Extracting Information from Spectra of Andromeda Red Giant Stars: Temperature and Chemical Abundance

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Introduction

Astronomers study the Andromeda Galaxy (M31) in order to find insights into the workings of our own Milky Way because of similarities between the two spiral galaxies. Studying M31 is advantageous because the galaxy can be viewed from afar, creating a complete image, while the Milky Way must be studied from the inside.

One of the important reasons for measuring metallicity (Fe/H) for stellar objects is its role in separating M31 RGB (red giant) stars from the foreground Milky Way dwarf stars. Even though snapshots of targets in Andromeda's halo are filtered photometrically for MW dwarf stars, a substantial number of "contaminants" are still observed because red giants are sparse in the outer halo (Gilbert et al. 2006).

It is important that metallicities are reliable because these measurements bring insight into understanding the physical structure of Andromeda. By looking at gradients and differences in metallicity, stellar substructures can be singled out. Different structures of a galaxy, such as the bulge (inner spheroid), disk, and tidal debris, can be isolated because their different histories of formation resulted in different chemical compositions (Gilbert et al. 2007; Kirby et al. 2009). Metallicities can explain the details of the hierarchical buildup of large spiral galaxies (such as the Milky Way and Andromeda) from small building blocks, such as dwarf satellites (Gilbert et al. 2009).

In this study a new method was developed to characterize stars and study their properties using a spectral matching program. This program pairs each individual science spectrum, from a master database of spectra of M31 stars, with a best-match template spectrum from a library of spectra that have been already extensively analyzed. The Indo-U.S. Library of Coudé Feed Stellar Spectra contains a comprehensive set of stellar spectra with wide coverage

of properties such as effective temperature, surface gravity, metallicity, and spectral type (Valdes et al. 2004). Through matching, new properties can be assigned to stars in the master database and known properties such as metallicity can be reconfirmed.

Methods

The science spectra obtained from the Keck Observatory with the DEIMOS instrument and stored in a master database at UC Santa Cruz were compared to the template/library spectra from The Indo-U.S. Library of Coudé Feed Stellar Spectra collected from the Kitt Peak National Observatory. All programs used for preparing and matching the spectra were written in Interactive Data Language (IDL).

Both the Keck/DEIMOS science and Coudé Feed library spectra were prepared before the comparison. Each science spectrum in the master database has been assigned a "zquality" after cross-correlation with a set of template spectra from the Sloan Digital Sky Survey (Gilbert et al. 2006). This value indicates the accuracy of the raw radial velocity estimation for the stellar object. A zquality of two signifies that the velocity measurement failed. Stars with a zquality of three or greater were used; a three is a marginal velocity while a four is a secure velocity from cross-correlation.

A reliable radial velocity estimation is needed in order to bring the spectra to rest-frame wavelengths accurately. The library spectra are stored in their rest wavelengths, but the raw science spectra are stored in their observed wavelengths. The science spectra were shifted into their rest wavelength in order to account for red/blue shift. Each data point (wavelength, spectral flux, inverse variance) has the wavelength value divided by a constant based on its raw radial velocity, $\lambda_{rest} = \frac{\lambda_{observed}}{1+\frac{v_{raw}}{c}}$, where c is the speed of light.

In order to compare the library and science spectra, their data points must have matching wavelength values. Due to red/blue shift, the science spectra have varying wavelength scales. Both the science and library spectra were re-binned to a common linear wavelength grid in order to facilitate comparison. The grid begins at 6450 Å and continues in intervals of 0.4 Å to 8930 Å. Simple linear interpolation was used in order to rebin the DEIMOS spectral data.

The science spectra are stored on file as two segments, a blue side and a red side. However, the total combined wavelength coverage varies for each individual spectrum. In order to facilitate the matching process, a standard interval of wavelengths was used. "Blue" refers to the wavelength interval 6450 Å to 7800 Å, while "red" refers to 7800 Å to 8930 Å. The library spectra were artificially broken into matching intervals to standardize the matching.

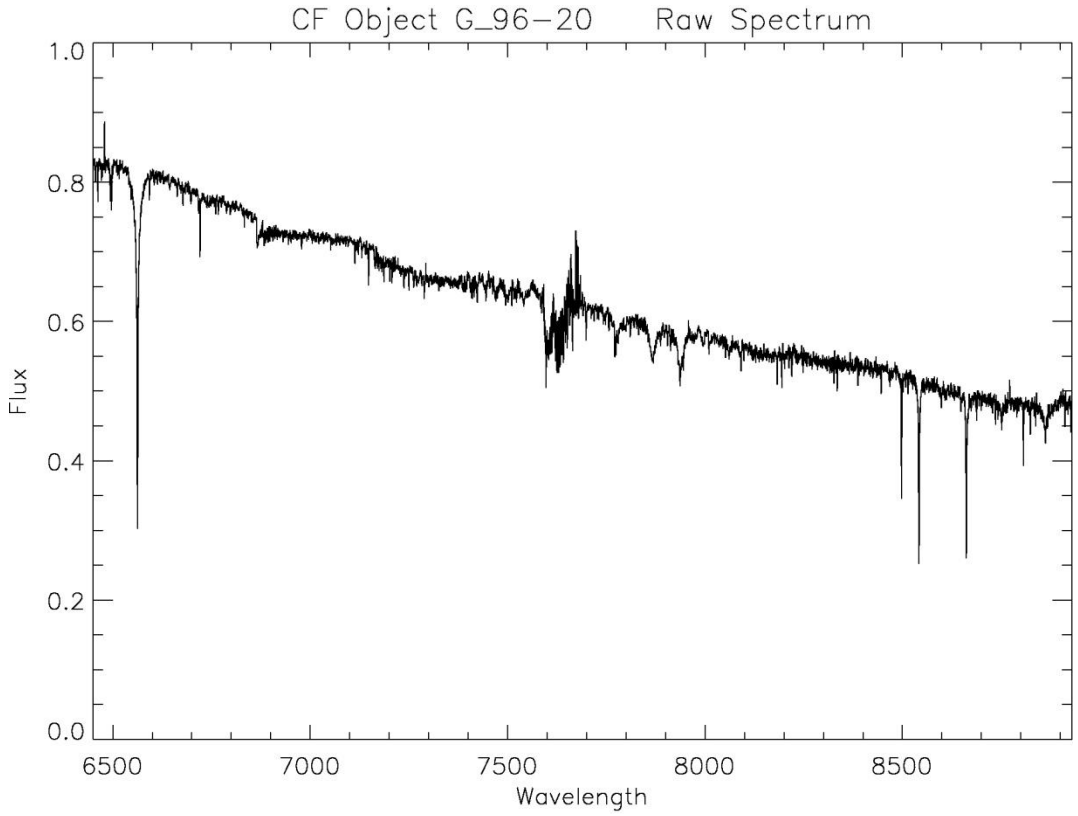

Fig. 1. – An example raw spectrum from the Coudé Feed Stellar Library. Notice the presence of telluric features at ~7600 Å and prominent Ca II absorption lines at ~8500 Å.

