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Photometry of a Star Cluster from CTO

Savannah Gramze,[1] Makennah Bristow,[1] Maria Galloway-Sprietsma,[1] and Natalia Guerrero[1]

[1] University of Florida, Gainesville, FL 32611 USA

1. BACKGROUND

Globular clusters are compact, spherical clusters of stars. They tend to be the oldest star clusters in a galaxy, which means that only the long-lived low mass stars are left on the main sequence. The more massive stars have evolved off of the main sequence onto the Red Giant Branch and beyond. Stars in globular clusters are assumed to all have approximately the same age, metallicity, and are at the same distance.

The goal of this lab was to plan and execute an observing run at the Campus Teaching Observatory (CTO) 14 in telescope and then make a Color-Magnitude Diagram out of observations of a globular cluster. Since globular clusters are made of stars at approximately the same distance, we do not need to worry as much about being exact about the effects of airmass across the sky.

2. METHODOLOGY

In preparation for heading to CTO, we had to go through target selection. We were given a list of cluster targets with each Right Ascension and Declination, and found that the clusters which would be easiest to observe on October 6, 2022 were Messier 13, Messier 2 and Messier 72. We decided on Messier 13, with Messier 2 as a backup. Additionally, we planned to observe several Landolt stars, standard stars with a known absolute brightness and flux that can be used to account for the effects of the atmosphere on our observations. I wrote some code which would search for Landolt stars within an angular radius of our target to ensure that our targeted stars would be above the horizon.

At CTO, we started by taking sky flats of the twilight sky with the V and I-Band filters. We then took Bias frames while waiting for astronomical twilight. At astronomical twilight, we started to align the telescope. We started to attempt to locate a Landolt star, but found that the stars in the table were very faint and impossible to locate with the CTO telescope. We tried to compare with a star chart, but we could not use our chosen Landolt standard. As a result of being unable to take observations of Landolt standard stars, we did not have enough information to do atmospheric correction to the data to account for airmass. Additionally, something was wrong with the telescope's record of the coordinates of Messier 13. We changed our target to Messier 2 and took exposures of Vega as a flux calibrator. At the end of the night, we took our Dark exposures and more Bias frames.

2.1. *Calibration*

$$[master\_flat - \frac{exptime\_flat}{exptime\_dark}(master\_dark)]_{ave}[\frac{(object - master\_bias) - \frac{exptime\_obj}{exptime\_dark}(master\_dark)}{(master\_flat) - \frac{exptime\_flat}{exptime\_dark}(master\_dark)}]_{pix} \tag{1}$$

Target Name	Exposure Time (s)	Filter Type	Number of Exposures	ObsTime (UTC)	Right Ascension	Declination
Bias	0.04	Photometric I	30	2022-10-06 22:57:46	-	-
Dark	20.0	Clear	20	2022-10-07 02:12:08	-	-
I-Band Flat	0.2	Photometric I	10	2022-10-06 22:55:58	-	-
V-Band Flat	0.1	Photometric V	10	2022-10-06 22:53:38	-	-
Messier 2 I-Band	20.0	Photometric I	20	2022-10-07 02:00:36	21h33m27s	-00°49'23.7"
Messier 2 V-Band	20.0	Photometric V	20	2022-10-07 01:51:05	21h33m27s	-00°49'23.7"
Vega I-Band	0.5	Photometric I	10	2022-10-07 00:58:06	18h36m56s	+38°47'1"
Vega V-Band	1.0	Photometric V	10	2022-10-07 00:56:21	18h36m56s	+38°47'1"

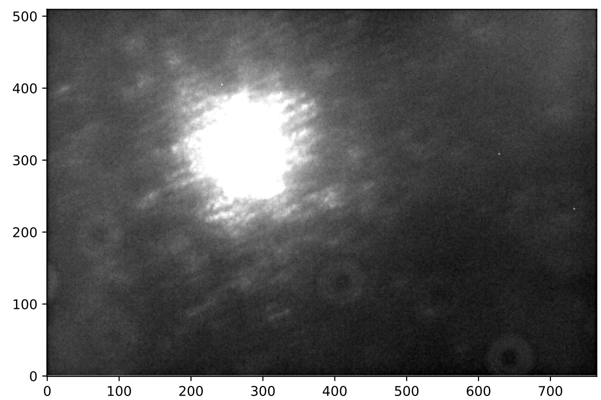

Figure 1. First iteration of image combination produces a blurry image due to poor tracking on the telescope.

