Exploring the Local Association: A Nearby, Young Kinematic Stream of Stars in the Solar Neighborhood

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ASTR 296B –Honors Research & Senior Thesis
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Abstract

During the course of my Honors Research Project, I worked with Dr. David James to determine whether a group of target stars are members of the Local Association. I did this by reducing spectroscopic data, taken by Dr. James, in order to determine the radial velocity and lithium contents of the stars. Using the radial velocity measurements, the kinematics of each star was then defined by determining their U,V,W space motions. Lithium measurements were used to establish star youth and provide further evidence to support membership of the Local Association.

I) Introduction

The focus of this honors project involves the analysis of stellar spectra to establish whether our target stars are members of the kinematic stream, also known as the Local Association (see Section III). I reduced spectroscopic data in order to determine the one-dimensional and three-dimensional kinematic motion of the target stars, as well as their lithium content. The kinematics will be used to establish bona fide membership of the Local Association in the Galaxy velocity frame, with their lithium measurements being used to establish stellar youth. Because an understanding of the Local Association is integral to the scientific goals of my project, let us begin with a definition of the Local Association. Subsequently, I provide a description of the data themselves, as well as the analysis steps required to derive the necessary kinematics and lithium data products. Moreover, a catalogue of the 1-D kinematic and lithium data for our sample stars is provided, in concert with extant 2-D motion vectors and distance (obtained using NASA's Hipparcos satellite [1]). Finally, a discussion is forwarded concerning the origin of those stars that make up the Local Association.

II) Defining the Local Association

The Local Association, also known as a kinematic stream, is a moving cluster of stars sharing similar 3-D kinematic motion in the Galaxy, which are in the solar neighborhood. Furthermore, the stars that make up the Local Association are young; typically less than 300 million years old. But how does one determine which stars are in fact a member of the Local Association rather than some random star that, in this point in time, is just by chance positioned close to the cluster? The answer lies in an examination of the stars' kinematics.

Stellar kinematics are defined by three components of motion (U, V, W) in the galaxy. Space motions are described below in Figure 2.1:

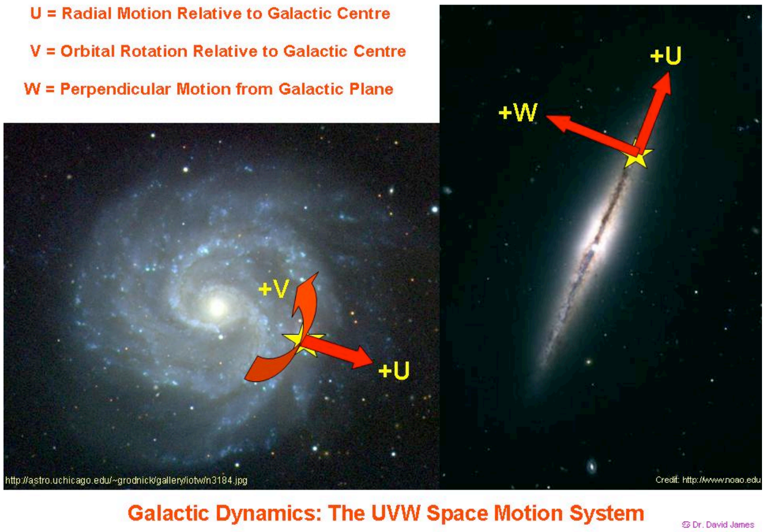


Figure 2.1: A graphical reprerentation of the U,V,W space motion reference system is shown, using an optical image of a sprial galaxy similar to our own Milky Way.

In order for the stars to be considered members of the kinematic stream, their space motions must be extremely close to one another, i.e., within about 5 to 10 km s^{-1}. If a star's space motions lie outside of these conditions, the star will eventually drift outside of the cluster, and, thus, would not be a member of the Local Association. This is described below in Figure 2.2.

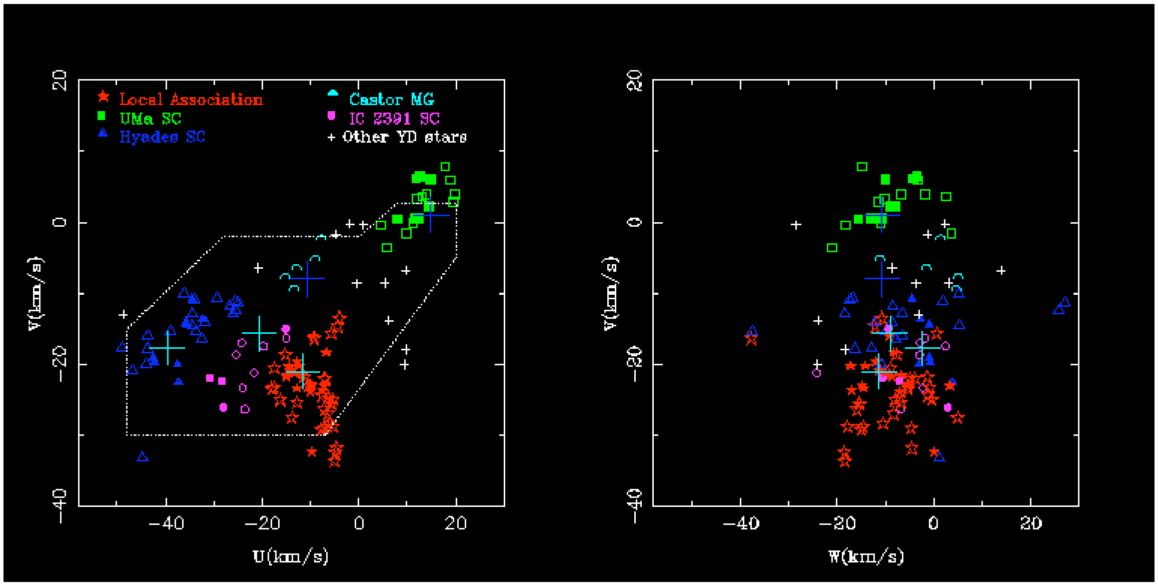
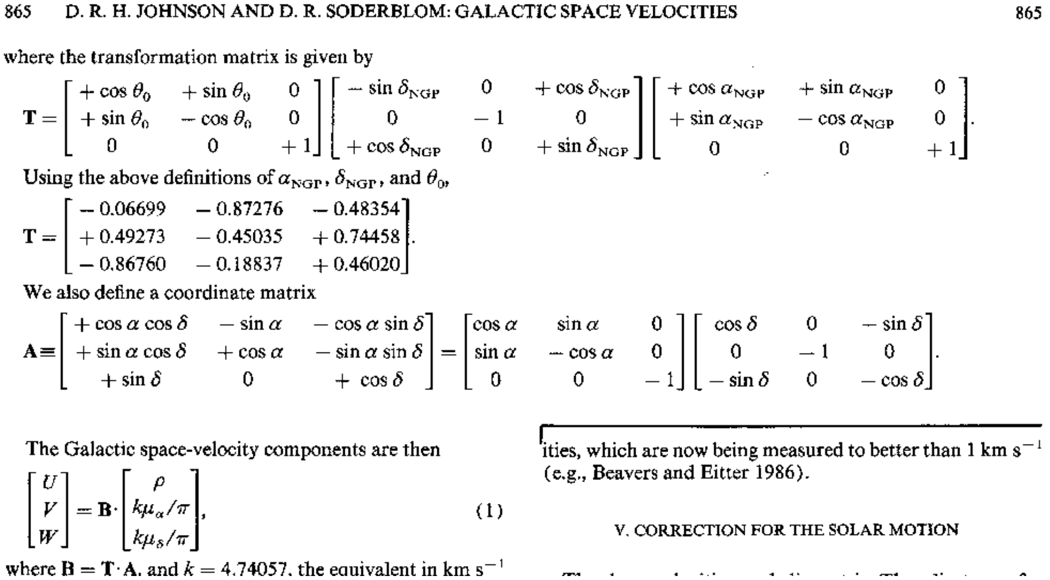