The library spectra have "bad regions," in which pixels at certain wavelengths do not store correct spectra data. These pixels have a set flux value of 0.0001. The number of "valid" pixels divided by the total number of data points was used to determine quality of the library spectra. This test statistic indicates how well the library spectrum covers the 6450 Å to 8930 Å range. The threshold can be manually adjusted before the spectra are processed, but a threshold of 0.75 was chosen for this project. The test statistic for the blue and red sides of the spectrum are calculated separately; both must have a quality greater than 0.75. Library spectra that did not reach the required threshold of "valid" pixels are excluded from the matching. Science spectra of stellar objects captured with masks a0_1, a0_2, a3_1, and a3_2 were excluded from matching because of insufficient coverage of the designated blue wavelength region. Quality control was not performed for the remaining science spectra used, as they have ample coverage of both the designated blue and red wavelengths intervals.

After removing the low-quality CF library spectra, bad data regions of both library and science spectra affected by telluric features, such as the A-band and B-band, were removed. These regions are overwhelmed by atmospheric features and thus do not store useful spectral data about the actual stellar object: 6860 Å – 6920 Å, 7160 Å – 7350 Å, 7590 Å – 7695 Å, and 8120 Å – 8360 Å. The library spectra were stored in their rest wavelengths, but the raw science spectra were stored in their observed wavelengths. The wavelength intervals of the telluric features apply to the observed wavelengths. Because the actual intervals that are cut must be consistent across all spectra regardless of the red/blue shift correction applied, an additional buffer was removed from each side of the intervals. An additional 5 Å was cut from the left side of the bands and 20 Å was cut from the right, since the majority of stars in the

Keck/DEIMOS database have large negative velocities (coming toward the Milky Way) and the spectra would be shifted right to reach their rest wavelengths.

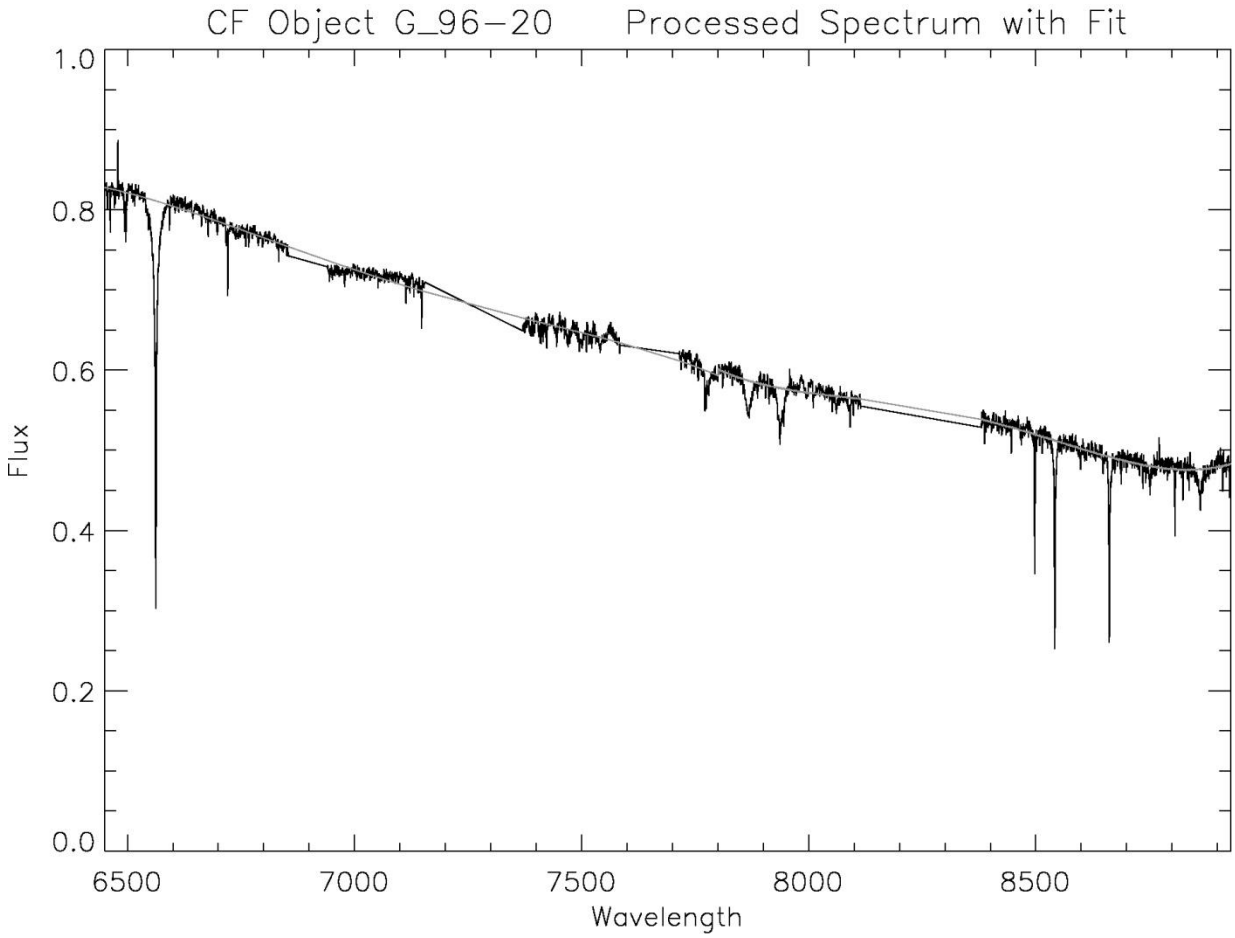

Fig. 2. – Example spectrum from Fig. 1. has been cleaned of telluric features and bad pixels remaining after the coverage filter. A low order polynomial fit has been applied.

