

Distance determination to six nearby galaxies using type IIP supernovae.

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Abstract. We use early optical photometric and spectroscopic data of six Type-IIP SNe to derive distances to their host galaxies using the expanding photosphere method (EPM). Our sample consists of luminous to sub-luminous SNe 1999gi, 2004et, 2005cs, 2008in, 2009md and 2012aw; having absolute V-magnitudes from -17 to -15 and host galaxy distances from 5 to 22 Mpc. The SN 2008in is peculiar in nature showing dual behavior of a luminous as well as sub-luminous event. The EPM distances for four of the events in our sample are derived for the first time. We take utmost care in minimizing the errors arising from photospheric velocity determination and the broadband filter responses, hence leaving out uncertainty in dilution factor models as the only major source of error. Our preliminary results indicate that EPM-derived distances using Dessart model is found to be consistent with the distances quoted in the literature. We find that EPM method is applicable only to the early (<50 d) photometric data of supernovae and dense spectroscopic data is necessary to estimate accurate distances.

Keywords. galaxies: distances and redshifts, (stars:) supernovae: general,(stars:) supernovae: individual (2012aw, 2004et, 2005cs, 2008in, 2009md, 1999gi)

1. Introduction

Supernovae owing to their high luminosity, are the objects of interest for extragalactic distance estimation. Type II supernovae are not used traditionally as standard candles for distance measurement. However, in case of type II-P SNe, assuming spherically symmetric expansion of their ejecta and radiating isotropically as a blackbody at a well defined temperature, we can apply the Expanding Photosphere Method (EPM; Kirshner & Kwan 1974) a variant of Baade-Wesselink method to determine distances to their host galaxies.

1.1. Expanding Photosphere Method

The EPM is fundamentally a geometrical technique, in which we compare the linear radii determined from the expansion velocity and angular radii of the supernova by fitting blackbody with the observed fluxes at different epochs.

Assuming homologous expansion, we may relate photospheric velocity v_{phot} , angular radius θ and distance D at time t and t_0 be the explosion epoch, we may write

$$\theta = \frac{v_{phot}(t - t_0)}{D} \tag{1.1}$$
$$t = D \left(\frac{\theta}{v_{phot}} \right) + t_0$$

Hence we get a linear equation, whose slope yields the distance to SN (D) and the y -intercept as the explosion epoch (t_0).

To determine θ we assume SN radiating isotropically as blackbody and accounting for the conservation of radiative energy we may write,

$$4\pi R^2 \cdot \pi B_\lambda(T_c) = 4\pi D^2 f_\lambda^{dered} \tag{1.2}$$

where $B_\lambda(T_c)$ is Planck Blackbody function at color temperature T_c and f_λ^{dered} is the extinction corrected (de-reddened) observed flux. Absorbing the R and D into θ we may write,

$$f_\lambda^{dered} = \theta^2 \pi B_\lambda(T_c) \quad (1.3)$$

Now introducing the wavelength dependent extinction A_λ and writing in terms of observed flux f_λ ,

$$f_\lambda = \theta^2 \pi B_\lambda(T_c) 10^{-0.4A_\lambda} \quad (1.4)$$

On minimizing the above equation with two or more known observed fluxes f_λ^{obs} and the Planckian blackbody model function we can determine the angular radius θ and the color temperature T_c both together. Thus to derive distance by EPM, all we need are observed flux f_λ and photospheric velocity v_{phot} .

One of the most important assumption that goes into EPM, is to consider the expanding photosphere radiating as blackbody. There might be a significant departure from a blackbody atmosphere and this will be directly reflected into the distance estimated by EPM. The thermalization layer from which the thermal photons are generated is significantly deeper than photospheric layer from which photons start to flow freely without any further scattering (i.e. the surface of last scattering at $\tau = \frac{2}{3}$), to take care of this discrepancy, we use ‘‘dilution factor’’ ξ as

$$\xi = \frac{R_{therm}}{R_{phot}} \quad (1.5)$$

and rewrite the equation (1.4) as,

$$f_\lambda = \xi^2 \theta^2 \pi B_\lambda(T_c) 10^{-0.4A_\lambda} \quad (1.6)$$

In principle this factor should depend upon many physical properties including chemical properties, density profile of the SNe etc. However, studies have shown (Eastman *et al.* 1996) that ξ more or less behaves as one-dimensional function of color temperature, T_c only. The computation of ξ requires realistic SN atmosphere models. Till date, two prescription for dilution factors are available, Hamuy *et al.* (2001) (hereafter H01) which is improved estimate of ξ over Eastman *et al.* (1996) used 63 stellar atmospheric models, whereas the other Dessart & Hillier (2005) (hereafter D05) which uses CMFGEN models for SN to determine ξ for different filter pass-band combinations.

