M31 Where are Thou: Using Photometry to Measure the Distance to M31

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ABSTRACT

This report aims to replicate Hubble's method of measuring extragalactic distances using Cepheid variable stars. In this case we will use M31-V1 as our Cepheid variable star located the Andromeda Galaxy. Using observational data from the Palomar Transient Factory, we performed aperture photometry to measure the apparent magnitude of M31-V1 over time, as well as confirm its periodic variability. We apply the Period-Luminosity Relation to determine M31-V1's absolute magnitude. Comparing the apparent and absolute magnitudes using the distance modulus, we found the distance to M31 to be 1.00 $\pm$ 0.019 Mpc. This report demonstrates how the Period-Luminosity Relation and the role of Cepheid variable stars are significant to our understanding of the scale of the universe.

Keywords: Cepheid variable stars (218) —Period-luminosity relation (1180) —Andromeda Galaxy (71) — Distance indicators (394) —Photometry (1234) —Variable stars (1761)

1. INTRODUCTION

Cepheid variable stars are known for their predictable periods of variability. They have been shown to have a luminosity correlated with their variability. The relation first suggested by H. S. Leavitt & E. C. Pickering (1912), now known as the Period-Luminosity Relation(PLR). This relation was proved useful by Edward Hubble with his work in photometry. In 1923, Edward Hubble observed several Cepheid stars in the M31 nebula. Today, M31 is known as the Andromeda galaxy, the closest neighboring galaxy to the Milky Way. In the 1920s, there was debate on whether spiral nebulae like M31 were inside the Milky Way or whether there were entire galaxies beyond the Milky Way. (N. R. Council 1920). Hubble's observations and using the known relation of the Cepheid's period-luminosity, he was able to determine the distance to M31. (E. P. Hubble 1925) These findings were significant to modern astronomy as this new method allowed astronomers to compare a star's absolute magnitude to how faint they appear to the observer in order to determine its distance. This method led to the discovery that M31 was not a spiral nebula in the Milky Way but an entire galaxy beyond the Milky Way, thus putting an end to the debate. This report will try to replicate Hubble's method by measuring the distance of M31 with the use of Palomar Transient Factory observations of M31-V1. The second section of this paper will go over the data we will be using. The third, will cover the analysis of the data we collected and the photometric techniques needed in this paper. The fourth section will cover the implications and impact these findings had when they were first discovered.

2. DATA

The data used in this report will come from the Palomar Transient Factory (PTF) observations of M31-V1. The PTF was a wide-field survey aimed at systematically explore the transient sky. The light curves detected are measured with the Palomar 60 inch telescope (N. M. Law et al. 2009). The data will come from these observations made in 2009 when the survey was conducted. Another part of our data used in this report will be right ascension, declination, and magnitudes of five field stars near M31-V1. This data comes from Kitt Peak National Observatory's 4m telescope. Part of a catalog that surveyed M31 and M33, this resulted in more than 360,000 stars being cataloged for M31 alone (P. Massey et al. 2006).

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3. ANALYSIS

3.1. *Extracting Known Variables*

The first thing to do is to load the positions of the target, M31-V1, and its comparison stars of known brightness. These comparison stars comes from P. Massey et al. (2006). It is important that we compare M31-V1 with these stars as M31-V1 is a Cepheid variable star. The known magnitudes of the reference stars will help calibrate the brightness scale of the images. All these reference stars are in the same image of M31-V1, with a fixed magnitude. This allows us to find the true brightness of M31-V1 as its luminosity fluctuates over time. 1 shows M31-V1 and the reference stars plotted from their R.A. and Dec. data in degrees. This shows how close the stars are positionally to the target.

