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. 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 hydrodynamical 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. We show that the dilution factors used in the EPM analysis were systematically too small at later epochs. We also show that the EPM blackbody assumption is suspect.

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.

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1. Distances from Supernovae

A reliable way to determine 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 Hubble Space Telescope (*HST*) projects (Freedman et al. 2001; Parodi et al. 2000) were awarded time 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 (Parodi et al. 2000) 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 (Phillips 1993) and hence that SNe Ia were correctable candles in much the same way that Cepheids are (Phillips et al. 1999; Goldhaber et al. 2001; Riess et al. 1995). This work and the development of highly efficient search strategies (Perlmutter et al. 1997) sparked two groups to use SNe Ia to measure the deceleration parameter and to discover the dark energy (Riess et al. 1998; Perlmutter et al. 1999).

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, Kirshner & Kwan 1974; Branch et al. 1981; Eastman & Kirshner 1989; Eastman et al. 1996) a variation of the Baade-Wesselink method (Baade 1926). 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 (Hershkowitz, Linder, & Wagoner 1986a,b; Hershkowitz & Wagoner 1987). The 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.

Both an advantage and disadvantage of EPM is that it primarily requires photometry. Spectra are only used to determine the photospheric velocity, colors yield the color temperature, which in turn is used to determine the appropriate dilution factor (from model results). 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 (Hamuy et al. 2001; Leonard et al. 2002). In spite of this the EPM method was successfully applied to SN 1987A in the LMC (Eastman & Kirshner 1989; Branch 1987) 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 (Hamuy et al. 2001; Leonard et al. 2002; Elmhamdi et al. 2003). All three groups found a distance of 7.5–8.0 Mpc. Leonard et al. (2003) 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, Baron et al. 1995, 1996; Lentz et al. 2001; Mitchell et al. 2002) was developed using the generalized stellar atmosphere code `PHOENIX` (for a review of the code see Hauschildt & Baron 1999). 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 photometric 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 distance modulus μ_X, which is a measure of the distance

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

where m_X is the apparent magnitude in band X and A_X is the extinction due to dust along the line of sight both in the host galaxy and in our own galaxy. Baron et al. (2000) 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.

2. Results

We used the above method to calculate the distance to SN 1999em. The models were taken from Model S15 of Woosley & Weaver (1995). The model was expanded homologously and the gamma-ray deposition was parameterized to be consistent with the nickel mixing found in SN 1987A (Mitchell et al. 2001). The abundances were taken directly from the model, and the effects of radioactive decay were taken into account. The results are summarized in Table 1. 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. (2002) and Hamuy et al. (2001) in $UBVRIZ$. The quoted errors are the $1-\sigma$ error in the determination of the mean distance, which we believe are reasonably accurate estimates of the true error which is difficult to determine formally. For our favored value (see below) of 12.5 Mpc we find a formal error of ± 1.8 Mpc if we add in quadrature the error in determining the effective temperature (~ 500 K), the error in determining the velocity (~ 500 km s^{-1}), and the formal error in the mean.

Table 1.

Data Set	μ	D (Mpc)	t_{exp}
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

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.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 1, which is 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.

3. 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. (2001) 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%. They 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 (Wang et al. 2003).

It is difficult to know exactly why the SEAM method gives such a different result from that of EPM. Leonard et al. (2002) found $t_{\rm exp} = 5.3$ d, and our date is somewhat earlier. Even with a similar explosion date (see Table 1) we find a larger distance. Figure 2 compares