The broad shape of each spectrum results from the response function of the DEIMOS spectrograph, the efficiency of the device as a function of wavelength, and the intrinsic properties of the stellar object, such as temperature and chemical composition. This response function is unique to each spectrum, varies from slit to slit within a given mask, and even changes due to the degradation of various optical elements of the DEIMOS instrument over time. Because the efficiency function varies slowly with wavelength, the science spectra were normalized with a low order polynomial. A 5^{th} degree polynomial was fit onto each side of the

spectra, blue and red. The spectra were normalized to a base point of zero: $flux_{divided} = \frac{flux_i}{flux_{fit}} - 1$. This mitigates the effect of the response function of the spectra and leaves the localized features of the stellar object intact. The same normalization process was applied to the library spectra for consistency.

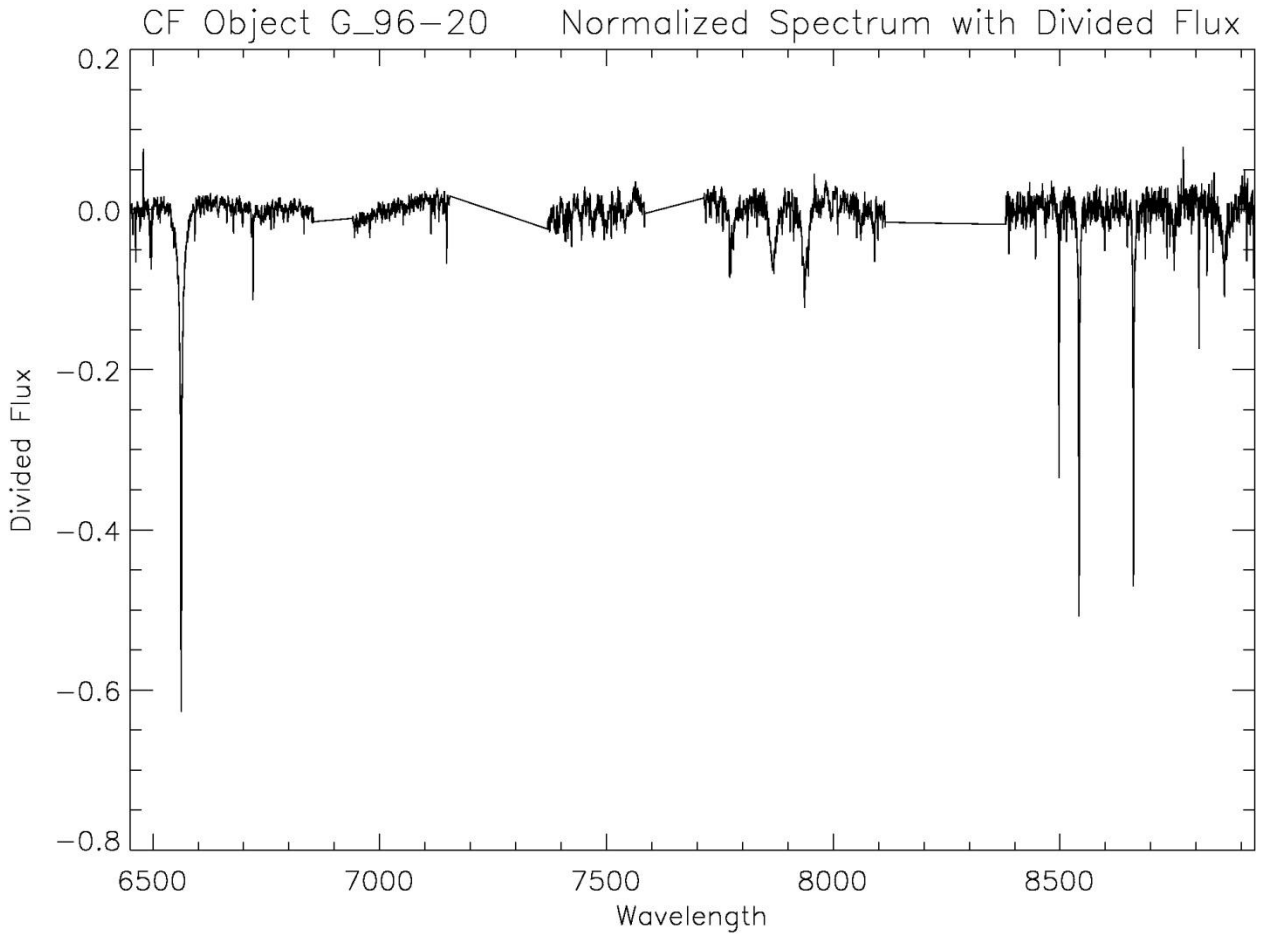

Fig. 3. – Processed example spectrum from Fig. 2. has been normalized to a base point of zero, leaving an overall flat continuum. Notice that spectral features such as the Ca II absorbance lines are still prominent.

The spectral matching program compares a prepared science spectrum from the master DEIMOS database with the CF library of known spectra. To refine the matching process, noise in the spectra must be taken into account. The CF library spectra are relatively low noise, but some science spectra have high noise. A test statistic was created in order to quantify the noise of a spectrum. Each individual pixel on a spectrum has an ivar, or inverse variance, value. This

value measures how accurate the flux value is at that particular wavelength, a data to noise ratio. For each pixel, the median flux across the whole spectrum is multiplied by the inverse variance at that individual pixel: $\frac{\tilde{x}}{\sigma^2}$. We set a noise threshold of three; if the test statistic was lower than the threshold, then that one pixel was labeled as bad data and was discarded from the spectral matching. Pixels were artificially discarded by setting their inverse variance to zero.

A variation of chi-square minimization was used for the spectral matching. The chi-square test statistic of a science spectrum was computed against each member of the library of template spectra: $X^2 = \frac{\sum(flux_{science} - flux_{library})^2}{\sigma^p * n}$. The power of the variance term on the denominator, set to two, could then be increased for noise compensation. Dividing by the number of pixels allows the test statistic to be compared between different science spectra. The template spectrum with the lowest chi-square value was selected as the best match. This library spectrum was used to obtain a best guess of spectral class, effective temperature, color index (B-V magnitude), and metallicity (Fe/H) of the science star in question. This process was repeated for all prepared science spectra.

