TYPE IIP SUPERNOVAE AS COSMOLOGICAL PROBES: A SPECTRAL-FITTING EXPANDING ATMOSPHERE MODEL DISTANCE TO SN 1999em

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Received 2004 September 7; accepted 2004 October 6; published 2004 October 19

ABSTRACT

Because of their intrinsic brightness, supernovae make excellent cosmological probes. We describe the spectral-fitting expanding atmosphere method (SEAM) 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 but 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 the SEAM and the 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 ≲ 6, with the James Webb Space Telescope, the SEAM may be a valuable probe of the early universe.

Subject headings: distance scale — stars: atmospheres — supernovae: individual (SN 1999em)

Online material: color figures

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 (SNe) are extremely bright and hence can be detected at cosmological distances with modern large telescopes. Because of their homogeneity, SNe Ia had long been thought of as good distance indicators since they roughly meet the astronomer’s definition of a “standard candle,” that is, that the luminosity at peak, , 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 that also were the hosts of SNe Ia. Distances obtained using Cepheids are considered to be among the most reliable in astronomy (purely trigonometrical 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 SNe 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 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

\[ L = 4\pi\varepsilon^2R^2\sigma T^4, \]

where \( R \) is the radius of the photosphere, \( T \) is the effective temperature, \( \sigma \) is the radiation constant, and \( \varepsilon \) is the “dilution factor,” which takes into account that in a scattering dominated atmosphere the blackbody is diluted (Hershkowitz et al. 1986a, 1986b; 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,

\[ R = \nu t; \]

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 the 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 was successfully applied to SN 1987A in the LMC (Eastman & Kirshner 1989; Branch 1987), which led to hopes that the EPM would lead to accurate distances,
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 $X$, $L_\lambda$ 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 $\mu_X$, which is a measure of the distance

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

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 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 2,451,480.94). We used observed photometry of Leonard et al. (2002) and Hamuy et al. (2001) in UBVRIZ. The quoted errors are the 1σ 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 $\pm 1.8$ Mpc if we add in quadrature the error in determining the effective temperature ($\sim 500$ K), the error in determining the velocity ($\sim 500 \text{ km s}^{-1}$), and the formal error in the mean.

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 fitted; 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. In addition, 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

![Synthetic spectra (dashed lines) compared to observed spectra (solid lines) at five different epochs. The observed spectra were obtained at Cerro Tololo Inter-American Observatory (CTIO) for October 30, November 2, and November 18 (Hamuy et al. 2001) and at HST and Fred Lawrence Whipple Observatory on November 5 (Baron et al. 2000), and the optical spectrum on November 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. [See the electronic edition of the Journal for a color version of this figure.]

**Table 1**

| Data Set                  | $\mu$ (Mpc) | $D$ (Mpc) | $t_{exp}$ |
|--------------------------|-------------|-----------|-----------|
| Five epochs including $U$| 30.07 ± 0.8 | 10.3 ± 4.5 | 5.2 ± 0.4 |
| Five epochs excluding $U$| 30.47 ± 0.39 | 12.4 ± 2.4 | 5.9 ± 0.3 |
| Five epochs excluding $U$ on fifth epoch | 30.49 ± 0.36 | 12.5 ± 2.3 | 5.9 ± 0.3 |
are more sensitive to errors in the explosion date than are later epochs. If the estimated time from the explosion is too small, the models will have radii that are too small \((R = vt)\). With a 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. Thus, we adopt the results of the bottom line of Table 1, which are in good agreement with the Cepheid result that \(\alpha\) varies these parameters, we should be able to reduce the uncertainties even more; thus, SNe IIP will become important cosmological probes.

3. DISCUSSION

The SEAM assumes that SNe 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 SNe, 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. 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 19%. It is difficult to know exactly why the SEAM gives such a different result from that of the EPM. Leonard et al. (2002) found \(t_{\exp} = 5.3\) days, and our date is somewhat earlier. Even with a similar explosion date (see Table 1), we find a larger distance. Figure 2 compares the color temperature \(T_{\text{BV}}\), the velocity at the photosphere (defined as \(\tau = \frac{1}{2}\)), and the dilution factor, \(\delta_{p}\), obtained using \(T_{\text{BV}}\), with those of Hamuy et al. (2001). The results agree very well at early times, but by the fourth 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 the EPM appears suspect. Figure 3 compares the best-fit diluted Planck function with our computed flux at the first epoch, where we have fitted 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 seems clearly superior to the EPM, since the assumption of blackbody emission is never realized in an SN. The 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. With a data set of spectral models that fit nearby SNe IIP, we will be able to determine the nucleosynthetic history of the first generation of stars.

We thank Doug Leonard and Mario Hamuy for helpful discussions on SN 1999em and Type IIP SNe. We thank the referee, Adam Riess, for improving the presentation of this work. This work was supported in part by NASA grant NAG5-3505, NSF grants AST-0204771 and AST-0307323, an IBM SUR grant to the University of Oklahoma, and NASA grants NAG 5-8425 and NAG 5-3619 to the University of Georgia. P. H. H. was supported in part by the Pôle Scientifique de Modélisation Numérique at ENS-Lyon. This research used resources of the San Diego Supercomputer Center, supported by the NSF; the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the US Department of Energy under contract DE-AC03-76SF00098; and the Höchstleistungs Rechenzentrum Nord. We thank all these institutions for a generous allocation of computer time.
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