Figure 2.2: Various kinematic streams, including the Local Association, are shown in both UV (left) and VW (right) space (Montes et al. 2001).

In order to calculate the space motions, certain parameters are needed. The first is stellar position in terms of Right Ascension/Declination [Ra/DEC] (which are analogous to longitude and latitude here on Earth). The second is distance, which can be determined from parallax measurements by the Hipparcos satellite. Proper motion is the third parameter needed to define the space motions, and is the relative motion in RA/DEC compared to background reference stars determined by the Hipparcos satellite. Therefore, the only unknown parameter is the radial velocity of the target star. An in depth description of how radial velocity is calculated will be given in the next section.

Once all four parameters are determined, they are used to populate a very complex matrix, whose solution provides the U, V, W space motions of the star. This matrix is shown below in Figure 2.3:



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where the transformation matrix is given by

$$\mathbf{T} = \begin{bmatrix} +\cos\theta_0 & +\sin\theta_0 & 0 \\ +\sin\theta_0 & -\cos\theta_0 & 0 \\ 0 & 0 & +1 \end{bmatrix} \begin{bmatrix} -\sin\delta_{\mathrm{NGP}} & 0 & +\cos\delta_{\mathrm{NGP}} \\ 0 & -1 & 0 \\ +\cos\delta_{\mathrm{NGP}} & 0 & +\sin\delta_{\mathrm{NGP}} \end{bmatrix} \begin{bmatrix} +\cos\alpha_{\mathrm{NGP}} & +\sin\alpha_{\mathrm{NGP}} & 0 \\ +\sin\alpha_{\mathrm{NGP}} & -\cos\alpha_{\mathrm{NGP}} & 0 \\ 0 & 0 & +1 \end{bmatrix}.$$

Using the above definitions of α_{NGP}, δ_{NGP}, and θ_0,

$$\mathbf{T} = \begin{bmatrix} -0.06699 & -0.87276 & -0.48354 \\ +0.49273 & -0.45035 & +0.74458 \\ -0.86760 & -0.18837 & +0.46020 \end{bmatrix}.$$

We also define a coordinate matrix

$$\mathbf{A} \equiv \begin{bmatrix} +\cos\alpha\cos\delta & -\sin\alpha & -\cos\alpha\sin\delta \\ +\sin\alpha\cos\delta & +\cos\alpha & -\sin\alpha\sin\delta \\ +\sin\delta & 0 & +\cos\delta \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ \sin\alpha & -\cos\alpha & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \cos\delta & 0 & -\sin\delta \\ 0 & -1 & 0 \\ -\sin\delta & 0 & -\cos\delta \end{bmatrix}.$$

The Galactic space-velocity components are then

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = \mathbf{B}\cdot\begin{bmatrix} \rho \\ k\mu_\alpha/\pi \\ k\mu_\delta/\pi \end{bmatrix}, \qquad (1)$$

where $\mathbf{B} = \mathbf{T}\cdot\mathbf{A}$, and $k = 4.74057$, the equivalent in km s^{-1}

ities, which are now being measured to better than 1 km s^{-1} (e.g., Beavers and Eitter 1986).

V. CORRECTION FOR THE SOLAR MOTION

Figure 2.3:The four parameters are defined by the following variables within the matrix: Position - α and δ represent Right Ascension [RA] and Declination [DEC] coordinates; Parallax (distance) is depicted as Π (in arcseconds); Proper Motions are represented by μ_α and μ_δ (in RA/DEC -- in arcseconds/yr); Finally, radial velocity is shown by ρ (in km/s). These matrices, and their explanation, are taken from Johnson & Soderblom (1987).

The matrix is solved using a computer program written specifically to calculate space motions, which our colleague Ms Alicia Aarnio (PhD Student) performed.

As previously stated, stars that make up the Local Association are relatively young in stellar terms In order to determine their age, an examination of their lithium content is necessary. Lithium is quickly proton-burned above 2.5 million Kelvin inside a star. The precise reaction path is: ^{7}Li(p,α)^{4}He and ^{6}Li(p,α)^{3}He (Bodenheimer 1965). Young stars do not have enough time to have proton-burned their natal lithium. Conversely, old stars have burned most of their lithium. Therefore, lithium is indicative of youth, and even can show that stars are coeval (the same age). Thus, lithium content can be used to further support our results if it is found that the stars whose space motions define them as being part of the Local Association are also young and relatively close in age.

