Measuring the Distance to Multiple Type Ia Supernova using Different Dust Extinction Methods

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We analyze the B filter light curves of ASAS-SN 16lg, ASAS-SN 18bt, and AT2021 gtp to measure the distance to the event using the distance modulus. For type Ia supernovae there is a widely understood relationship between the decline rate of the B filter and the distance to the supernova. By incorporating the V filter, we work to create a dust extinction calculation to more accurately account for absorption due to stellar and interstellar dust clouds between the object and our location. Many methods to account for dust extinction exist so we study the benefits and precisions of these models.

Introduction

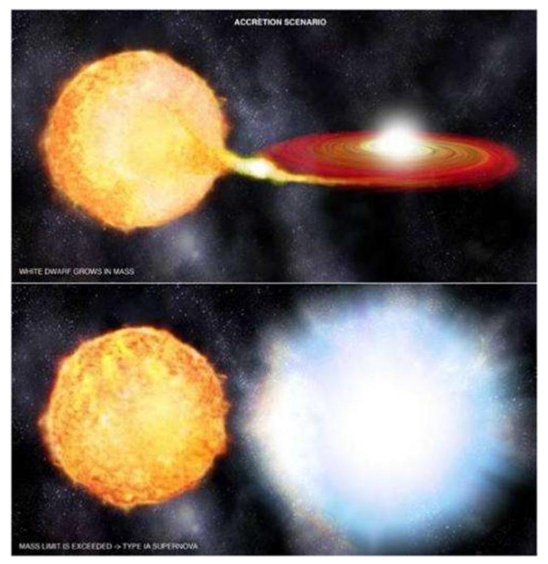


Fig. 1_1
Artist depiction of a type 1a supernova.

Type 1a supernovae are an incredible phenomenon that takes place in some binary star systems. A white dwarf, the remnant of a dead low-mass star, can accrete matter off a companion star. The white dwarf will continue to accumulate matter until it reaches the Chandrasekhar limit. At this point the weight of the accreted matter is so strong that the white dwarf begins nuclear fusion of all the remaining hydrogen atoms at the same time. This phenomenon can outshine its host galaxy. Because of the uniform nature of these explosions, a relationship between distance and decline in the brightness can be used to calculate the distance to the supernova and give important insight into expansion of the universe, the Hubble constant, and help map the nearby universe. We seek to improve our measurement of the distance by applying an observational correction for interstellar dust extinction.

Methods

Using the astronomers telegram and the Rochester astronomy database from 2015-2021 to find targets, the B.E.A.R. Team has observed many type Ia supernovae. We focused on ASAS-SN 16lg, ASAS-SN 18bt, and AT2021gtp. ASAS-SN 15li, ASAS-SN 15ln, PTSS-17ygs, SN2017bgp, and SN J081659.74+511233.7 were all excluded due to overall signal-to-noise ratios under 20 or less than 5 nights' worth of usable observations. Data images were dark and flat calibrated to remove electronic and illumination errors within the imaging system. We then removed images with blurry stars, a background gradient, and low signal to noise ratios. Pictures are stacked with others from the same night and filter, decreasing the amount of data points but increasing the signal. Maxim DL is then used to perform photometry, differential for ASAS-SN 18bt and ensemble for ASAS-SN 16lg and AT2021 gtp. This process subtracts a reference star (differential) or stars' (ensemble) magnitude from the targets to remove fluctuations due to sky conditions. It is important to pick stable reference stars because any variability within the star will be subtracted as if it was a fluctuation due to the sky. This data is then exported to Excel where a gaussian fit is created for the decline rate of the supernova's brightness.

