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Cosmology with Type IIP Supernovae

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Peter Nugent and Mario Hamuy

Abstract

Type IIP supernovae (SNe IIP) are among the most well-understood cosmic explosions. Not only do we have direct observations of nearly a score of their progenitors prior to the supernova event, the explosion itself is well understood to be that of a single red supergiant star undergoing core collapse and depositing $\sim 10^{51}$ ergs of energy into its atmosphere. While the past two decades have been dominated by the success of using Type Ia supernovae as standardized candles, over the same time SNe IIP have seen a marked increase and improvement in their use as cosmological probes. Here we review the variety of methods currently in use to make SNe IIP cosmic rulers for measuring distances across the observable universe. These methods span the range of highly detailed comparisons with explosion models to those which are purely photometric.

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1 Introduction

Perhaps the most stunning discovery in cosmology around the turn of this century has been the observation that the expansion of the universe is accelerating, propelled by a mysterious dark energy. The only direct evidence for this conclusion is distance measurements to Type Ia supernovae (SNe Ia) performed by several independent teams starting with the observations by Riess et al. (1998) and Perlmutter et al. (1999). This discovery has since been verified independently through several other methods, most notably via observations of the mass density of the universe via baryon acoustic oscillations (Anderson et al. 2012) coupled with measurements of the geometry of the universe via the CMB (Planck Collaboration et al. 2014). The mystery of dark energy lies at the crossroads of astronomy and fundamental physics, the former tasked with measuring it and the latter saddled with explaining it. The astronomical community must do all it can to perform innovative and independent tests of dark energy.

SNe II as cosmological probes have lagged behind their brighter and better calibrated cousins, SNe Ia, but their status in cosmology is rising. Recent studies have utilized new samples of SNe II and demonstrated that a subset of SNe II, the SNe IIP, have outstanding cosmological utility. Unlike the other members of the core-collapse supernova family, SNe IIP maintain a massive hydrogen envelope prior to explosion. The shock from core collapse rips through this envelope, and the expansion of the atmosphere coupled with a slowly receding hydrogen recombination wave powers a ~ 100 day *plateau* phase of the optical light curve from which these SNe II gain the moniker “P.” From analyses of their optical light curves and spectra (Chugai 1994), they evidently suffer little subsequent interaction with the surrounding medium – they are the result of the putative red supergiant exploding into a near vacuum. Recent results from spectropolarimetric studies also suggest that, at least during the plateau epoch, the ejecta and electron-scattering photosphere are quite spherical (Leonard and Filippenko 2001). Given this, SNe IIP have the potential to be excellent distance indicators and are unlikely to suffer similar systematics as those which have been encountered by SNe Ia (Cao et al. 2015; Dilday et al. 2012; Sullivan et al. 2010). Here we review a variety of current methods in measuring distances to SNe IIP and the underlying theory behind them.

2 EPM: Expanding Photosphere Method

Because SNe IIP possess nearly blackbody atmospheres, it is possible to use their observed fluxes and temperatures to derive their angular sizes which, in combination with the physical radii derived from spectroscopic observations, afford the possibility of estimating distances. This technique is known as the “expanding photosphere method,” hereafter. Kirshner and Kwan (1974) first applied this

method, assuming that SNe IIP emitted like perfect blackbodies. Later on, the method was refined by incorporating distance correction factors (a.k.a. “dilution factor” and denoted by ζ) that account for the departure of the SN atmosphere from a blackbody.

Assuming that continuum radiation arises from a spherically symmetric photosphere, a photometric measurement of its color and magnitude determines its angular radius θ ,

$$\theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\lambda(T) 10^{-0.4[A_h(\lambda) + A_G(\lambda)]}}}, \quad (1)$$

where R is the photospheric radius, D is the luminosity distance to the SN, $B_\lambda(T)$ is the Planck function at the color temperature of the blackbody radiation in the SN rest frame, f_λ is the observed flux density, $A_h(\lambda)$ is the dust extinction in the host galaxy, and $A_G(\lambda)$ is the foreground extinction in the galaxy.

The factor ζ_λ accounts for the fact that a real SN does not radiate like a blackbody at a unique color temperature. The SN atmosphere has a large ratio of scattering to absorptive opacity, a ratio which varies with wavelength due to line blanketing and varying continuous absorption. The result is that the photosphere, which lies at a larger radius than the thermalization depth where the color temperature is set, radiates less strongly than a blackbody at that temperature, and the color temperature itself depends upon the photometric bands employed to measure it. The role of ζ_λ is to convert the observed angular radius into the photospheric angular radius, defined as the region of total optical depth $\tau = 2/3$ or the last scattering surface.

A measurement of the photospheric radius R can then convert the angular radius to the distance to the SN. Because SNe are strong point explosions, they rapidly attain a state of homologous expansion in which the radius at a time t is given by

$$R = R_0 + v(t - t_0), \quad (2)$$

where v is the photospheric velocity measured from spectral lines, t_0 is the time of explosion, and R_0 is the initial radius of the shell. Combining these equations, and neglecting R_0 which rapidly becomes insignificant owing to the rapid expansion (typically $v \sim 10^9 \text{ cm s}^{-1}$),

$$\frac{\theta_i}{v_i} \approx \frac{(t_i - t_0)}{D}. \quad (3)$$

This equation shows that photometric and spectroscopic data at two or more epochs are needed to solve for D and t_0 .