Raw data from the spectrograph must be treated to remove instrumental signature and placed on a standardized fundamental system, which will allow us to maximize the precision and accuracy of the data products, which will then yield radial velocities and lithium content. These processes are described in the following section.

III) Observations and Data Reduction

During February 1998, each of the Local Association candidate stars were observed at high resolution using the echelle spectrograph at the coude station of the 1.9m telescope situated at Mount Stromlo Observatory, Canberra, Australia. The observations were performed using a 79 lines/mm echelle grating and a 2Kx4K Tektronics CCD camera as detector, with a 1.2 arcsecond entrance slit. This set-up yielded a FWHM of cross-correlated ThAr arc lines of 0.18 Angstroms at 6700 Angstroms (which is a resolving power of R=37000), and a useful wavelength range of ~5000-7500 Angstroms.

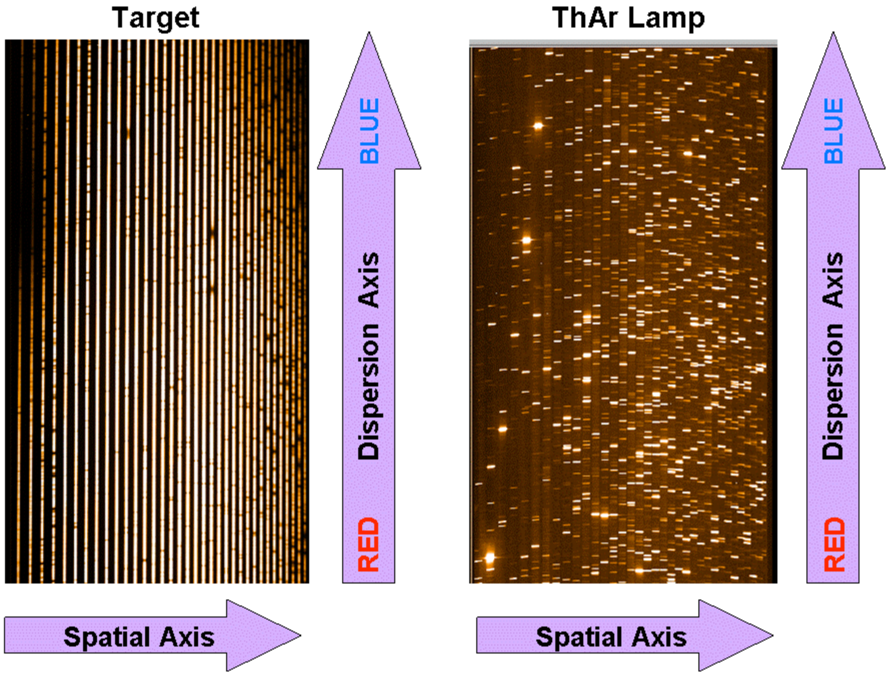


Figure 3.1: An echelle spectrum is shown for a target star (left) and a thorium argon comparison lamp (right). The scattering of the light from the red region to the blue region is represented on the y-axis, Because of the small size of the CCD chip, the spectrum must be "stacked" on top of itself in order to fit. This spatial axis is represented on the x-axis. The dark lines on the spectrum of the target star are absorption lines from atoms found in the star's atmosphere, while the bright lines on the ThAr lamp spectrum are emission lines due to the electronic transitions on excited electrons in thorium or argon atoms.

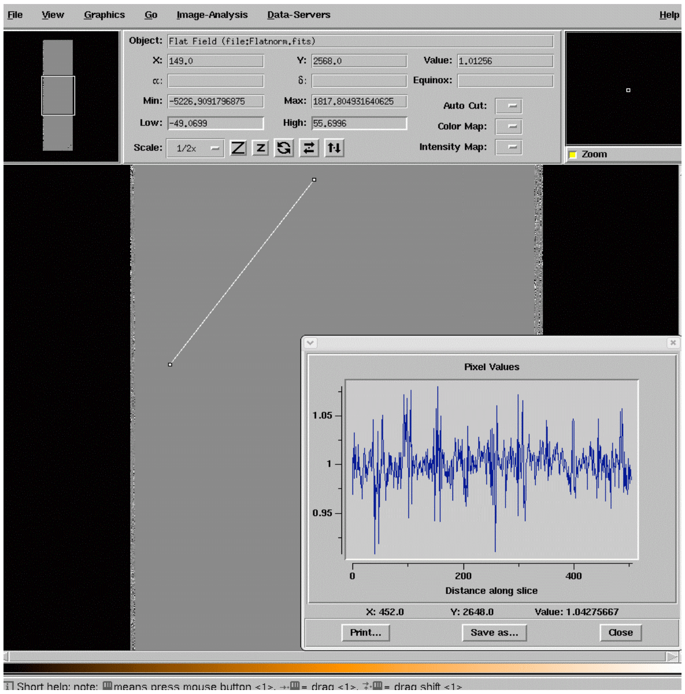
The input catalogue consisted of chromospherically active stars, taken from Henry et al. (1986), which were also detailed in the Hipparcos satellite astrometric catalogue. We chose chromospherically active stars because their high magnetic activity is a strong indication of stellar youth, a key property of stars that make up the Local Association. Physical characteristics of our target stars are detailed in Table 1, where we show their coordinates (Right Ascension [RA] and Declination [DEC]), photometric data (V-band magnitudes & B-V colors), and their astrometry (parallax and proper motions). Each star in the input catalogue was observed using the telescope and spectrograph described above. A series of discrete analysis processes must be followed in order to derive radial velocities and lithium content from the raw spectroscopic data obtained for each target star; these are outlined below.

a) *Bias Subtraction*

These "bias images" represent the case where the CCD camera shutter remains closed so the only signal measurable on the detector is that due to the initial charge level from the electronic controller. A series of bias images were taken, from which a median master bias frame was created. This master bias frame is subtracted from each data frame on an image-by-image basis. This eliminates the bias level charge from each target image.

b) *Flat- Fielding*

Because of imperfections in the silicon chip within the device, there are pixel-to-pixel response variations of the CCD camera. The purpose of flat-fielding is to get rid of these variations. In order to do this, a continuum Tungsten comparison light source was used to create a fairly uniform illumination across the chip. A series of "flat" images is then median-combined into a master flat field. The median process allows us to eliminate cosmic ray events. Next, a high order polynomial function is fitted across each row of the master flat field image. Each row of the Master Flat Field is subsequently divided by its own polynomial fit. The result is known as a "Balance Frame." For each row in this Balance Frame, the actual number of counts is close to 1.0, except where there are deviations due to pixel-to-pixel variations. Finally, all the science images are divided by the Balance Frame to eliminate this variation.