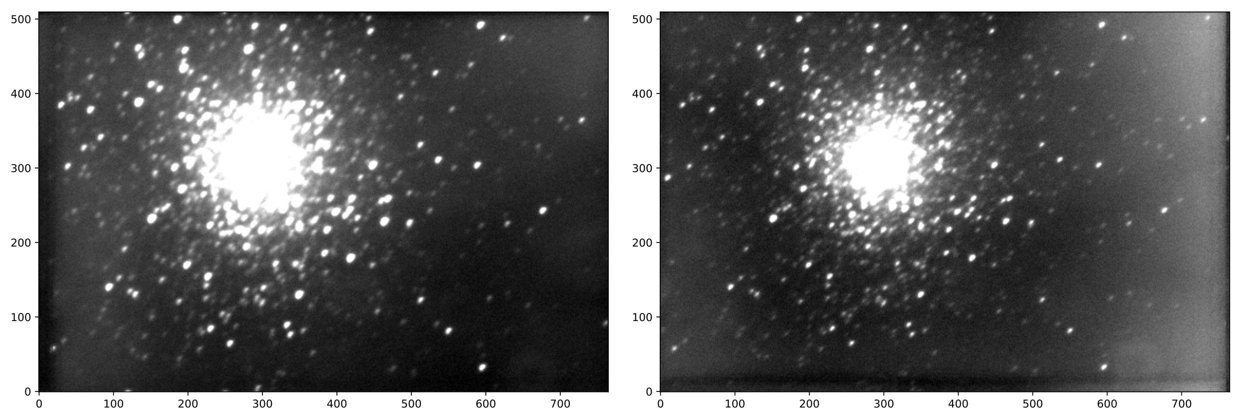

Figure 2. The final combined images of Messier 2. Left is in I-Band, right is in V-Band. Note that the core of the globular cluster is brighter in I-Band, as most of the stars in a globular cluster are brighter in redder light due to being cooler.

We calibrated our science data by first creating a master bias image by median combining our bias frames. We then created a master dark by subtracting the master bias from each dark frame, and then median combining the images. We then made master flats for both filters by subtracting the master bias from each flat frame, then subtracting the exposure time corrected master dark from each flat frame, and finally median combining the flats into two master flats, which were then normalized.

The flats were taken as sky flats at the beginning of the night. The CCD was removed from the telescope to aim the telescope at Polaris to center it, but was replaced on the telescope imperfectly. As a result, location-dependent artifacts such as dust on the optics were not removed correctly. In the calibrated science images, the "donuts" from dust particles on the optics are visible due to this.

Each science image, of Messier 2 and of Vega, was calibrated by subtracting the master dark and then dividing by the master flat of the image's filter, as per Equation 1.

2.2. *Image Combination*

As the telescope was imperfect at tracking, the standard method of combining the calibrated science frames by median combining would not work and would instead create a blurry image, as seen in Figure 1.

To correct for the shift between images, I first found the position of a star on one image, well isolated from other stars. I then used `DAOStarFinder` with a fwhm of 4 and a threshold of 3σ to locate stars on the image. For each image, I found the distance between the chosen star and the stars found with `DAOStarFinder`, selecting the nearest star to the reference. I then used `numpy.roll` to 'roll' the pixels in each image so that they lined up with the reference image.

