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M31: Measuring the Distance to the Andromeda Galaxy

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ABSTRACT

Measuring distances to stars within the Milky Way Galaxy is fairly challenging. However, to determine the distance to another galaxy, specifically the Andromeda Galaxy (M31), one must go through a more extensive process. Astronomers cannot employ the method of triangulation for galaxies due to immensely large distances and very small parallax angles, so in this study we will use the distances and luminosities of stars with galactic coordinates nearing M31 to compare to the galaxy's ground-based photometry. These nearby stars are called Cepheid variables, a variation of the method pertaining to standard candles that is specifically used for relatively nearby galaxies. Knowing M31's absolute and observed luminosities, we can calculate the distance to it. Following this process, we reach the conclusions that the distance to the Andromeda Galaxy is $(0.731489 \pm 0.00802621)$ Mega parsecs (Mpc), such that its absolute magnitude is (-5.70077 ± 0.0415254). The implications of this study are that M31 is the closest large, spiral galaxy to the Milky Way and is therefore part of the Local Group of galaxies within our Universe.

1. INTRODUCTION

Calculating the distances to galaxies is essential to understanding the cosmological nature of our universe. Each measurement of distance can be used to determine the velocity of galaxies using Hubble's Law, with the luminosity the distance gives insight toward the total energy the galaxy produces, and using additional calculated properties, one can also make inferences on the theoretical dark matter distributions within the galaxy in question. Beyond measuring the distance for the sake of understanding, the options above describe the possible routes of study after computation. When calculating distances to galaxies, astronomers will also consider methods involving the light fluctuations coming from rotating galaxies, the red-shifting nature of distant galaxies, and supernova standard candles to measure these near incomprehensible lengths. In this study, we employed the method using Cepheid stars as standard candles.

After collecting the data needed for the target galaxy and reference stars, we show one of the images chosen and cross-reference it with a plot of the reference stars with the target to verify its location in the image. We continue to define a small circular aperture centered at the coordinates of the M31 galaxy, and the reference stars, and subtract the background photon counts, while also calculating the uncertainty in the counts. Next we analyze each image's photometry, calculating the best zero-point magnitude for each image to ultimately use to find the magnitude of the target. We verify the variability of the galaxy's magnitude compared to the Cepheids by comparing their light curves as a function of time (in units of helio-Julian dates). In the next step, we show the variability to be periodic, calculate the period, and plot the light curves now as a function of phase. Using the period-luminosity relation visualized in section 2, we solve for absolute magnitude and, using this value, calculate the distance to M31. As always, we must conclude the study by estimating the uncertainty in the distance.

Due to the possible implications of this study, it is essential that the calculations be made carefully and precisely. Section 2 describes the data collected for this study: how it was collected, what observatory was the data taken from,

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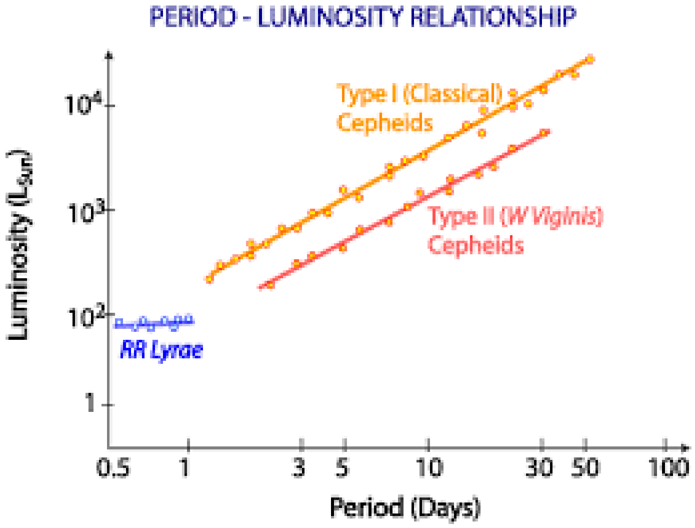

Figure 1. Type I Cepheid stars typically have pulsation periods of less than 10 days, Type II Cepheids have pulsation periods between 10 and 100 days, and RR Lyrae are more common than other Cepheids yet much less luminous.

and at what times the data was measured. In section 3, the reader will find the explanations of what the data means along with plots and models to visualize our reasoning. Ultimately, in section 4 we will discuss the results of this study and our interpretations.