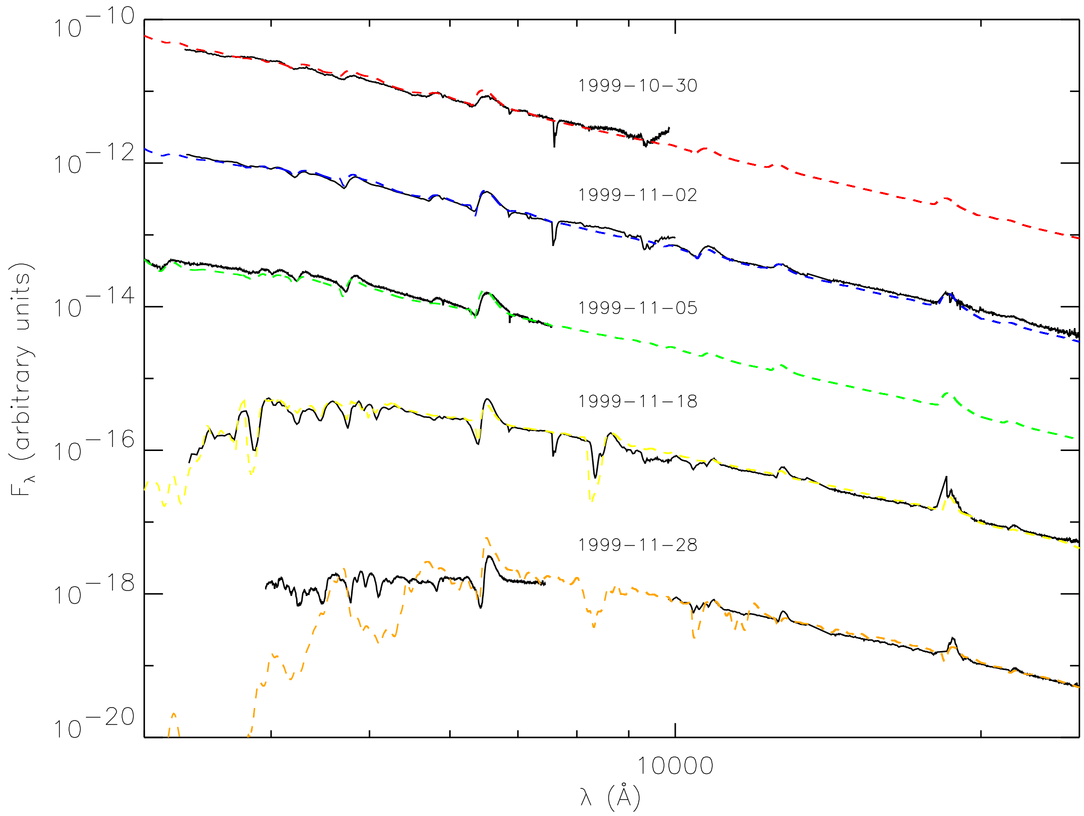

Fig. 1.— The synthetic spectra (dashed lines) are compared to observed spectra (solid lines) at 5 different epochs. The observed spectra were obtained at CTIO for Oct 30, Nov 2, and Nov 18 (Hamuy et al. 2001), at *HST* and FLWO on Nov 5 (Baron et al. 2000) and the optical spectrum on Nov 28 was obtained at Lick (Leonard et al. 2002) while the IR was obtained at CTIO (Hamuy et al. 2001). The observed fluxes have been offset for clarity.

the color temperature T_{BV}, the velocity at the photosphere (defined as $\tau = 2/3$), and the dilution factor, ζ_{BV}, obtained using T_{BV} with those of Hamuy et al. (2001). The results agree very well at early times, but by the 4th epoch the dilution factors disagree by 40% and by nearly a factor of 3 at the fifth epoch. Comparing only two epochs, if one mistakenly uses a dilution factor that is too small at the later time, the distance obtained will be too small. With hindsight Hamuy et al. (2001) recognized this fact when they found that they obtained distances close to the Cepheid value when they restricted their analysis to early times where our dilution factors agree. However, the whole foundation of EPM appears suspect. Figure 3 compares the best fit diluted Planck function with our computed flux at the first epoch where we have fit the observations very well. It is clear that a Planck function does not fit the SED at all. Thus, we find that the diluted blackbody assumption is too simplistic, particularly at later times. That the EPM approach works at early times seems coincidental, but it may be that in the hot early phases the color temperature is reasonably accurate, we will explore this in detail in future work.

The SEAM method seems clearly superior to EPM since the assumption of black-body emission is never realized in a supernova. SEAM should be testable by the Nearby Supernova Factory (Aldering et al. 2002) 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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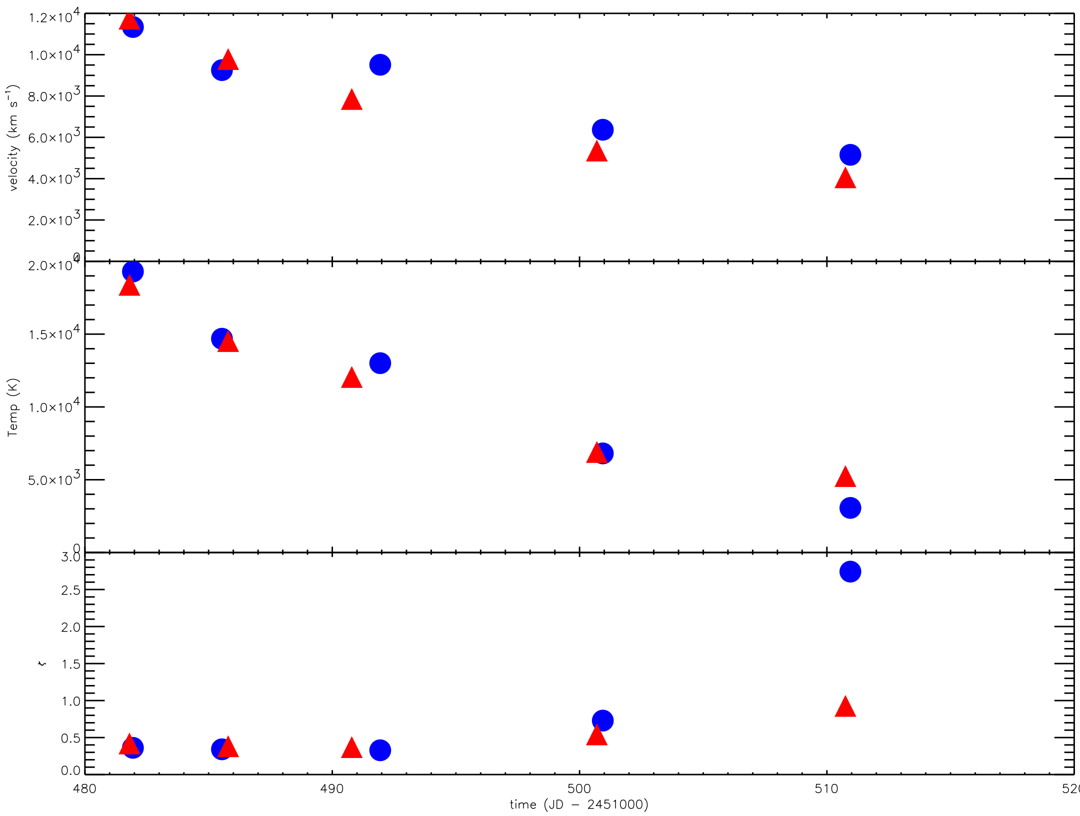