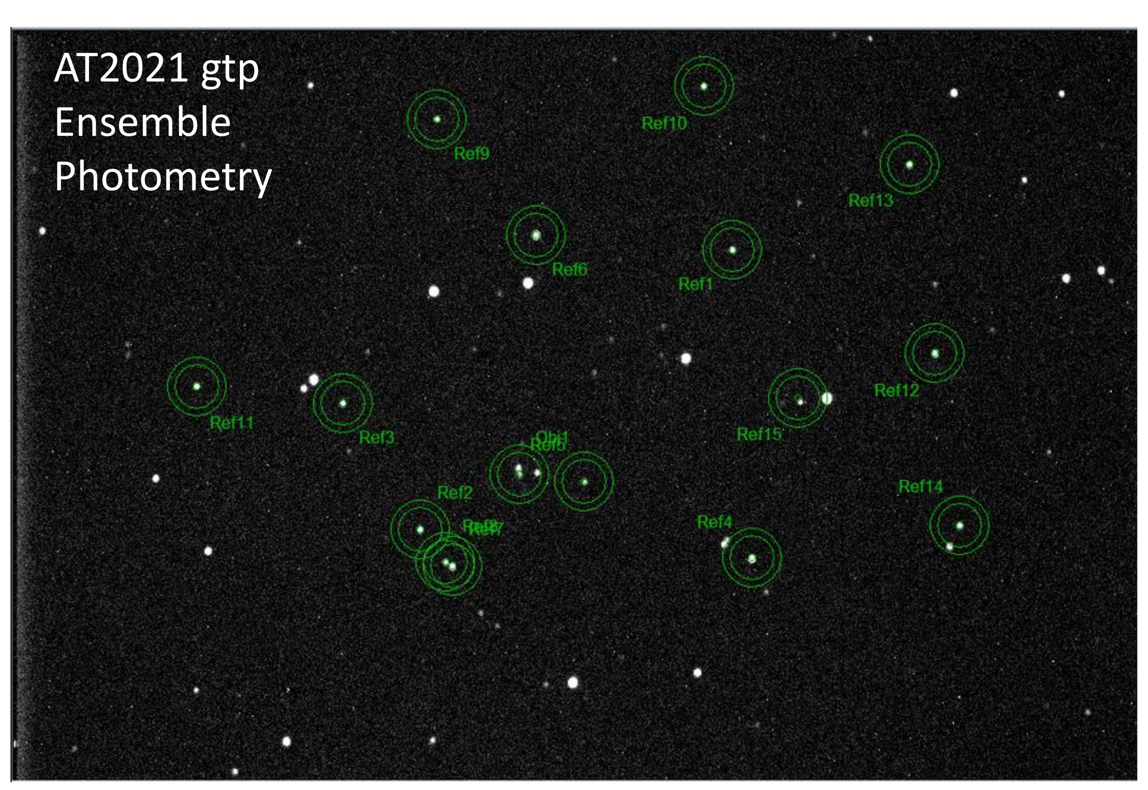


Fig. 2
Choices made for reference stars for AT2021 gtp ensemble photometry. We use the VizeR astronomical database to calculate the reference stars' actual magnitudes by using the logarithmic average for magnitudes. When we work with ensemble photometry, do an average for all the stars then average all those averages.

Important Equations for Type 1a Supernova Distance Measurements

$$Redshift\ Corrected\ Time = \frac{Time - Time_0}{1+z} + Time_0$$

$$\text{Gaussian Mag} = Mag_{Max} * e^{\frac{(RCT-RCT_0)^2}{2\sigma^2}} + Shift$$

$$\text{Distance Modulus} = m - M + E(B-V) * R = 5\log\frac{d}{10}$$

$$M = -21.726 + 2.68\Delta_{15-Day}$$

$$\text{Residuals} = (Mag_{obs} - Mag_{Gaus})^2$$

$$\text{Squares} = (Mag_{obs} - Mag_{Ave})^2$$

$$R^2 = (1 - \frac{\sum Residuals}{\sum Squares})^2$$

$$\text{Logarithmic Average for Magnitudes} = -2.5 * \log(\frac{1}{2}\sum_{i=1}^{n} 10^{\frac{-Mag}{2.5}})$$

