DISTANCE DETERMINATION TO EIGHT GALAXIES USING EXPANDING PHOTOSPHERE METHOD

SUBHASH BOSE AND BRIJESH KUMAR
Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263002, India; email@subhashbose.com, bose@aries.res.in

Received 2013 November 28; accepted 2013 December 30; published 2014 February 3

ABSTRACT

Type IIP supernovae (SNe) are recognized as independent extragalactic distance indicators; however, keeping in mind the diverse nature of their observed properties as well as the availability of good quality data, more and newer events need to be tested for their applicability as reliable distance indicators. We use early photometric and spectroscopic data of eight Type IIP SNe to derive distances to their host galaxies by using the expanding photosphere method (EPM). For five of these, the EPM is applied for the first time. In this work, we improved EPM application by using SYNOW estimated velocities and by semi-deconvolving the broadband filter responses while deriving color temperatures and blackbody angular radii. We find that the derived EPM distances are consistent with that derived using other redshift-independent methods.

Key words: distance scale – galaxies: individual (NGC 3184, NGC 6946, NGC 5194, NGC 3953, NGC 4303, UGC 2890, NGC 3389, NGC 3351) – supernovae: general – supernovae: individual (1999gi, 2004et, 2005cs, 2006bp, 2008in, 2009bw, 2012aw)

Online-only material: color figures

1. INTRODUCTION

The hydrostatic nuclear burning phases of massive stars with initial masses greater than about 8 $M_\odot$ result in an onion-skin-like stratification of nucleosynthesis yields as well as the unprocessed material consisting of iron core and successive zones of lighter elements up to helium and hydrogen (Arnett 1996; José & Iliadis 2011). It is understood that supernovae (SNe) explosions mark the end stages in the life of these stars (Heger et al. 2003; Smartt 2009), and the explosion results in the collapse of the iron core into a stellar mass compact object followed by shock-driven heating and expulsion of the outer stellar envelope, although the exact mechanism of the explosion and the chemical yields from explosive nucleosynthesis are not fully understood (Woosley & Weaver 1995; Janka 2012; Burrows 2013).

A majority of core-collapse events showing hydrogen lines in their optical spectra are classified as Type II SNe (Filippenko 1997), and their progenitors are thought to have retained enough hydrogen until the time of explosion. About 90% of all Type II events are subclassified as Type IIP (Smartt et al. 2009; Arcavi et al. 2010; Smith et al. 2011). The V-band light curves of Type IIP SNe are described by a fast rise (up to 10–15 days post explosion), a long plateau phase for about 100 days, which is sustained by the cooling down of shock-heated expanding ejecta by hydrogen recombination, and then an exponential decline powered by radioactive decay of newly formed $^{56}$Co (Bose et al. 2013). The study of pre-SN stars from the archival pre-explosion images undoubtedly proves that the progenitors of Type IIP SNe are red supergiant stars (Smartt et al. 2009; Poznanski 2013).

Observations of Type IIP SNe have been used to determine distances to their host galaxies by using the expanding photosphere method (EPM), which is a variant of Baade–Wesselink method, developed and implemented first by Kirshner & Kwan (1974) for two SNe. The EPM provides an estimate of cosmological distances, independent of the extragalactic distance ladder, and offers an alternative to verifying results obtained with other tools, e.g., SN Ia. Schmidt et al. (1992, 1994) applied EPM to several Type IIP SNe out to 180 Mpc to constrain the value of the Hubble constant ($H_0$). Eastman et al. (1996) quantified the dilution factors of SN atmospheres relative to the blackbody function and gave a firm theoretical foundation to the EPM. However, there have been discrepancies in the distances derived using the EPM, e.g., a value in the range of 7–8 Mpc is obtained for SN 1999em (Hamuy et al. 2001; Leonard et al. 2002a; Elmhamdi et al. 2003), while a value of 11.7±1.0 Mpc is derived using Cepheids (Leonard et al. 2003). Subsequently, the spectral-fitting expanding atmosphere method (seam) employing the full NLTE SN model atmosphere codes has been used to derive distances to SN 1999em (Baron et al. 2004; Dessart & Hillier 2006), and the estimated value was found to be in fair agreement with the Cepheid distance. However, the seam is computationally intensive and can only be applied to events having high signal-to-noise spectra at early phases. The EPM needs to be explored further.

Jones et al. (2009) derived EPM distances to 12 Type IIP SNe by using two sets of SN atmospheres, three filter subsets, and the photospheric velocity estimated from Doppler shifts of spectral lines, and they found a variation in EPM distances up to 50%, depending on the models and subsets used. Recently, Vinkó et al. (2012) applied the EPM to SNe 2005cs and 2011dh, both in M51 and both having densely sampled light curves and spectra, and they derived distance in good agreement with that in NED the database. Takáts & Vinkó (2012) applied the EPM to five Type IIP SNe and found that photospheric velocities estimated using SYNOW models of spectral lines are preferred.

