

## TYPE II SUPERNOVAE AS STANDARDIZED CANDLES

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### ABSTRACT

We present evidence for a correlation between expansion velocities of the ejecta of Type II plateau supernovae and their bolometric luminosities during the plateau phase. This correlation permits one to standardize the candles and decrease the scatter in the Hubble diagram from  $\sim 1$  mag to levels of 0.4 and 0.3 mag in the  $V$  and  $I$  bands, respectively. When we restrict the sample to the eight objects that are well in the Hubble flow ( $cz > 3000$  km s<sup>-1</sup>), the scatter drops even further, to only 0.2 mag (or 9% in distance), which is comparable to the precision yielded by Type Ia supernovae and is far better than the “expanding photosphere method” applied to Type II supernovae. Using SN 1987A to calibrate the Hubble diagrams, we get  $H_0 = 55 \pm 12$ .

*Subject headings:* distance scale — galaxies: general — supernovae: general

### 1. INTRODUCTION

Distances to cosmological objects are the path to getting the expansion rate and the age of the universe. From observations of high- $z$  objects, it is possible to measure how the expansion rate changes with time and derive fundamental parameters, such as the geometry, deceleration, and energy content of the universe. This experiment has been recently done by two groups of astronomers using Type Ia supernovae (SNe Ia; Riess et al. 1998; Perlmutter et al. 1999). Their observations revealed the surprising result that the universe is presently accelerating owing to a nonzero cosmological constant, a form of dark energy that permeates space and dominates the total energy content of the universe, a result largely unanticipated by modern physics. If confirmed, the result from SNe Ia would be a revolution in astrophysics. Before we can fully believe this result, we need independent checks. Although SNe II are not as bright as the SNe Ia, they are the most common type of SN, and they offer the potential to be used as distance indicators using models of their atmospheres, a technique known as the “expanding photosphere method” (EPM; Schmidt et al. 1994; Hamuy 2001). The scatter in the Hubble diagram shows that the precision in an EPM distance is  $\sim 20\%$  (Hamuy 2001), which proves significantly larger than the 7% precision yielded by SNe Ia (Hamuy et al. 1996; Phillips et al. 1999), thus hampering the use of SNe II for the determination of cosmological parameters.

In principle, the apparent magnitudes of stellar objects can be used to derive distances, as long as a class of objects with known luminosities can be identified. Although SNe II display a wide range in luminosities at all epochs—making it hard to use them as standard candles—in this Letter we show that the envelope expansion velocities of the plateau subclass (Barbon, Ciatti, & Rosino 1979) are highly correlated with their luminosities during the plateau phase. This finding allows us to standardize the candles and use them to derive distances with precisions comparable to those delivered by SNe Ia.

### 2. OBSERVATIONAL MATERIAL

Table 1 lists the 17 plateau SNe II (SNe IIP) included in this study. These are all SNe IIP for which we have (1) precise

optical photometry uncontaminated by host galaxy light and (2) optical spectroscopy. This table lists the specific data sources along with characteristic  $VI$  magnitudes and velocities of the expanding ejecta (derived from the minimum of the Fe II 5169 Å line and duly corrected for host galaxy redshifts) for the plateau phase. Redshifts in the cosmic microwave background frame come from the NASA/IPAC Extragalactic Database or our own measurements.

### 3. LUMINOSITY-VELOCITY RELATION

Bolometric light curves were derived by Hamuy (2001) for these SNe using (1)  $BVI$  photometry, (2) empirical bolometric corrections, (3) reddening corrections due to our own Galaxy (Schlegel, Finkbeiner, & Davis 1998), (4) host galaxy extinction corrections (assuming that all SNe reach the same color at the end of the plateau), and (5) redshift-based distances ( $H_0 = 65$ ). The light curves were all placed in the same time-scale, using explosion times derived from the EPM analysis and considerations about the discovery and predisccovery image epochs. The resulting bolometric luminosities confirmed the well-known fact that SNe IIP display a wide range (7.5 mag peak to peak) of plateau luminosities. We also noticed that objects with brighter plateaus have higher envelope expansion velocities. Figure 1 compares the characteristic plateau luminosity and velocity of these SNe (both measured 50 days after explosion, which is nearly the middle of the plateau). A remarkable correlation emerges where SN 1992am and SN 1999br appear as extreme objects with high and low velocities, respectively. A weighted least-squares fit yields  $v_p \propto L_p^{0.33(\pm 0.04)}$ , with a reduced  $\chi^2$  of 0.7.