Analysis

Before fitting the data, we account for the time-delay caused by expansion of the universe. As the universe expands, light takes longer to reach us. The observed times must be corrected for this. We then create a gaussian fit for our data points. To test the accuracy of the fit, we calculate an R^2 value. An R^2 value of 1 indicates the fit is a perfect representation of the data points. One we calculate the best gaussian fit, we use the distance modulus. The m is the maximum absolute magnitude of the supernova, calculated by taking the peak fit magnitude and adding the reference star's magnitude (found using the VizieR database and logarithmically averaging all measurements in that filter). Then we calculate M using the decline rate relationship for 1a supernovae. Δ_{15-Day} is the difference in magnitudes of the gaussian fit at its maximum and 15 days after. Then we correct for dust extinction. This is tricky because most galaxies have not been studied for how much dust exists within them, so a guess must be made based on the type and orientation of the galaxy. However, this is very inaccurate. It's common to assume the absorption is minimal in most galaxies and only calculate absorption in the Milky Way. In hope of better accounting for host extinction we look at the dust extinction term of the distance modulus represented by E(B-V)*R or E(B-V), the difference in emission of the light in the B and V filter$_3$. We reviewed different interpretations of this and compared them to previous observations. For ASAS-SN 18bt, we tried a multitude of dust corrections using the E(B-V) equation because we had others' measurements to compare our results to. We decided to plot the difference in B and V magnitudes for each night against the time the images were taken. Once we made the plot, we tried a linear fit and a gaussian fit. When using the gaussian E(B-V) fit we subtracted the fit magnitudes from the B filter magnitudes and created a new gaussian fit. We attempted this method thinking both B and V emission curves were gaussians and a gaussian subtracted by a gaussian should equal a gaussian. When then subtracted the gaussian E(B-V) from the B filter gaussian because we thought the dust extinction should be proportional to the amount of light emitted. This new fit was then used to calculate the 15-day decline rate and we removed the dust correction term from our distance modulus. We then tried this method, but without the shift factor in the gaussian E(B-V) fit. A decision was made to not include the shift factor because it does not dictate the shape of the graph. There is also going to be a natural difference in location on the Y-axis of different filtered gaussians because the reference stars and targets don't necessarily have the same color ratios. Our next attempt was to use the 15-day decline rate of the gaussian E(B-V) fit as the dust correction term. As a different method, we tried using the slope of our linear E(B-V) fit as the E(B-V)*R term. The Y-intercept was left off because we only needed the ratio of light in the two filters. The final attempt to make a better dust extinction method was subtracting the maximum value of the B-filter gaussian fit from the V-filter gaussian fit. This value was used as the dust extinction term in the distance modulus.

		ASAS-SN 16lg		
Column1	Column2	Column3	Column4	Column5
RCT (JD)	Mag	Time Since Peak	Time 0	2457676
2457673.49	14.5869567	-2.51432871	Sigma	7.6
2457674.46	14.5565094	-1.537157599	Shift factor	14.9
2457680.36	14.5948835	4.358103273	Max Mag	-0.35
2457694.02	14.8727883	18.02293703		
2457687.18	14.7782165	11.17548544		
Average	14.6778709		Residuals	Squares
			0.00033553	0.00826538
RCT (JD)	Gaussian	Time Since Peak	3.3269E-07	0.01472861
2457673	14.5762329	-3	6.6906E-05	0.0068869
2457674	14.5619117	-2	3.8182E-05	0.0379928
2457675	14.5530167	-1	9.3552E-06	0.01006924
2457676	14.55	0	Sums	
2457677	14.5530167	1	0.00045031	0.07794294
2457678	14.5619117	2		
2457679	14.5762329	3	R^2	0.99422256
2457680	14.5952691	4		
2457681	14.618109	5		
2457682	14.6437128	6		
2457683	14.6709903	7		
2457684	14.698877	8		

