Calibration of Shape-Luminosity Relation for Type Ia Supernova

Hanzhang Feng
(Northwestern University)

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Abstract

This paper utalized delta-15 method to construct a shape-luminosity relation of type Ia supernova using g-band light curve from Bright Transient Survey of Zwicky Transient Facility, and redshift-independent distance recorded by NASA/IPAC Extragalactic Database.

The resulting model is $M_{peak,g} = 2.26 \pm 0.27\Delta m_{15,g} - 20.6 \pm 0.48$. This model estimated Hubble constant of $68.43 \pm 1.5 km/s/Mpc$, $64.91 \pm 5.6 km/s/Mpc$ for SNe Ia with redshift less than 0.04, 0.023 respectively.

1 Introduction

A Supernova explosion (SNe) is an explosion that happens at the end of evolutionary stage of massive astronomical objects. Evolving from different progenitors, SNe can be classified into 4 categories: Ia, Ib, Ic, and II. Among these categories, type Ib, Ic, and II SNe are called core-collapse supernova. Such supernova occurs when the inward gravitational pressure of a massive star exceeds its outward pressure from core fusion and degeneracy, result in a gravitational collapse of its core. Such core collapse result in a neutron star or a black hole, while ejecting the outer layer of the progenitor star to the surrounding interstellar medium.

On the other hand, type Ia supernova (SNe Ia) are the re-ignition of white dwarf in binary system. White dwarf is the end stage of less massive star. As the core nuclear fusion stops, such star would experience gravitational contraction until the electron degeneracy pressure balances gravitational pressure. At this stage, most of the outer layers of star is expelled, and the remaining core is the white dwarf. Typically, white dwarfs are stable and gradually cool down in a timescale of billion years. However, if a white dwarf is in a binary system, it can accrete mass from its companion. When the total mass of white dwarf exceeds the Chandrasekhar limit, the core nuclear fusion is re-ignited, releasing tremendous amount of energy to explode white dwarf completely into supernova remnant (SNR).

Due to its mass accretion property, SNe Ia produces fairly consistent peak luminosity and hence are widely used as standard candle. In the past, it was believed that the dispersion of peak absolute luminosity of SNe Ia is negligible (Tammann et al., 1994). However, Phillips (1993) found that the peak luminosities of SNe Ia are scattered by $\pm 0.8mag, \pm 0.6mag, \pm 0.5mag$ in B, V, I band. Phillips (1993) also suggested that the dispersion of peak luminosity has an linear relationship with the 'stretch' of the light curve of SNe Ia. A light curve is a series of magnitude plotted against time, and the 'stretch' describes the width and height of the light curve. Phillips (1993) found that the wider the light curve, the larger the peak luminosity of SNe Ia. In another word, SNe Ia with longer rise and fade time of its luminosity are brighter. The stretch factor used in Phillips (1993) are Δm_{15}, which is the decay of apparent magnitude after 15 days from the time of peak magnitude.

This paper adopted the Δm_{15} method of Phillips (1993), to calibrate this shape-luminosity relation for SNe Ia, and use the calibrated model to estimate distance of SNe Ia and hence the Hubble constant.

2 Data

Data used in this paper is aquired from the Bright Transient Survey (BTS) of Zwicky Transient Facility (ZTF) (Perley et al. (2020)), and NASA/IPAC Extragalactic Database (NED) (Steer et al. (2017)). BTS is a spectroscopic supernova survey aiming at northern sky. Its sample explorer provides coordination, redshift, peak magnitude, timescale, and extinction for each transients. The ALeRCE's pipeline of ZTF provides light curve data of detection and non-detection in g, r band for each transient. For this paper, only the g-band detection data is used for analysis. NED is a comprehensive database for extragalactic objects. It allows query by name as well as by cone search from certain object or coordinate. NED integrates data from various astrophysics literature to provide a redshift-independent distance for extragalactic objects.

Data sets used in this paper are divided into two parts: the training set and the test set. The training set is a list of SNe Ia that has measurements of redshift-independent distance. Such SNe are typically within 100Mpc. According to Hubble's law, $v = H_0 D$, and approximate Hubble constant of about 70 km/s/Mpc, a distance of 100 Mpc corresponds to a redshift of 0.023. A query filtering classification = SN Ia, z <0.023, and quality cut of pre/post peak coverage on BTS sample explorer returns a list of 128 SNe Ia. For each SNe Ia, a cone search was conducted with NED, using the coordination recorded on BTS as center, and 30 arcsec as radius. The cone search returns all nearby extragalactic objects, as well the host galaxy of these SNe Ia. Among the 128 SNe Ia, 35 have host galaxies with recorded redshift-independent distance. These 35 SNe Ia constructs the training set. Their light curve were obtained using ALeRCE query.