### 4. TYPE II SUPERNOVAE AS STANDARD CANDLES

The tight luminosity-velocity correlation and the inverse-square law imply that the distance to a SN IIP can be derived from measurements of the apparent magnitude and envelope velocity. To test this hypothesis we used  $VI$  magnitudes measured on day 50 (corrected for dust extinction) and expansion velocities derived at the same epoch (see Table 1). The bottom panel of Figure 2 presents the Hubble diagram in the  $V$  filter for all SNe but SN 1987A (which is not in the Hubble flow), while the top panel shows the same magnitudes after correction for expansion velocities. A least-squares fit yields the following

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TABLE 1  
REDSHIFTS, MAGNITUDES, AND EXPANSION VELOCITIES OF THE 17 TYPE II SUPERNOVAE

SN	$cz_{\text{CMB}}$ ( $\pm 300 \text{ km s}^{-1}$ )	$A_{\text{GAL}}(V)$	$A_{\text{host}}(V)$ ( $\pm 0.3 \text{ mag}$ )	$V_p$	$I_p$	$v_p$ ( $\text{km s}^{-1}$ )	References
1986L .....	1293	0.099	0.00	14.57(05)	...	4150(300)	1
1987A .....	...	0.249	0.22	3.42(05)	2.45(0.05)	2391(300)	2, 3
1988A .....	1842	0.136	0.00	15.00(05)	...	4613(300)	1, 4
1990E .....	1023	0.082	1.00	15.90(20)	14.56(0.20)	5324(300)	1, 5
1990K .....	1303	0.047	0.50	14.50(20)	13.90(0.05)	6142(2000)	1, 6
1991al .....	4484	0.168	0.15	16.62(05)	16.16(0.05)	7330(2000)	1
1992af .....	5438	0.171	0.00	17.06(20)	16.56(0.20)	5322(2000)	1
1992am .....	14009	0.164	0.30	18.44(05)	17.99(0.05)	7868(300)	1
1992ba .....	1165	0.193	0.00	15.43(05)	14.76(0.05)	3523(300)	1
1993A .....	8933	0.572	0.00	19.64(05)	18.89(0.05)	4290(300)	1
1993S .....	9649	0.054	0.30	18.96(05)	18.25(0.05)	4569(300)	1
1999br .....	1292	0.078	0.00	17.58(05)	16.71(0.05)	1545(300)	1
1999ca .....	3105	0.361	0.30	16.65(05)	15.77(0.05)	5353(2000)	1
1999cr .....	6376	0.324	0.00	18.33(05)	17.63(0.05)	4389(300)	1
1999eg .....	6494	0.388	0.00	18.65(05)	17.94(0.05)	4012(300)	1
1999em .....	669	0.130	0.18	13.98(05)	13.35(0.05)	3557(300)	1
2000cb .....	2038	0.373	0.00	16.56(05)	15.69(0.05)	4732(300)	1

REFERENCES.—(1) Hamuy 2001; (2) Hamuy & Suntzeff 1990; (3) Phillips et al. 1988; (4) Benetti, Capellaro, & Turatto 1991; (5) Schmidt et al. 1993; (6) Capellaro et al. 1995.

solution:

$$V_p - A_v + 6.504(\pm 0.995) \log \left( \frac{v_p}{5000} \right) \\ = 5 \log (cz) - 1.294(\pm 0.131). \quad (1)$$

The scatter drops from 0.95 to 0.39 mag, thus demonstrating that the correction for expansion velocities standardizes the luminosities of SNe II significantly. It is interesting to note that most of the spread comes from the nearby SNe, which are potentially more affected by peculiar motions of their host galaxies. When we restrict the sample to the eight objects with  $cz > 3000 \text{ km s}^{-1}$ , the scatter drops to only 0.20 mag. This implies that the standard candle method can produce relative

distances with a precision of 9%, which is comparable to the 7% precision yielded by SNe Ia.