In order to improve the accuracy of our study, we used SYNOW (Branch *et al.* 2001, Branch *et al.* 2001, Elmhamdi *et al.* 2006) to model the spectra for each of the event to determine their photospheric velocities v_{phot} at different phases. Further to remove the effect of filter response which is intrinsically embedded in observed flux, we convolve the response function $\mathfrak{R}_\lambda(\lambda')$ for each pass-band filter with the blackbody model to obtain the synthetic model flux. be the normalized response function of a particular filter whose effective wavelength is λ , then the convolved synthetic flux b_λ is,

$$b_\lambda(T_c) = \int_0^\infty \mathfrak{R}_\lambda(\lambda') \pi B(\lambda', T_c) d\lambda' \quad (1.7)$$

Hence in the equation 1.6, the blackbody flux is replaced with convolved blackbody flux b_λ for each filter and rewritten as,

$$f_\lambda = \xi^2 \theta^2 b_\lambda(T_c) 10^{-0.4A_\lambda} \quad (1.8)$$

Table 1. Adopted parameters

SN	E(B-V)	Reference epoch (JD)	Recession Velocity ($km\ s^{-1}$)
SN1999gi	0.21	2451518.3 ± 3.1	552
SN2004et	0.41	2453270.5 ± 0.9	45
SN2005cs	0.05	2453549.0 ± 1.0	463
SN2008in	0.098	2454825.6 ± 2.0	1567
SN2009md	0.1	2455162.0 ± 8.0	1308
SN2012aw	0.075	2456002.6 ± 0.8	778

Table 2. Table of derived EPM distances to host galaxies and comparison with NED result.

Host galaxy	SN event	EPM Distance ^a Mpc	Distance Modulus	NED Distance ^b Mpc
NGC 3351/M95	SN 2012aw	9.83 ± 0.41	29.96 ± 0.09	10.11 ± 0.98
NGC 6946	SN 2004et	5.86 ± 0.76	28.84 ± 0.28	5.96 ± 1.97
NGC 3184	SN 1999gi	11.62 ± 0.29	30.33 ± 0.05	11.95 ± 2.71
NGC 4303/M61	SN 2008in	14.51 ± 1.38	30.81 ± 0.21	16.46 ± 10.84
NGC 5194/M51a	SN 2005cs	8.01 ± 0.62	29.52 ± 0.17	7.91 ± 0.87
NGC 3389	SN 2009md	23.29 ± 1.96	31.84 ± 0.18	21.29 ± 2.21

^aEPM distances are using D05 prescription.

^bNED (<http://ned.ipac.caltech.edu/>) distance is mean value of all redshift independent distances listed in NED for the galaxy. Errors are the STD DEV of the listed distances.

2. Sample selection and data

For the EPM study we select a sample of six recent II-P SNe viz., 1999gi (Leonard *et al.* 2002), 2004et (Sahu *et al.* 2006), 2005cs (Pastorello *et al.* 2006, Pastorello *et al.* 2009), 2008in (Roy *et al.* 2011), 2009md (Fraser *et al.* 2011) and a very recent event 2012aw (in preparation Bose *et al.*); which comprises of normal to sub-luminous type events having good photometric and spectroscopic follow-up including early plateau phase. Among these, 1999gi, 2004et and 2012aw are normal events; 2005cs and 2009md are sub-luminous whereas 2008in lies in between normal and sub-luminous II-P events. The adopted parameters from literature are tabulated in Table 1, $E(B - V)$ are used to de-redden corresponding photometric and spectroscopic data, *Recession velocity* are used to doppler correct spectra and *reference epoch* are the explosion epochs adopted in corresponding literature, in reference to these epochs we independently estimate explosion epochs from EPM.

