

Photometric Analysis of White Dwarf Calibration Candidates for the Dark Energy Survey

H. Hope Head

Department of Energy, Visiting Faculty Program

Austin Peay State University, Department of Physics and Astronomy
Clarksville, TN, 37044

Fermi National Accelerator Laboratory
Batavia, IL 60510-0500, USA
August 6, 2012

Prepared in partial fulfillment of the requirement of the Office of Science, Department of Energy's Visiting Faculty Program under the direction of Douglas L. Tucker and J. Allyn Smith in the Center for Particle Astrophysics at Fermi National Accelerator Laboratory.

Abstract

This summer's project involved the selection of white dwarf stars for calibration of the Dark Energy Survey from data obtained on the WIYN-0.9m telescope at Kitt Peak National Observatory (KPNO). The project was comprised of the completion of photometric calibration and included data processing, astrometry, and photometry of these data. Data reduction and analysis techniques were used to calculate extinction coefficients and zeropoints to correct for observing through the Earth's atmosphere. This project concluded with determining exo-atmospheric calibrated magnitudes for eleven white dwarfs in all filters, with some filters having a few more stars complete. Future work will include completing the reduction and analysis for the current data, repeating this project for more calibration candidates, and obtaining follow-up spectroscopy on the observed white dwarfs to further narrow the data to a suitable sample of calibration stars.

I. Introduction

Over the course of the summer, I worked with the Experimental Astrophysics Group (EAG) on the Dark Energy Survey (DES). The goal of DES is to determine the nature of dark energy and its impact on the acceleration of the Universe. This astronomical survey will use a new and powerful camera, called DECam, to observe a portion of the sky in the southern hemisphere to study a specific form of supernovae, baryon acoustic oscillations, galaxy clusters, and weak gravitational lensing[1]. These particular observations will enable four different methods to be used in order to examine the dark energy content of the Universe.

My contribution to the survey is in support of photometric calibration, a process which entails the measurement of the intensity of an astronomical object's electromagnetic radiation as compared to the known magnitude, or brightness, of a defined standard star or object [2]. For my project, I used data collected from a telescope located at the Kitt Peak National Observatory (KPNO). These data contained images of DA white dwarfs (WDs), which are the remnant cores of stars that have ended their nuclear lives and have pure-hydrogen atmospheres [3]. These stellar remnants are important for comparing intensities since they are thermal sources which lose their stored energy at a rate defined by radiative cooling laws. DA white dwarfs also exhibit simple spectra, consisting of blackbodies imprinted with hydrogen Balmer lines. These characteristics are significant because they make these white dwarfs good calibration sources for future DES data. To be considered a potential calibration object, candidates must have good calibration qualities such as photometric stability, low levels of interstellar reddening, and a lack of low-mass companions [3]. My project involved performing data reduction and photometric standardization to further the hunt for a suitable sample of WD candidates to be used in calibrating the Dark Energy Survey.

II. Processing

In order for data from the telescopes to be useful, they must first be processed to remove the electronic signatures and physical features present in the raw images. Processing the images is important for flattening out features and distortions that would otherwise cause a lack of uniformity in the background signal. These distortions were taken out through the use of IRAF*[4], a collection of software packages developed specifically for astronomical images. The first of the features dealt with was the readout and amplifier noise from the camera's electronics. When a CCD imager is "read" by a computer a voltage has to be applied. This voltage affects the photon count picked up by the pixels, and adds a static-like background noise to all the images taken. This artificial signal and the noise created during the amplification process are measured in an image known as a bias frame. Bias frames are zero-second exposures taken each night of an observing run with the shutter closed. This allows for only the signal from the applied voltage and amplifier to appear. Multiple exposures are taken for a combining process, during which the pixel counts are averaged to decrease the significance of any variation. This averaged image is then referred to as the master bias frame for a night of an observing run. This image is then subtracted from the science images from the corresponding night to remove the average background noise [5]. See Figure 1 for the noticeable effect bias subtraction has on the data.

