Distance Calibration of M100 using SN2006X

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During the ten week NSF sponsored REU program at San Diego State University I was able to create light curves of a type Ia supernova and from that derive a distance of 12.4 ± 4.1 Mpc to its host galaxy, M100.

Introduction

Type Ia supernovae are known to be one of the most accurate distance indicators we have on astronomical scales. They are rare events, however we were lucky enough to have one occur in a galaxy for which we already have a well calibrated distance. Previous studies were done on a number of Cepheid variable stars within the M100 galaxy, which yielded a distance of 15.2 ± 1 Mpc (Freedman et. al. 2001). The intention of my research project this summer was to provide a comparison between these two different means of distance calibration. This was a rare opportunity as only about ten type Ia supernovae have gone off in galaxies that we have been able to calibrate by means of Cepheid studies. The distance to M100 is intrinsic, and therefore in theory there should be no deviation in the value we derived in researching SN2006X and the known Cepheid scaled distance.

Observations and Reduction

SN2006X was discovered on February 7, 2006 by Shoji Suzuki and Marco Migliardi on the outer arm of the face-on M100 spiral galaxy (Quimby et. al. 2006). The images I examined were taken by the robotic KAIT telescope at the Lick observatory just outside of San Jose. They numbered 61 in total over the course of about 60 days, from February 8, 2006 to April 27, 2006 in the *UBVR* and *I* bands. The original raw frames had first to be changed from a real format to an integer number of the counts for each pixel using the IRAF task *chpixtype*. The next step in the reduction process was to look at each of the 61 images using the IRAF task *imexam* and determine the seeing by recording the Full Width at Half Maximum (FWHM) of a number of stars in each frame. I also took note of any obvious irregularities in the images at that point. It was then time to take care of all the cosmic ray hits in each frame. This was done by using the IRAF task *cosmicray* interactively and then manually going over each frame with the *imedit* task to clean out any rays that the program had missed. With the cleaned images I was ready to go ahead with the photometry. The first step here was to decide which stars to use as the local standard stars. I settled on a total of five local standard stars to produce the standard magnitudes for the supernova (Figure 1).

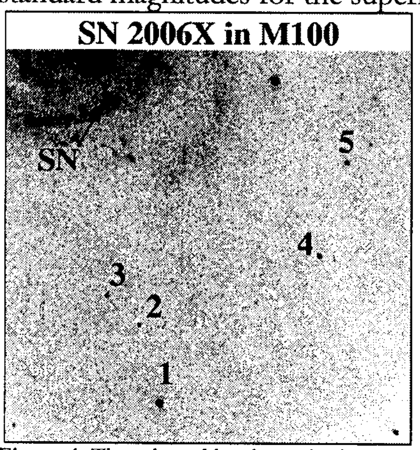

Figure 1. The selected local standard stars

Star Number	B	σ_B	V	σ_V	R	σ_R	I	σ_I
1	15.413	0.026	14.763	0.025	14.411	0.007	14.083	0.004
2	18.483	0.025	17.135	0.027	16.140	0.019	15.255	0.003
3	18.758	0.018	17.979	0.026	17.528	0.012	17.052	0.033
4	17.727	0.012	17.354	0.029	16.986	0.010	16.676	0.029
5	17.551	0.026	16.952	0.001	16.625	0.017	16.299	0.007

Table 1. The magnitudes of the local standard stars.

The local standard stars were chosen based on a number of criteria such as if they were reasonably bright, not too close to other stars or the edge of the image, and not near the saturation value of the CCD. Images of the M100 field along with standard star fields were taken on two photometric nights by Dr. Weidong Li using the Nickel telescope at Lick Observatory and used to determine the standard *BVRI* magnitudes of the local standards (see Table 1). Unfortunately, no data for the *U* band was taken on those photometric nights and so I was not able to calibrate my *U* band data onto the standard system.

Point-spread function (PSF) photometry was performed on the supernova and five local standard stars in each image. To create the PSF, the task *psf* was run and stars that had a circular contour plot with low noise levels were accepted. The task *allstar* was then run and an .als file was created with our PSF-fitted magnitudes. All this information was then put into five files, one for each filter, using *txdump*. The instrumental magnitudes were then transformed to the standard system, and the results are listed in Table 2.

