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THE EXPANDING PHOTOSPHERE METHOD APPLIED TO SN 1992am AT $cz=14\,600$ km/s[1]

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ABSTRACT

We present photometry and spectroscopy of SN 1992am for five months following its discovery by the Calan/CTIO SN search. These data show SN 1992am to be type II-P, displaying hydrogen in its spectrum and the typical shoulder in its light curve. The photometric data and the distance from our own analysis are used to construct the supernova's bolometric light curve. Using the bolometric light curve, we estimate SN 1992am ejected approximately $0.30\mathscr{M}_\odot$ of ^{56}Ni, an amount four times larger than that of other well studied SNe II. SN 1992am's host galaxy lies at a redshift of $cz=14\,600$ km s^{-1}, making it one of the most distant SNe II discovered, and an important application of the Expanding Photosphere Method. Since $z=0.05$ is large enough for redshift-dependent effects to matter, we develop the technique to derive luminosity distances with the Expanding Photosphere Method at any redshift, and apply this method to SN 1992am. The derived distance, $D=180^{+30}_{-25}$ Mpc, is independent of all other rungs in the extragalactic distance ladder. The redshift of SN 1992am's host galaxy is sufficiently large that uncertainties due to perturbations in the smooth Hubble flow should be smaller than 10%. The Hubble ratio derived from the distance and redshift of this single object is $H_0=81^{+17}_{-15}$ km s^{-1} Mpc^{-1}. In the future, with more of these distant objects, we hope to establish an independent and statistically robust estimate of H_0 based solely on type II supernovae.

1. INTRODUCTION

In the past three years a few highly successful SN search programs have produced a dramatic increase in the number of SNe discovered. Of the wealth of new objects suited for extensive investigations, none is more interesting than SN 1992am. SN 1992am was discovered on 1992 July 26 by R. Antezana in the course of the Calan/Tololo SN Search (Phillips & Maza 1992), a collaborative effort between the University of Chile and Cerro Tololo Inter-American Observatory (CTIO) (Hamuy *et al.* 1993). A spectrum taken on 1992 July 29 with the CTIO 4 m telescope revealed P-Cygni lines of Hα and Hβ (Phillips & Maza 1992), demonstrating that this supernova is of type II. The spectrum also revealed narrow Hα emission at a redshift of $z=0.0487$ from the underlying galaxy, making this one of the most distant SNe II yet discovered, and an appealing object on which to apply the Expanding Photosphere Method (EPM).

EPM (Kirshner & Kwan 1974) has been applied to several nearby SNe II (Schmidt *et al.* 1992; Eastman *et al.* 1993). The advantages of EPM are that the method is independent of local calibrators, does not presume a narrow range of luminosities, and can be applied at great distances in the same way as it is applied nearby. Although other methods for measuring galaxy distances have been developed that have small intrinsic scatter (Jacoby *et al.* 1992), the resulting nearby distances, though well determined, do not necessarily give accurate values for the global expansion rate of the universe. Observed peculiar velocities in the Hubble flow (Aaronson *et al.* 1982; Lynden-Bell *et al.* 1988; Mathewson *et al.* 1992; Lauer & Postman 1992) are large enough to create 10% uncertainties in the value of H_0 determined from objects at the distance of the Coma cluster. Additional concern is raised from the instructive N-body calculations of Turner *et al.* (1992) which show that in a flat CDM universe, an average error of 15% can be expected in H_0 even when perfect distances are known for objects out to four times the Virgo cluster distance (approximately the distance to the Coma Cluster). On the other hand, it is difficult to evaluate methods such as the Sunyaev-Zel'dovich effect (Birkinshaw *et al.* 1991) and gravitational lenses (Narayan 1991) (which like EPM, give distances without external calibration); they have only been applied at very large distances, and cannot be compared with more local distance methods.

Here we present photometry and spectroscopy of SN 1992am for the five months that followed its discovery and discuss the properties of the explosion. These observations are more than sufficient to measure the distance to the SN using the Expanding Photosphere Method. SN 1992am, with $cz=14\,600$ km s^{-1}, has a sufficiently large recession velocity that perturbations in the smooth Hubble flow should be less than 10%. For example, the peculiar velocity associated with the Great Attractor, 600 km s^{-1}, (Lynden-Bell *et al.* 1988) is less than 5% of the recession velocity of SN 1992am. The redshift effects on the EPM distance determination are not negligible at $z=0.05$, so we develop a method to derive EPM luminosity distances at any redshift. We obtain the distance to SN 1992am using this approach, and discuss its relation to the Hubble Constant.

TABLE 1. Spectra of SN 1992am.

