal of distributing it to the community, the most
useful addition would be improving the automation of the error checking. Of the
time consuming tasks left in the analysis, this seems to be the one most amenable to
improvement. For example, a line-to-line comparison utility program could be written
and integrated into the script. Another, more esoteric, improvement of the software
would be rewriting how the input database files are generated. Right now, they are
generated by a collection of perl scripts that are specialized for GCS data files and
those of other sources I have collected, and those scripts will not be immediately useful
for the next project because the format of the input files will undoubtedly be different.
For this, a more generalized input routine is desirable. In the course of this work, I
have found that bookkeeping is the bane of a researcher working with a large data set,
and any utilities to reduce this sort of error would save the user time and frustration.

A simple direction for future work would be to improve the statistics of the poorly
represented streams. The two metal rich groups of the Helmi stream need about fifteen
more stars each for a robust KS test. The metallicity bins were designed by Helmi
to focus on three peaks of a trimodal metallicity distribution, and the isochrone age
dating of the groups yield somewhat different ages. Knowing the chemical composition
of each group, rather than just one, would assist in determining the stream’s origin.
It may also be fruitful to form an appropriate thick disk comparison sample for the
Helmi stream. Given the chemical similarities observed with the thick disk in this
work, a focused test to find chemical differences is desirable because it appears the
Helmi stream might just be a kinematic overdensity of thick disk stars. The Hyades
stream is also a tempting target. There are many bright members of this stream that
are appropriate for chemical tagging analysis, and although recent work has already
been published on the Hyades cluster’s contribution to the stream (Famaey et al.
2007; Pompéia et al. 2011), further chemical analysis can compare the composition
of the stream, cluster, and the disk at large - all important constraints for any origin
hypothesis.

Another possibility is to measure more elements using the reduced spectra on-hand.
With the tools already set up, the task of measuring a new element becomes a matter
of extracting the appropriate orders from the reduced data, collecting the atomic data, calculating a new grid of synthetic spectra, and finally running the script. In principle, this could be done very quickly considering the number of stars that can be analyzed in short order. Interesting choices for further analysis include oxygen and magnesium because of their low scatter among thick disk stars. Oxygen has the least scatter, but it is also more observationally difficult to measure. Another interesting choice would be hafnium because of its utility in nucleocosmochronology as a reference element. Hafnium is typically paired with thorium for the purposes of the age measurement, and the Th II line at 5989 Å is accessible in the spectra, though the line is very weak and blended. Europium is also used as a reference element with thorium, so the [Th/Hf] ratio could be compared alongside [Th/Eu], a test of the nucleosynthetic properties of Hf and Eu.

A third possibility is a focused study of the Sirius stream. The low [Eu/La] measured in the Sirius stream is a compelling reason for closer study because a simple prediction of the inner Lindblad resonance origin is a inner disk signature for the stream, which is not what is observed. Of the three classical streams considered in this work, the Sirius stream is the least studied in the context of its origins. It would be interesting to attempt to identify evaporated members of UMa in the Sirius stream in a similar manner as Pompéeia et al. (2011) does for the Hyades stream. This would include the identification of G and F dwarfs in the cluster nucleus for spectral analysis and a more comprehensive sample of Sirius stream stars, and the results would help explain the chemical evolutionary relationships between the cluster, the stream, and the Galactic disk. Given the proximity of the UMa cluster nucleus at ≈25 parsecs, there should be many bright targets.
REFERENCES


Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Reviews of Modern Physics, 29, 547


Castelli, F. 2005, Memorie della Societa Astronomica Italiana Supplementi, 8, 34


Kappeler, F., Beer, H., & Wisshak, K. 1989, Reports on Progress in Physics, 52, 945
Kolmogorov, A. 1933, Giornale dell’ Istituto Italiano degli Attuari
Kratz, K.-L., Farouqi, K., & Pfeiffer, B. 2007, Progress in Particle and Nuclear Physics, 59, 147
Kurucz, R. L. 1970, SAO Special Report, 309
—. 2005, Memorie della Societa Astronomica Italiana Supplementi, 8, 14


120


Sbordone, L., Bonifacio, P., Castelli, F., & Kurucz, R. L. 2004, Memorie della Societa Astronomica Italiana Supplementi, 5, 93


