Type IIP Supernovae as Cosmological Probes: A SEAM Distance to SN 1999em

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Abstract

Due to their intrinsic brightness, supernovae make excellent cosmological probes. The realization that Type Ia supernovae (SNe Ia) could be used as correctable candles led to the discovery of the dark energy by two independent groups. Several searches are planned to discover SNe Ia both nearby and at high redshift. While these programs will reduce systematics in the SNe Ia sample and lead to important results on the cosmic equation of state, having an independent method is important to lend confidence in the results. We describe the SEAM method for obtaining distances to Type IIP supernovae (SNe IIP) and present a distance to SN 1999em for which a Cepheid distance exists. Our models give results consistent with the Cepheid distance, even though we have not attempted to tune the underlying hydrodyamical model, we have simply chosen the best fits. This is in contradistinction to the expanding photosphere method (EPM) which yields a distance to SN 1999em that is 50% smaller than the Cepheid distance. We emphasize the differences between SEAM and EPM. Since SNe IIP are visible to redshifts as high as $z \lesssim 6$, with the *JWST*, SEAM may be a valuable probe of the early universe.

DISTANCES FROM SUPERNOVAE

Determining accurate distances is a "Holy Grail" of astronomy and particularly cosmology. In order to determine the values of the fundamental cosmological parameters, an accurate distance indicator visible to high redshift is required. Supernovae are extremely bright and hence can be detected at cosmological distances with modern large telescopes. Due to their homogeneity, SNe Ia had long been thought of as as good distance indicators since they roughly meet the astronomer's definition of a "standard candle", that is that the luminosity at peak $L_{\rm max}$ is approximately constant. Two Key Projects[1, 2] on the Hubble Space Telescope (*HST*) were awarded to use Cepheid variable stars to determine distances to the Virgo cluster and to determine the Hubble constant to 10% accuracy. An additional aim of the program of Sandage and collaborators[2] was to calibrate the luminosity of SNe Ia by obtaining Cepheid distances to galaxies which also were the hosts of SNe Ia. Distances obtained using Cepheids are considered to be the among the most reliable in astronomy (purely trigonometric methods cannot be used at distances in the Hubble flow), but they are not free of systematic errors and Cepheids are too dim to be observed at large distances. The reliability of SNe Ia as distance indicators improved significantly with the realization that the luminosity at peak was correlated with the width of the light curve[3] and hence that SNe Ia were correctable candles in much the same way that Cepheids are[4–6]. This work and the development of highly efficient search strategies[7] sparked two groups to use SNe Ia to measure the deceleration parameter and to discover the dark energy[8, 9].

All of the work with SNe Ia is empirical, based on observed SNe Ia template light curves. Another method of determining distances using supernovae is the "expanding photosphere method" (EPM)[10–13] a variation of the Baade-Wesselink method[14]. The EPM method assumes that for SNe IIP, with intact hydrogen envelopes, the spectrum is not far from that of a blackbody and hence the luminosity is approximately given by

$$L = 4\pi\,\zeta^2\,R^2\,\sigma\,T^4$$

where R is the radius of the photosphere, T is the effective temperature, σ is the radiation constant, and ζ is the "dilution factor" which takes into account that in a scattering dominated atmosphere the blackbody is diluted[15–17]. The effective temperature is found from observed colors, so in fact is a color temperature and not an effective temperature,

the photospheric velocity can be estimated from observed spectra using the velocities of the weakest lines,

$$R = v\,t,$$

the dilution factor is estimated from synthetic spectral models, and t comes from the light curve and demanding self-consistency.

This method suffers from uncertainties in determining the dilution factors, the difficulty of knowing which lines to use as velocity indicators, uncertainties between color temperatures and effective temperatures, and questions of how to match the photospheric radius used in the models to determine the dilution factor and the radius of the line forming region[18, 19]. In spite of this the EPM method was successfully applied to SN 1987A in the LMC[11, 20] which led to hopes that the EPM method would lead to accurate distances, independent of other astronomical calibrators. Recently, the EPM method was applied to the very well observed SN IIP 1999em[18, 19, 21]. All three groups found a distance of 7.5–8.0 Mpc. Leonard et al.[22] subsequently used *HST* to obtain a Cepheid distance to the parent galaxy of SN 1999em, NGC 1637, and found 11.7 ± 1.0 Mpc, a value 50% larger than that obtained with EPM.