2. DATA

The study begins with 2790 images taken from the Palomar Transient Factory (PTF) from October 2009 to October 2016. Each image taken is of the same general area of the sky, pointing the telescope at the right ascension (R.A.) and declination (Dec.) coordinates approximating (10.684793, 41.269065)[1] in degrees. Ideally, every image in that general area should be usable, however when displayed, many images have data missing due to imperfections within pixels on the Charge-Coupled Device (CCD) detector. Additionally, the images should contain the actual target (M31) in view as well as the five Cepheid reference stars. The celestial coordinates of the reference stars, along with their R band magnitudes, are given in a separate text file. R band filters have an effective wavelength about 7000 $\AA$. Cepheids are important to this study because they are stars whose luminosities are closely corresponding to the periods of their variability. Using their observed magnitudes and the known period-luminosity relationship for Cepheid stars, shown in Figure 1, we can calculate the distance to the Andromeda Galaxy. As a result of the above specifications, choosing the appropriate image is essential to getting accurate results.

3. ANALYSIS

To begin, we define a function that collects the data from the 2790 files and choose a single image to display by verifying that all the reference stars and target galaxy are present, and by specifying the vmin and vmax of the image to interpret the pixels in a colormap that is visually appealing. An example of such an image is shown in Figure . Ideally, one should also choose an image that has no missing pixel values, however choosing such an image should not affect calculations in following steps. Cross-referencing this image with the plot, Figure , of the celestial coordinates of the target and reference stars, we verify that the image displayed before is visually representative of the data needed. In the next function, we return a two element list representing the photon counts within a circular aperture after the background light has been removed. The function is run with x and y parameters for a specified location, the image file, and a radius for the size of the circle to output the counts and the uncertainty in the counts measurement. At this point, we conduct a photometric analysis of each reference star and target galaxy, creating a structured array with the name, date of observation, magnitude, and error in magnitude. The photometry function is central to the study as it references every other method defined before and uses the $m = m_{zp} - 2.5\log_{10}(\text{counts})$ equation to ultimately calculate the target's magnitude relative to each image's zero-point magnitude. In this equation, m is the magnitude of the

[1] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

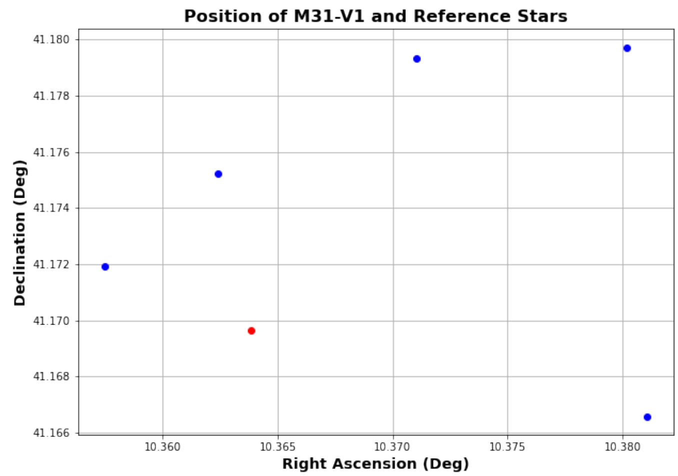

Figure 2. Centered about (10.684793°, 41.269065°), this plot displays the locations of the reference stars and target galaxy.