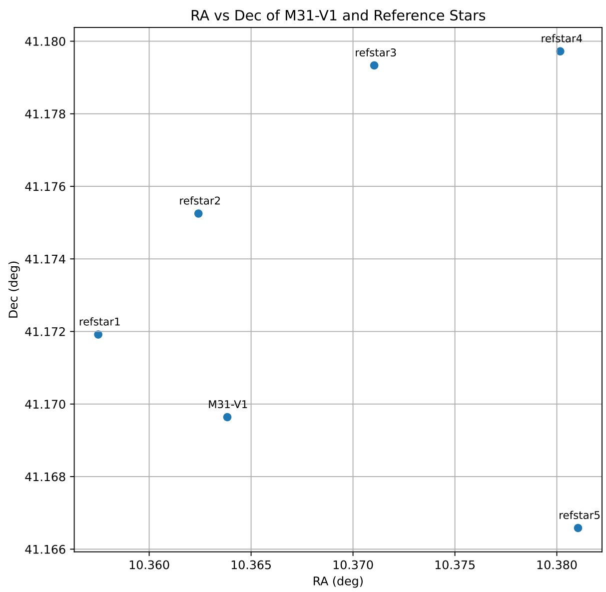

Figure 1. Positional data of M31-V1 and the reference stars taken from P. Massey et al. (2006).

3.2. *Background Subtracted Counts*

The next step in the process is to get the counts which is the true flux of the target M31-V1. Each M31-V1 image contains data that includes light from the target as well as noise and the sky background. We need to eliminate the noise and the sky background in order to isolate the light from the target, as well as to eliminate the local background information. For each position of the star, we ~~want to~~ measure the total counts in a circular aperture. Next, we estimate the sky background using the annulus. The annulus is the region around a star, but doesn't include the star. We use the annulus to identify a region, so we can take the mean of those pixels. The mean value represents the estimate of the background brightness per pixel. That mean is then taken and multiplied to the aperture area in order to get an estimate of how much background brightness is affecting the star's measurement. With this value, we subtract it from the total light in the aperture to get the total light from the star. Now that we have the total light from the star, we can next find the magnitude of the star.

3.3. *Determining the Magnitude of the Target*

To find the magnitude of the target from the data we have, first we ~~need to~~ get the subtracted counts for all the reference stars and the target. Obtained from the previous step, this allows us to examine the stars true flux without the background brightness. We then take this and compute the zero point using the reference stars with their already known magnitudes.

$$m_{zp} = m_{ref} + 2.5 \log(\text{counts}) \tag{1}$$

Using Equation 1, we can calculate the zero point. m_{ref} represents the known magnitude of the reference star. *counts* represents the total counts from the reference star. We take the zero point of each of reference star to calibrate the image in order to convert any count to a magnitude. This now gives us way to calculate the magnitude of M31-V1.

$$m = m_{zp} - 2.5\log(\text{counts}) \tag{2}$$

We use Equation 2 to determine the magnitude of the target. m_{zp} is taken from Equation 1, and *counts* refers to the true flux of M31-V1. This gives us the apparent magnitude of M31-V1 not the absolute magnitude which is found later using the Period-Luminosity relation. To do this we first need to find the period of the star which will be determined in a later step. The difference between the apparent and absolute magnitude is that we calculated the apparent magnitude using photometry of the data.

3.3.1. *Plotting Magnitude vs Time*

After calculating the magnitude of the target, we want to verify that our data is correct. To check this we plot the magnitude of the star and plot it against the Julian Date that it was captured on.

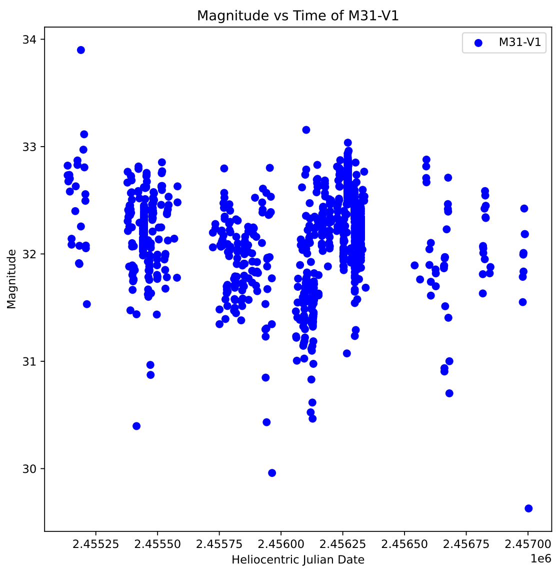

Figure 2. Scattered Plot of M31-V1's magnitude. This highlights the periodic variability its magnitude, reinforcing the fact that this is a Cepheid variable star.