Because of their high intrinsic luminosity, Type IIP SNe have been detected out to $z = 0.6$ and are expected to be more abundant at higher redshifts (Hopkins & Beacom 2006). After finding a correlation between plateau luminosity and the photospheric velocity, Hamuy & Pinto (2002) first established Type IIP SNe as standardizable candles. This standard candle method (SCM) is consistent with red supergiants as their progenitors. Using model light curves of Type IIP SNe, Kasen & Woosley (2009) gave a firm theoretical basis to the tight relationship between luminosity and expansion velocity, though they found a sensitivity to progenitor metallicity and mass. Olivares E. et al. (2010) applied the SCM to 37 nearby ($z < 0.06$) SNe with a relative distance precision of 12%–14%, though they
found systematic differences between distances derived using the EPM and SCM.

The observed midplateau properties of Type IIP SNe form a sequence from subluminous $M_V \sim -15$ mag, low-velocity $v \sim 2000$ km s$^{-1}$ to bright $\sim -18$ mag, high-velocity $\sim 8000$ km s$^{-1}$ events (Hamuy 2003). Recently, a spectroscopically subluminous IIP showing light curve properties similar to a normal luminosity event have also been observed, e.g., SN 2008in (Roy et al. 2011) and SN 2009js (Gandhi et al. 2013). Several bright events showing signs of circumstellar interaction have been observed, e.g., SNe 2007od (Inserra et al. 2011) and 2009bw (Inserra et al. 2012). The main factors governing the observed properties are the nature and environments of progenitors. In view of the diversity in the properties of Type IIP SNe, as well as the availability of good quality data for several events in the literature, more and newer events need to be tested for its applicability as reliable distance indicators. In this work, we extend the EPM analysis to eight Type IIP SNe, with sufficient early-time photometric and spectroscopic data to test the full applicability of the EPM and know the limitations and strength of the method.

The paper is organized as follows. The basic components of the EPM are briefly described in Section 2. The sample and data are given in Section 3. The EPM analysis, sources of errors, and results are presented and discussed in Section 4, followed by discussions on individual events and summary in Section 5.

2. METHOD

The EPM is fundamentally a geometrical technique (Kirshner & Kwan 1974; Schmidt et al. 1992), in which we compare the linear radii determined from the velocity of SN expansion with that of angular radii estimated by fitting the blackbody to the observed SN fluxes at different epochs. For extragalactic SNe, it is not possible to measure radii directly as they are seen as point sources; however, we may relate the linear radius $R$ and the angular radius $\theta$ as $\theta = R/D$, where $D$ is the distance to the SN. Furthermore, assuming a spherically symmetric expansion of the photosphere moving with velocity $v_{\text{ph}}$ at time $t$ and neglecting other deceleration factors such as gravity and the interstellar medium, we may write the above geometric relation as

$$ t = D \left( \frac{\theta}{v_{\text{ph}}} \right) + t_0, $$

where $t_0$ is the time of explosion. We use this linear equation to determine $D$ and $t_0$. Given $t_0$, we can estimate $D$ for each value of $\theta/v_{\text{ph}}$, and alternatively, the relation can also be solved to estimate unique values of $D$ and $t_0$. We note that for many SNe, the latter is not known with sufficient precision, and the method can also be used to get an independent estimate of $t_0$ as well as to test the consistency of the fitted parameters.

Thus, to derive the distance by the EPM, we only need values of $v_{\text{ph}}$ and $\theta$ at different $t$. The former is derived from low-resolution optical spectroscopic data, whereas the latter is estimated from broadband photometric data.

2.1. Determination of $v_{\text{ph}}$

The determination of the expansion velocity of an SN at the photosphere $v_{\text{ph}}$ at time $t$ is a nontrivial issue, and several approaches have been developed in the literature; see Takáts & Vinkó (2012) for a summary on the merits and demerits of various approaches. The photosphere represents the optically thick and ionized part of the ejecta that emits most of the continuum radiation as a diluted blackbody, and it is understood to be located in a thin spherical shell where the electron-scattering optical depth of photons is $2/3$ (Dessart & Hillier 2005). In Type IIP SNe, no single measurable spectral feature is directly connected with the true velocity of photosphere; however, during the plateau phase, it is best represented by blue-shifted absorption components of the P-Cygni profiles of Fe II at 4924 Å, 5018 Å and 5169 Å. In the early phases ($t \lesssim 10–15$ days) of SNe, the Fe II lines are either weak or absent, and in such cases the He I 5876 Å line can be used to estimate photospheric velocity with an accuracy of 2%–4% (e.g., Vinkó & Takáts 2007; Takáts & Vinkó 2006); however, at later phases ($t > 20$ days), He I lines disappear and Na I D lines start to dominate in the same spectral region. We can estimate velocities either by measuring the Doppler shift of the absorption minima using the splot task of the IRAF (denoted as $v_{\text{ph}}$) or by modeling the observed spectra with SYNOW ($v_{\text{ph}}$). We use both methods in this work.