object in question, m_{zp} is the zero-point magnitude for the image, and *counts* are the photon counts within the defined circular aperture. Now, in Figure , we plot the magnitudes calculated against time for each of the five reference stars and the target. The purpose of doing this is to prove that the magnitude of the reference stars is relatively constant compared to the Andromeda Galaxy's varying luminosity. An important aspect to note is that the variability in the magnitudes seem periodic, giving us insight to calculate the period of M31 by measuring the frequency and power of each peak in the light curve, period and frequency are inversely related. The peak with the most power corresponds to the best frequency measurement and, as a result, the best period calculation. From there, we plot the variability in the magnitude of M31 again, but now using a phase to clearly show the change in brightness instead of using all the Julian dates on the abscissa. This displays the data as a single curve superimposed on itself, as if the observer were looking at a single period, . There exists a strong correlation between the apparent brightness of Cepheid stars and the period (Leavitt & Pickering 1912). Since the Cepheids are in the Small Magellanic Cloud, their distances from Earth are enormous relative to the distances between the stars themselves. Under this assumption, one could make the claim that the period is directly correlated to the luminosity. This relation could be understood through the equation: $M = a\log_{10}(P) + b$, where M is the absolute magnitude, P is the period, and $a = -2.86$ with $b = -1.42$ are constants that help us understand the data's relations in the V and I bands to the R band, which is the filter the data was taken with (Udalski et al. 1999). Solving the data with this equation leads us to the conclusion that the absolute magnitude of M31 is (-5.70077 ± 0.0415254). Finally, the distance was calculated using the formula: $m - M = 5\log_{10}(d/10pc)$, where M is the same value that was solved for above, m is the median apparent brightness taken from the target's light curve, d is the distance to be solved for, and $10pc$ means 10 parsecs. Since this was calculated in parsecs and not in Mega parsecs, the units the answer should be in, it is necessary to multiply the resultant d by 10^{-6}. The distance to the M31 galaxy is therefore $(0.731489 \pm 0.00802621)$ Mega parsecs. Uncertainties in both M and d are calculated under the uncertainty propagation principle with given quantities for $\sigma_a = 0.025$ and $\sigma_b = 0.018$.

4. CONCLUSION

The Andromeda Galaxy (M31) is a galaxy that is close to the Milky Way. Cepheid variable stars were used as a form of standard candles to calculate the distance to this galaxy; resulting in the conclusion that it is 0.731489 ± 0.00802621 Mega parsecs away. This result was reached by first calculating the magnitudes of the reference stars (Cepheids) and comparing them to the galaxy, whose absolute magnitude was -5.70077 ± 0.0415254. The calculations found here are similar to that which one would find searching the NASA/IPAC Extragalactic Database (NED), but since there are slight variations, the implication of this study is that it is improving the definition of M31's distance and magnitudes.

Although one can reach many important conclusions from measuring distances to galaxies, one limitation lies in that we cannot predict the red-shift of the galaxy very accurately using only the measurements in this paper. The ideal answer lies in the spectroscopy of the object, which we do not have. However, we know that the Andromeda Galaxy

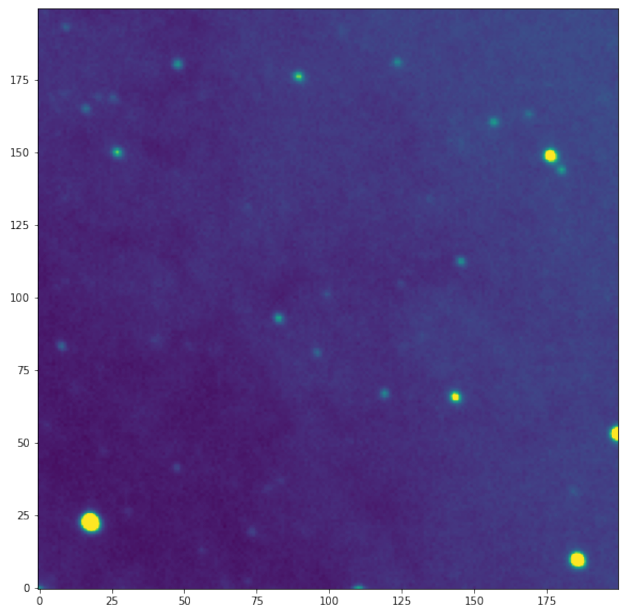

Figure 3. Centered about (10.684793°, 41.269065°), this image is one of 2790 that display the Andromeda Galaxy and the reference stars.