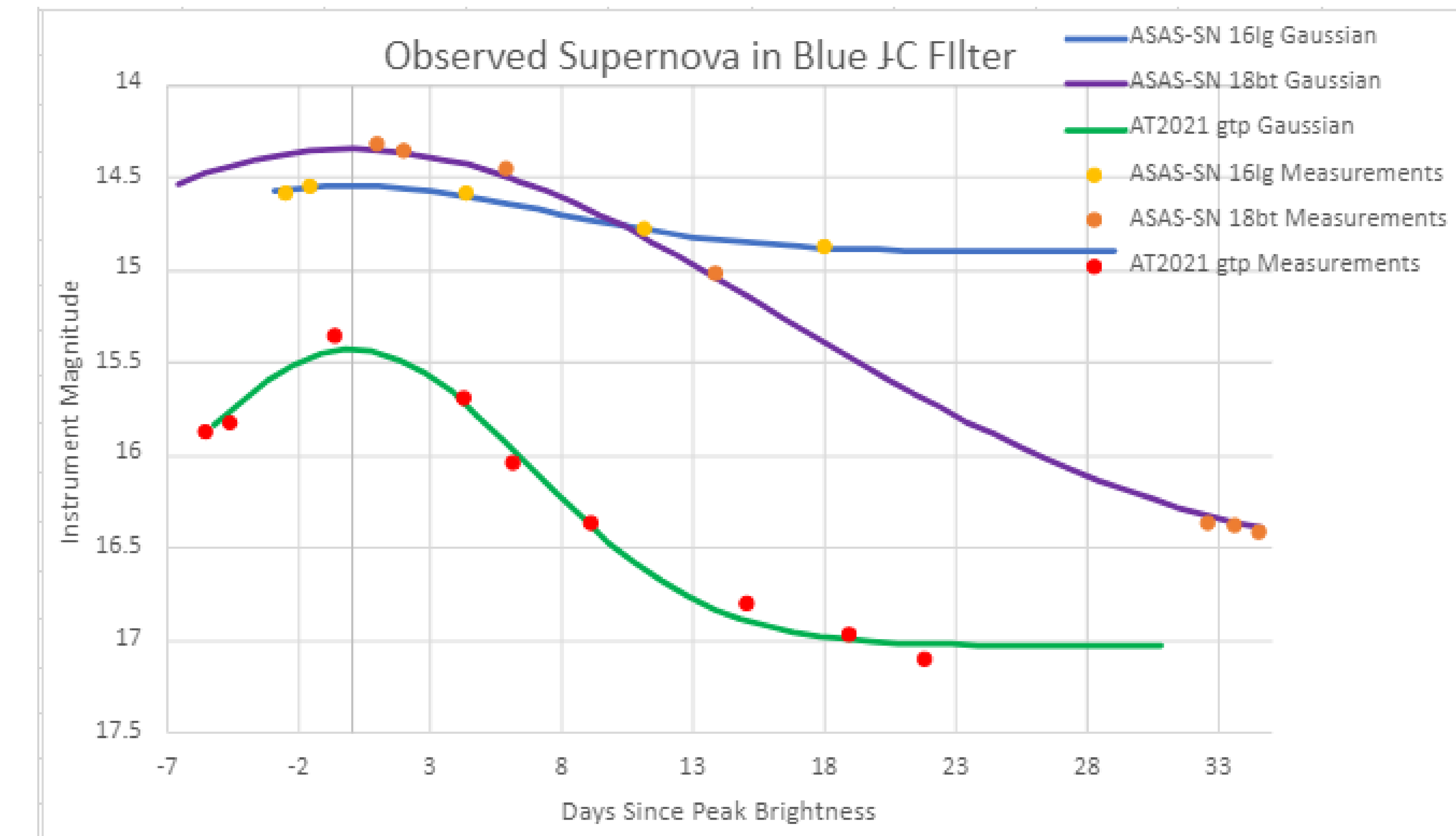
		ASAS-SN 18bt		
Column1	Column2	Column3	Column4	Column5
RCT (JD)	Mag	Time Since Peak	Time 0	2458162.61
2458163.62	14.324	1.008487435	Sigma	16.300166
2458164.6	14.356	1.984037475	Shift Factor	16.6351917
2458168.54	14.458	5.926650356	Max Mag	-2.286476
2458176.46	15.021	13.84347365		
2458195.2	16.372	32.58990633		
2458196.25	16.381	33.63356272	Residuals	Squares
2458197.17	16.424	34.55604955	0.0008461	1.01952294
Average	15.3337143		9.1983E-05	0.95592522
			0.00136649	0.76687551
RCT (JD)	Gaussian	Time Since Peak	0.0003998	0.09779022
2458156	14.5294375	-6.614656751	0.00217577	1.07803722
2458157	14.4804142	-5.614656751	0.00031889	1.09680737
2458158	14.4385327	-4.614656751	0.00092942	1.18872294
2458159	14.4042497	-3.614656751	Sums	
2458160	14.3779432	-2.614656751	0.00612845	6.20368143
2458161	14.3599062	-1.614656751		
2458162.61	14.3487158	0	R^2	0.99901213
2458162.68	14.3487362	0.068919629		
2458163.62	14.3530877	1.008487435		
2458164.6	14.3655908	1.984037475		