Clearly, the determination of distances relies on our knowledge of ζ_λ . The first theoretical dilution factors were computed by Eastman et al. (1996) (E96) from detailed non-LTE models of SNe IIP encompassing a wide range in luminosity, density structure, velocity, and composition. They found that the most important variable determining ζ was the effective temperature; for a given temperature, ζ

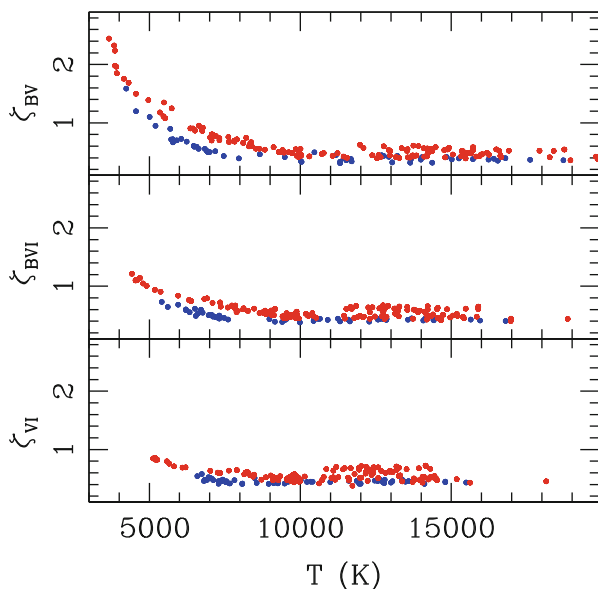


Fig. 1 Dilution factors as a function of color temperature, computed from E96 (blue dots) and D05 (red dots) atmosphere models for three filter subsets (From Jones et al. 2009)

changed by only 5–10 % over a very large variation in the other parameters. More recently, Dessart and Hillier (2005) (D05) computed dilution factors using their own set of non-LTE SN models. Although the D05 dilution factors present the same pattern with temperature as E96, they are systematically higher than E96 by $\sim 15\%$. The origin of these differences is unclear.

In practice, EPM involves measuring the photometric angular radius of the SN (Eq. 1) by fitting Planck curves $B_\lambda(T)$ to observed broadband magnitudes. Here S is the filter combination used, e.g., $S = BV, VI, BVI, \dots$. With two wavelengths the solution is exact. For >3 wavelengths, a method of least squares must be used to find the color temperature and the parameter θ . The dilution factor must be determined for the same photometric system employed in the observations. Figure 1 shows ζ factors for three filter combinations, where the systematic differences between E96 (blue dots) and D05 (red dots) atmosphere models can be clearly seen.

The application of the EPM can be exemplified from the well-observed SN 1999em. Using BVI magnitudes and photospheric velocities derived from $H\beta$, Jones et al. (2009) computed the EPM quantity θ/v as a function of time for three filter subsets and the two sets of dilution factors (E96 and D05). As expected from Eq. 3, Fig. 2 shows that θ/v increases linearly with time. A least-squares fit permits one to solve for D and t_0 , yielding in this case, $D = 9.3 \pm 0.5$ Mpc and $D = 13.9 \pm 1.4$ Mpc using the E96 and D05 models, respectively. A valuable external comparison can be made with the Cepheid distance to NGC 1637, the host galaxy of SN 1999em, namely, $D = 11.7 \pm 1.0$ Mpc (Leonard et al. 2003).

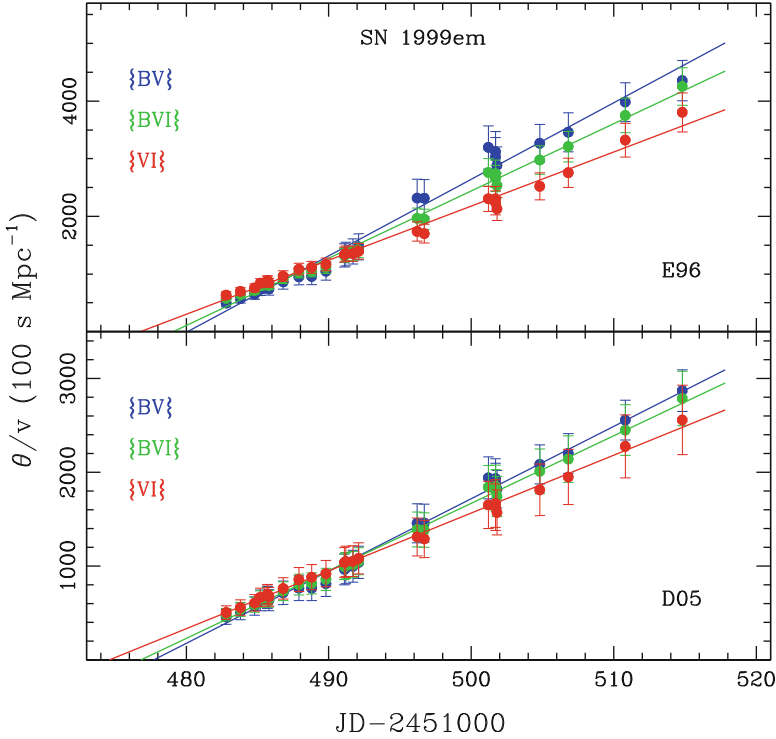


Fig. 2 The ratio θ/v (Eq. 3) as a function of time for SN 1999em using the BV, BVI, and VI filter sets. The ridge line corresponds to unweighted least-squares fits to the derived EPM quantities. The *upper* and *lower* panels show the results using E96 and D05 dilution factors, respectively (From Jones et al. 2009)