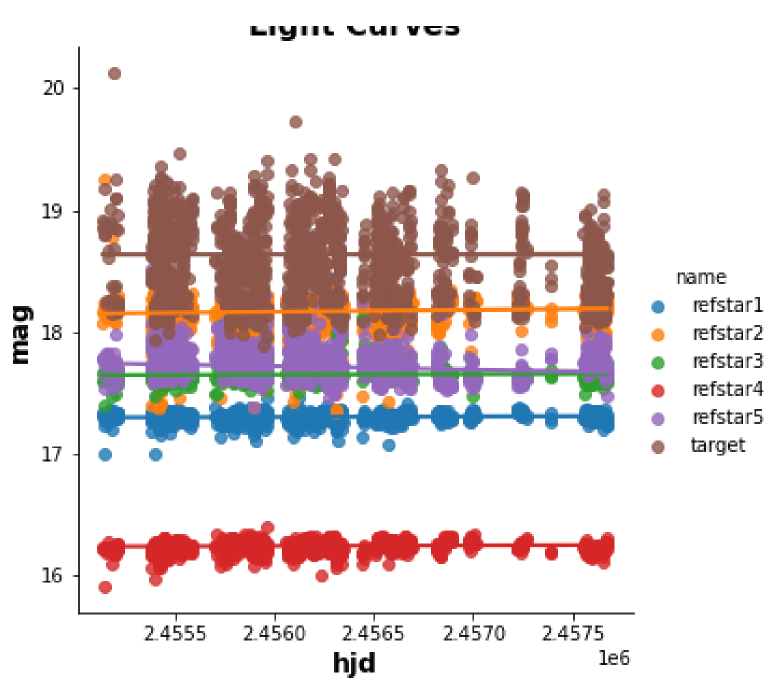

Figure 4. In all the refstars, there is little variation shown in the magnitude data. In the target, the data fluctuates greatly, seemingly without any order.

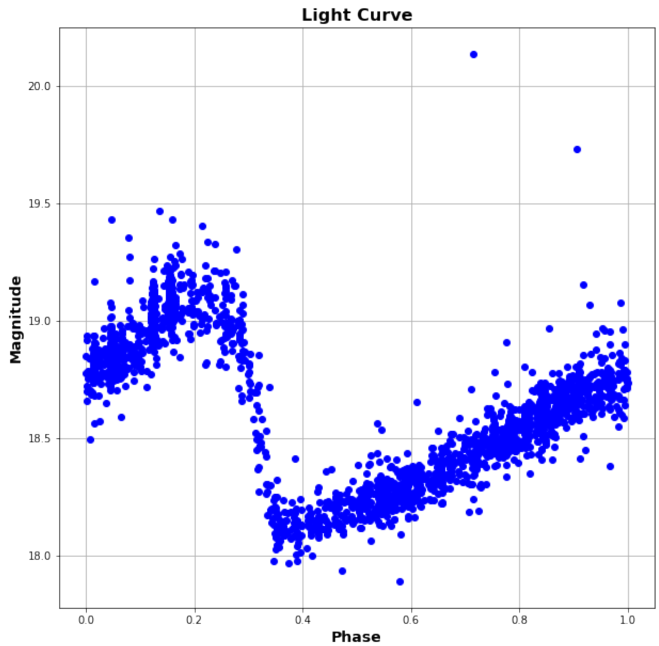

Figure 5. This plot is the same as but superimposed to view the variability per period with more clarity.

is blue-shifted; further proving our conclusion that there exists a short distance to M31 since usually only galaxies in the Local Group are known to be moving towards us.

REFERENCES

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