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STANDARD STAR SYSTEM FOR INTERMEDIATE-BAND CAH PHOTOMETRY: SARA U42A AND U55 DATA

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ABSTRACT

Multicolor CCD observations of red stars have been made over the past fifteen years with different telescopes, filters and camera systems. The purpose of this study was to develop a more efficient way of converting all the data to the same standard photometric system. A calcium hydride filter was also used as a discriminator between red giants and red dwarfs, and standard values for the $R - L(CaH)$ color index were calculated. A brief description of the different transformation methods is provided, focusing on transforming data from the U55 ($R - L$) system to the U42a system. Results from each system were compared to ensure the accuracy of these methods. Values from the U55 system proved to be essentially the same as those for the U42a system.

Subject headings: methods—data analysis—astronomical databases: miscellaneous—stars: late type—stars: low-mass

1. INTRODUCTION

Red dwarf stars are a major component of the universe, constituting more than half the mass of the Milky Way and about four fifths of the stellar population. Because of their low mass (0.075-0.500 $M_{\odot}$) and corresponding low luminosities, it can be difficult to detect and collect good data for red dwarfs (van Dokkum & Conroy 2010). Sampling of the local red dwarf population is only complete out to about 30 light years. Another complication is that red dwarfs and red giants are both late K or M spectral types, so while red stars are easily identifiable, it is not obvious whether a red star is a close dwarf or a distant giant. Red giant stars are more concentrated toward the galactic plane. Photometric studies of red dwarfs tend to focus on high galactic latitudes where most faint red stars are low luminosity dwarfs and subdwarfs.

The main focus of the study described in this paper is to provide a more efficient way to analyse data for red dwarf stars using an intermediate-band calcium hydride (CaH) filter with the broadband R and I filters. This filter is centered at 683 nm (FWHM = 13 nm) and is used for discerning luminosity differences between dwarfs and giants. The intermediate bandwidth allows for a better flux measurement at that portion of the spectrum than one would get using a broadband filter (Robertson & Furiak 1995) but is not as restrictive as a narrow-band filter. Plotting the $CaH - r$ color index as a function of $R - I$ shows a clear separation between the two, with dwarfs having a higher value of $CaH - r$ (Robertson & Scott 2000). Our goal is to create a standard $R - L$ color index for stars currently in the Landolt catalogs. This system should improve dwarf/giant discrimination and permit surveys for red dwarfs at lower galactic latitudes. Instrumental values measured on several photometric systems will be used to construct these $R - L$ values.

However, different telescopes, filters, and cameras produce different photometric results, even if they have the same specifications. The study of red dwarf stars can be improved through the use of a standard star system in which $R - L$ values are provided for Landolt standard stars. This will permit inter-comparisons of instrumental color indices measured on different systems. This project used standard stars from Landolt (1983 & 1992). These catalogs contain mostly early type stars, but also include some K and M stars that are particularly useful for red star photometry.

In the past, the procedure for calculating transformation coefficients and converting to a standard system was not only time-consuming, since each night had to be processed individually, but also a little less accurate since the results were based on one night only. This project made this process more objective and effective by doing multi-linear least squares reductions. This process is explained in detail by Harris, Fitzgerald, and Reed (1981) and is compared to earlier methods described by Hardie (1962). Using linear least squares fits allows the astronomer to combine several nights of data instead of solving for transformation coefficients one night at a time and then averaging coefficients. It helps to more effectively determine global parameters in the transformation equations, such as extinction coefficients and color terms, and more standard stars can be used to determine those parameters. It also helps to better establish higher-order

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TABLE 1
PHOTOMETRIC SYSTEMS USED FOR CAH PHOTOMETRY.

Photometric Filter	Camera	Broad-Band *BVRI* Filters	CaH Filter
BSUO	Photometrics Star1	(1)	(1)
NURO	Photometrics Tek 512	(2)	(2)
U55	Apogee U55	(3)	(2)
U42a	Apogee U42	(3)	(2)
U42b	Apogee U42	(3)	(3)

color terms and create more accurate photometry for each individual night (Harris et al. 1981).