**IRAF* is the Image Reduction and Analysis Facility, a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.

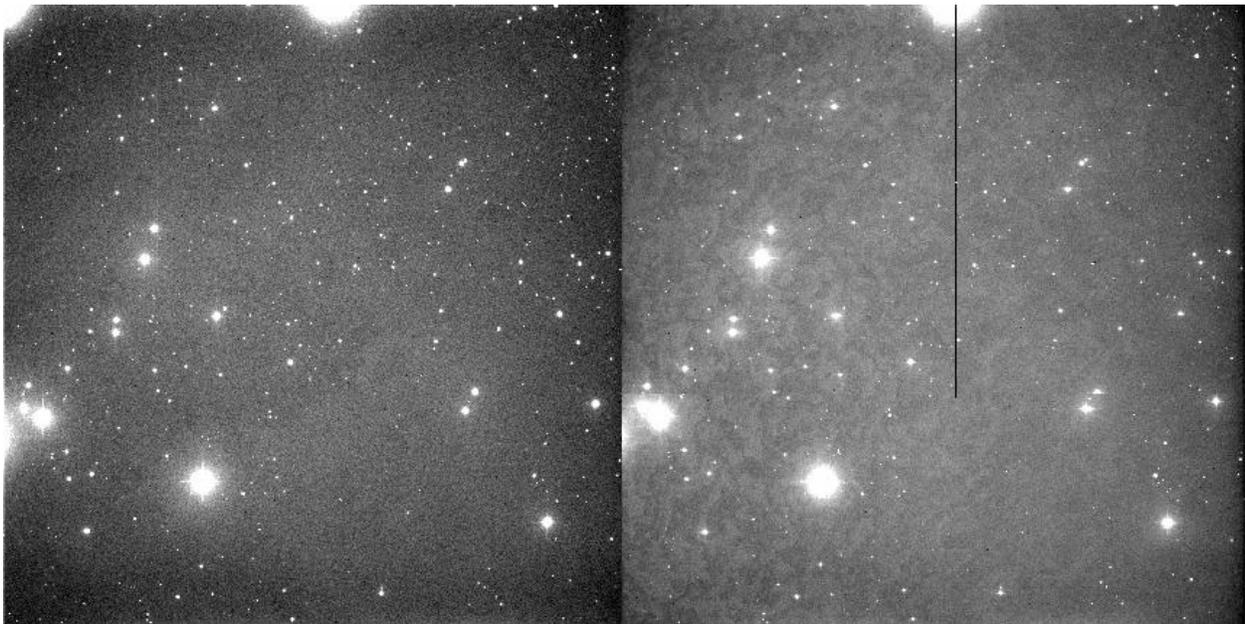


Figure 1: An image before and after bias subtraction, showing the fringing and bad column features becoming more prominent after background variation was corrected. Due to display scaling, only the non-uniform illumination pattern is readily seen in the original image.

The next correction is the physical distortion caused by debris on the camera, filters, and optics system, as well as the variation in quantum efficiency for the CCD with respect to the wavelength of incoming light. Before the beginning of a night's observations, the telescope is lined up to a "white spot" attached to the inside of the dome. Lamps are then directed towards this circle and images are taken at the exposure times needed in each of the different filters to reach one-third to one-half of the full-well capacity of the CCD. These very bright images are useful because they show the shading effects caused by dirt and dust that has accumulated onto the instrument and the quantum efficiency changes occurring across the camera. These images are called flat fields, and are used to remove the distortions introduced by this unwanted debris and changing efficiency. Just like the bias frames, multiple flat frames are taken and averaged together. Unlike bias frames though, dirt and dust can accumulate on the individual filters, and as stated before, the quantum efficiency changes with the wavelengths of light, so a master flat frame has to be made for each filter used [6].

The last physical effect involves the silicon of the CCD chip itself. When shorter wavelength photons hit the silicon chip, they interact with only the first layer. However, longer wavelengths are capable of penetrating through the first layer, reflecting off the backing structures, and going back through the silicon from the other side. This effect causes interference with incoming photons, and leads to a pattern being created on the images where reduced or enhanced quantum efficiency, or the ratio of photon to electron conversion, occurs. In order to subtract this so-called "fringing" effect, science frames in the affected filters are median combined with a minmax rejection to bring out the fringing pattern. This fringe frame is then run through a scaling process that centers the photon counts on zero. In doing so, the subtraction of the fringe frame removes the fringing effects for the images [7].