In order to verify whether the spectral matching program was functioning correctly, spectra of Milky Way globular cluster red giants, also obtained with the DEIMOS instrument (Kirby 2008), were processed with the same method and matched against the CF Library. These MW red giants have a high signal to noise ratio and verified [Fe/H] measurements (Pritzl et al. 2005), making those apt standards for checking both the matching algorithm and the accuracy of the properties of CF Library objects themselves.

Results and Discussion

Various tests were performed in order to evaluate the reliability of the spectral matching program. For each science–library pair of spectra matched together, two color indices were compared, one from the science spectra (V – I) and the other from the library spectra (B – V color). To obtain these values, the difference between the magnitudes of light of a star viewed through two filters (blue and visible) was calculated. As expected, the two color indices plotted together exhibit a moderately strong linear relationship, as they both measure the color, and consequently temperature, of a star.

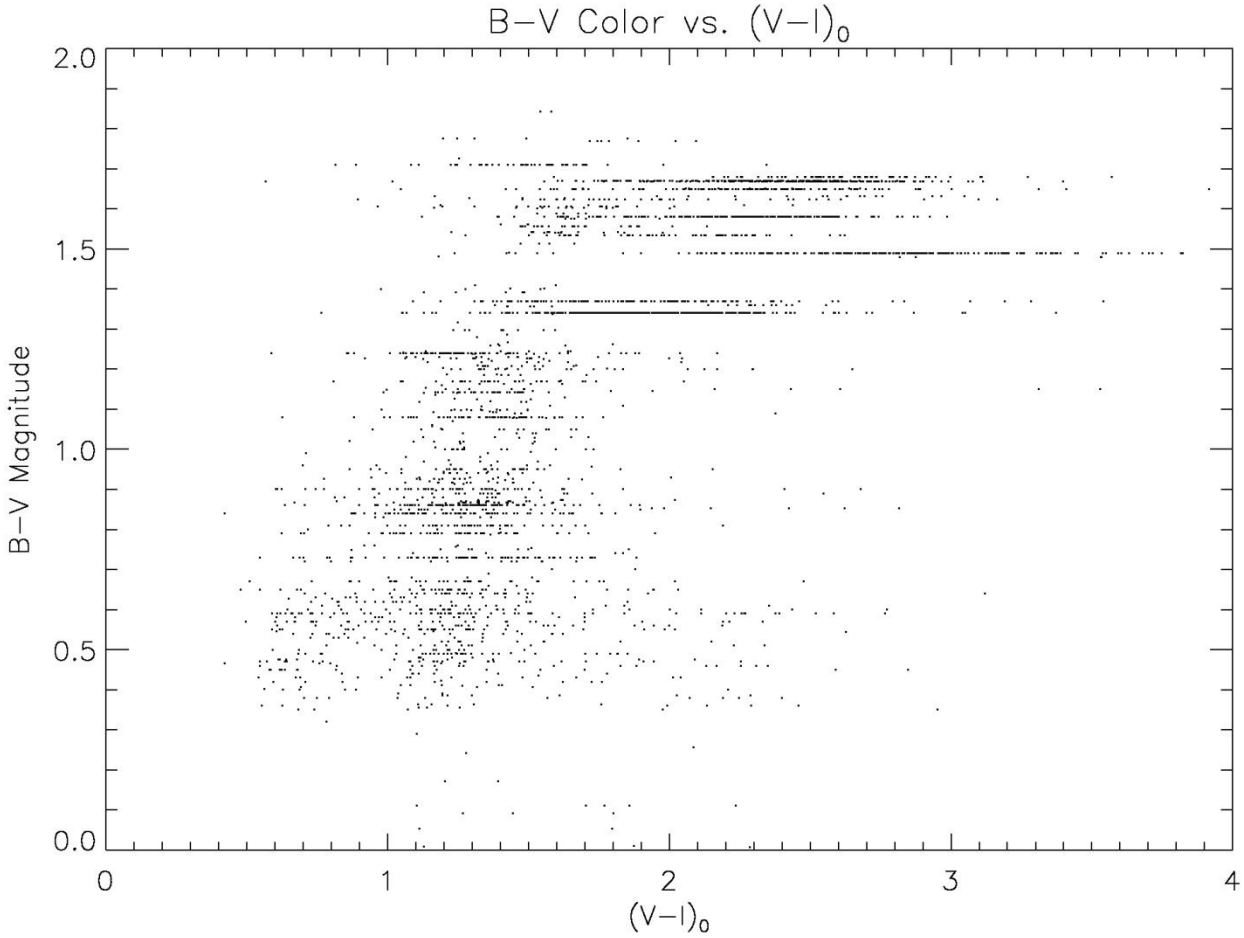

Fig. 4. – B–V Color vs. $(V - I)_0$ for matched pairs of science/library spectra. A moderately strong linear relationship appears as expected, as both values are color indices.

Plotting the (B – V) color indices against the effective temperatures of the CF library spectra reveal an inverse relationship, as expected from the Hertzsprung-Russell diagram. After the matching process, a plot of $(V - I)_0$ (science spectrum) against effective temperature (matched library spectrum) also reveals an inverse relationship.