While the D05 models yield consistent distances with the Cepheid distance, the E96 models lead to significantly lower distances. Independent EPM analysis of SN 1999em can be found in Hamuy et al. (2001), Leonard et al. (2002), and Dessart and Hillier (2006).

Using 12 well-observed SNe, Jones et al. (2009) constructed the Hubble diagrams shown in Fig. 3. The top one corresponds to the VI filter subset and the E96 models, while the bottom one was obtained with the D05 models. As expected, there is a systematic difference in the H_0 values obtained with the E96 ($H_0 = 91 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and D05 models ($H_0 = 52 \text{ km s}^{-1} \text{ Mpc}^{-1}$) owing to the systematic differences in the dilution factors. The internal precision of each of these implementations is $\sim 0.3 - 0.4 \text{ mag}$, which implies an internal precision $\sim 0.15 - 0.2 \%$ in distance.

One great advantage of distances determined by EPM is that they are independent of the “cosmic distance ladder.” Photometric and spectroscopic observations at two epochs and a physical model for the SN atmosphere lead directly to a distance. Moreover, additional observations of the same SN are essentially independent

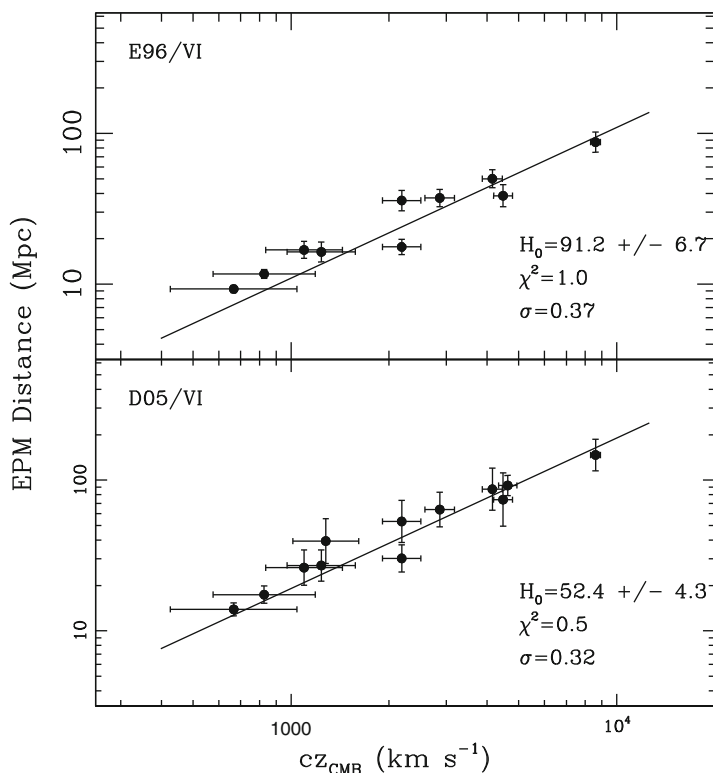


Fig. 3 (*Top*) Hubble diagram using the VI filter subset and E96 dilution factors. (*bottom*) Same as above but with D05 models (From Jones et al. 2009)

distance measurements as the properties of the photosphere change over time. This provides a valuable internal consistency check. However, the method requires us to know the dilution factors, which are still affected by systematic uncertainties.

Additional analysis of individual SNe can be found in Schmidt et al. (1994a), Takáts and Vinkó (2006), Vinkó et al. (2012), and Takáts et al. (2015), whereas Schmidt et al. (1992, 1994b), and Bose and Kumar (2014) provide studies of 10, 5 and 8 SNe, respectively.

3 SEAM: Spectral Expanding Atmosphere Method

In the (SEAM), observed spectra and photometry are combined with detailed theoretical modeling of the observed spectral energy distribution of individual SNe to accurately determine their luminosities and hence the distances to these stellar explosions. While the SEAM is similar to the EPM in spirit, it avoids the use of dilution factors and color temperatures as described in Sect. 2 as one fits individual SNe epoch by epoch. Velocities are determined accurately by fitting the

synthetic to the observed spectra. The radius is still determined by the relationship $R = vt$ which is an excellent approximation given SNe IIP reach homologous expansion quickly after explosion. The explosion time is found by demanding self-consistency between multiple epochs. This method is in the spirit of the Baade method (Baade 1926; Branch et al. 1981; Kirshner and Kwan 1974) and the more detailed expanding photosphere method of Eastman and collaborators (Eastman and Kirshner 1989; Schmidt et al. 1992).