The final step of processing involves going back to the electronic effects. The reason this step is done last is to ensure the images have been trimmed during the other processes such that the column and row locations of pixels all line up and don't shift from image to image. With CCDs, it is common to have pixels that are "dead" or "hot". This language refers to the behaviors of these pixels: "dead" pixels are those that do not respond to photons or electronic signals, and therefore remain completely dark. In contrast, "hot" pixels are those that always appear oversaturated and bright [8]. While the areas affected by these pixels are considered useless for science purposes, they can cause problems for other procedures, like astrometry, and therefore must be removed from the processed images. The removing of these bad pixels is done through defining the location of the columns and rows affected, and then having a program take these locations, average the good pixel counts around them, and mask in a synthetic signal for the bad pixels. With this final step accomplished, the processing of the images is complete, and the images are ready for astrometric measurements. See Figure 2 for a comparison between an original or "raw" image and a fully processed image.

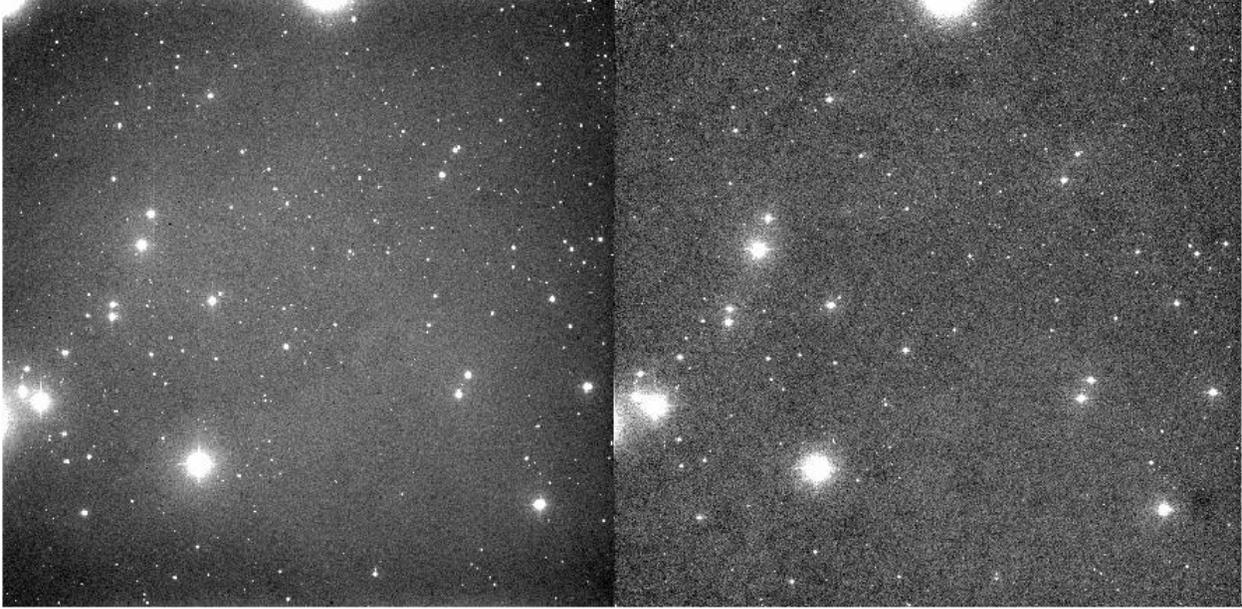


Figure 2: A processed image before and after bias, flat, fringing, and bad pixel correction. While it can be argued that the original image is more aesthetically pleasing, the processed image is far more useful for scientific purposes.

III. Astrometry

Astrometry is the measurement of the positions and movements of stars and other celestial bodies. Its fundamental function is to provide astronomers with a reference frame to report their observations in [9]. For this project, the intention was to astrometrically calibrate the images so that the x,y position of a star in an image was linked to its position in the sky. This allows for the cross-identification of stars in the data with external catalogs based upon their sky coordinates. In this way, magnitudes of these stars could be compared to those reported by other surveys for the same stars. This comparison is important for determining how the magnitudes of the new data need to be corrected in order to fit into a standardized system. The standardizing process will be explained more thoroughly in the photometry and data reduction section.