Table 2. Photometric Observations of SN 2006X

UT Date[a]	Day[b]	B (σ_B)	V (σ_V)	R (σ_R)	I (σ_I)
2006-02-08	1.20	17.148(0.086)	15.731(0.091)	14.885(0.079)	14.794(0.086)
2006-02-09	2.15	16.762(0.083)	15.451(0.085)	14.588(0.079)	14.481(0.085)
2006-02-10	3.16	16.416(0.109)	15.227(0.100)	14.370(0.094)	14.221(0.100)
2006-02-12	5.04	16.070(0.091)	14.852(0.115)	14.047(0.096)	13.827(0.100)
2006-02-21	14.14	15.526(0.059)	14.129(0.087)	13.565(0.060)	13.457(0.069)
2006-02-22	15.12	15.556(0.053)	14.125(0.080)	13.555(0.040)	13.455(0.046)
2006-02-23	16.15	15.589(0.043)	14.103(0.069)	13.563(0.061)	13.508(0.062)
2006-02-24	17.13	15.671(0.059)	14.109(0.053)	13.597(0.065)	13.558(0.080)
2006-03-19	40.12	17.873(0.479)	15.262(0.463)	14.343(0.460)	13.714(0.463)
2006-03-22	43.10	17.876(0.086)	15.519(0.050)	14.574(0.021)	13.892(0.062)
2006-03-27	48.06	18.144(0.034)	15.805(0.053)	14.902(0.049)	14.188(0.265)
2006-04-18	70.02	18.426(0.040)	16.432(0.057)	15.678(0.032)	15.217(0.032)
2006-04-27	78.98	18.573(0.041)	16.653(0.079)	15.948(0.022)	15.554(0.016)

Note. — All photometric observations were made with the Katzman Automatic Imaging Telescope.

[a]yyyy-mm-dd.

[b]Days since discovery, 2006-02-07.81 UT (HJD 2,453,773.81).

Analysis

What was left was to extract a few key pieces of information from our light curves and derive a final distance. The distance modulus is given by the formula $\mu=m\text{-}M\text{-}A$, where m is the apparent magnitude, M in the absolute magnitude, and A is the extinction. In order to derive our apparent magnitude, a template fit (Altavilla et. al. 2004) was made based on observations of well-observed type Ia supernovae of the past. Historically the template fit of the *B* band is the most defined as it was difficult to observe in redder band-passes with photographic technology. We opted to do our analysis from this point on in the *B* band in the interest of using the most defined templates available. Figure 2 displays our final light curves with a fit based on the *B*-band template. With that fit we were able to determine the supernova's peak apparent magnitude to have been $m_B = 15.50 \pm 0.08$ mag.

Type Ia supernovae are excellent standard candles, meaning that they are known to have rather consistent absolute magnitudes of about M_B = -19.3 mag. However there is actually some deviation among them and nature was nice enough to give us a trend to go by. It has been found that a type Ia that sharply rises and falls quickly in its luminosity as compared to other type Ia supernovae are dimmer than average. With this knowledge and our fitted curve, we could decipher our particular supernova's maximum absolute brightness. This figure came out to be $M_B = -19.15 \pm 0.19$ mag, using the relations of Phillips et al. (1999). What was left to find was our extinction value. Figure 3 displays our supernova's color curve as well as the Lira relation (Phillips et. al. 1999). The Lira relation is a calibration tool used to determine the reddening of supernovae. All type Ia supernovae have been found to have similar intrinsic colors during the period of 30 to 90 days after maximum. Analysis of past unreddened type Ia supernovae have allowed us to compile this fit to use as a comparison to recent supernovae such as SN2006X so we can accurately determine their reddening.