Object: Flat Field (file:Flatnorm.fits)
X: 149.0
Y: 2568.0
Value: 1.01256
α:
δ:
Equinox:
Min: -5226.9091796875
Max: 1817.804931640625
Low: -49.0699
High: 55.6996
Scale: 1/2x

X: 452.0
Y: 2648.0
Value: 1.04275667

Short help: note: means press mouse button <1>, = drag <1>, = drag shift <1>

Figure 3.2: An image of the master flat field is shown. The inset-box represents a cut across the image (from white line), where each "spike" shows the presence of pixel-to-pixel variations.

c) *Spectral Order Tracing*

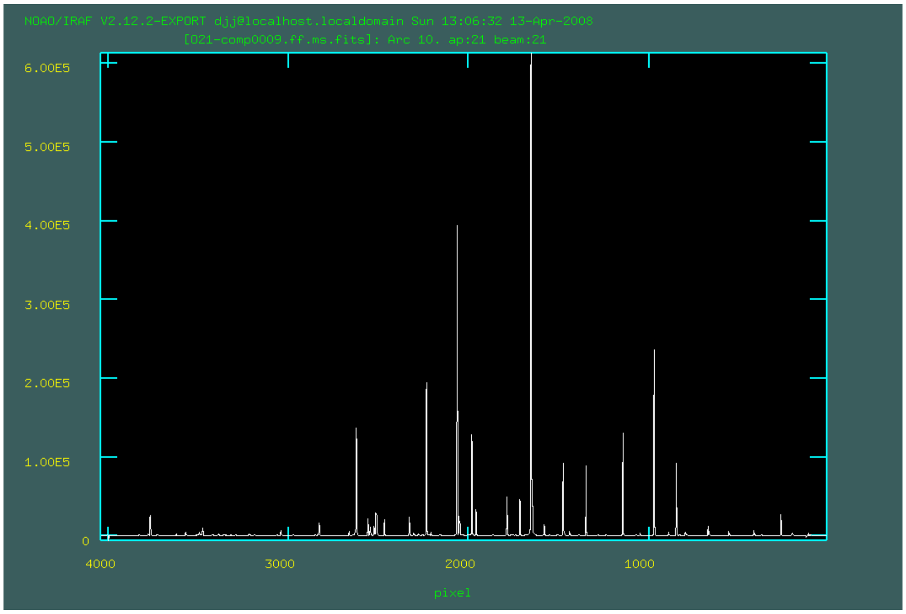
In order to extract the spectral data from the CCD images, the analysis algorithm must physically know where the data are on each image. Therefore, we performed a "tracing" algorithm to detect ordered, structured brightness enhancements on the images, which in effect are the spectral orders (See Figure 3.1).

d) *Data Extraction*

The extraction algorithm adds up the light along the traced spectral orders, taking into account "sky" background. This results in the creation of one-dimensional spectra for each echelle order. It is important to note that the spectra are in counts versus pixels, which must be converted into a fundamental measurement system in order for a proper spectral analysis to be performed.

e) *Wavelength Calibration*

Detector pixels have no scientific meaning, so this axis on each spectrum must be converted into wavelength, which is a fundamental unit of measure. In order to do this, a thorium argon comparison lamp is used to find the relationship between pixel and wavelength. In other words, the ThAr comparison lamp is used to create a conversion factor between pixels and wavelength. Figure 3.3 shows a ThAr comparison lamp spectrum in terms of pixels and wavelength that will be used to create this conversion spectrum.



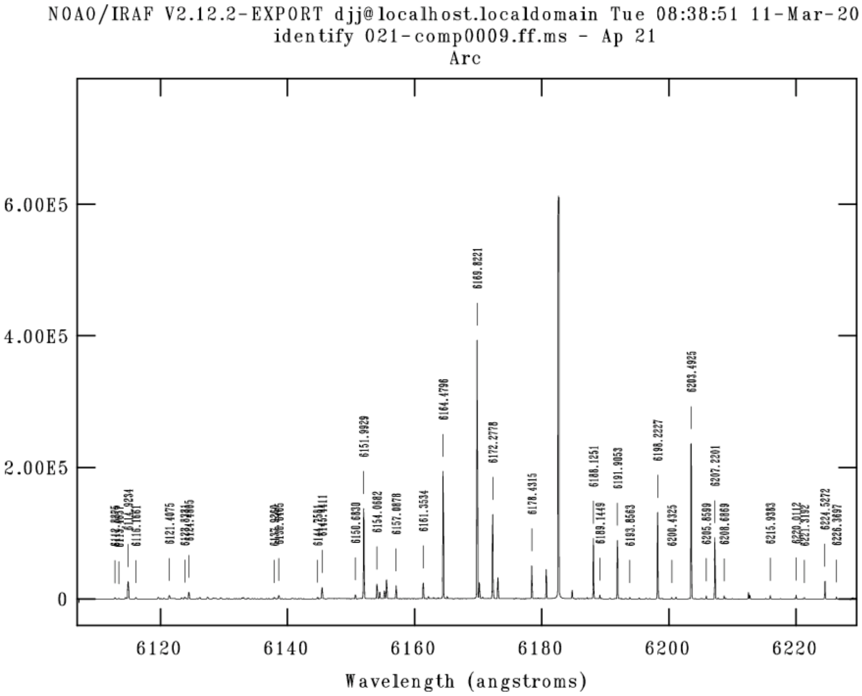


Figure 3.3: The emission lines of the ThAr comparison lamp are known in counts versus pixels (above). Because of the quantum properties of the thorium and argon atoms, the emission lines in counts versus wavelength is also known. This conversion factor is applied to all scientific data in order to convert pixels to wavelength, which is a scientific standard unit of measure.

f) *Scattered Light Subtraction*

Because of imperfections in the spectrograph, some starlight is scattered all over the CCD camera. This can be eliminated in the background estimation stage.

g) *Dispersion Correction*

The pixel-to-wavelength calibration images are applied to the target spectra, which converts them from pixel to wavelength. At this stage, the data are ready to be used to calculate radial velocities and lithium content. Figure 3.4 shows reduced spectra in the lithium region, which are ready for analysis.