Figure 3 shows the same analysis but in the  $I$  band. In this case the scatter in the raw Hubble diagram is 0.80 mag, which drops to only 0.29 mag after correction for expansion velocities. This is even smaller than the 0.39 spread in the  $V$  band, possibly due to the fact that the effects of dust extinction are smaller at these wavelengths. The least-squares fit yields the following solution:

$$I_p - A_i + 5.820(\pm 0.764) \log \left( \frac{v_p}{5000} \right) \\ = 5 \log (cz) - 1.797(\pm 0.103). \quad (2)$$

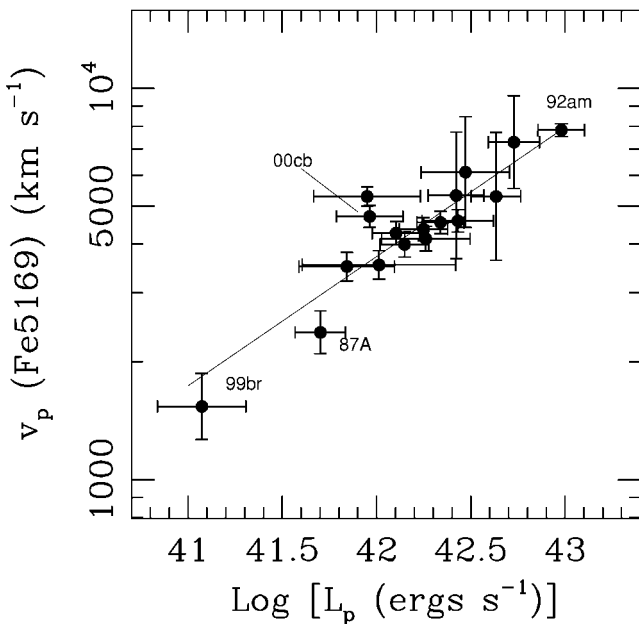


FIG. 1.—Expansion velocities from Fe II  $\lambda 5169$  vs. bolometric luminosity, both measured in the middle of the plateau (day 50). Ridge line is a weighted fit to the points and corresponds to  $v_p \propto L_p^{0.33(\pm 0.04)}$  (with reduced  $\chi^2$  of 0.7).

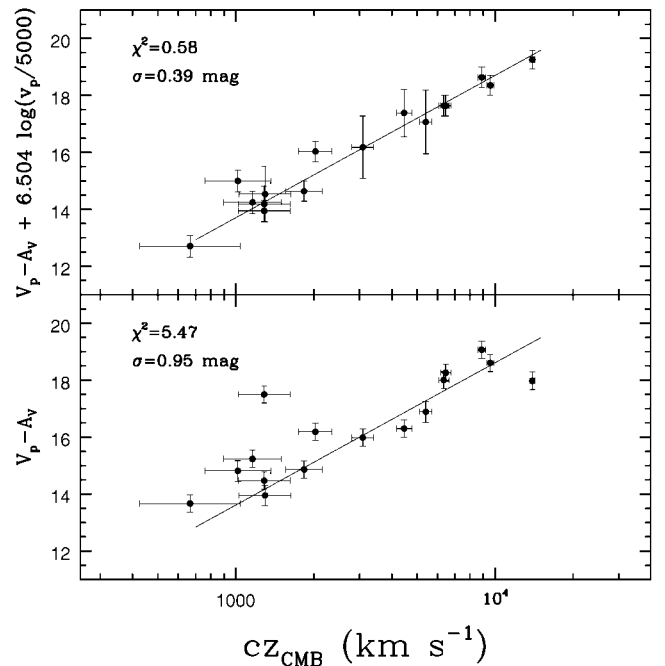


FIG. 2.—Bottom: Raw Hubble diagram from SNe IIP  $V$  magnitudes. Top: Hubble diagram from  $V$  magnitudes corrected for envelope expansion velocities.

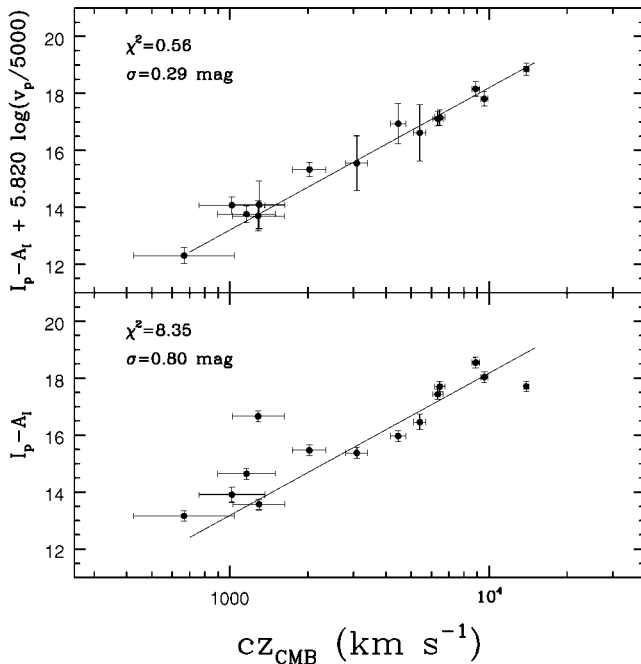


FIG. 3.—*Bottom*: Raw Hubble diagram from SNe IIP  $I$  magnitudes. *Top*: Hubble diagram from  $I$  magnitudes corrected for envelope expansion velocities.