To begin the astrometry process, the first thing extracted from each image was the rough Right Ascension and Declination (RA and Dec) for the center of the frame, which are analogs of longitude and latitude for the night sky [10]. These coordinates, along with other pieces of information, are stored for each image in the object frame's "header". This extracted information and the image are then entered into SExtractor [11], a program that takes the input image and rough location and creates a catalog of detected objects in the frame and cross-references the locations to a catalog from a different survey. In our case, we used the 2-Micron All Sky Survey (2MASS)[12] because it is a survey of the entire sky, which includes the sections that will be surveyed in the DES footprint. The output catalog gives a rough estimate of each star's location within the field, but this estimate is usually not a perfect match, so more corrections are done

with IRAF using the `ccmap` routine. See Figure 3 for an example of how the astrometry was made more precise through the use of SExtractor and then the `ccmap` routine.

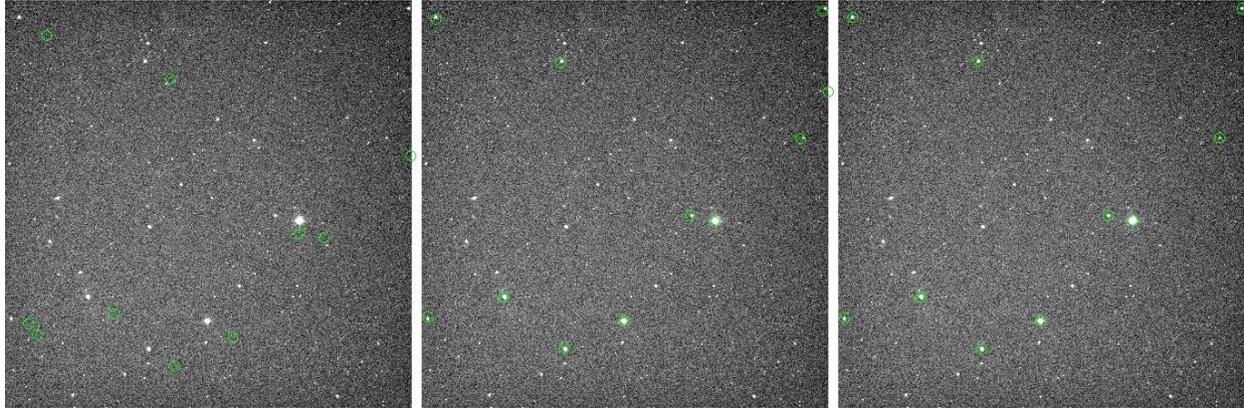


Figure 3: Three images side by side, showing the original RA and Dec locations, the corrected locations, and finally the `ccmap` corrections for fixing the centering. The green circles indicate the positions of stars from the 2MASS catalog. Note how the positions improve as one goes from the left image to the right image.

IV. Photometry and Data Reduction

As stated before, photometric calibration is a form of measuring the intensity of an astronomical object's electromagnetic radiation as compared to a known magnitude for a defined standard object. For this project, the photometry was done using a combination of SExtractor and IRAF. SExtractor was used to extract the magnitudes of all the objects in the astrometry files that had been detected. These files were checked to see if the white dwarfs were found and extracted by doing a search for their RA and Dec, and those that were not found were extracted using the `phot` command in IRAF, which acts as a photometry package.

After extraction, the first step of data reduction was to create a combined southern hemisphere standards data sheet using the SDSS `u'g'r'i'z'` photometric system [13]. This was created to compare these known magnitudes to the instrumental magnitudes of the standard stars observed in the data. In order to compare the data, the colors, or difference between magnitudes, that were reported and their respective errors given in the original standard star files had to be converted to actual magnitudes and uncertainties using the following equations:

$$\begin{array}{ll}
 r = r & \sigma_r = \sigma_r \\
 r + (g-r) = g & \sigma_g = \text{sqrt}((\sigma_r)^2 + (\sigma_g)^2) \\
 g + (u-g) = u & \sigma_u = \text{sqrt}((\sigma_g)^2 + (\sigma_{(u-g)})^2) \\
 r - (r-i) = i & \sigma_i = \text{sqrt}((\sigma_r)^2 + (\sigma_{(r-i)})^2) \\
 i - (i-z) = z & \sigma_z = \text{sqrt}((\sigma_i)^2 + (\sigma_{(i-z)})^2)
 \end{array}$$