With modern detailed NLTE radiative transfer codes, accurate synthetic spectra of all types of supernovae can be calculated. The **S**pectral-fitting **E**xpanding **A**tmosphere **M**ethod (SEAM)[23–26] was developed using the generalized stellar atmosphere code `PHOENIX` (for a review of the code see Ref. [27]). While SEAM is similar to EPM in spirit, it avoids the use of dilution factors and color temperatures. Velocities are determined accurately by actually fitting synthetic and observed spectra. The radius is still determined by the relationship $R = vt$, (which is an excellent approximation because all supernovae quickly reach homologous expansion) and the explosion time is found by demanding self consistency. SEAM uses all the spectral information available in the observed spectra simultaneously which broadens the base of parameter determination. Since the spectral energy distribution is known completely from the calculated synthetic spectra, one may calculate the absolute magnitude, M_X, in any particular band X,

$$M_X = -2.5 \log \int_0^\infty S_X(\lambda)\, L_\lambda\, d\lambda + C_X$$

where S_X is the response of filter X, L_λ is the luminosity per unit wavelength, and C_X is the zero point of filter X determined from standard stars. Then one immediately obtains a

TABLE I:

Data Set	μ	D (Mpc)	$t_{explosion}$
5 epochs including U	30.07 ± 0.8	10.3 ± 4.5	5.2 ± 0.4
5 epochs excluding U	30.47 ± 0.39	12.4 ± 2.4	5.9 ± 0.3
5 epochs excluding U on 5th epoch	30.49 ± 0.36	12.5 ± 2.3	5.9 ± 0.3

distance modulus μ_X, which is a measure of the distance

$$\mu_X \equiv m_X - M_X - A_X = 5 \log (d/10\text{pc}),$$

where μ_X is the apparent magnitude in band X and A_X is the extinction due to dust along the line of sight either in the host galaxy or in our own galaxy. Baron et al.[28] found that the early spectra were quite sensitive to the assumed reddening and hence determined a value of $E(B-V) = 0.1$ for SN 1999em. The SEAM method does not need to invoke a blackbody assumption or to calculate dilution factors.

RESULTS

We used the above method to calculate the distance to SN 1999em. The models were taken from Model S15 of Woosley and Weaver[29]. The model was expanded homologously and the gamma-ray deposition was parameterized to be consistent with the nickel mixing found in SN 1987A[30]. The abundances were taken directly from the model, and the effects of radioactive decay were taken into account. The results are summarized in Table I. The explosion date is given as the number of days prior to discovery on 1999 October 29 (HJD 2451480.94). We used observed photometry of Leonard et al.[19] and Hamuy et al.[18] in $UBVRIZ$.

Figure 1 compares observed and model spectra, details of the modeling will be discussed elsewhere. Overall the fits are excellent, except on November 28 where the blue part of the spectrum is poorly fit, this is due to the fact that at this late time the spectrum forms over a much larger mass range of the ejecta and so we are sensitive to the detailed mixing of both nickel and helium which we have not attempted to adjust in the models. If we exclude the U band from the calculation the scatter is considerably reduced. Additionally, when the U band is included the inferred explosion date is nearer to the date of discovery

which produces a systematic rise in the SEAM distance with time. Errors in the explosion date primarily affect the absolute magnitudes of the early spectral models since they are more sensitive to errors in the explosion date than are later epochs. If the estimated time from explosion is too small, the models will have radii which are too small ($R = vt$). With smaller emitting area, they will be dimmer and hence appear to be closer. Errors in t are particularly important at the earliest epochs. The results of neglecting the U band entirely are nearly identical with those if we include the U data except for the one on November 28. The ability to compare synthetic spectra with observational spectra is clearly an advantage of the SEAM method. Thus, we adopt the results of the bottom line of Table I, which are in good agreement with the Cepheid result and show that quality fits to SNe IIP can give distances accurate to 20%, *without adjusting metalicities, helium mixing, or nickel mixing.* Once we have completed a large grid of models which vary these parameters we should be able to reduce the uncertainties even more, thus SNe IIP will become important cosmological probes.

DISCUSSION

The SEAM method assumes that supernovae are spherically symmetric, which is not strictly true. However, polarization data indicate that SNe IIP seem to be more spherically symmetric than other types of core collapse supernovae, most likely because the large intact hydrogen envelope sphericizes the explosion. Thus SNe IIP appear to be the most promising candidates for using the SEAM method. Leonard et al.[31] found evidence for polarization in SN 1999em at 7–163 days after discovery. Modeled in terms of oblate electron scattering atmospheres, the asphericity was about 7%. The found some tendency for increasing polarization with time. This is consistent with polarization studies of Type Ib/c supernovae where the polarization appears to increase the closer one gets to the central explosion mechanism[32].