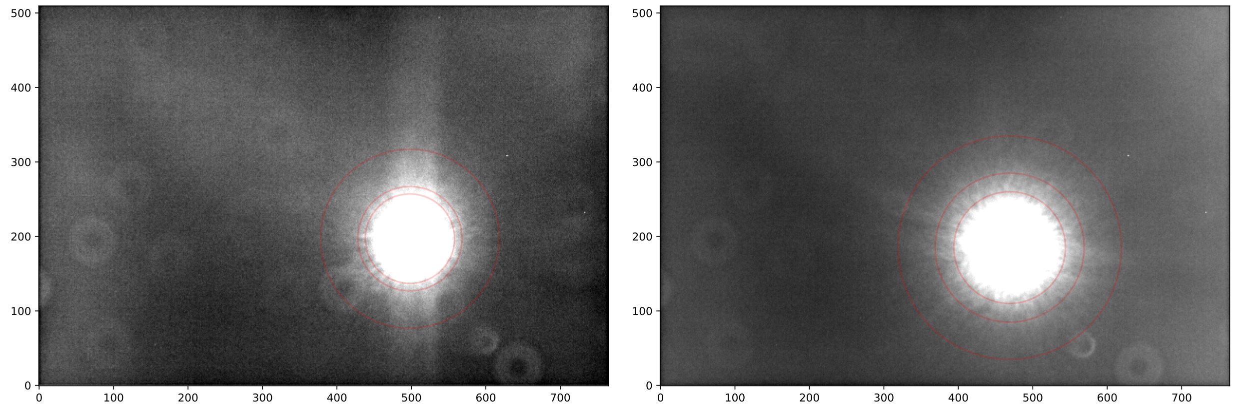

Figure 3. The final combined images of Vega, with the aperture and annulus overlaid in red. Left is in I-Band, right is in V-Band. Note that Vega is extremely bright.

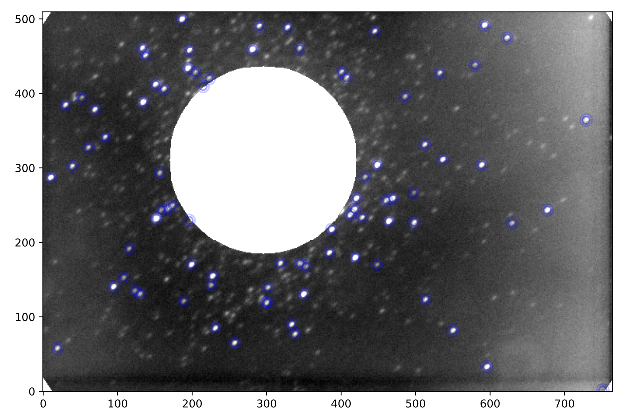

Figure 4. V-Band image of Messier 2 with the central core and corners of the image masked out for aperture photometry.

Images that were too shifted to accurately find the reference star were removed from the data set. Finally, I was able to median combine each image for a better signal to noise ratio.

The images of Vega were well behaved, and so I performed standard median combination on the star.

I also shifted the I-Band and V-Band final images of Messier 2 so that the stars were aligned, using the same shifting algorithm with `numpy.roll`.

2.3. *Photometry*

The center of a Globular Cluster contains many thousands of stars all packed into a very small area. It is extremely difficult to resolve the stars in the core of a Globular Cluster, so I masked the final images of Messier 2 to remove the core of the cluster. I also masked the far corners of the image. The version used in photometry is shown in Figure 4.

I used the shifted final images of Messier 2 to perform aperture photometry. I used apertures with a radius of 5, and I made annuli with an inner radius of 5 and an outer radius of 8 around each star in the masked images. I performed aperture photometry using `aperture_photometry`. I used `ApertureStats` to find the mean of the annuli around the stars, and then applied that mean to the area of each aperture. I then removed the background from each aperture sum.

I then placed an aperture over Vega with a radius of 60, and an annulus with an inner radius of 70 and an outer radius of 120 for the I-Band image of Vega. I used an aperture of radius 75, with an annulus of inner radius 100 and an outer radius of 150 for the V-Band image. I subtracted the background from Vega by subtracting the area of the aperture times the mean of the annulus background. The V-Band image of Vega was slightly over-exposed, but I still went through with using it to find the magnitudes of Messier 2.

I converted the background subtracted aperture sums of Messier 2 and Vega in both filters from ADU/px to e/px/s by multiplying by the gain and dividing by the exposure time.