SYNOW (Fisher et al. 1997, 1999; Branch et al. 2002) is a highly parameterized spectrum synthesis code with a number of simplified assumptions: a homologous expansion, a spherical symmetry, a line formation that is purely due to resonant scattering in which the radiative transfer equations are solved by Sobolev approximation, and the most important assumption—an LTE atmosphere with a sharp photosphere radiating like a blackbody. However, despite such simplified assumptions, the basic physics of the expanding photosphere is preserved, which gives rise to the P-Cygni profiles for each spectral line. As a result, the underlying continuum of the synthetic spectra will not match the observed ones because of the obvious fact that the physics of the continuum is significantly different and definitely not in LTE, but the P-Cygni profiles will be well reproduced in synthetic spectra that are directly related to the velocity of line formation layers. SYNOW also has the potential to reproduce line blending features in synthetic spectra, as in the case of the Fe II line, and these are moderately contaminated by other ions, with the Ba II, Sc II and Ti II ions being the most prominent. Takáts & Vinkó (2012) have compared the velocities determined from SYNOW and CMFGEN as the later model solves the NLTE radiation-transfer equations for expanding photosphere, and it has been shown that the velocities from each of these models are very much consistent with each other.

2.2. Determination of $\theta$

In order to determine $\theta$ at time $t$, we assume that the SN is radiating isotropically as a blackbody, and hence accounting for the conservation of radiative energy we may write

$$ f_{\lambda}^{\text{obs}} = \theta^2 \pi B_{\lambda}(T_c) 10^{-0.4A_{\lambda}}, $$

where $B_{\lambda}(T_c)$ is the Planckian blackbody function at color temperature $T_c$, $A_{\lambda}$ is the interstellar extinction, and $f_{\lambda}^{\text{obs}}$ is the observed flux.

In practice, the value of $f_{\lambda}^{\text{obs}}$ from the expanding photosphere of an SN has a significant departure from a true blackbody emission because the thermalization layer from which the thermal photons are generated is significantly deeper than the photospheric layer defining the last scattering ($r = 2/3$) surface. As a result, while comparing blackbody flux with that of $f_{\lambda}^{\text{obs}}$, the value of $\theta$ corresponds to the thermalization layer, whereas the value of $v_{\text{ph}}$ corresponds to the photospheric layer; therefore, to take care of this discrepancy, the “dilution factor” $\xi$ is
introduced (Wagoner 1981) as
\[ \xi = \frac{R_{\text{therm}}}{R_{\text{ph}}} \]
and we rewrite the Equation (2) as
\[ f_{\lambda}^{\text{obs}} = \xi^2 \theta^2 \pi B_{\nu}(T_c) 10^{-0.4A_{\lambda}}. \]

Here \( \xi \) is termed as the distance correction factor, since the distance derived without accounting for flux dilution will be overestimated by a factor of \( 1/\xi \). In principle, \( \xi \) depends on many physical properties, including the chemical composition and density profile of the ejecta. However, Eastman et al. (1996) have shown that \( \xi \) behaves more or less as a one-dimensional function of \( T_c \) only. The computation of \( \xi \) requires realistic SN atmosphere models, and to be compared with the blackbody model, this requires a high computing power and detailed physics of the SN atmosphere, which is beyond the scope of this paper. However, with the advent of faster and powerful computing, it is possible to execute such model codes. To date, two prescriptions for the dilution factor are available, independently by Eastman et al. (1996) and by Dessart & Hillier (2005) (hereafter D05). An improved estimate of \( \xi(T_c) \) based on the models of Eastman et al. (1996) was provided by Hamuy et al. (2001) (hereafter H01). In this paper, we use prescriptions of both H01 and D05.

In principle, the value of \( f_{\lambda}^{\text{obs}} \) should be obtained from accurate spectrophotometry. However, because of easy availability, it is derived from the photometric data taken using broadband filters. Consequently, the broadband filter response is inherently embedded within the quoted magnitudes. In order to remove the effect of the filter response in the observed flux \( f_{\lambda}^{\text{obs}} \) when compared with the blackbody model \( \pi B(\lambda', T_c) \) flux, we convolve the response function for each passband filter with the blackbody model to obtain the synthetic model flux. If \( \mathcal{R}_{\nu} (\lambda') \) is the normalized response function of a particular filter whose effective wavelength is \( \lambda \), then the convolved synthetic flux \( b_{\lambda} \) is
\[ b_{\lambda}(T_c) = \int_{0}^{\infty} \mathcal{R}_{\nu} (\lambda') \pi B(\lambda', T_c) d\lambda'. \]

Hence, the blackbody flux is replaced with the convolved blackbody flux \( b_{\lambda} \) for each filter, and Equation (2) is rewritten as
\[ f_{\lambda}^{\text{obs}} = \xi^2 \theta^2 b_{\lambda}(T_c) 10^{-0.4A_{\lambda}}. \]

In this paper, we adopted the response function \( \mathcal{R}_{\nu} \) for each of UBVRI filters from Bessell (1990).

In principle, we should be able to use all filter passband (UBVRI for optical) combinations to apply the EPM. However, in practice all passbands are not suitable for such a study; the fast decaying magnitude in the \( U \) band makes the SN too faint for good observations, so the \( U \) band is generally not included for the EPM. The \( R \) band is also unsuitable for the EPM because of contamination from the strong \( \text{H} \alpha \) emission in Type II SNe. Hence, only three filter combinations are available for the EPM study, viz., \{BV\}, \{BVI\}, and \{VI\}, in combination with two sets of dilution factors obtained from H01 and D05.