2. OBSERVATIONS

The different systems that have been used for red dwarf research using the CaH filter with the Kron-Cousins colors are summarized in Table 1. The U42 camera was used with two different CaH filters, hence the suffixes a and b. Data that were collected between July 2006 and April 2007 were from the system that is designated U42a. This is the primary camera used to establish the standard photometric system since its observations were so extensive and is still in use at this time.

Standard stars from Landolt (1983 & 1992) were observed and instrumental magnitudes of r and l formed the basis of the $R - L$ color index. While the RI photometry will not be altered for the standard stars, such values will be computed for the program stars. One of the goals of this project is to transform the observations made by the U55 camera system to the same $R - L$ photometric system as defined by these standard stars observed on the U42a system.

Mean extinction coefficients for $BVRI$ colors have been previously determined empirically for the Ball State University Observatory (BSUO), National Undergraduate Research Observatory (NURO) and SARA observations. In these reductions no statistically significant second-order transformation terms have been derived. Mean extinction coefficients were also published for Kitt Peak (Landolt & Uomoto 2007). Based on these values, a mean extinction coefficient for the R filter was adopted as 0.11 mag·airmass^{-1}. Given an effective wavelength of 683 nm for the L(CaH) filter, a mean extinction value of 0.10 mag·airmass^{-1} was computed. All stars observed on the U42a system produced $R - L$ values defined by

$$R - L = (r - 0.011X) - (l - 0.010X) + 2.43, \qquad (1)$$

where X is the airmass. The constant 2.43 was added to produce an $R - L$ value of 0.0 when $R - I = 0.0$. There were 146 Landolt standard stars with $R - L$ values on the U42a system. These stars served as the primary standard stars for the catalog. Program stars observed on the U42a $R - L$ system provided additional data points to test reliability of transformations from the other photometric systems. The limited number of red dwarf standard stars and the absence of very red giant standards make supplemental red star observations quite helpful. Figure 1 shows the $R - L$ vs. $R - I$ two-color diagram for the original set of standard stars.

This particular paper focuses on five nights of data from the U55 system. A second project (Spengler, Farris & Robertson 2012) dealt with data from the National Undergraduate Research Observatory (NURO) system.

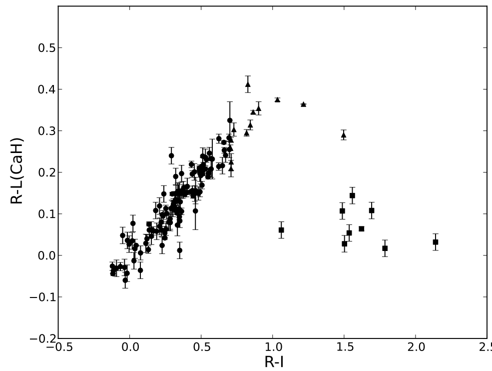

FIG. 1.— The $(R-L)$ - $(R-I)$ diagram for the 146 original U42a standard stars.

These data were used primarily to evaluate the effectiveness of the data reduction process to be adopted in this study.

3. DATA ANALYSIS

3.1. *Transformation Coefficients using IRAF*

Data reduction in the past was accomplished in IRAF[2], calibrating one night at a time. Values of parameters which are expected to remain relatively constant were averaged and the individual nightly reductions repeated using these average parameters. For basic data reduction, the IRAF routines *imred* and *ccdred* packages were used. CCD aperture photometry was done on each image using the *digiphot*, and *daophot* packages. The *fitparams* task in IRAF was used for this process. Observations having unusually high residuals that reflected incorrect identification or physical obstructions were eliminated. The model used for transformation to the standard system is represented by

$$r = R + r_1 + r_2X + r_3(R - I) + r_4X(R - I) + r_5(R - I)^2 + r_6T, \qquad (2)$$

where T is a term for the time of observation. A similar equation for each color is solved in IRAF. The task *invertfit* was run to apply the parameters and solve for the magnitudes and color indices on the standard system and to determine residuals. The process of computing average transformation coefficients was somewhat arbitrary and complex. A more coherent process was desired. The data analysis methods presented by Harris et al. (1981) were seen as a solution to this problem.