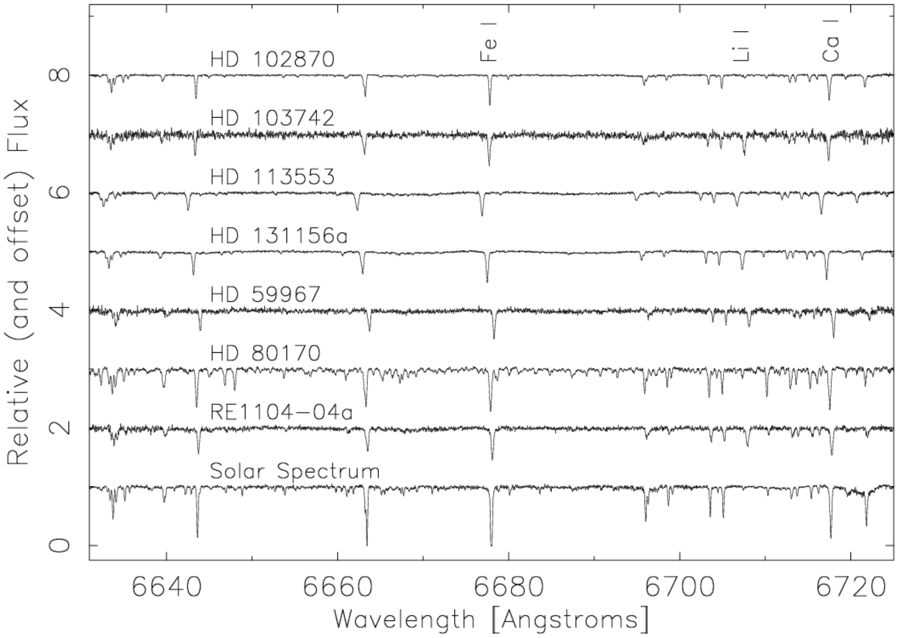
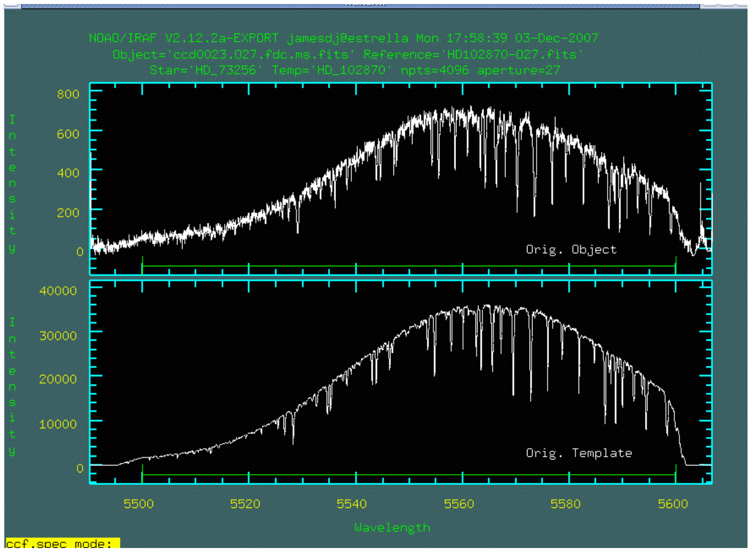


Figure 3.4: Completely reduced data of some of our target stars are shown in relation to the solar spectrum in the lithium wavelength region.

IV) Analysis, and Products

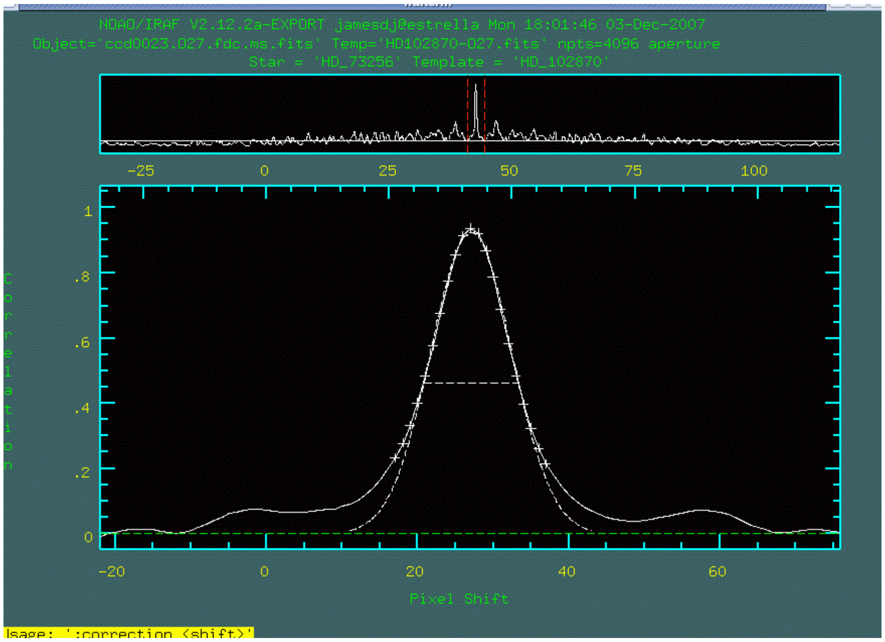
The first step in determining radial velocities is achieved by measuring the Doppler Shift between a target star spectrum and the spectrum of a star of known radial velocity (called a radial velocity standard star). An example of this comparison is seen in Figure 4.1.



```
NOAO/IRAF V2.12.2a-EXPORT jamesdj@estrella Mon 17:58:39 03-Dec-2007
Object='ccd0023.027.fdc.ms.fits' Reference='HD102870-027.fits'
Star='HD_73256' Temp='HD_102870' npts=4096 aperture=27
```

Figure 4.1: The spectrum of an object star (above) is compared to the spectum of a standard star (below). Both spectra lie in the same wavelength region.