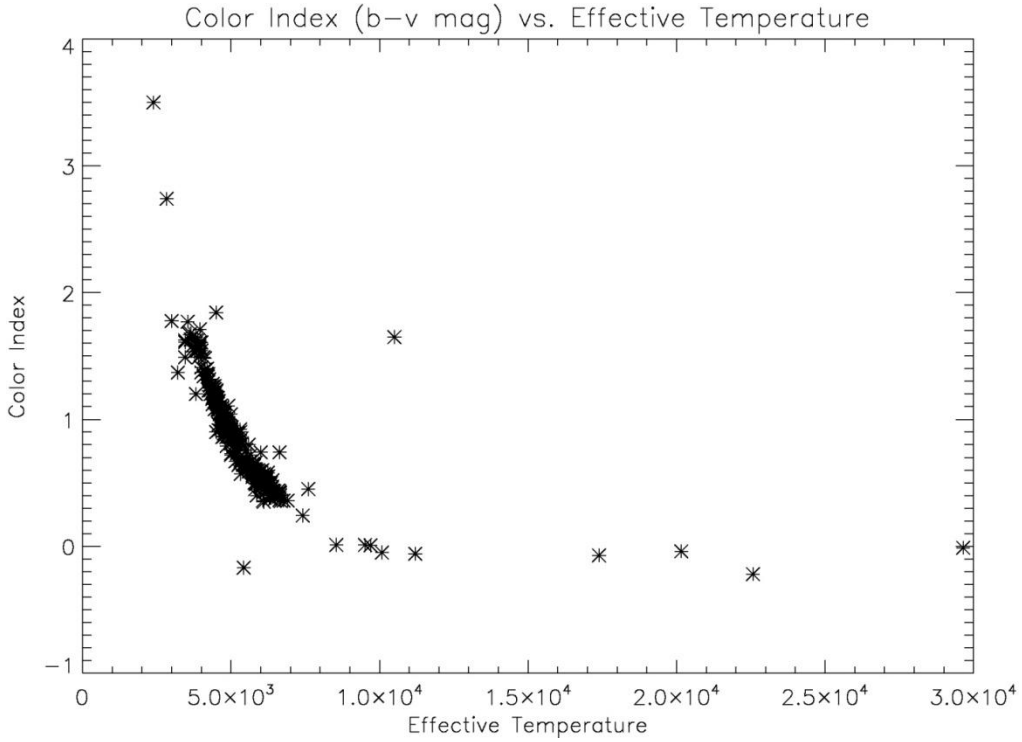

Fig. 5. – B–V Color vs. Effective Temperature for stars in the Coudé Feed Library. A strong inverse relationship appears as expected, from the Hertzsprung-Russel diagram.

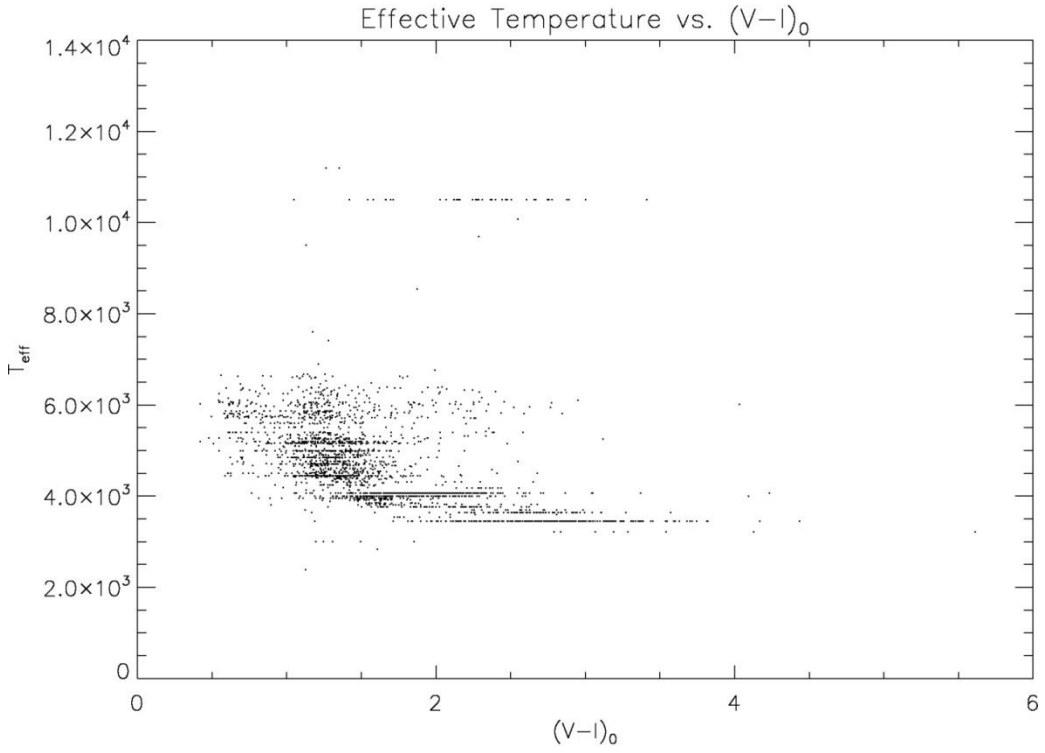

Fig. 6. – Effective Temperature vs. $(V - I)_0$ for matched pairs of science/library spectra. An inverse relation appears but is weaker than in Fig. 5.

Comparison of metallicities also showed the effectiveness of the program. The master database of Keck/DEIMOS spectra provides a photometric and spectroscopic metallicity [Fe/H] for each stellar object. The photometric metallicities [Fe/H] are estimated from the stars' position in a (I, V–I) color magnitude diagram (Gilbert et al. 2006**)**. For dwarf stars (main sequence stars), the photometric estimates of [Fe/H] are expected to be naturally inaccurate, since they were derived with the false assumption that the stars were M31 red giants. The spectroscopic metallicities are estimated from the strength of a stellar spectrum's calcium triplet located at approximately 8500 – 8660 Å, compared to globular cluster red giants (Gilbert et al. 2006**)**. These metallicities are systemically vulnerable to noise.

Each stellar object is also assigned an m31class. Stars in the master database are placed into seven subcategories, ranging from –3 to +3 (Gilbert et al. 2006**)**. Stars with an m31class greater than zero are classified as M31 red giants, while stars with an m31class less than zero

are classified as foreground Milky Way dwarf stars. These classification estimations range from strong (–3, +3) to weak (–1, +1).

Plotting the spectroscopic [Fe/H] against the photometric [Fe/H] values for stars classified as M31 red giants (m31class > 0) reveals a moderately strong one-to-one relation. As expected, there is a clear difference for m31class < 0, as the data points on the $[Fe/H]_{spec}$ vs. $[Fe/H]_{phot}$ plot lie below the line marking a one-to-one relation. $[Fe/H]_{spec}$ measurements for MW white dwarfs are systematically low, because those stars have weak Ca II absorption lines (Gilbert et al. 2006).