Fig. 2.— The EPM parameters $v(\tau = 2/3)$, T_{BV}, and dilution factor ζ_{BV} from our models (filled circles) are compared with those of Hamuy et al. (2001) (filled triangles). While there is good agreement at early epochs, by the fourth epoch the two results differ by 40%.

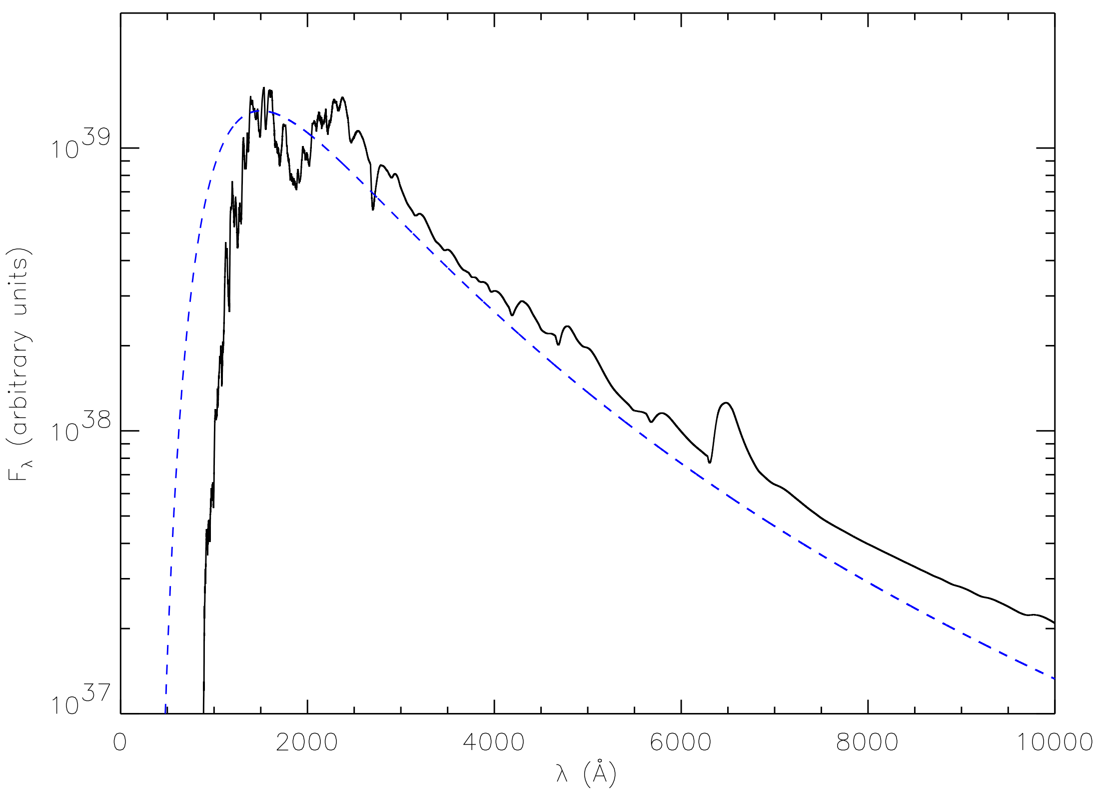

Fig. 3.— The flux from our model (solid line) compared with the best fit diluted blackbody flux (dashed line).

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