In reference to the preceding discussions, we are required to solve for \( \xi \) and \( T_c \). Hence, we construct \( X \) using Equation (6) and recast in terms of broadband photometric fluxes,
\[ X = \sum_{j=BVI} \left[ f_{\lambda}^{\text{obs}} - \xi^2 \theta^2 b_{\lambda}(T_c) 10^{-0.4A_{\lambda}} \right]^2. \]

On minimizing, we obtain the quantities “\( \theta \)” and “\( T_c \)” simultaneously; it should also be noted that \( \xi(T_c) \) is itself the function of \( T_c \). Thus, we separate out \( \theta \) by using the known \( \xi \) prescription for the particular filter combination used.

### 3. DATA

The sample of Type IIP SNe consists of two subluminous SNe 2005cs and 2009md; two normal-luminosity SNe 1999gi and 2012aw; three bright SNe 2004et, 2006bp, and 2009bw; and an intermediate luminosity SN 2008in that has peculiar characteristics. The basic properties of SNe and their host galaxies are given in Table 1. The time of explosion \( t_{\text{exp}} \) is determined from observational nondetection in optical bands and is constrained with an accuracy of a day for SNe 2005cs, 2004et, and 2012aw, whereas for the remaining SNe it is usually constrained by matching the spectra with the known templates of Type IIP SNe, and the accuracy lies between two and eight days. The total interstellar reddening \( E(B - V)_{\text{tot}} \) given in Table 1 includes combined reddening due to the Milky way and the host galaxy. For most of these SNe, the value of reddening is constrained quite accurately. Moreover, in this work, the values of extinction in different filters (required as input in Equation (7) and derived using adopted reddening) are estimated assuming the line-of-sight ratio of total-to-selective extinction \( R_v = 3.1 \), though a different reddening law toward the sightline of highly embedded SNe cannot be ruled out. We study the implication of the variation in reddening on the distance determinations in Section 4.

The criterion for selecting the present sample has been the availability of photometric and spectroscopic data on at least three phases by 50 days after explosion. We restricted the use of data for EPM analysis up to the phase 50 days, as the value of \( \xi \) depends on the color temperature and varies sharply below 5 K K, i.e., about 50 days post explosion for Type IIP SNe. The BVRI photometric data are collected from the literature, and Figure 1 shows the photometric data used in this paper. Barring SN 2009md, we have a dense coverage of early-time (<50 day) data for all the events. A typical photometric accuracy for events brighter than 15 mag is 0.02 mag, while for fainter events it is poorer.

We obtained the wavelength- and flux-calibrated spectra either from the SUSPECT\(^1\) database or from the corresponding authors of papers (see Table 1). A typical spectral resolution in the visible range of spectra lies between 5 and 10 Å (~300 to 600 km s\(^{-1}\)) at 5500 Å. For SN 2004et, we have also included six epoch spectra between +11 days and +16 days from Takáts & Vinkó (2012). The spectra were corrected for the respective recession velocity of their host galaxy before estimating the photospheric velocity. Table 2 provides values of photospheric velocities derived using both methods described in Section 2.1, i.e., \( v_{\text{pha}} \) and \( v_{\text{phs}} \). A detailed description of the SYNOW modeling of spectra and the determination of \( v_{\text{phs}} \) and its error followed in this work is given elsewhere (Bose et al. 2013). We briefly describe the method below. As we are only interested in obtaining the photospheric velocity, we fit the observed and synthetic spectra locally around \( \text{Fe} \, \text{II} \) lines (4923.93, 5018.44, and 5169.03 Å) within 4700 to 5300 Å, and in early phases where \( \text{Fe} \, \text{II} \) lines are not available we fit around the \( \text{HeI} \) 5876 Å line within 5500 to 6200 Å only, since employing the whole wavelength range may introduce an overestimation or underestimation of photospheric velocities.

\(^{1}\) http://nhn.nhn.ou.edu/~suspect/
uncertainty in deviation from the optimal value, and this is attributed to the 

Velocity derived using 

Notes.

Table 1

| ID (SN) | Host Galaxy | $v_{rec}$ (km s$^{-1}$) | $t_{ref}$ (JD) | $E(B - V)_{host}$ | $M_V$ | References |
|---------|-------------|------------------|---------------|-----------------|------|------------|
| SN 1999gi | NGC 3184 | 552 | 1518.2 ± 3.1 | 0.21 ± 0.09 | -16.3 | Leonard et al. (2002b) |
| SN 2004et | NGC 6946 | 45 | 3270.5 ± 0.9 | 0.41 | -17.1 | Sahu et al. (2006); Takáts & Vinkó (2012) |
| SN 2005cs | NGC 5194 | 463 | 35.90 ± 1.0 | 0.05 ± 0.02 | -15.1 | Pastorello et al. (2006, 2009); Baron et al. (2007) |
| SN 2006bp | NGC 3953 | 987 | 3834.5 ± 2.0 | 0.40 | -17.1 | Immler et al. (2007); Quimby et al. (2007) |

Notes. The columns are (1) identification of SN; (2) identification of supernova host-galaxy; (3) recession velocity of the galaxy used for Doppler correction; (4) the reference epoch in JD since 2450000.0, these are adopted explosion epoch from corresponding literature; (5) the total reddening $E(B - V)_{host}$ toward the line of sight of SN; (6) approximate absolute visual magnitude at $t_{ref}$; (7) references for $t_{ref}$, $E(B - V)_{host}$, $M_V$, and the photometric and spectroscopic data.