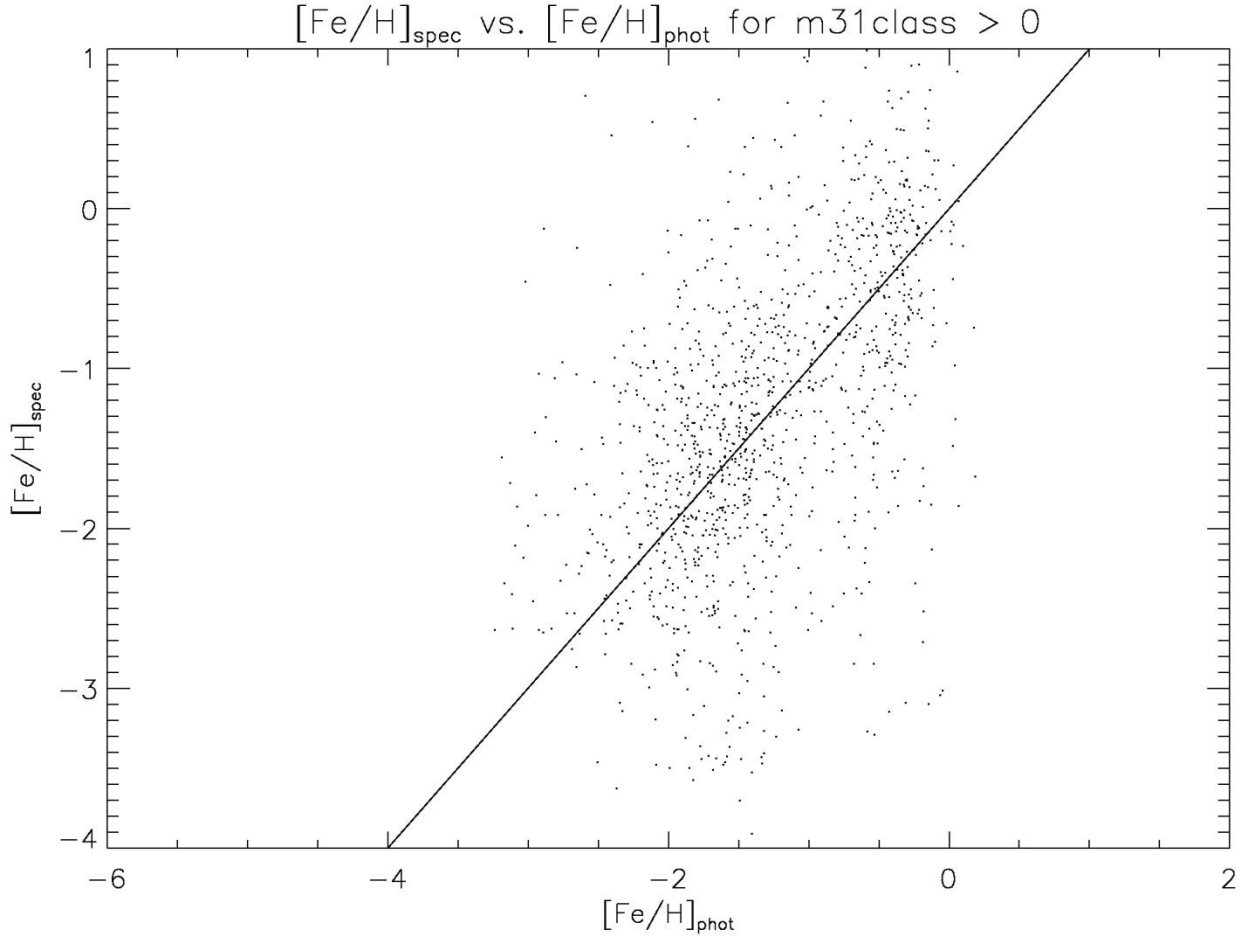

Fig. 7. – Spectroscopic [Fe/H] vs photometric [Fe/H] for M31 RGB stars (m31class > 0). A moderately strong one-to-one relation appears because both photometric and spectroscopic metallicites are relatively accurate.