The target spectrum is then "cross-correlated" against the standard star spectrum. In mathematical terms, this process can be described as follows. A Fourier transform is applied to each spectrum, which are then multiplied together. The inverse of the Fourier transform is taken of the resulting product, which is called a "cross correlation function". The shift of the peak from "zero" represents the Doppler Shift between the two spectra (i.e. the radial velocity), whereas its width represents the rotational velocity of the target star. An example of a cross correlation function is shown in Figure 4.2.



```
NOAO/IRAF V2.12.2a-EXPORT jamesdj@estrella Mon 18:01:46 03-Dec-2007
Object='ccd0023.027.fdc.ms.fits' Temp='HD102870-027.fits' npts=4096 aperture
Star = 'HD_73256' Template = 'HD_102870'
```

Figure 4.2: The shift of the peak from "zero" on this cross correlation function represents the radial velocity of the target star. The width of the function shows the star's rotational velocity.

The radial velocity is the fourth and final parameter needed to determine the U, V, W matrix. Once all the radial velocities are found, the U, V, W, matrix is applied in order to determine the space motions for each star.

Lithium content was determined using two different methods. In the first instance, a Gaussian function was fit along the lithium absorption line using limits where the lithium absorption feature blended back into the local continuum level. The second process used to calculate lithium abundance was by integrating the area under the absorption line. A graphical representation of these two processes is described below in Figure 4.3.

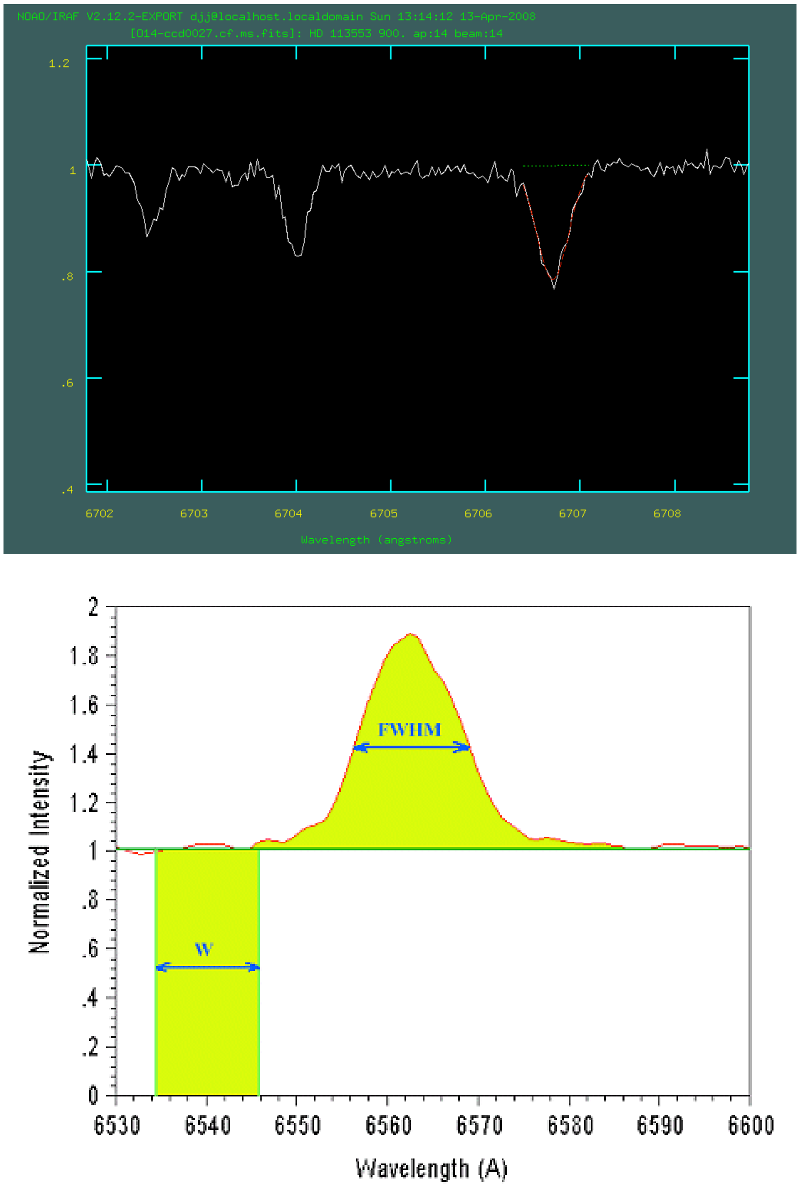


Figure 4.3. The Gaussian fit across the lithium absorption line gives a value for the lithium equivalent width in the target star (above). The equivalent width measurement (below) is the same as turning an absorption line into a rectangle of exactly the same area as measured from the continuum line.

V) Results

The results of a spectroscopic analysis for the Mount Stromlo data yield both radial velocities and lithium equivalent widths using cross correlation, Gaussian fitting, and direct integration methods described above (see Section IV). These data products are presented in Table 2, where we list date of observation (column 3), heliocentric radial velocities (column 4), and lithium equivalent widths (columns 5 & 6). For each target star, we derived two lithium abundance values in the form of equivalent widths by using the Gaussian fit method and the integration method.

The two lithium equivalent width values for each star were plotted against each other in order to determine how self-consistent the two measurement methods are (see Figure 5.1). Initially, we assumed a 10% measurement error on each system, which the comparison figure shows as appropriate.