		AT 2021 gtp		
Column1	Column2	Column3	Column4	Column5
RCT (JD)	Mag	Time Since Peak	Time 0	2459309.21
2459303.64	15.8783535	-5.56970018	Sigma	6.73309475
2459304.62	15.8264162	-4.592449886	Shift Factor	17.0251387
2459308.56	15.3616649	-0.656379802	Max Mag	-1.5998043
2459313.47	15.701305	4.259459142		
2459315.36	16.0420086	6.149690812		
2459318.37	16.3705037	9.151621256	Residuals	Square
2459324.22	16.8057686	15.01044887	0.00011081	0.12291652
2459328.12	16.9674339	18.91074847	0.00476953	0.16203187
2459331.06	17.1070777	21.84742301	0.00507704	0.75218005
Average	16.228948		0.00020043	0.27840718
			0.0050498	0.03494634
RCT (JD)	Gaussian	Time Since Peak	0.0003781	0.02003802
2459304	15.8397043	-5.21345017	0.00740747	0.33272202
2459305	15.7098191	-4.21345017	0.00071405	0.54536141
2459306	15.5975429	-3.21345017	0.0081387	0.7711118
2459307	15.5094868	-2.21345017	Sums	
2459308	15.4511054	-1.21345017	0.03184593	3.01971521
2459309	15.4261382	-0.21345017		
2459310	15.4362132	0.78654983	R^2	0.989454
2459311	15.4806715	1.78654983		

Table 1
Shows the calculated magnitudes and redshift corrected time as well as the constants used in the gaussians and the R^2 values that show the goodness of fit for the gaussians.

References

1) NASA/CXC/M.Weiss
2) Whittet, D C B, "Dust in the Galactic Environment", 2003, IoP Publishing
3) W. Li *et al* 2019 *ApJ* **870** 12
4) Rogers, Patrick, 2021,"USING LIGHT CURVES TO MEASURE THE DISTANCE TO SUPERNOVAE ASAS-SN 18BT AND AT2021GTP" [POWERPOINT PRESENTATION]



Graph 1
This graph shows the measured magnitudes and light curves of the three supernovae we studied in this project. In this graph we can see that different supernova have different gaussian shapes although all can be defined by a gaussian curve.

Conclusions

When we used the gaussian E(B-V) fit, the calculations disagreed with our previous calculations 59.2±.7 Megaparsecs (Mps) and that made by W. Li *et al. (*52.7±1.2 Megaparsecs) by orders of 10 Mpcs. Because of this we decided to stop attempting to use the gaussian E(B-V) fit for dust corrections. When we took the slope of the linear fit and used it in the distance modulus, we got a similar result to our previous one using dust maps. The calculation using dust maps yielded a distance of 59.2±0.7 Mpc, while the linear E(B-V) calculation proposed a distance of 59.5 Mpc. This method was then applied to AT2021 gtp. The yielded result was 38.6 Mpcs for AT2021 gtp. We also did a dust map correction to ASAS-SN 16lg because we did not have any data in the V filter to apply the new method. Our result was a distance of 108.7 Mpcs. When we calculated ASAS-SN 18bt's distance using the difference in peak magnitudes of the B and V-filters, our result was a distance of 56.7 Mpcs, much closer to the measurement done by W. Li *et al.* Because we only have one supernova to try these corrections on, we cannot draw a firm conclusion. More investigation into these dust corrections will have to be done.

Distance Measurements for ASAS-SN 18bt

	Distance M=m-M+E(B-V)*R=5log(d/10)
Slope	59539472.2
Peak	56671124.37
Gaussian Fit	35104880.99
Add E(B-V) 15day	68019945.44
E(B-V) No shift	40988875.04

Table 2
We can see the distances of ASAS-SN 18bt using the five different methods. Using the slope of the linear fit and the difference in peak brightness of the B and V filter provided the most precise measurements.

Future Work

The process of fitting the gaussian and calculating the distance modulus is time-consuming. Since we now have access to MATLAB, future work will be to create a MATLAB program capable of fitting a gaussian and exporting the distance calculations. A lot of time was spent testing methods on ASAS-SN 18bt, so we must apply corrections to AT2021 gtp and other supernovae that were observed by the BEAR Team. Additionally, more type Ia supernovae will have to be observed. With more observed supernovae we can also begin to construct our own calculated Hubble constant, better incorporating the expansion of the universe.

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