Table 2

| Phase | $v_{pha}$ | $v_{phs}$ |
|-------|---------|---------|
| 4.7* | 13.20 ± 0.30 | 12.79 |
| 6.8* | 10.30 ± 0.40 | 11.09 |
| 7.8* | 10.00 ± 0.40 | 11.07 |
| 30.7 | 4.85 ± 0.07 | 5.18 |
| 35.7 | 4.20 ± 0.10 | 4.67 |
| 38.7 | 4.05 ± 0.10 | 4.47 |
| 89.6 | 1.60 ± 0.20 | 2.78 |

Notes. Velocity derived using vsysow is denoted as $v_{pha}$, whereas by locating the absorption trough as $v_{phs}$. The phases are expressed in days with reference to the $t_{ref}$ adopted in Table 1, while velocities are given in units of $10^3$ km s$^{-1}$. Velocities at phases marked with asterisks are estimated using He i lines.

as different lines form at different layers. After attaining the optimal fit of observed spectra locally, we only vary model parameter $v_{ph}$ to get an eye estimate of the maximum possible deviation from the optimal value, and this is attributed to the uncertainty in $v_{ph}$ for that spectrum. We note that P-Cygni profiles are quite sensitive to $v_{ph}$, hence the best fits are easily attainable through eye inspection. The typical uncertainty in velocities estimated by deviation seen visually from best-fit absorption troughs varies between 50 and 500 km s$^{-1}$ with a typical value of ~150 km s$^{-1}$. This is consistent with the values obtained using automated computational techniques, viz., $\chi^2$-minimization and cross-correlation methods employing all spectra (Takáts & Vinkó 2012). A comparison of $v_{pha}$ and $v_{phs}$ is also made, and deviations as large as 1000 km s$^{-1}$ are seen
in early spectra for a few SNe, while random deviations are apparent at later epochs to the level of quoted uncertainty. We study the implication of using these velocities on the distance determinations in Section 4.

4. EPM ANALYSIS

At each \( t \) for which photometric data is available, we derive the value of \( \theta \) for three sets of filter combinations and for two sets of \( \xi \) prescriptions. Wherever spectroscopic data do not coincide with the epoch photometric data point, the value of \( v_{\text{ph}} \) at \( t \) is derived by a polynomial interpolation of the third or fourth order. It is noted here that in comparison to photometry, spectroscopy derived by a polynomial interpolation of the third or fourth order.

The source of error in \( v_{\text{ph}} \) is random in nature, and the relative error in it varies between 2% and 5%, whereas in \( \theta \) it varies between 5% and 10%. While interpolating velocities at desired photometric epochs, the errors are estimated by the Monte Carlo method with a sample size of 1000. For the final EPM fit, the error in \( \theta/v_{\text{ph}} \) is propagated from \( \theta \) and \( v_{\text{ph}} \), and the weighted least-squared fitting is performed to estimate distance and explosion epoch. The error in finally derived distance for each filter subset is estimated by Monte Carlo technique with a sample size of 1000.

It can be seen from Table 3 that for each prescription, we derive three sets of \( D \) and \( t_0 \), corresponding to each of the three filter sets. Barring SN 2009bw, the values of \( D \) and \( t_0 \) for each of the filter sets are consistent within uncertainties. Therefore, we combine individual distances and explosion epochs derived for each filter set to compute the mean values of \( D \) and \( t_0 \) for D05 and H01 \( \xi \) prescriptions. The quoted uncertainty in the mean values is the standard deviation of the values obtained for the three filter sets, and it can be seen that statistical errors in the mean value are consistent with the errors derived in individual filter sets, barring the case of SN 2009bw that has deviant values for the VI set. It can be noted that the relative precision with which EPM distances are derived for either of the atmosphere models (D05 or H01) lies between 2% and 13%, with a median value of 6%.

Another source of error in \( D \) and \( t_0 \) is the value of \( E(B - V) \). Although we have taken its value from literature and adopted values derived using the most reliable method, its precise determination is extremely difficult, and it can introduce
systematic errors in the determination of EPM distance. We have studied the effect of \( E(B - V) \) for SN 2012aw by varying its value for each filter subset. Figure 13 shows the variation of EPM distance and explosion epoch with \( E(B - V) \). The variation of distance differs significantly among each filter subset; however, the overall variation in distance is not very significant. In order to further study the effect of \( E(B - V) \) variation on the EPM results for each SNe, we derive mean distances and explosion epochs with the upper and lower limit of \( E(B - V) \) and tabulate them in Table 4. We took this approach to estimate deviations of EPM results from corresponding \( E(B - V) \) errors because of its systematic dependence on analysis, and we found that it would have been inappropriate to propagate \( E(B - V) \) errors all throughout the analysis. It is noted here that EPM results have a nonlinear dependence on the \( E(B - V) \) and thus the resulting tabulated errors are asymmetric. The relative variation in \( D \) is found to lie between 0% and 9%, with a median value of 5%.