3.2. *Calculating Multiple Night Transformation Coefficients*

The multi-linear least squares process was accomplished by three different processes to verify the accuracy of results. A Fortran program provided by Reed was initially written to process seven nights of UBV data. Modifications were made so that it would process VRI photometry for five nights. The program matched observation star IDs with those in Landolt's catalog and

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

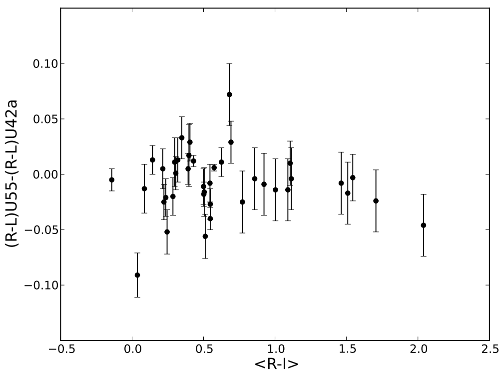

FIG. 2.— Differences between $R - L$ on the U42a and U55 systems. The linear regression on these data produced a slope and intercept both statistically consistent with zero. The weighted mean difference was 0.0003 mag.

allowed the user to solve for V, $V - R$, and $R - I$. The program provides values of transformation coefficients with errors, transformed values and residuals for all standard stars used in the solution. There were m zero-point terms and m airmass terms (for m nights), and three color terms over all the nights. Stars with high residuals could be deleted and the data re-calibrated. As program modificaition progressed, it was decided that alternative reduction techniques would be beneficial to verify the results. In addition to the modified Fortran program, data were reduced using Microsoft Excel and SPSS.

The primary processing of the data from the U55 camera was done with Microsoft Excel. Excel can only process 15 parameters at a time, which limits the number of nights that can be done all at once. This wasn't an issue for this data set since there were only five nights, but it is a limit for the U42a and NURO data sets which involve 15 and 14 nights of data each. The information from the standard star observation files was used to create an array of coefficients for zero-point (Z), airmass (X), and the color terms R, $R - I$, and $R - L$. The processing originally calculated a different linear extinction coefficient for each night, but it was ultimately decided to replace individual extinction coefficients with an average value. Data from each night did not always contain a sufficiently large range in airmass for nightly extinction coefficients to be reliable.

Because the U55 and U42a cameras are so similar, and the filters, telescope and site are essentially the same, it was decided to try a direct comparison of values of $R - L$ determined in the same manner rather than using the $R - L$ values in a transformation process. First, $R - L$ was calculated for all the stars using the formula given previously, see equation (1) from §2.1. These values were compared to U42a for any stars with observations on both systems. The difference between the $R - L$ values was calculated and plotted as a function of $R - I$. The results are shown in Figure 2. Theslope of the linear regression curve through these data was 0.004 ± 0.009 which is leads one to conclude that there are no systematic differences between the two cameras. Data from both the U55 and the U42a system were combined into one catalog without doing any transformations and the calculated values for $R - L$ on the U55 were used as standard values.

Equations were set up for linear least squares. The

TABLE 2
FITTING PARAMETERS

Term	R	Err_R	$R - I$	Err_{R-I}
$(R - I)^2$	0.022	0.013	0.055	0.010
$X(R - I)$	-0.154	0.045	...	...
$R - I$	0.254	0.064	1.140	0.012
$< X >$	0.142	0.014	0.083	0.010
$Z1$	-0.186	0.020	-0.260	0.014
$Z2$	-0.176	0.021	-0.256	0.014
$Z3$	-0.193	0.021	-0.268	0.014
$Z4$	-0.222	0.020	-0.252	0.014
$Z5$	-0.181	0.021	-0.286	0.014