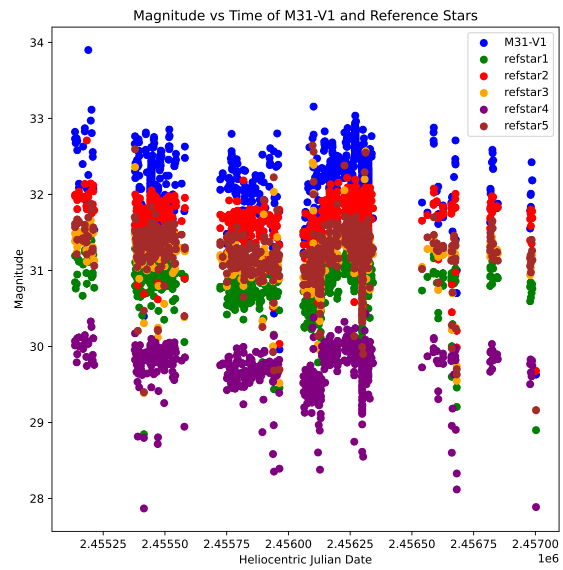

Figure 3. Scattered Plot of M31-V1 and Reference Stars magnitude. Comparing to Fig 2, the reference stars magnitudes tend to stay around a constant magnitudes.

First we plotted the magnitude for M31-V1 in Figure 2, notice how the magnitude of the star has a significant scatter. Next, we plotted the reference stars magnitudes over time. Notice how the reference stars magnitude's are mainly consistent in their magnitudes vs how erratic M31-V1's magnitude changes. This shows that the target's variability is consistent with that of a Cepheid Variable Star (L. T. Evans 2001).

3.4. *Determining the Period of M31-V1*

The next step now is to determine the period of M31-V1. To do this we need to pull the light curves of M31-V1 which is the apparent magnitude taken from the previous step over time. Next we use the Lomb-Scrangle periodogram to find the best-fit period of variation. This would result in us getting the power and frequency of the best-fit period. We then take the inverse of the frequency at the maximum power value to find the period. Next we need to determine the phase which is done by taking the modulo of the data's Julian date over the period, then divide that result by the period. This would result in us folding the data into one phase cycle. Figure 4 shows the plotted phase-folded light curve. The graph aligns, showing a periodic trend. This is important to determine the absolute magnitude of M31-V1, as this value is used in the Period-Luminosity Relation.

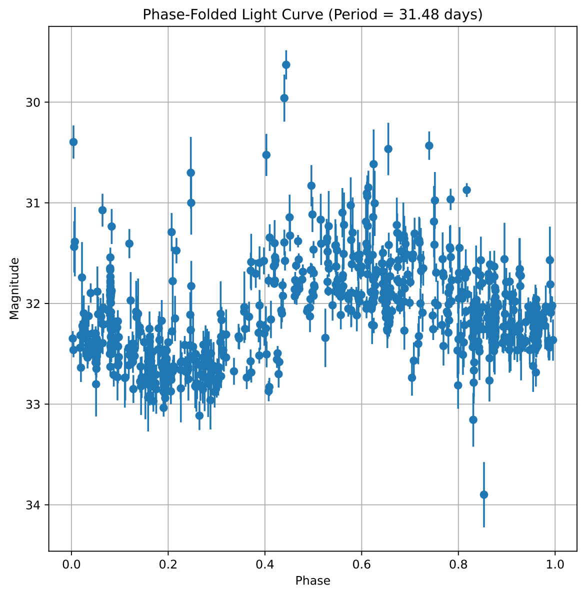

Figure 4. Error-bar plot of the Phase-folded Light Curve.