Once the data was converted, the observed data was separated by filter, because the extinction coefficients and zeropoints needed to change the instrumental magnitudes to standardized magnitudes are filter specific. To elaborate, the extinction coefficient is a measure of the light scattered out of the incoming optical path from a star due to the atmosphere. The zeropoint is a magnitude offset created arbitrarily between the instrumental magnitude corrected with the extinction coefficient and the actual magnitude above the atmosphere [14]. In order to calculate these two variables, the filter separated data was matched using TOPCAT, an astronomical plotting package [15], via RA and Dec with the standard star sheet so that spreadsheets with only observed standard star data remained. These matched data sheets were then plotted in TOPCAT, and data points were removed that were over-saturated, had magnitude uncertainties greater than 3%, or had focusing errors. The remaining data were plotted with airmass (the relative amount of atmosphere a star was viewed through normalized to the observer's zenith) versus the delta magnitude (standard magnitude minus instrumental magnitude). A linear correlation was fit to the plotted data, and the slope was determined to be the extinction coefficient, while the y-intercept became the zeropoint. See Figure 4 for an example of one of these procedures. Once these variables were determined for every filter in each night of every directory, the exo-atmospheric magnitudes for the white dwarfs were determined via:

$$\text{Exo-Atmospheric Calibrated Mag.} = \text{Instr. Mag.} + \text{Zpt} - (\text{Extinction Coefficient} * \text{Airmass})$$

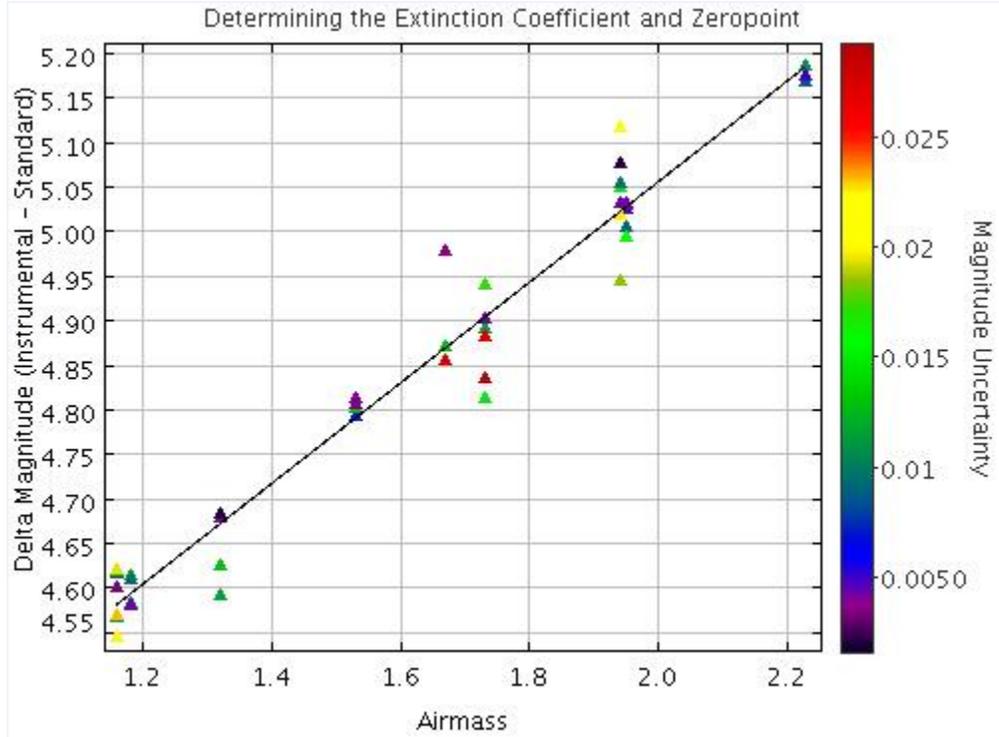


Figure 4: A linear correlation plot showing the calculation of the extinction coefficient (slope) and zeropoint (y-intercept) for a u-band filter. The color scale gives the uncertainty of the observed magnitudes.