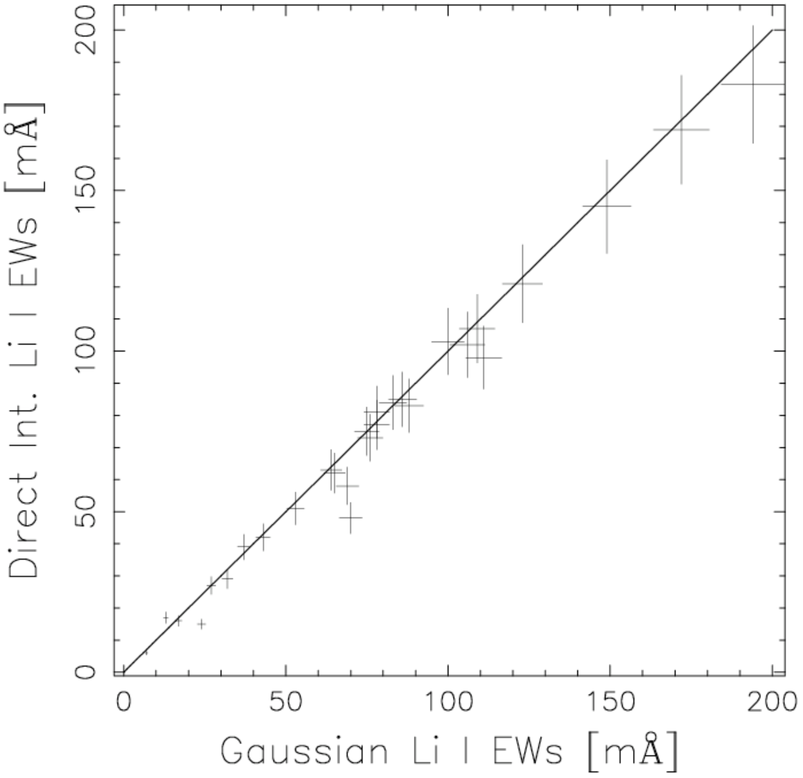


Figure 5.1: The lithium content values found for each target star using a Gaussian fit were plotted against the values determined by direct integration. There is a 10% error on each data point. The solid line represents equality between the two data sets, and is not a fit to the data.

In order to determine the age of the target stars and gain further insight into which stars are members of the Local Association, we compared each star's lithium abundance to the lithium abundance of the stars in both the Pleiades and Hyades star clusters. Because we know that the Hyades is a 700 million year old cluster and the Pleiades is a

100 million year old cluster, we can determine the age of our Local Association candidate stars in relation to the two clusters. Stars that have similar lithium equivalent widths as the Hyades stars will also have a similar old age. Stars whose equivalent width values lie close to those of the Pleiades cluster will be relatively young, and, therefore, will more probably be a member of the Local Association. The comparison of the Pleiades cluster, the Hyades cluster, and our target stars is shown in Figure 5.2.

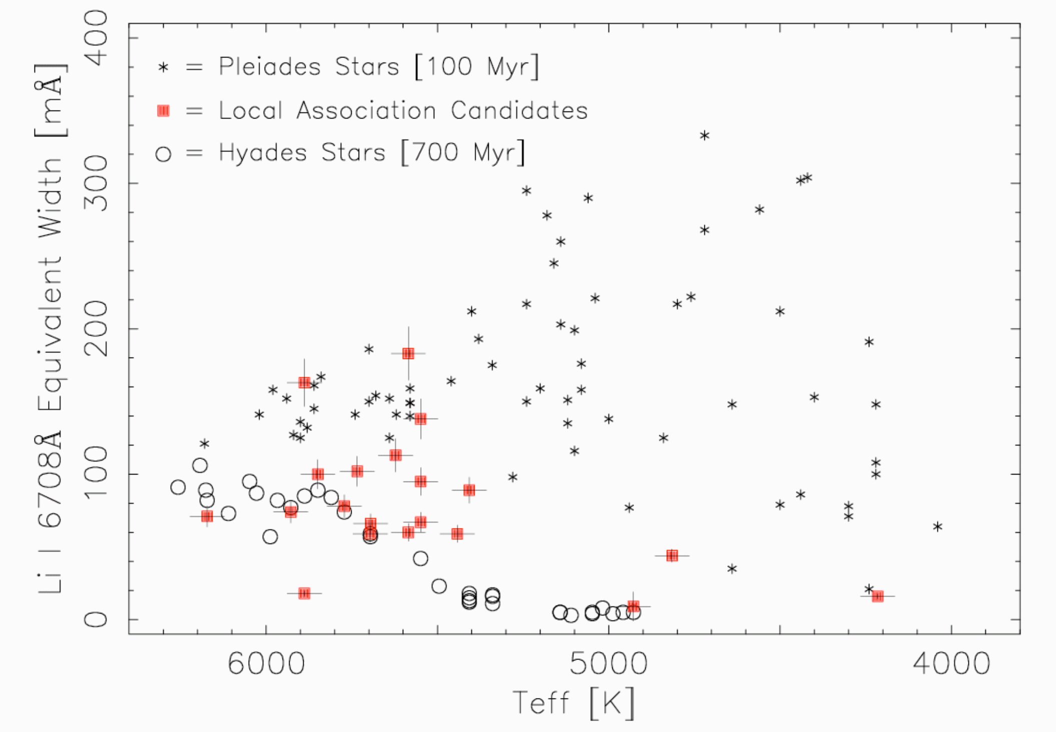


Figure 5.2: Temperature is plotted against lithium equivalent widths for Pleiades stars, Hyades stars, and our target stars. Stars that share similar lithium abundances as the Hyades cluster are old in age (close to 700 million years old), while stars that have similar equivalent widths as the Pleiades cluster are young in age (close to 100 million years old). Stellar youth is a key property of Local Association stars, so those target stars whose lithium equivalent widths lie near the Pleiades cluster will more likely be a member of the Local Association. Lithium data and ages for the Pleiades and Hyades cluster members are taken from Soderblom et al. (1993) and Thorburn et al. 1991) respectively.

Finally, the radial velocity values found for each target star were used to determine space motions by the method described above (see Section II). Table 3 lists the U, V, W kinematic vectors (columns 3-5) for each target star.