The SEAM uses all the spectral information available in the observed spectra simultaneously; hence, the determination of the underlying parameters is more robust than the use of generalized dilution factors in the EPM. Since the spectral energy distribution is known completely from the calculated synthetic spectra, one can just integrate the spectrum in a given photometric band to determine the absolute luminosity and compare to the observed apparent magnitude to measure the distance modulus. Extinction corrections are usually determined by fitting the earliest observations which, due to the very high temperatures, are in the Jeans' tail and thus sensitive to extinction by dust (Baron et al. 2000).

Codes which have been used to carry out this line of work include CMFGEN (Dessart et al. 2008) and PHOENIX (Baron et al. 2004). In general, these codes solve the fully relativistic radiation transport equation along with the non-LTE rate equations (for some ions) while ensuring radiative equilibrium (energy conservation). Use of these codes have led to some excellent fits to many different types of SNe (Baron et al. 1995; Dessart et al. 2011; Mitchell et al. 2002; Nugent et al. 1995); however, given the low polarization seen during the plateau phase (Leonard and Filippenko 2001), implying a nearly spherical atmosphere, coupled with the facts that the ejecta are dominated by hydrogen and their progenitors are well understood (Smartt et al. 2009), SNe IIP make ideal SNe for the application of the SEAM.

The SEAM allows one to measure supernova luminosities with the following two assumptions: (1) homologous expansion, $v \propto r$, from which it follows that the velocity of a given matter element is constant and hence that the position of a reference radius is given by $v_0 t_R$, where v_0 is determined by the spectral fit. (2) A high-quality fit to the spectrum across several epochs implies that the model parameters were accurately determined. The underlying density profile of the atmosphere and elemental abundances are parameters to be fit and often come from explosion models (Woosley and Heger 2007). However, one often assumes that the atmosphere follows a decaying exponential or power law and the abundances are some fraction of solar. Figure 4 shows a PHOENIX fit to SN 1993W during the plateau phase. The fit is a near perfect match to the spectrum and highlights the effects of metallicity on the overall SED.

Both Baron et al. (2004) and Dessart and Hillier (2005) provide excellent fits to several epochs of SN 1999em and find distances via the SEAM in agreement with the Cepheid distance provided by Leonard et al. (2003) with uncertainties on the order of 10–15 %. SEAM has also been applied to the well-observed SNe 2005cs and 2006bp (Dessart et al. 2008). While the SEAM is not currently amenable for

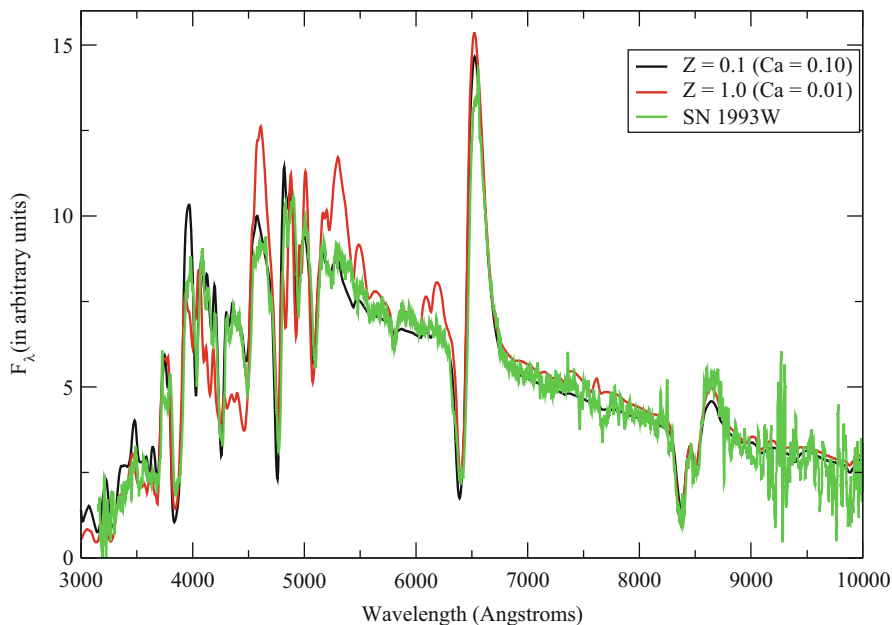


Fig. 4 PHOENIX fits to SN 1993W a SN IIP observed in the Hubble flow. Here we have varied the metallicity from a tenth solar to solar holding all other parameters fixed. The overall fit to the spectrum is excellent and highly favors the low metallicity model. Deviations in flux are $<5\%$ at almost all wavelengths

high-redshift SNe IIP cosmology, given the upcoming launch of the *James Webb Space Telescope*, this will be possible.

4 SCM: Standard Candle Method

As cosmological probes, SNe II have not yet reached the status or precision of SNe Ia, but their potential has improved in the last decade as a result of several studies including two doctoral theses (Hamuy 2001; Leonard 2000) that have utilized new samples of SNe II and demonstrated that SNe IIP are particularly promising as distance indicators. For this subset, the EPM (see Sect. 2) and its descendant, the spectral expanding atmosphere method (SEAM, see Sect. 3) can be replaced by a more practical empirical method which requires less input data (Hamuy 2003; Hamuy and Pinto 2002).