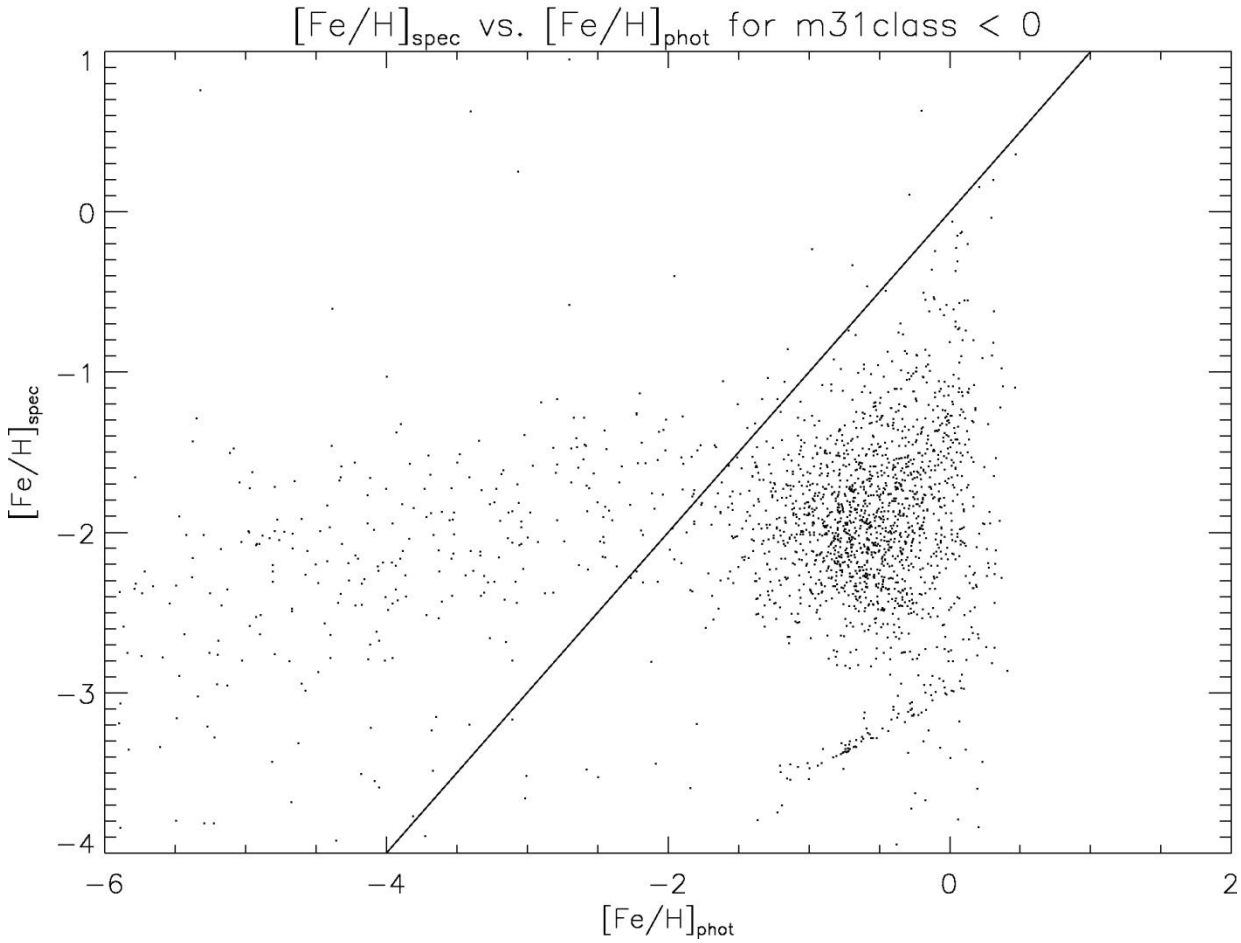

Fig. 8. – Spectroscopic [Fe/H] vs photometric [Fe/H] for MW dwarf stars (m31class < 0). The data points are well below the one-to-one line, due to inaccurate photometric metallicities and weak Ca II absorbance lines for spectroscopic [Fe/H] calculations.

A strong one-to-one correlation between $[Fe/H]_{match}$, the metallicity estimated through matching, and $[Fe/H]_{phot}$ would indicate that the spectral matching program is performing successfully. Although the plots of $[Fe/H]_{match}$ vs. $[Fe/H]_{phot}$ (m31class > 0) show a moderately strong relation, a large cluster of data points is systematically greater than the one-to-one line; estimations of metallicity from the spectral matching program are too high.

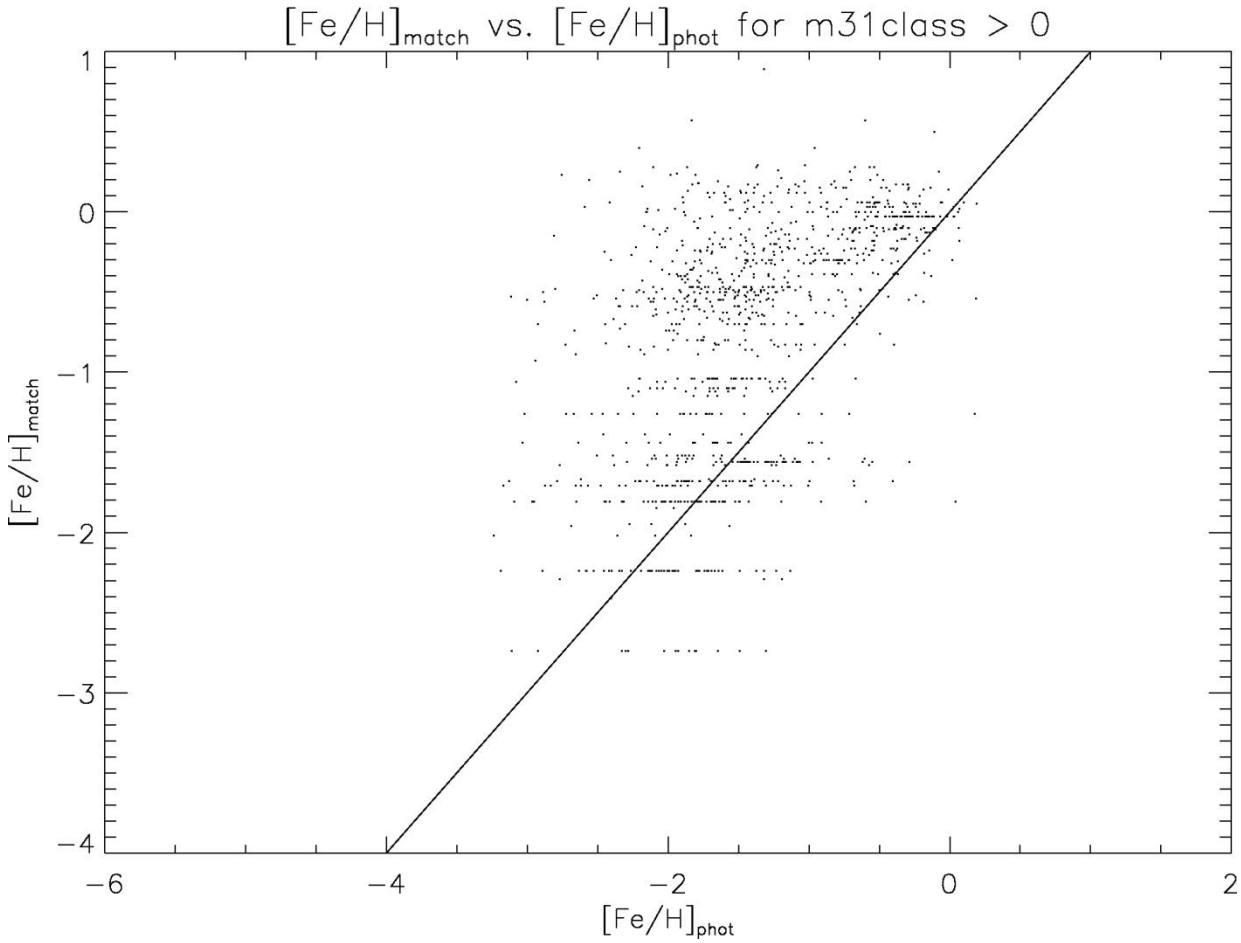

Fig. 9. – Matched [Fe/H] vs. photometric [Fe/H] for matched pairs of science/library spectra. There is a moderately strong relation, but a cluster of data points lies above the one-to one line, suggesting that metallicity estimations are systematically too large.

Though the straightforward chi-square minimization matching algorithm is already providing some initially encouraging results, further refining changes are clearly desired in order to obtain more reliable matches for the DEIMOS/Keck and Coudé Feed spectra.

Spectra of Milky Way globular cluster red giants with high signal to noise ratio and verified literature [Fe/H] measurements were used to identify limitations of the spectral matching program and the accuracy of the metallicity measurements from the CF Library. Although plotting matched [Fe/H] against the verified literature values reveals a stronger one-to-one relation than that shown in Fig. 9., the spread of the [Fe/H] pairs was greater than

expected, suggesting that the low signal to noise ratio of the M31 spectra is not the sole problem.