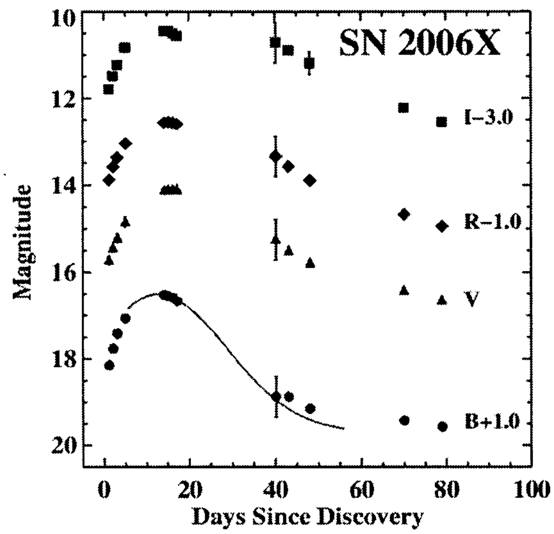

Figure 2. Our final light curve with a fit applied to the B band

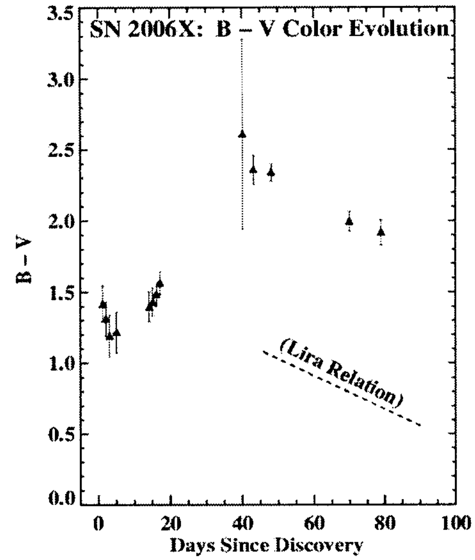

Figure 3. Color plot diagram of SN2006X and the Lira relation

We determined that our type Ia has 1.25 ± 0.2 magnitudes of reddening. This is an extraordinary amount, and it means that only about one percent of the *B* band light actually made it through the dust! Using a dust map for the Milky Way (Schlegel et. al. 1998) we found that only a minuscule amount of the reddening was due to dust in our Galaxy, about 0.03 magnitudes. This meant that the dust within M100 contributed 1.22 magnitudes of the reddening. The extinction was then found using the formula $A_B = R_B \bullet E(B-V)$, where A_B is the extinction in the *B* band, R_B is the extinction coefficient for the *B* band, and *E(B-V)* is the reddening in the *B* band. The combination of the extinction due to the Milky Way and the host dust would give us our final extinction value. However, the proper extinction coefficient in the *B* band for dust in the M100 has yet to be determined. The well known Galactic extinction coefficient of 4.1 could easily be applied for extinction due to the Milky Way, giving us a total of 0.12 magnitudes by our Galaxy. However, without R_B for the M100 we could not proceed. We settled on accepting an average *B* band coefficient value of 3.33 ± 0.11 (Wang et al. 2006) that was derived from research done on the dust in 109 galaxies hosting type Ia supernovae. With this figure we derive that 4.06 magnitudes of extinction due to the host galaxy existed, yielding a total *B*-band extinction value of 4.18 magnitudes. With this final value we found a final distance modulus of μ=30.47 mag to SN 2006X. A distance could finally be found by the relationship $D = 10^{(\mu+5)/5}$ and our final value for the distance to the M100 galaxy comes out to be 12.4 ± 4.1 Mpc.

Conclusions

Our value of 12.4 ± 4.1 Mpc is in agreement with the Cepheid calibrated distance of 15.2 ± 1 Mpc, which hints that with more precision we may get a value that matches even more closely. With an accurate value for R_B we could be more confident in the comparison of our two scaling methods, but as things are we unable to make a very precise comparison. The true coefficient in the *B* band in M100 could actually be quite different from the average value of 3.33 that we applied, and so we have to acknowledge that our final distance has a rather large uncertainty. It was proposed during my final talk that the extinction coefficient for M100 could be found by working the Cepheid study backwards. If one works the numbers backwards, using our values for absolute maximum, apparent maximum, and reddening along with the claimed distance of 15.2 Mpc, a value of 2.97 is derived for R_B, which seems to be a reasonable value. If a through study of the dust in M100 were to be done any deviation from our theoretical value of 2.97 could be attributed to error or differences between our scaling methods. Future work would include analysis in the other filter bands in which reddening is a less significant factor; however templates in those bands are not as thoroughly defined. Much remains to be done with the data on SN2006X and the progress I made will hopefully be of some value to the scientific community.

Acknowledgements

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