3.5. *Estimating the Distance to M31 using the Period-Luminosity Relation*

Now that the period of M31-V1 has been determined we can now use the Period-Luminosity Relation to get the absolute magnitude. Getting the absolute magnitude will result in us finding the estimated distance to M31. H. S. Leavitt & E. C. Pickering (1912) demonstrated a relationship between a star's apparent brightness with its periodicity. Equation 3 puts that relationship into a formula we can use (P. Lanoix et al. 1999).

$$M = alog_{10}(P) + b \tag{3}$$

Taking a look at the equation, P represents the period, which we found in the previous step. Variables a and b are constants taken from the average of the V and I band relations. Usually, to measure brightness of stars, we use either the V or I bands, and for this report we will be using R band data. The reason we usually do not use the R band in determining brightness is due to $H\alpha$ contamination. This contamination comes from hydrogen atoms that drop down an energy level. $H\alpha$ adds extra light into the frame that does not come from the star itself. This would create inaccuracies in our measurements, since we are trying to measure M31-V1's brightness. To work around this, we will use the results from A. Udalski et al. (1999) where we can estimate $a = -2.86$ and $b = -1.42$. These values are the average of the V and I bands respectively. Once the absolute magnitude of the star is determined we can calculate the distance modulus to in turn get the distance of M31. Eq 4 compares the apparent magnitude to the absolute magnitude. This tells us how dim the star looks due to distance.

$$\mu = m - M \tag{4}$$

$$\mu = 5log_{10}(d_{pc}) - 5 \tag{5}$$

$$d_{pc} = 10^{\frac{m-M+5}{5}} \tag{6}$$

We can derive the distance calculation by isolation d_{pc} in Eq 5 and would result in us getting this equation to determine distance in parsecs Eq 6. In order to get it in mega parsecs we take the dist and divide it by 10^6 to convert. By using this, we find that the distance to M31 is 1.00Mpc.

3.6. *Calculating Measurement Uncertainty*

These calculations are not perfect; the distance to M31 is not exactly 1 mega parsec away. We need to identify the uncertainty of the measurement we took so we know how confident we are in the result. We can calculate the uncertainty of the absolute magnitude. To do this, we identify the sigma values of a, b, and P. We can take the sigma results for a and b from A. Udalski et al. (1999) since that is where we also initially obtained our a and b values. The results being $\sigma_a = 0.025$ and σ_b Now that we have these values we can calculate the uncertainty in the absolute magnitude using Eq 7 which is $\pm$ 0.042.

$$\sigma_M = \sqrt{\left(\log_{10}(P) \cdot \sigma_a\right)^2 + \sigma_b^2 + \left(\frac{a}{P \cdot \ln 10} \cdot \sigma_P\right)^2} \tag{7}$$

Now that we have the absolute magnitude uncertainty, we can now get the uncertainty for the distance. Using uncertainty propagation, we use Eq 8 to find the uncertainty of our distance measurement which is $\pm$ 0.019 Mpc.

$$\sigma_D = \frac{\ln 10}{5} \cdot D \cdot \sigma_M \tag{8}$$

4. CONCLUSIONS

This report is a replication of Edward Hubble's method of measuring distance using a Cepheid variable star in M31. By analyzing photometric observations from the Palomar Transient Factory, we were able to measure the apparent magnitude of M31-V1 over time, as well as confirm its periodic variability. Using the Period-Luminosity Relation, we were able to translate the measured period to obtain the absolute magnitude. Finding the apparent magnitude required the use of photometric calibration of nearby reference stars. Once found, we applied the distance modulus formula to calculate the distance to M31. By this method, we found the distance to be 1.00 $\pm$ 0.019 Mpc. This confirms that M31 lies beyond the Milky Way, validating Hubble's method of measuring distance using Cepheid variable stars. Hubble's method revolutionized our understanding of the scale of the universe. Before this, there were two methods of thought for our understanding of the universe. One group believed there to be spiral nebula's like M31 are contained within the Milky Way, while another group believed there to be entire galaxies beyond the Milky Way. Hubble's method settled this by discovering that M31 is located further than the span of the Milky Way, highlighting that there are more galaxies beyond us.

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