The test set was obtained from BTS sample explorer and ALeRCE query limiting redshift <0.04, which corresponds to distance of about 200Mpc according to Hubble's law. This set contains 652 candidates.

3 Methods and Analysis

For each light curve, the zero point of time axis is set by the time of first detection. A polynomial fit of degree 5 was applied to each light curve. For each SNe Ia in training set, the peak magnitude and Δm_{15} were recorded from light curve fit, the redshift and extinction were from BTS and the redshift-independent distance was recorded from NED. The absolute peak magnitudes of these SNe Ia were calculated by

$$M_{peak} = m_{peak} - 5log(\frac{d}{10pc}) - K_{corr} - A_V, \tag{1}$$

where M_{peak} is the absolute peak magnitude, m_{peak} is the fitted apparent magnitude, K_{corr} is the K-correction term, and A_V is the extinction. For K correction, this paper follows Blanton & Roweis (2007) and approximate $K_{corr} = -2.5log(1 + z)$. The model of shape-luminosity relation is constructed by fitting linear regression of absolute peak magnitude against Δm_{15}.

For each SNe Ia in the test set, apparent peak magnitude and Δm_{15} are calculated in the same way, and the absolute peak magnitude is calculate by fitting the Δm_{15} into shape-luminosity model. With redshift and extinction recorded from BTS, the distance of each SNe Ia can be calculated by

$$d = 10^{\mu/5+1}, \mu = m_{peak} - M_{peak} - K_{corr} - A_V, \tag{2}$$

The Hubble constant is estimated by fitting linear regression of distance against redshift times speed of light

$$cz = H_0 D \tag{3}$$

4 Results

Among the 35 Sin the training set, 13 failed to generate a reasonable polynomial fit. These SNe were excluded from the training set. The resulting fit of light curve are shown in Fig1, with the red dot indicating the magnitude at 15 days past peak luminosity. Among the remaining 24 light curves, 4 still have a second turning point, which is not physical for a light curve. However, These turning points were later than 15 days past peak magnitude, hence do not affect the estimation of Δm_{15}.

A plot of calculated absolute peak magnitude against Δm_{15} of training set is shown in Fig. The linear regression fit gives shape-luminosity model of

$$M_{peak,g} = 2.26 \pm 0.27 \Delta m_{15,g} - 20.6 \pm 0.48. \tag{4}$$

This model for g-band magnitude is consistent with modes in Phillips (1993), $M_{peak} = a + b\Delta m_{15}$, where a, b are given by

band	a	b
B	-21.726(0.498)	2.698(0.292)
V	-20.883(0.417)	1.949(0.292)
I	-19.591(0.415)	1.076(0.273)

Table 1: Shape-luminosity model from Phillips (1993)

The apparent peak magnitude and Δm_{15} of test set was calculated in the same manner. All data points with failed or unreasonable polynomial fit are discarded. For the resulting 560 SNe Ia, the absolute peak magnitudes were calculated using the g-band shape-luminosity model. The distances of these SNe Ia were calculated using Eq(2). A plot of velocity (redshift times speed of light) against distance is shown in Fig3. The linear fit gives Hubble's constant of $68.43 \pm 1.5 km/s/Mpc$.

Additionally, the same procedure was applied to the 128 SNe Ia in the original training set. The resulting plot of velocity-distance is shown in Fig4. The Hubble constant calculated from this set is $64.91 \pm 5.6 km/s/Mpc$.

5 Conclusions

This paper utilized SNe Ia data from ZTF and distance data from NED to construct a shape-luminosity model for SNe Ia light curve in g-band. The resulting model is $M_{peak,g} = 2.26 \pm 0.27\Delta m_{15,g} - 20.6 \pm 0.48$, which is consistent with Phillips (1993). The absolute peak magnitudes estimated from this model yields Hubble constants of $68.43 \pm 1.5 km/s/Mpc$ for SNe Ia with redshift <0.04, and $64.91 \pm 5.6 km/s/Mpc$ for SNe Ia with redshift <0.023. These values are close to the current Hubble constant of about $70 km/s/Mpc$. One way of improving this model is to fit the light curve with a different method, such as skewed Gaussian, to avoid multiple turning points. Another way is to increase the sample size of training set by looking for SNe Ia from database other than ZTF BTS and are from galaxies with redshift-independent distance measurement.