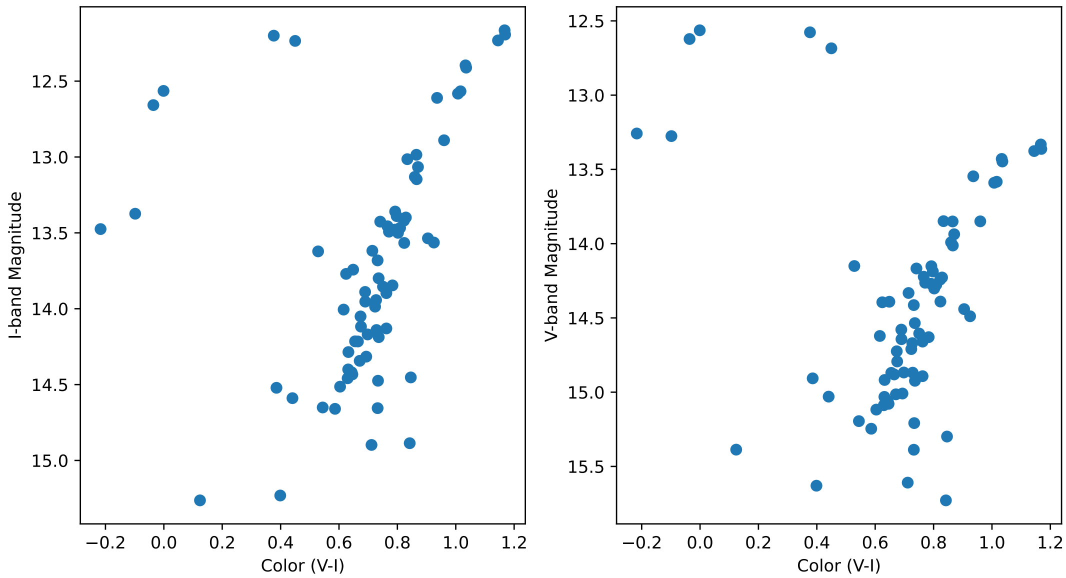

Figure 5. Color-Magnitude Diagram of Messier 2. The horizontal axes are the color, with the magnitude in I-Band subtracted by the magnitude in V-Band for each star. The vertical axes are the I-Band magnitude for the left Color-Magnitude Diagram, and the V-Band magnitude for the right.

$$m_1 - m_{ref} = -2.5log_{10}(\frac{I_1}{I_{ref}}) \tag{2}$$

Assuming that Vega has a magnitude of 0 in both I and V-Band, I found the magnitudes of each star in the images using Equation 2. I used my nearest star code to match the stars in both shifted images, so that if the distance between stars in the I-Band and V-Band images was less than one pixel, their magnitudes were subtracted to find the color. I then made two Color-Magnitude Diagrams. Both had horizontal axes of Color where I subtracted the I-Band magnitude of each star from the V-Band magnitude. The only difference between the two Color-Magnitude Diagrams was the choice in which magnitude filter to use for the vertical axis.

3. RESULTS

The Color-Magnitude Diagram for Messier 2 found from observations using the 14 in CTO telescope is presented in Figure **??**. There is a good amount of scatter in the Color-Magnitude Diagram, especially for the faintest of stars. The six outlier stars on the top left, with a lower magnitude and color than any other star in the diagram, are outliers. They are either from incorrectly fit apertures on the edges of the images, or they are from field stars not associated with Messier 2. There are stars that are along the same line of sight as Messier 2, so these younger stars may be just from the Galaxy.

The Color-Magnitude Diagram has a slope that goes from higher magnitudes and lower color to lower magnitudes and higher color, from the bottom left to the top right of the Color-Magnitude Diagram. For stars on the main sequence, we expect to see a trend perpendicular to the one we observe. Messier 2 is 55 000 lyr away and has an estimated age of 13 Gyr, close to the age of the universe. Messier 2 does contain stars on the main sequence, but they are very faint as they are only low mass stars. Only the least massive stars still exist on the main sequence for Messier 2, so all of the brighter stars we see are evolved stars on the Red Giant Branch. The most massive stars which were associated with Messier 2 have since long disappeared into neutron stars, black holes, and white dwarfs.

4. CONCLUSION

We observed Messier 2 with the 14 in telescope at CTO. We also observed Vega as a standard star. As Vega is a very bright star, so some of our images were over exposed. We were originally going to observe Messier 13 as well as some Landolt standard stars, but those plans fell through as we could locate neither at CTO. Having backup plans for observation runs is very important to having results at the end of the night. If we were able to plan again, we would have made sure to find standard stars that were 6th magnitude or brighter, to make them easier to see with the telescope. We would ensure that we have finder charts for each standard star. We would also put in the coordinates of Messier 13 by hand to avoid the strange problem with the telescope not slewing to the globular cluster. As we only observed one standard star, we were able to convert our fluxes to magnitudes, but we were unable to account for the difference in air mass and atmospheric effects. Thankfully, the lack of correction for air mass did not affect the shape of the Color-Magnitude Diagram, as all of the stars in Messier 2 are within one region of the sky and the globular cluster contains stars all at the same distance from Earth. The result of the Color-Magnitude Diagram was a very evolved sample of stars, which is expected due to the age of Messier 2. Almost all of the stars observed were on the Red Giant Branch.