Table 3 compares the mean value of distances with host galaxies that are taken from NED and are derived using redshift-independent methods, such as Cepheid, Tully–Fisher, SCM, and surface brightness fluctuation, with those derived using the EPM. The comparison clearly illustrates that the distance derived using the D05 prescription is in better agreement with the NED ones, whereas the ones using the H01 prescription are systematically lower in each of the cases. Similar systematic differences in the two atmosphere models (D05 and H01) have also been reported in the EPM implementation to 12 Type IIP SNe by Jones et al. (2009).

For D05 models, a comparison of distances derived using \( v_{phys} \) and \( v_{phs} \) (see Table 6) indicate that, barring a few cases, there is notable difference in both of the value of distances. For SN 2005cs and 2009md, the difference is as high as 18% and 15%, respectively; for SN 1999gi, 2004et, and 2009bw, the values differ by 6% to 9%. However, for SN 2006bp, 2008in, and 2012aw, the difference is quite negligible and lies between 0% and 3%, which is within the internal precision of both values. The EPM analyses of the individual cases are discussed in Section 5.
Table 5

| Host Galaxy | Supernova Event | \( D_{\text{EPM}} \) (Mpc) | \( D_{\text{NED}} \) (Mpc) |
|-------------|----------------|----------------|----------------|
| NGC 3184    | SN 1999gi      | 11.62 ± 0.29  | 11.95 ± 2.71 |
| NGC 6946    | SN 2004et      | 5.86 ± 0.76   | 5.96 ± 1.97  |
| NGC 5194    | SN 2005cs      | 7.97 ± 0.55   | 7.91 ± 0.87  |
| NGC 3953    | SN 2006bp      | 18.82 ± 1.04  | 18.45 ± 1.60 |
| NGC 4303    | SN 2008in      | 14.51 ± 1.38  | 16.46 ± 10.8 |
| UGC 2890    | SN 2009bw      | 15.93 ± 0.32  | ...          |
| NGC 3389    | SN 2009md      | 23.29 ± 1.96  | 21.29 ± 2.21 |
| NGC 3351    | SN 2012aw      | 9.83 ± 0.41   | 10.11 ± 0.98 |

Notes. \( D_{\text{NED}} \) denote distances to host galaxies as collected from \texttt{ned} (http://ned.ipac.caltech.edu) and derived using redshift-independent methods (see Section 4). \( D_{\text{EPM}} \), taken from Table 5, denote EPM distances derived using D05 atmosphere model and SYNOW-derived velocities \( v_{\text{phs}} \). For SNe 2004et and 2012aw, the distance are with fixed \( t_0 \).

Table 6

| SN Event | \( D_{\text{phs}} \) (Mpc) | \( D_{\text{phs}} \) (Mpc) |
|----------|----------------|----------------|
| SN 1999gi | 11.62 ± 0.29  | 12.72 ± 0.47  |
| SN 2004et | 5.41 ± 1.00   | 4.96 ± 0.88   |
| SN 2005cs | 7.97 ± 0.55   | 6.56 ± 0.42   |
| SN 2006bp | 18.82 ± 1.04  | 18.13 ± 1.18  |
| SN 2008in | 14.51 ± 1.38  | 14.52 ± 1.39  |
| SN 2009bw | 15.93 ± 0.32  | 16.92 ± 0.62  |
| SN 2009md | 23.29 ± 1.96  | 26.84 ± 3.78  |
| SN 2012aw | 11.27 ± 0.88  | 11.27 ± 0.92  |

Notes. \( D_{\text{phs}} \) denote EPM distances derived using SYNOW model velocities, i.e., \( v_{\text{phs}} \), whereas, \( D_{\text{pha}} \) denote the ones derived by locating the absorption minima of Fe II lines, i.e., \( v_{\text{pha}} \). For consistency, the D05 prescription and unconstrained explosion epoch have been used for all the cases.

5. DISCUSSIONS

In the following, we will discuss results for each of the events and any anomalies that are found in the results.

**SN 1999gi.** The photometric and spectroscopic data are taken from Leonard et al. (2002b), and the EPM fitting is shown in Figure 2. For the H01 \( \xi \) prescription, we derived a distance of 8.87 ± 0.34 Mpc, whereas Leonard et al. (2002b) and Jones et al. (2009) derived values of 11.1 ± 2.0 Mpc and 11.7 ± 0.8 Mpc, respectively. We attribute a lower value of distance in our case to the method adopted in this work, i.e., velocity estimates using SYNOW, which is significantly different in some epochs, and the filter response deconvolution in the spectral energy distribution (SED) fitting, as well as the lower number of data points available for SN 1999gi. Removing the first photometric point, our EPM implementation yields a value of \( \sim 10 \) Mpc.

For the D05 prescription, we derived a value of 11.62 ± 0.29 Mpc, whereas Jones et al. (2009) derived a value of 17.4 ± 2.3 Mpc. It is noted that the latter have excluded the first spectroscopic data point and have used the spectroscopic epochs for EPM fitting, in contrast to photometric epochs used in the present work, see Section 4. Our estimate for D05 is in good agreement with the other redshift-independent estimate, see Table 5.