When the eight most distant objects are employed, the spread is 0.21 mag, similar to that obtained from the  $V$  magnitudes.

Overall, the standard candle method is characterized by a scatter of between 0.39 and 0.20 mag. Evidently more objects in the Hubble flow are required to pin down the actual precision of this technique. The choice of 50 days only has the purpose to represent approximately the middle of the plateau phase, and it is possible that other choices could deliver even better results. In its present form, the method appears very promising for the determination of cosmological distances. Note also that this precision is better than that yielded by EPM (20% in distance, or 0.43 mag; Hamuy 2001), and the standard candle technique is far less complicated. It requires only a few spectra and photometry around day 50. A few extra photometric and spectroscopic observations are required during the plateau in order to solve for dust extinction in the host galaxy. The time of explosion is also required. Since the duration of the plateau does not vary much among the different SNe II, it would suffice to get some photometric observations during the plateau/neb-

ular phase transition. Alternatively, an EPM analysis can help at determining  $t_0$ , but this requires early-time observations.

The standard candle method can be used to solve for the Hubble constant, provided a distance calibrator is available. Among the objects of our sample, only SN 1987A has a precise distance in the Cepheid scale. Assuming a Large Magellanic Cloud distance of 50 kpc, we get  $H_0 = 54 \pm 13$  from the entire sample of  $V$  magnitudes. When we restrict the sample to the eight most distant objects, we get  $H_0 = 55 \pm 15$ . The  $I$  magnitudes yield  $H_0 = 53 \pm 10$  and  $56 \pm 12$ , respectively. These values agree comfortably well with the  $63 \pm 4$  value from Cepheids/SNe Ia (Hamuy et al. 1996; Phillips et al. 1999). Clearly, more calibrators are required to improve this estimate, especially considering that given its compact progenitor, SN 1987A is not a prototype of the plateau class and its light curve is quite different than that of typical plateau events. It will be interesting to see the results from SN 1999em that will soon have a Cepheid distance measured with the *Hubble Space Telescope*.

The specific task of checking the cosmic acceleration indicated by SNe Ia requires observing SNe II at the maximum possible redshift. For a typical SN II with  $M_V = -17.5$  during the plateau phase, the apparent magnitude at  $z = 0.3$  should be  $\sim 23$ . Discovering such SNe is clearly feasible nowadays. Obtaining such spectra will be difficult but certainly not impossible with the currently available 8 m class telescopes. In the worst case scenario, the standard candle method can produce distance moduli with a precision of 0.39 mag so that 13 SNe II at  $z = 0.3$  should allow us to measure the distances of such objects with a precision of 5% and provide a robust check on the results of SNe Ia.

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#### REFERENCES

- Barbon, R., Ciatti, F., & Rosino, L. 1979, *A&A*, 72, 287  
 Benetti, S., Capellaro, E., & Turatto, M. 1991, *A&A*, 247, 410  
 Capellaro, E., Danziger, I. J., Della Valle, M., Gouffes, C., & Turatto, M. 1995, *A&A*, 293, 723  
 Hamuy, M. 2001, Ph.D. thesis, Univ. Arizona  
 Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., & Avilés, R. 1996, *AJ*, 112, 2398  
 Hamuy, M., & Suntzeff, N. B. 1990, *AJ*, 99, 1146  
 Perlmutter, S., et al. 1999, *ApJ*, 517, 565  
 Phillips, M. M., Heathcote, S. R., Hamuy, M., & Navarrete, M. 1988, *AJ*, 95, 1087  
 Phillips, M. M., Lira, P., Suntzeff, N. B., Schommer, R. A., Hamuy, M., & Maza, J. 1999, *AJ*, 118, 1766  
 Riess, A. G., et al. 1998, *AJ*, 116, 1009  
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525  
 Schmidt, B. P., et al. 1994, *ApJ*, 432, 42  
 ———. 1993, *AJ*, 105, 2236