V. Results

No. of Total WDs in Data	36
No. of u' Obs.	13
No. of g' Obs.	13
No. of r' Obs.	13
No. of i' Obs.	12
No. of z' Obs.	11

Table 1: This table gives the final count for white dwarfs in the data and the number which have completed the process to having exo-atmospheric calibrated magnitudes by filter.

VI. Conclusions and Future Work

While the work is part of an ongoing program, this summer's project successfully completed the processing, astrometry, and photometry procedures, and began the reduction and analysis of the data for several white dwarfs in the survey area. The standard stars observed were used to determine extinction coefficients and zeropoints for each usable night and applied these to the white dwarfs in the observations. Some of these white dwarfs have already undergone the first stage of the correction process for standardizing the magnitudes for them. Work on this project will be continued at Austin Peay State University and will include completing the reduction and analysis of the white dwarfs observed at Kitt Peak as well as repeating this project for data from the Cerro Tololo Inter-American Observatory (CTIO), which will add up to 115 more white dwarfs for analysis. Spectroscopy will also be taken of these calibration candidates to determine effective temperatures, surface gravities, and possible Helium contamination in the atmosphere. The combined effort of the photometric calibration and spectroscopy will further determine which white dwarfs observed will become calibration stars for DES.

VII. References

- [1] The Dark Energy Survey. Internet: www.darkenergysurvey.org, [June 16, 2012].
- [2] Sterken, Christiaan; Manfroid, J. (1992), *Astronomical photometry: a guide*. [On-line]. 175. Available: http://books.google.com/books/about/Astronomical_photometry.html?id=ojzepXhy9DIC [June 17, 2012].
- [3] J.B. Holberg and Pierre Bergeron. "Calibration of Synthetic Photometry Using DA White Dwarfs". *The Astronomical Journal*. 132, pp. 1221-1233, Sept. 2006.
- [4] IRAF. "Image Reduction and Analysis Facility." Internet: <http://iraf.noao.edu/>. May 19, 2012. [June 17, 2012].
- [5] Diffraction Limited. "Imaging with MaxIm DL: Bias Frame Calibration". Internet: www.cyanogen.com/help/maximdl/Bias_Frame_Calibration.htm. [July 12, 2012].
- [6] Paul B. Eskridge. "Andreas Observatory Spectrograph Manual: Flat-Field Correction." Internet: frigg.physastro.mnsu.edu/spec_flat.html. [July 12, 2012].
- [7] Rein Warmels. "Fringe Correction". Internet: www.atnf.csiro.au/computing/software/midas/Hypertext/doc/95NOV/vol2/node68.html. Jan. 22, 1996 [July 12, 2012].
- [8] Nasim Mansurov. "Dead vs Stuck vs Hot Pixels". Internet: mansurovs.com/dead-vs-stuck-vs-hot-pixels. Aug. 17, 2011 [July 20, 2012]
- [9] Jean Kovalevsky and P. Kenneth Seidelmann. *Fundamentals of Astrometry*. [On-Line]. Available: www.cambridge.org/gb/knowledge/usbn/item1159830/?sit_locale=en_GB. [July 20, 2012].
- [10] Sribd. "Right Ascension and Declination". Internet: www.scribd.com/doc/40016482/Right-Ascension-and-Declination. [July 20, 2012].
- [11] Emmanuel Bertin. "SExtractor". Internet: www.astrometric.net/software/sextractor. Oct. 15, 2009 [July 20, 2012].
- [12] "The Two Micron All Sky Survey at IPAC". Internet: www.ipac.caltech.edu/2mass/. Dec. 13, 2006 [July 20, 2012].
- [13] J. Allyn Smith *et al.* (2002, April). "The u'g'r'i'z' Standard-Star System". *The Astronomical Journal*. [On-Line]. 123, pp. 2121-2144. Available: http://www.apsu.edu/sites/apsu.edu/files/astronomy/2002_JA_Smith_ugriz_Standards.pdf. [June 20, 2012].
- [14] Radu Corlan. "GCX User's Manual: Multi-Frame and All-Sky Reduction". Internet: gcx.sourceforge.net/html/node9.html#SECTION009210. Jan. 17, 2005 [Aug. 5, 2012].
- [15] TOPCAT, <http://www.star.bris.ac.uk/~mbt/topcat/>. [June 20, 2012].