It is difficult to know exactly why the SEAM method gives such a different result from that of EPM. Leonard et al.[19] found $t_{\rm explosion} = 5.3$ d, and our date is somewhat earlier. Even with a similar explosion date (see Table I) we find a larger distance. Comparing dilution factors used in the EPM analyses[12] with those we compute using the prescription of Hamuy et al.[18] we don't find drastic differences althougth the differences increase with

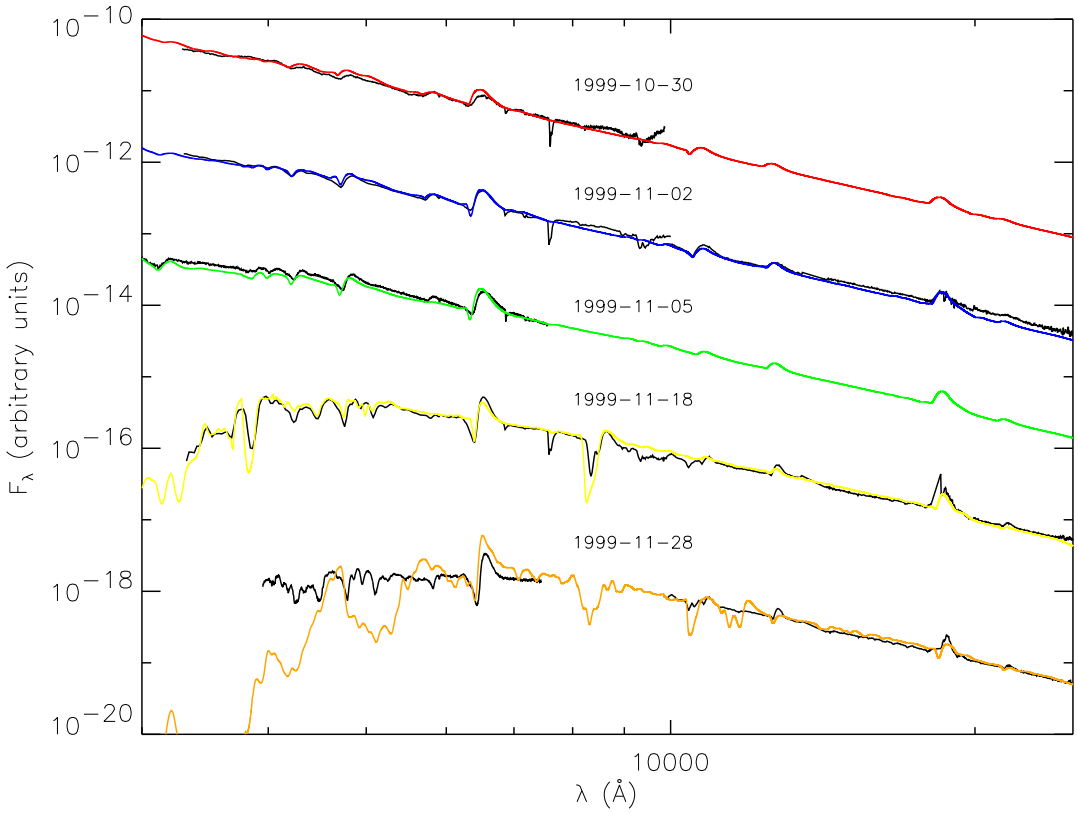

FIG. 1: The synthetic spectra are compared to observed spectra at 5 different epochs. The observed spectra were obtained at CTIO for Oct 30, Nov 2, and Nov 18[18], at *HST* and FLWO on Nov 5[28] and the optical spectrum on Nov 28 was obtained at Lick[19] while the IR was obtained at CTIO[18]. The observed fluxes have been offset for clarity.

time. It seems likely that the diluted blackbody assumption is too simplistic, particularly at later times. Since in a scattering dominated atmosphere there is no true "photosphere", the use of particular lines to define the velocity of the photosphere seems to be the most problematic assumption of the EPM. SEAM fits the velocities of the lines with detailed calculation of the line and continuum transfer which appears to be the largest difference between our results and EPM.

The SEAM method seems clearly superior to EPM and it should be testable by the Nearby Supernova Factory[33] if they follow a dozen or so SNe IIP in the Hubble flow that they will discover. An independent cosmological probe is highly desirable.

SNe IIP may be detectable to high redshifts with the James Webb Space Telescope

(*JWST*). With a dataset of spectral models that fit nearby SNe IIP we will be able to determine the nucleosynthetic history of the first generation of stars.

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