**SN 2004et.** We used 21 epochs of photometric data taken from Sahu et al. (2006) and Takáts & Vinkó (2012) to derive the EPM distance. For this event the time of explosion is determined observationally with an accuracy of a day, and hence an EPM fitting is attempted and shown with \( t_0 \) as free and fixed parameters, respectively, in Figures 3 and 10. For the D05 prescription, we derive an EPM distance of 5.41 ± 1.00 Mpc and 5.86 ± 0.76 Mpc, respectively, which are consistent with each other as well as with the host galaxy distances derived using other methods. For the former, \( t_0 \) is estimated as 1.96 ± 2.35 days, which is also consistent with the time of explosion adopted from literature (\( t_{\text{ref}} \)). Takáts & Vinkó (2012) derived an EPM distance of 4.8 ± 0.6 using D05 prescriptions and SYNOW velocities.

However, it is noted that the \( \{VI\} \) fit is quite inconsistent in comparison to the \( \{BV\} \) and \( \{BVI\} \) sets. In order to understand this discrepancy, we looked into the possibility of a lower value of \( E(B-V) \). Sahu et al. (2006) stated that they found an equivalent width of 1.7 Å for Na ID from low-resolution spectra, which corresponds to total \( E(B-V) = 0.43 \) mag, employing an empirical relation of Barbon et al. (1990). On adopting a similar empirical relation by Turatto et al. (2003), which we find more convincing, we arrive at a much lower value of \( E(B-V) \) which is 0.26 mag. Being backed by this possibility of lower \( E(B-V) \), we rederive EPM distances considering only the Galactic reddening value of 0.29 mag (Schlafly & Finkbeiner 2011) and arrive to EPM distances 5.59, 5.65, and 10.8 Mpc, respectively, which are fairly consistent with each other. Despite favorable results with lower \( E(B-V) \), we cannot rule out the higher value of \( E(B-V) \approx 0.40 \) mag, which was derived by Zwitter et al. (2004) using high resolution spectra.

![Figure 3](https://example.com/figure3.png)

(A color version of this figure is available in the online journal.)
SN 2005cs. We have used 14 epochs of spectroscopic data and 22 epochs of photometric data from Pastorello et al. (2006, 2009). This is another event for which the explosion epoch is constrained observationally within a day, hence we have done the fitting by keeping $t_0$ as free (Figure 4) as well as fixed (Figure 11). We obtain a distance of 7.97 ± 0.55 Mpc and 7.49 ± 0.14 Mpc, respectively. In the case of free $t_0$, we arrived at an explosion epoch of −0.87 days, which is well within uncertainty and consistent with that known observationally. Hence, in this case, it is absolutely unnecessary to fix the explosion epoch.

The EPM has been applied to this SN (Takáts & Vinkó 2006), and a distance of 7.1 ± 1.2 Mpc has been determined. However, for this $E(B - V) = 0.11$ has been used, and the value of reddening was updated to 0.05 by Pastorello et al. (2009), which we adopt in our work; this accounts for the higher value of $D$ estimated in this work. Vinkó et al. (2012) has presented an improved distance estimate of 8.4 ± 0.7 Mpc for the host galaxy M51 by applying the EPM on both 2005cs and 2011dh. Another EPM estimate for the SN has been presented by Dessart et al. (2008), in which they derived a distance of 8.9 ± 0.5 Mpc. Both of these EPM estimates are in good agreement with our results.

SN 2006bp. Photometric data presented by Quimby et al. (2007) is available for the $UBVri$ filter, but because of the lack of $\xi$ prescriptions for Sloan Digital Sky Survey filter, viz., $\{BVi\}$ or $\{VI\}$, $\{rt\}$ data may not be directly used. Therefore, we have carried out an EPM analysis using the $\{BV\}$ subset only, and the results are shown in Figure 5. For the D05 $\xi$ prescription, we derived a distance of 18.82 ± 1.04 Mpc. Dessart et al. (2008) has also applied the EPM to the SN, in which they estimated the distance using a recomputed set of dilution factors and obtained a distance of 17.5 ± 0.8 Mpc, which is consistent with our estimate within the limit of errors.

SN 2008in. We used photometric data at 21 epochs from Roy et al. (2011) to estimate the EPM distance. The spectroscopic coverage of the event is not very good, especially within +50 days, and hence we had to largely rely upon interpolation (see Table 2). It is noteworthy to mention that we found the velocity profile of the event to be quite less varied, and overall velocities are much less than other normal type events. This is also supported by the fact that it is classified as spectroscopically subluminous (Roy et al. 2011). The EPM fitting is shown in Figure 6, and we derive a distance of 14.51 ± 1.38 Mpc and $t_0 = −4.97 ± 1.91$ days for the D05 prescription. Utrobin & Chugai (2013) has estimated the explosion epoch for this event using hydrodynamical modeling and estimated an explosion epoch nearly four days prior to our adopted reference epoch, thus showing a very good agreement with EPM estimated $t_0$.