NOTE. — The coefficient values of the four global parameters and the zero points for the five nights are provided with their errors. The second-order color extinction coefficient for $R - I$ was essentially zero in the first reduction and was eliminated from the model.

following equation used $r - R$ as the dependent variable.

$$\begin{aligned} r - R = & \alpha_1 + \alpha_2 X + \alpha_3 (R - I) \\ & + \alpha_4 X(R - I) + \alpha_5 (R - I)^2 \end{aligned} \tag{3}$$

and the color index was computed from

$$r - i = \beta_1 + \beta_2 X + \beta_3 (R - I) + \beta_4 X(R - I) + \beta_5 (R - I)^2 \tag{4}$$

where r and R are the instrumental and standard red magnitudes, respectively, X is the airmass for that particular observation, and $R - I$ is the color index on the standard system.

To find transformation coefficients, linear regression was done on the data included in equations (3) and (4). Values of $R - I$ were produced first, and then values were computed for R. The process was applied to standard stars first, since they had catalog values to use for comparison. The results of the regression analysis included the values for each coefficient and standard errors. The parameters are given in Table 2. The standard deviations for the solutions were 0.016 for $R - I$ and 0.020 for R.

Upon confirming that the standard error and standard deviation of the residuals were small enough to show that this method works, R magnitudes and $R - I$ color indices were computed for the program stars. To check the consistency of the computations for the program stars, the data were compared to those from the NURO system (Spengler et al. 2011). There were about 43 common observations here, so each one was graphed in a plot of the difference in $R - L$ (U55 - NURO) as a function of $R - I$ (the two values for $R - I$ were averaged for each data point). These results are plotted in Figure 3. The linear fit to these data gives both a slope and intercept of zero, within the errors. The standard deviation of the data points for this line was 0.025 mag.

4. CONCLUSIONS

Standard magnitudes were calculated from two different systems using two different methods (the data from NURO were processed with Fortran, rather than Excel), and the differences between the two were used to determines how well these new procedures work. Given the uncertainties in the individual data points, it was concluded that all stars were successfully put onto the same standard $R - L$ photometric system over the broad color range of $0.5 < R - I < 2.5$.

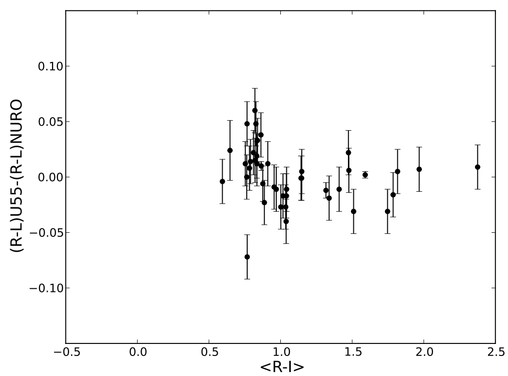

FIG. 3.— Differences between $R-L$ on the U42a and U55 systems. The linear regression on these data produced a slope and intercept both statistically consistent with zero. The standard error in a linear regression was 0.025 mag.

The values of $R-L$ determined using the U55 camera system are essentially the same as those determined with the U42a system. The values of $R-L$ determined using the U55 system produce $R-L$ values consistent with those determined from the NURO system over a range of 2 magnitudes in $R-I$. The combined observations of the U55 and the U42a systems provide $R-L$ standard values for 176 stars in the Landolt catalogs. The integrated $R-L$ color indices from all three systems will result in an additional 442 stars with $R-L$ values on essentially the same system.

5. FUTURE WORK

Standard systems are best constructed from stars of as broad a range of colors/temperature as possible. It would be beneficial to study the spectral types of the standard stars whose data have already been obtained, and then make observations to add standard stars in where deficiencies exist. Observing procedures in the future should improve extinction coefficients by observing stars over a wider range of airmass on each night, so that they don't have to be averaged over an entire set of multiple-night data. Efforts will be made to obtain more standard stars over the entire range of right ascension.

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