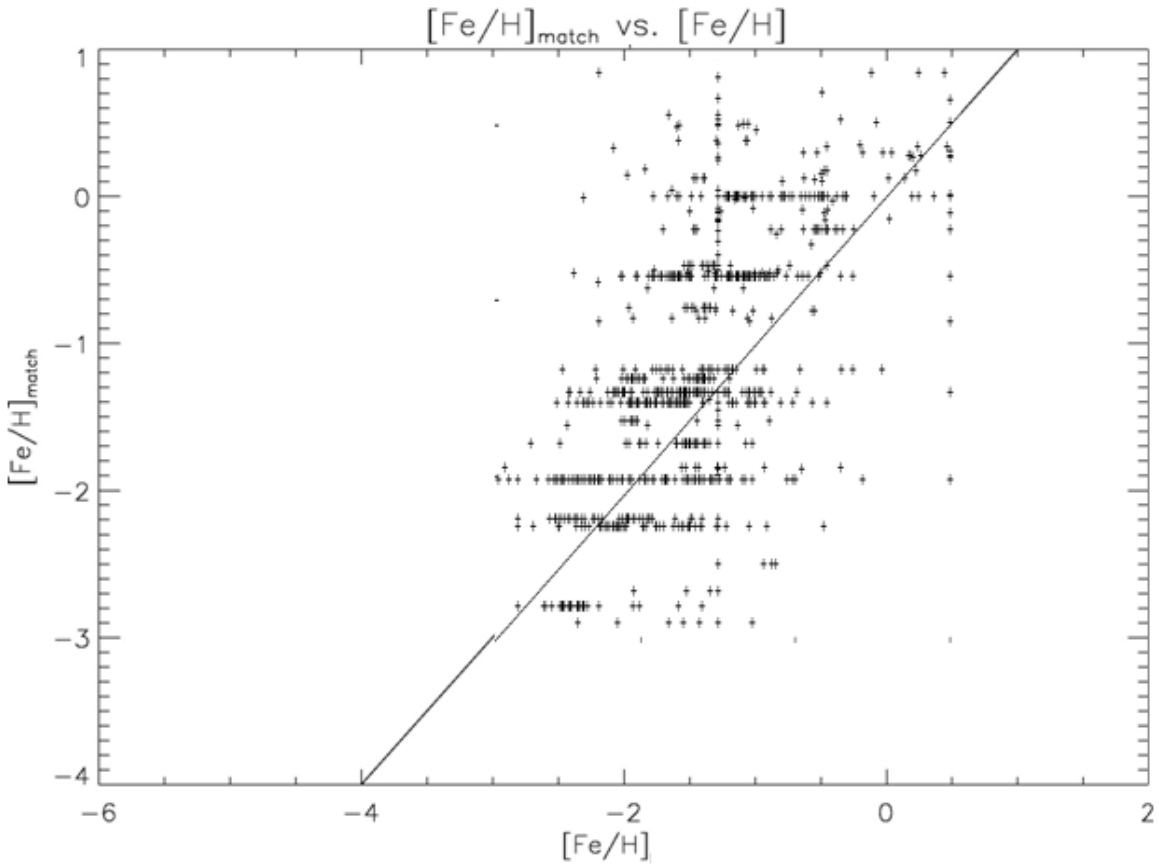

Fig. 10. – Matched [Fe/H] vs. Literature [Fe/H] for matched pairs of CF Library and MW GC red giants. This plot shows a stronger one-to-one relation than Fig. 9., and reconfirms that the program returns higher matched [Fe/H] values for higher metallicity estimates.

Our matching method could be improved by several means. The science spectra are provided raw, but the CF spectra have undergone processing as outlined in **(**Valdes et al. 2004**)**, thus requiring additional processing before both sets of spectra are normalized to a baseline of zero. Thus, further pre-processing for the Keck/DEIMOS spectra may be required in order to maintain consistency. Visual inspection for spectra with low noise will be performed to verify that the chi-square minimization step is working correctly.

Additionally, the current method of matching assumes that post-normalization, "matching spectra" should have spectral features in the same location with similar widths and

heights. However, the science spectra have relatively large noise compared to the library spectra and important features, such as the Calcium II absorbance lines, are less prominent. With the chi-square minimization, the individuals with smaller features and noise add up and dwarf the effects of larger and more important spectral features. Although changing the power of the inverse variance multiplier when calculating the test statistic lowered the effect of noise and consequently the overall variance of the matches, the Fe/H plots did not move closer to the one-to-one line and overall matching quality did not noticeably improve.

There are additional methods to use various scaling weights to further change the nature of the noise and small features in the spectrum. For example, the height or a power function, of the library spectra could be used as additional weights in the chi-square computations. Additionally, the properties, such as [Fe/H], that are matched to science spectra could be weighted based on multiple best matches instead of only one. This shall be a focus for the future refinements of the method presented here.

Conclusion

The spectral matching method presented provides an alternative method to determine the characteristics of a star. Once the spectral matching program is further refined so that the library spectra are reliably matched to the science spectra, the radial velocity information will be used to isolate the spectra from the master database into three subsamples: M32 stars, M31 disk stars, and M31 spheroid stars. We will then compare the distributions of various characteristics across these three subsamples: spectral class (effective temperature), color indices, and metallicity (Fe/H). The future goal is to determine whether the disk and bulge (spheroid) of Andromeda contain similar types of stars. This analysis will ultimately be applied to all of the DEIMOS/KECK spectra in the database. The disk and spheroid of M31 were likely

formed through different processes: the spheroid mostly by accretion, the disk entirely through in-place (in situ) star formation (Kirby et al. 2009). This proposition can be verified by measuring their chemical abundances. These properties imprint how fast the stars formed, where they formed, and how the stars around them were forming. It's safe to say that most extragalactic astronomers have devoted their careers to studying the history of star formation in the universe. As Andromeda is the best laboratory for studying star formation over an entire galaxy, sorting out how the disk and spheroid came to be is an important question. It helps us figure out how our own Milky Way structures, and us, came to be.

This method of determining the characteristics of stars through spectral matching can be extended beyond the science (Keck/DEIMOS) and library (Coudé Feed) spectra used in this report. A future target is to apply this technique to any set of science and template spectra, with modifications depending on the format of the provided spectra.

References

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