The approach advocated by Hamuy and Pinto (2002) is a particularly significant development since it is motivated by sound physical principles. In more luminous SNe IIP, the hydrogen recombination front is maintained at higher velocities, pushing the photosphere farther out in radius. When a SN IIP is on the plateau phase, a period which lasts for around 100 days, a strong correlation is expected

and observed between the velocity of the weak Fe II lines near 5000 Å and the luminosity. This method is referred to as the (SCM).

Calibration of the SCM requires line-of-sight extinction corrections, which was determined by the authors in one of two ways. When the SN leaves the plateau phase, the photospheric temperature should be close to that of recombination, and thus the observed color at this point will provide a reddening estimate. Alternatively, for well-studied SNe IIP, one can employ detailed modeling of a series of high signal-to-noise spectra to determine the extinction. Here, deviations between the line profiles of selected absorption features and those expected given the observed spectral energy distribution (SED) can be used to estimate selective extinction. Application of these techniques to 24 SNe IIP in the Hubble flow (Fig. 1 of Hamuy 2003) yields a *I*-band Hubble diagram with a scatter of only 0.29 magnitudes. This corresponds to a precision of 15 % in distance, which compares favorably to the 10 % achievable with SNe Ia.

This work was extended by Nugent et al. (2006) who made two improvements to the SCM which greatly simplifies its use – especially at high redshift. The first was to realize that the velocity of the Fe II lines follows a power-law decline as a function of time during the first 100+ days and that the velocity at day 50 can thus be determined by extrapolation using the following equation:

$$V(50) = V(t) * (t/50)^{0.464 \pm 0.017}. \quad (4)$$

This greatly reduces the time pressure of obtaining a spectrum at that phase or obtaining two spectra around day 50 and interpolating. It was also noted that the $H\beta$ line was tightly correlated with Fe II 5169 Å and thus was also useful for determining the velocity of the SNe IIP, which was further refined by Poznanski et al. (2010) to:

$$v_{\text{Fe II}} = (0.84 \pm 0.05) v_{H\beta}. \quad (5)$$

Given the higher signal to noise of the $H\beta$ line, this is a much easier measurement to make, especially for faint and/or high-redshift SNe IIP.

The second modification of the Hamuy and Pinto (2002) method they explored made use of the restframe $V - I$ color during the plateau phase at day 50 to perform an extinction correction rather than relying on colors at the end of the plateau phase or on detailed modeling. They were able to empirically retain a tight Fe II velocity-luminosity relation using the observed $V - I$ color at this epoch with the following relationship:

$$M_I = -4.6 \log_{10} (V_{\text{Fe II}}/5000) + 0.7 [(V - I) - 0.53] - 17.43 \quad (6)$$

with the zero point of this relationship determined by assuming a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Poznanski et al. 2010). The SCM has now been used subsequently by several authors (D’Andrea et al. 2010; de Jaeger et al. 2015; Olivares E. et al. 2010; Poznanski et al. 2009) with Hubble diagrams comprised of scores of SNe IIP achieving <15 % scatter in distance. Figure 5 shows one of the latest Hubble diagrams using the SCM (Poznanski et al. 2010).

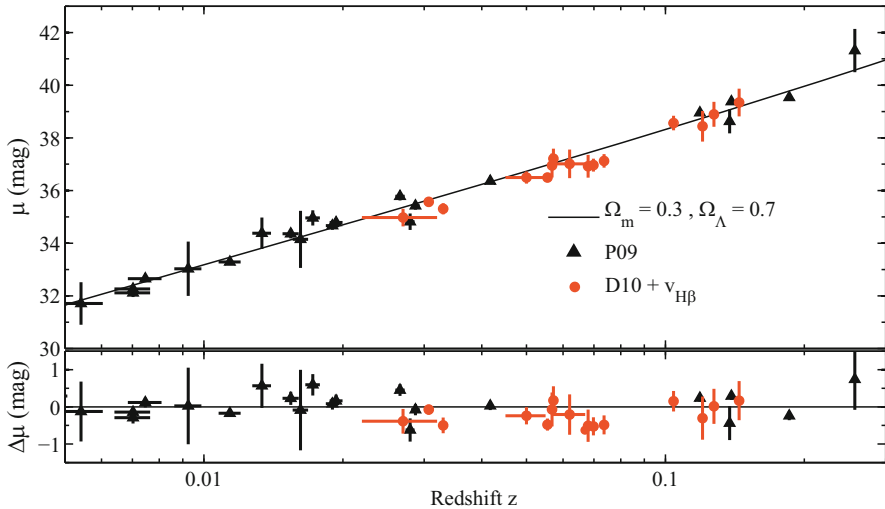


Fig. 5 Hubble diagram (*top*) and residuals from the concordance cosmological model (*bottom*) using the SCM as applied to the data taken from Nugent et al. (2006) and Hamuy and Pinto (2002) as seen in Poznanski et al. (2009) (*black triangles*). In addition, data from D’Andrea et al. (2010) (*orange circles*) as reevaluated by Poznanski et al. (2010) using the $H\beta$ correction seen in Eq. 5 is shown

It is worth noting that this empirical correlation between velocity, color, and luminosity has a sound footing in theory. There have been several studies on the light curves of SNe IIP during the plateau phase (Litvinova and Nadezhin 1985; Nadyozhin 2003; Popov 1993; Young and Branch 1989) which have hinted at this; however, they were all limited in their treatment of radiative transfer by assuming the diffusion approximation or very low spectral resolution. In Kasen and Woosley (2009), they applied a novel method which coupled a multi-wavelength implicit Monte Carlo radiation transport code to a one-dimensional hydrodynamics solver. Using models from Woosley and Heger (2007), they were able to show that their improved models are able to reproduce the photospheric velocity evolution as seen in Eq. 4, the underlying $V-I$ color relationship and the correlation between velocity and luminosity as seen in Eq. 6. Interestingly, their work also hinted at the light curve decline-luminosity relationship that will be described further in Sect. 6.