3. Preliminary Results

EPM is applied to each of these six events and corresponding distance and explosion epoch are determined for each set of dilution factor models viz., D05 and H01 with each of three filters subsets BV , BVI and VI . For the SNe 2012aw, 2005cs and 2004et, EPM is also applied by fixing explosion epochs to their observationally constrained explosion epochs having accuracy less than a day and thus keeping Distance as the only free parameter for EPM fit. Figure 1 is the EPM fit for SN 2012aw with both explosion epoch and distance, while the Figure 2 is the EPM fit with fixed explosion epoch having distance as only free parameter. Similar EPM fits are done for all other events and

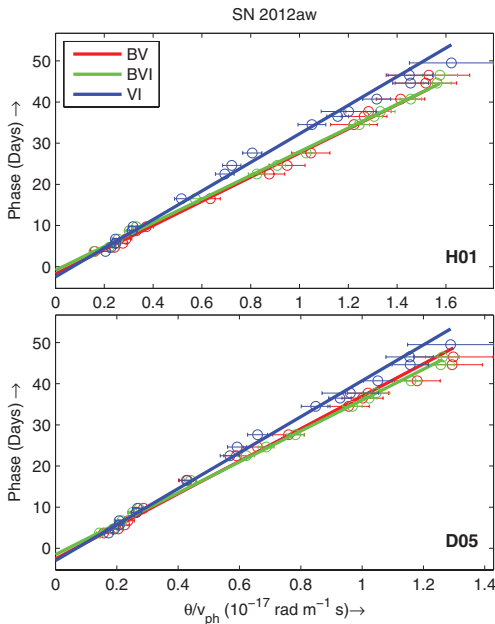


Figure 1. EPM fitting for SN 2012aw using both D05 and H01 prescriptions.

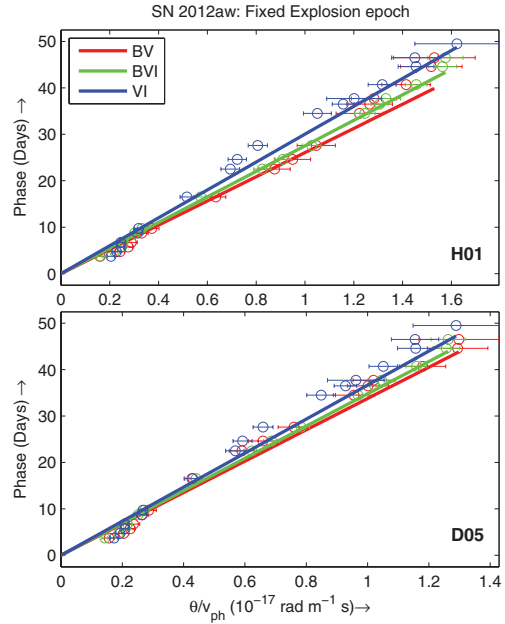


Figure 2. EPM fitting for SN 2012aw using both D05 and H01 prescriptions with fixed explosion epoch and Distance as the only free parameter.

EPM determined distances using D05 prescription are tabulated in Table 2 (a detailed analysis is in preparation, Bose *et al.*). The EPM distances using D05 are found to be more consistent than those by H01 with NED listed distances for corresponding galaxies.

4. Conclusion

The D05 prescription of dilution factors are found to be more suitable and accurate for EPM analysis. Also the SYNOW derived photospheric velocities significantly improve the accuracy of distance determination.

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Discussion

BERSTEN: Have you compared your results of distance and t_{pxp} with the paper of Jones *et al.* 2010. In this paper they used the same atmospheric models that you use in this work (DO5)? It would be very interesting to know how the results compare.

BOSE: No, we haven't compared with this particular paper, however, the mean of redshift independent distances from NED, with which we compare our result, some has SEAM distances included also. Moreover SEAM and EPM are quite different in terms of technique used, in SEAM, dilution factors are not used separately, since the SED used in this case is not LTE approximation, the SED used in SEAM, itself taken into account the non-LTE atmosphere of SN. However the comparison of these two methods will be interesting.

FOLLATELLI: Have you computed H_0 based on your distances?

BOSE: Our sample is quite small. Only comprising of 6 events, hence it cannot be used to construct Hubble diagram. Furthermore, 5 of the events are nearby (<15 Mpc). Thus it is not suitable to compute H_0 from this sample. However, in future more EPM based new studies will be added to this sample and may be used to compute H_0 .