SN 2009bw. Figure 7 shows the EPM fitting for this event. It is noted that even though we had photometric data starting from +5 days (see Figure 1), because of single spectra at +4 days and the unavailability of any other spectra before +18 days, we could only include data points within +10 to +50 days for the EPM fit. This was necessary to do because in the early phase the velocity profile is quite steeper than later phases, and thus in such phases the velocity interpolation might go wrong because of the fewer number of spectroscopic data.
Using both dilution factor prescriptions, we find that the distances derived using band sets \{BV\} and \{BVI\} are very much consistent with each other, whereas the distance derived using the \{VI\} subset is significantly higher and the explosion epoch is also very off (see Table 3). Thus, the EPM fit of the \{VI\} subset is quite inconsistent with the rest of two band sets, and the explosion epoch is not consistent with the SN age estimated from spectra and light curve evolution. This particular inconsistency can be justified by the fact that \{VI\} band sets are at the cooler ends of the SED as compared with the \{BV\} and \{BVI\} band sets. As in the early phase, the SED is hotter, and the estimation of the SED parameters, viz., $\theta$ and temperature, using the \{VI\} band set will be more prone to errors if the photometric magnitude uncertainty is significant as in the literature data of SN 2009bw.

Using the D05 prescription, we derive a distance of $15.93 \pm 0.32$ Mpc. Tully et al. (2009) derive a distance of 11.1 Mpc to the host galaxy using the Tully–Fisher method. No other redshift-independent distance estimate is available for this galaxy. However, we note that Inserra et al. (2012) adopted a distance of 20.2 Mpc based on the redshift of the galaxy.

SN 2009md. Figure 8 shows the EPM fit for this event. Extremely large errors in $\theta/v_{ph}$ quantity can be noted and are attributed entirely to large photometric errors, as errors in photometric magnitudes have amplified exponentially in fluxes and propagated all throughout to $\theta/v_{ph}$ quantities. Using the D05 prescription, we obtained a distance of $23.29 \pm 1.96$ Mpc and a time of explosion of $4.15 \pm 1.97$ days. Fraser et al. (2011) has applied the SCM to this event and derived a distance of 18.9 Mpc using optical data and of 21.2 Mpc using near infrared data.
Figure 9. Same as Figure 2, but for SN 2012aw.
(A color version of this figure is available in the online journal.)

Figure 10. Same as Figure 2, but for SN 2004et with fixed explosion epoch at JD 2453270.5.
(A color version of this figure is available in the online journal.)

Figure 11. Same as Figure 2, but for SN 2005cs with fixed explosion epoch at JD 2453549.0.
(A color version of this figure is available in the online journal.)

For this case, the EPM result is consistent with that derived using the SCM.

SN 2012aw. This is a well-studied nearby event. The explosion epoch is known to be fairly accurate with an error of ±0.79 days (see Bose et al. 2013 and references therein). Figure 12 and Figure 9 show the EPM fit, respectively, with fixed and free $t_0$. For the D05 prescription, we derive a distance of $9.83 \pm 0.41$ Mpc and $11.27 \pm 0.88$ Mpc with explosion $t_0 = -2.36 \pm 0.75$. No previous EPM study exists for the galaxy NGC 3351, but recent Cepheid (Freedman et al. 2001) and Tully–Fisher (Russell 2002) distance estimates are in good agreement with our result.

6. SUMMARY

In this study, we present EPM distances for eight host galaxies, derived using photometric and spectroscopic data of Type IIP SNe. The SNe have midplateau absolute V magnitudes in the range of $-17$ to $-15$. A detailed EPM analysis is performed for five of the events, viz., SN 2004et, 2008in, 2009bw, 2009md, and 2012aw, for the first time. We use two dilution factor models, three filter subsets, and two methods for photospheric velocity determination. The values of reddening are known quite accurately, and for a few of the events the explosion epochs are constrained observationally with an accuracy of a day. We find that EPM-derived distances using the two models above differ by 30% to 50%. The EPM distances derived using Hamuy’s model (Hamuy et al. 2001) are found to be systematically lower...
than that of Dessart ones (Dessart & Hillier 2005). For all the events in our sample, the distances using the Dessart model is found to be consistent with that derived using other redshift-independent methods, i.e., Tully–Fisher, SCM, Cepheid, and surface brightness fluctuation. We also note that the EPM method is applicable only to the early (<50 day) photometric data of SNe.

We have also studied the effects of two methods of velocity estimation on the derived distance. It is found that SYNOW model velocities are significantly different than those estimated by locating the absorption trough of P-Cygni. The distances derived from two different velocity determination methods have notable differences as high as 15% to 18%; however, we did not find any systematic trend of this difference. This suggests the difference is the direct effect of the measurement error of the absorption minima method when the photospheric lines are blended or weak relative to continuum.

We thank M. Fraser, C. Inserra, A. Pastorello, and K. Takats for providing their respective spectra of SN 2009md, SN 2009bw, and SN 2005cs and early spectra of SN 2004et. Their invaluable contribution has helped immensely for the preparation of this work and for enriching our sample of SNe. We gratefully acknowledge the services of the NASA ADS and NED databases and also the online supernova spectrum archive (SUSPECT), which are used to access data and references in this paper. Authors are also thankful to the referee whose thoughtful comments and suggestions have significantly improved this work.