5 PPM: Photospheric Magnitude Method

The (PMM), developed by Rodríguez et al. (2014), is a generalization of the previously described SCM for various epochs throughout the photospheric phase. A “photospheric magnitude” is defined as:

$$\mathcal{M}_{\lambda,i} = M_{\lambda,i} - 5 \log \left(\frac{10 \text{ pc}}{R_i} \right), \quad (7)$$

where $M_{\lambda,i}$ is the standard broadband absolute magnitude and R_i is the photospheric radius of the SN. Here the subindex i denotes the time t_i of the observation. Equation 7 is similar to the definition of distance modulus, except that the photospheric magnitude is an “ad hoc” absolute magnitude just above the photosphere. As mentioned in Sect. 2, the photospheric radius at a given time can be approximated as,

$$R_i \simeq v_i(t_i - t_0), \quad (8)$$

where v_i is the photospheric velocity measured at time t_i from the absorption minima of weak P-Cygni profiles in a spectrum. Combining Eqs. 7 and 8, we obtain

$$\mathcal{M}_{\lambda,i}^* = \mathcal{M}_{\lambda,i} - 5 \log \left(\frac{t_i - t_0}{100 \text{ days}} \right) = m_{\lambda,i} - \mu - 5 \log \left(\frac{10 \text{ pc}/100 \text{ days}}{v_i} \right), \quad (9)$$

where $m_{\lambda,i}$ is the apparent broadband magnitude of the SN at time t_i (properly corrected for dust extinction and K-terms) and μ is the distance modulus. The temporal behavior of $\mathcal{M}_{\lambda,i}^*$ was examined in the V and I band-passes by Rodríguez et al. (2014), using four nearby SNe IIP with precise distances. As shown in Fig. 6,

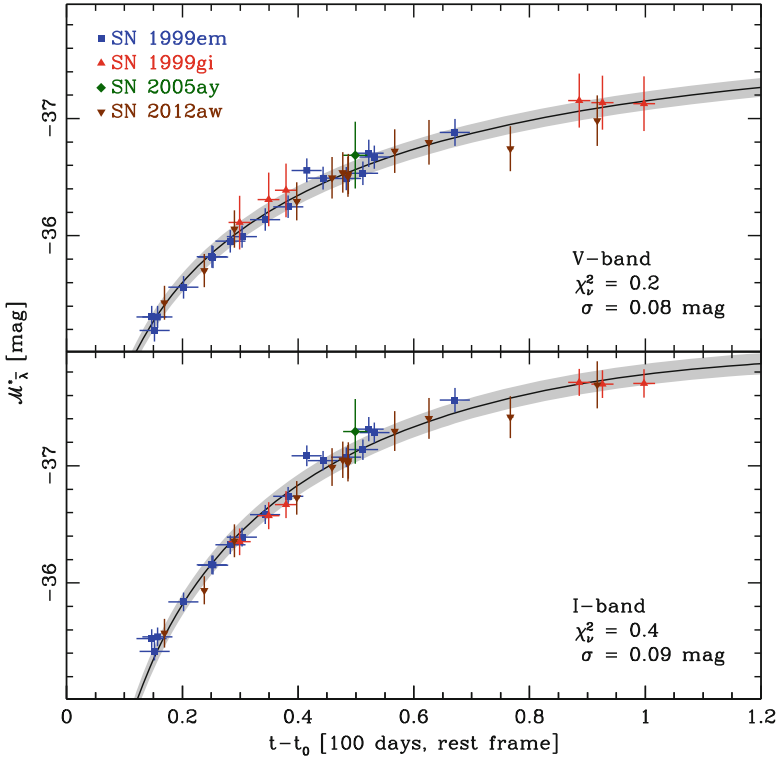


Fig. 6 Evolution since time of explosion of $\mathcal{M}_V^*$ and $\mathcal{M}_I^*$ for four nearby SNe II with known distances (Figure from Rodríguez et al. 2014)

the time evolution of $\mathcal{M}_V^*$ and $\mathcal{M}_I^*$ with respect to the explosion time is quite similar for all four SNe. Although the small scatter in $\mathcal{M}_V^*$ and $\mathcal{M}_I^*$ was obtained with four SNe only, it suggests a high degree of homogeneity of SNe IIP with a dispersion of 0.09 mag, implying that the PMM could deliver distances with a precision up to 4 %.

As can be seen from the right-hand side of Eq. 9, the fact that all four SNe have nearly the same $\mathcal{M}_{\lambda,i}^*$ for a given epoch i implies a “luminosity-velocity” relationship at all epochs during the photospheric phase, thus showing that the PMM is a generalization of the SCM.