References

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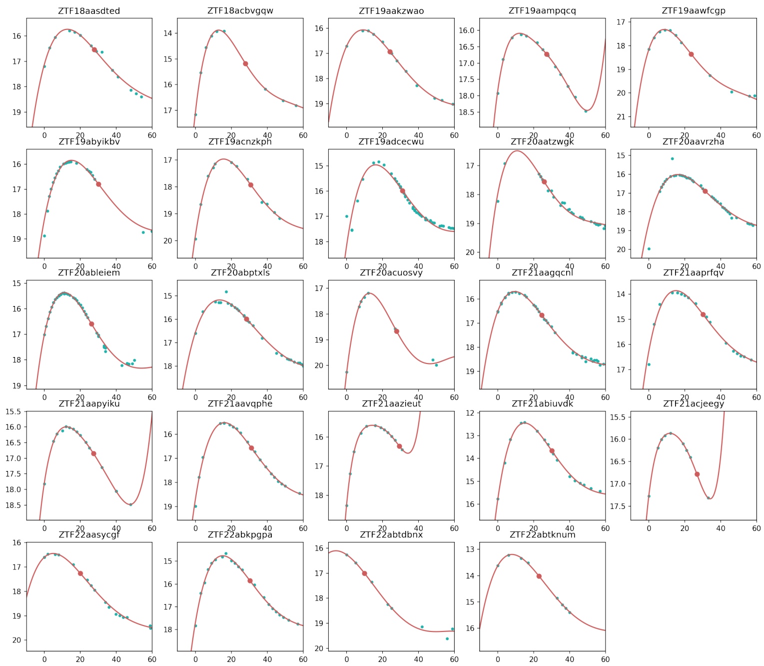

Figure 1: Plot and polynomial fit of lightcurves in training set. For each plot, x axis is days since first detection, y axis is apparant magnitude, red dot indicates magnitude at 15 days past peak luminosity.

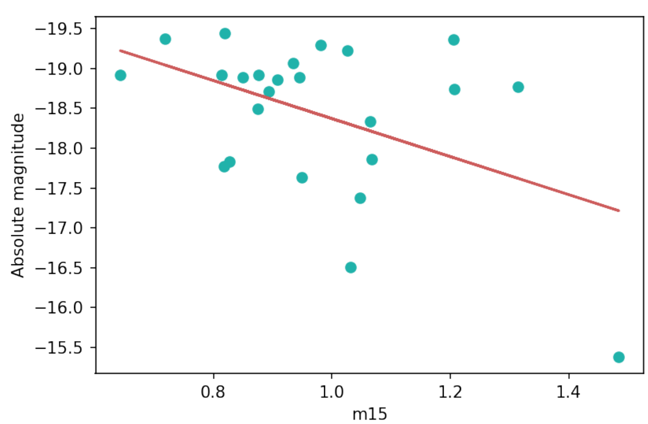

Figure 2: calculated absolute peak magnitude against Δm_{15} of training set

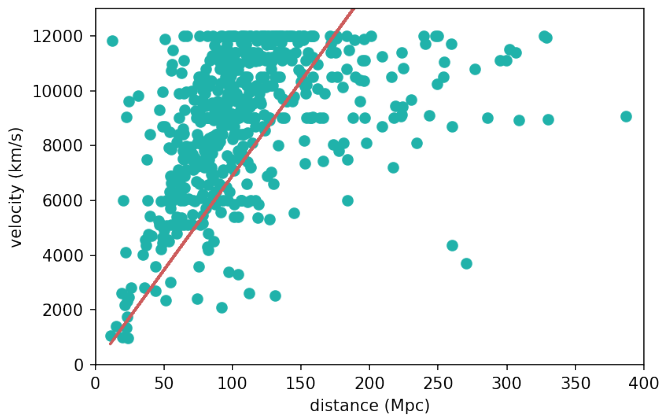

Figure 3: Plot of velocity against distance for SNe in test set.

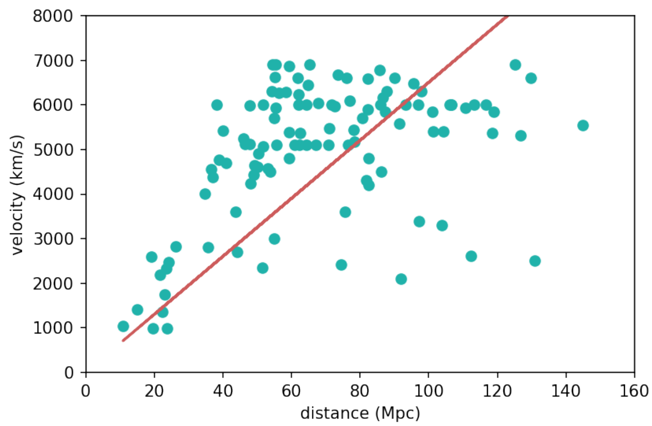

Figure 4: Plot of velocity against distance for SNe in original training set.