UV and VW space motion plots were then created in order to determine if our target star motions matched the kinematic criteria for known members of the Local Association. We transposed our new data points on top of the UVW dataset of Montes et al. (for their Local Association stars -- refer to Figure 2.2), to look for new Local Association members from our survey. These plots are shown below in Figure 5.3.

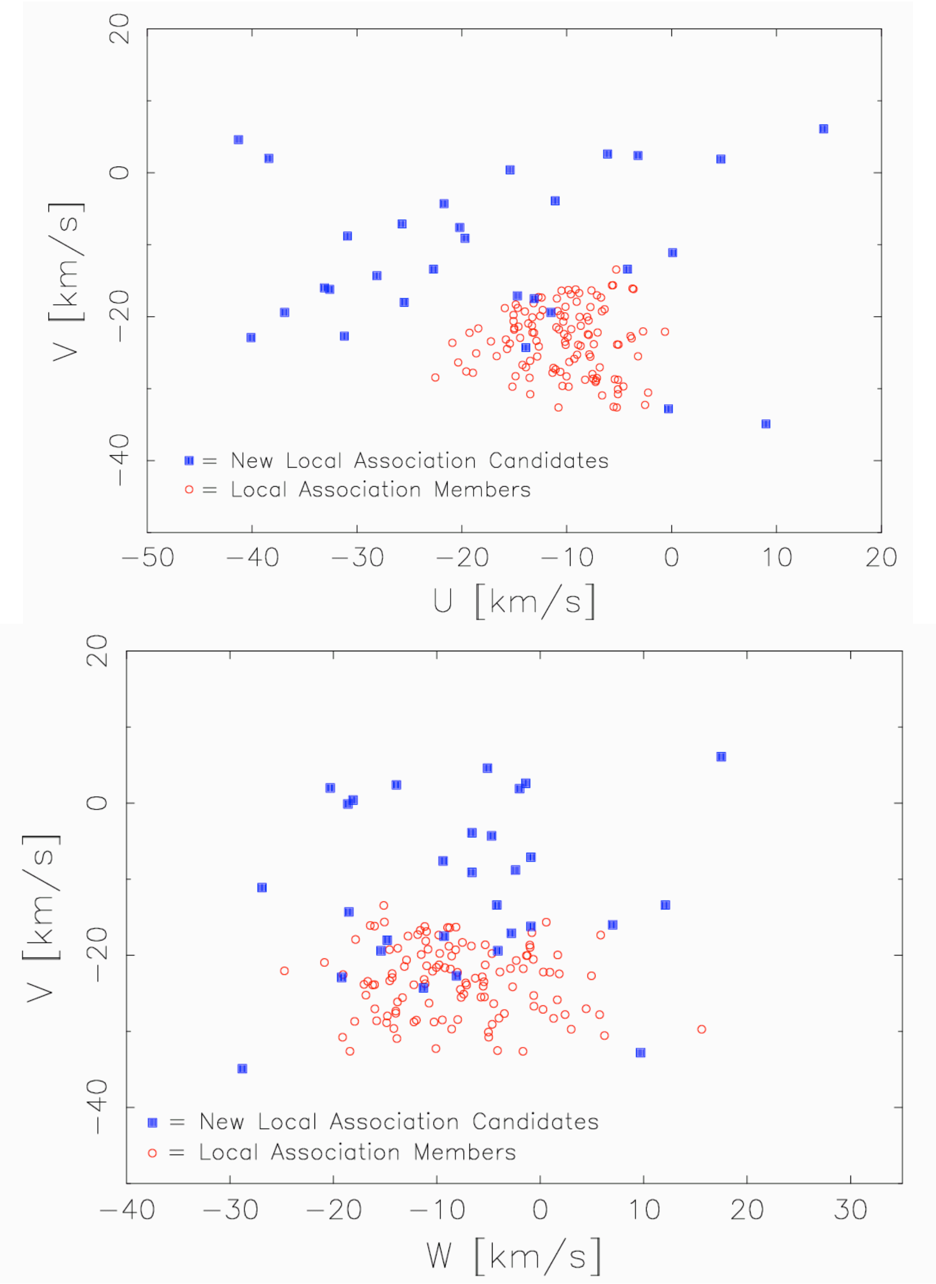


Figure 5.3: The space motions of our target stars are shown in blue on the UV plot (above) and VW plot (below). Kinematic data for known Local Association members are plotted in accordance with the Montes et al. results (see Figure 2.2), and are shown in red. The candidate stars whose motions lie in the vicinity of those of the known Local Association stars are also most likely to be ***new*** *members of the kinematic stream.*

For each target star in our sample, we checked to see where the target lies in UV and VW space, and compared their positions to those of the known Local Association stars. As we can see from the plots in figure 5.3, many of our target stars lie outside the range of UV and VW velocities occupied by the *bona fide* Local Association stars. Based on this visual judgment, we have assigned each of our targets a Local Association membership status in both UV and VW space. These membership assignments are listed in Table III (column 6). We should note that stars are probable members **only** if they satisfy the kinematic criteria in both UV and VW space. In total, 6 of our 31 candidates are probable members of the kinematic stream known as the Local Association, based on their U, V, W space motions.

VI) Summary and Conclusions

For my honors thesis I studied the Local Association, also known as a kinematic stream. In order to accomplish this, I reduced spectroscopic data of our target stars in order to determine their radial velocities and lithium contents. These one-dimensional radial velocities were used to derive the U, V, W space motions for each target star. The lithium data were used to judge stellar youth by comparison with the young Pleiades open cluster (100 Myr) and the older Hyades (700Myr). Our new U, V, W kinematic data were compared to known Local Association stars in order to determine the membership of our target stars in this kinematic stream. We found that 6/31 (19.4%) of our candidate stars have 3-dimensional space motions consistent with the range that defines that Local Association.

Because of time constraints, we were unable to use our lithium abundance values to verify that our six new probable Local Association members are indeed young. Other considerations for future projects will be to determine whether the rejected candidate stars are members of other nearby kinematic streams in the Galaxy (e.g. Montes et al. Color Plot; see Figure 2.2).

VII) References

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