This calibration allows one to calculate distance moduli to other SNe with photometric and spectroscopic data ($m_{\lambda,i}$, v_i) at the same epoch via

$$\mu = m_{\lambda,i} - 5 \log v_i - \mathcal{M}_{\lambda,i}^*. \quad (10)$$

Figure 7 shows the resulting V and I Hubble diagrams derived from a sample of 50 low- z SNe IIP. Restricting the sample to 13 SNe in the Hubble flow (cz_{CMB}

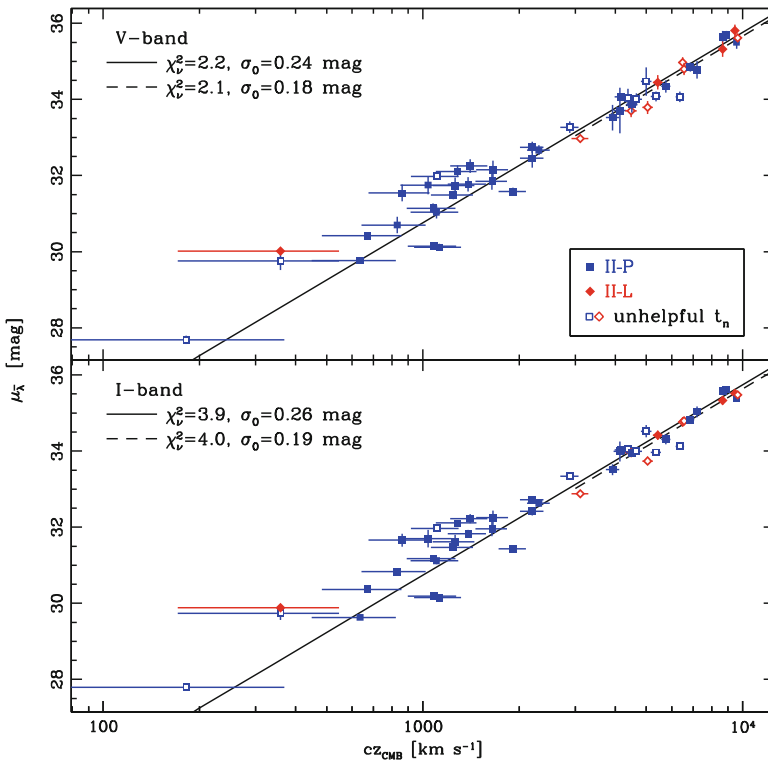


Fig. 7 Hubble diagram obtained from 50 SNe II using the PMM (Figure from Rodríguez et al. 2014)

$> 3000 \text{ km s}^{-1}$) a mean scatter of 0.12 mag is derived, implying the potential to achieve precisions of 6 % in relative distances. With the $\mathcal{M}_{\lambda,i}^*$ calibration shown in Fig. 6, a Hubble constant of $68\text{--}69 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is obtained.

6 PCM: Photometric Candle Method

In the era of the upcoming big surveys such as the LSST, a large number of SNe will be discovered and spectroscopic follow-up will be impossible for all but a fraction of these objects. This will prevent the use of the methods described above to measure distances from SNe IIP. Thus, a purely photometric method to standardize the SN luminosities will be an asset for the next generation surveys. To address this issue, de Jaeger et al. (2015) has recently developed the (PCM) to obtain purely photometric distances from SNe II, only using light curve and color-curve parameters.

The PCM makes use of an empirical correlation found by Anderson et al. (2014) between the SN peak luminosity and the slope of the plateau, in which brighter SNe show a steeper decline (Fig. 8).

This is the underlying idea of the PCM but generalized to magnitudes measured at any epochs during the plateau. To correct and standardize the SN magnitudes, de Jaeger et al. (2015) used the apparent magnitude, the slope of the plateau (s_2), and a

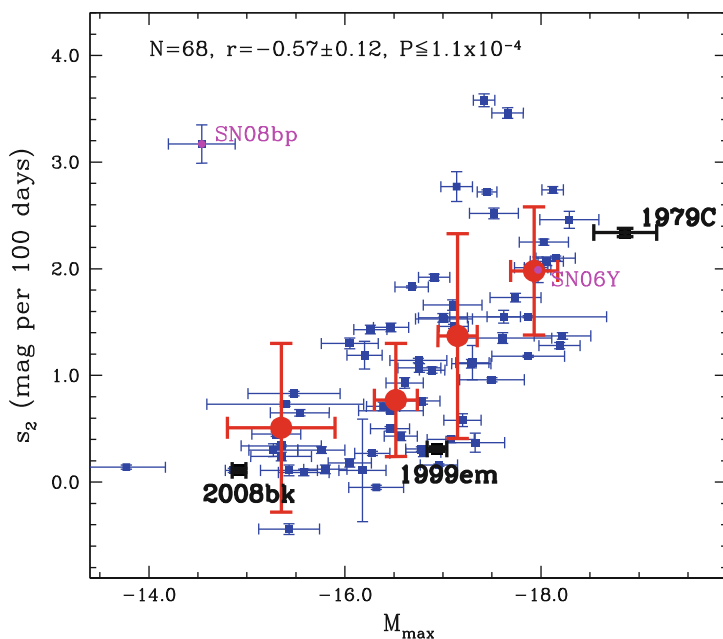


Fig. 8 Peak magnitude, $M_{\max}$, versus decline rate, s_2 for SNe II (Figure from Anderson et al. 2014)

color term to take into account the dispersion caused by host-galaxy extinction. The magnitude is standardized by minimizing the scatter in the Hubble diagram, i.e., by performing a least-squares fit to the following equation,

$$m_{\lambda 1} + \alpha s_2 - \beta(m_{\lambda 2} - m_{\lambda 3}) = 5 \log z + ZP, \quad (11)$$

where $m_{\lambda 1,2,3}$ are observed magnitudes with different filters at some epoch during the plateau phase, properly corrected for galactic extinction and K-terms, while α , β , and ZP are free-fitting parameters. Using high-quality data for 38 SNe II in the Hubble flow ($c z_{CMB} > 3000 \text{ km s}^{-1}$) obtained during the Carnegie Supernova Project, de Jaeger et al. (2015) found that the Hubble diagram with the smallest dispersion was the one built from r -band magnitudes and $V - i$ colors measured close to the middle of the plateau (55 % of the time from the explosion to the end of the plateau). As shown in Fig. 9, the RMS from the best fit model is 0.44 mag, which allows one to measure relative distances with a precision of ~ 20 %. A similar dispersion of 0.43 mag was obtained using NIR data (Y and J bands), implying that using NIR filters does not cause a significant improvement for the PCM. Although

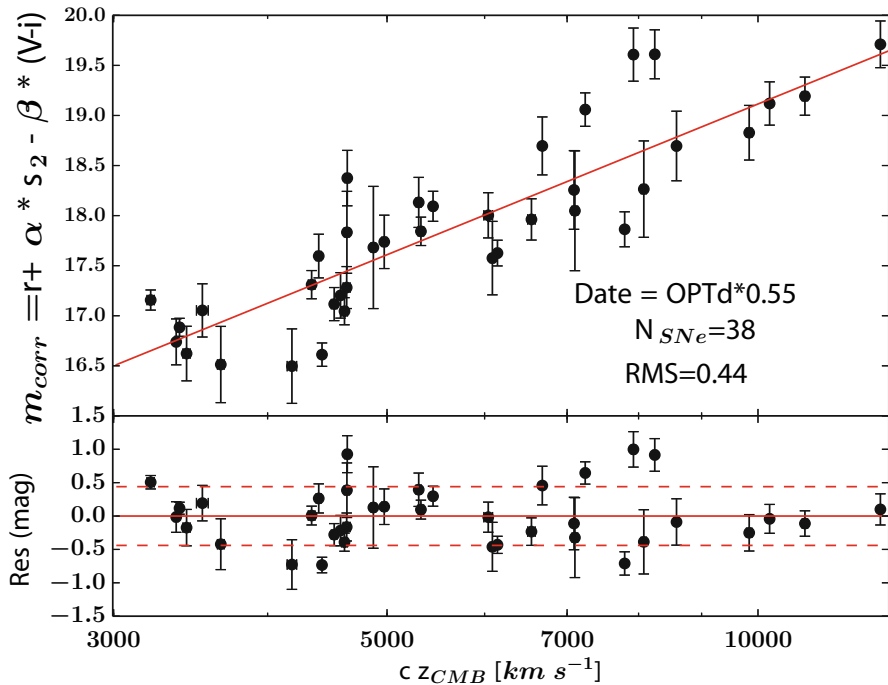


Fig. 9 Hubble diagram obtained with the PCM from r -band magnitudes and $(V - i)$ colors measured close to the middle of the plateau (55 % of OPTd, the time from the explosion to the end of the plateau) of 38 SNe II in the Hubble flow (Figure from de Jaeger et al. 2015)

the precision of the PCM is not as good as the other methods discussed above, it is a very promising technique for the upcoming era of large imaging surveys, where having spectroscopy for every SNe will be impossible.

7 Conclusions

SN Ia measurements of dark energy are no longer limited by statistical uncertainties, rather systematic uncertainties are the dominant source of error. The foremost systematic source of potential bias is familiar to most studies of high-redshift objects: evolution. Specifically, as one looks further back in time, do the SNe Ia continue to behave the same way? While several programs have been created to measure, test, and constrain SNe Ia systematics, here we have explored an entirely independent and novel test of the cosmology inferred from SNe Ia: construction of SN IIP Hubble diagrams. The reasons for this are clear: SNe IIP are readily detected to $z \sim 0.4$, have recently been calibrated by a wide variety of methods, and are unlikely to be impacted by the same degree and direction of evolution as SNe Ia, thus providing an independent test of the accelerating Universe.

8 Cross-References

- ▶ [Electron Capture Supernovae from Super Asymptotic Giant Branch Stars](#)
- ▶ [Hydrogen-Rich Core-Collapse Supernovae](#)
- ▶ [Introduction to Supernova Polarimetry](#)
- ▶ [Light Curves of Type II Supernovae](#)
- ▶ [Supernova Progenitors Observed with *HST*](#)
- ▶ [The Progenitor of SN 1987A](#)

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