Date	Julian Date (2440000+)	Wavelength coverage (Å)	Telescope	Observer
1992 Jul 29.4	8832.9	3200–7500	CTIO 4.0 m	Phillips
1992 Aug 3.5	8838.0	4200–7100	Lick 3.1 m	Filippenko and Matheson
1992 Sep 3.4	8868.7	6300–9200	MMT	Kirkpatrick
1992 Sep 21.5	8869.0	4200–9900	Lick 3.1 m	Filippenko, Matheson, and Ho
1992 Oct 1.4	8896.9	3800–9900	MMT	Kirshner

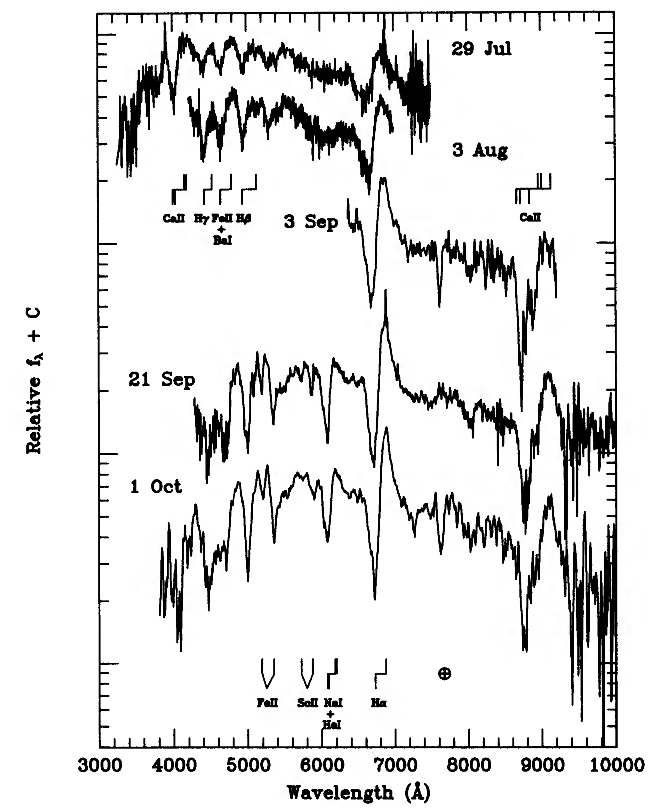

FIG. 1. Spectroscopic observations of SN 1992am during the photospheric phase. The observations are not corrected for the redshift of the host galaxy, 14 600 km s^{-1}.

2. OBSERVATIONS AND DISCUSSIONS

Optical spectra of SN 1992am were obtained using CCD spectrographs on the CTIO 4 m, Lick 3.1 m, and Multiple Mirror Telescopes. Each spectrograph was used in a long slit mode, which enables simultaneous observation of the SN and the adjacent background. Although we expect the relative flux calibration within each spectrum is better than 10%, all observations were taken with narrow slits, and therefore each zero point is somewhat uncertain. These observations are listed in Table 1 and are displayed in Figs. 1 and 2.

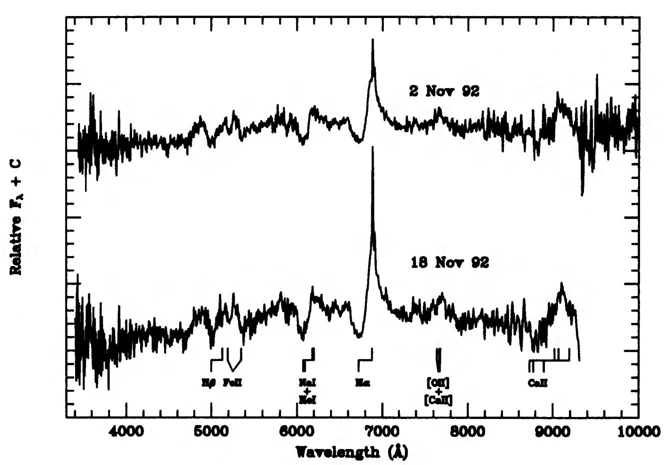

FIG. 2. Spectroscopic observations of SN 1992am during the nebular phase. The observations are not corrected for the redshift of the host galaxy, 14 600 km s^{-1}.

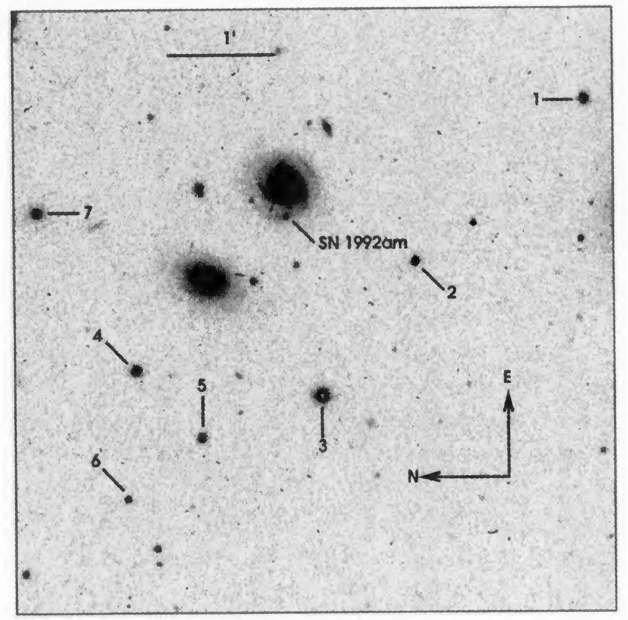

FIG. 3. A *V* band CCD image of SN 1992am taken with the FLWO 1.2 m telescope taken on 1992 October 3, which shows the position of the SN and the photometric standard star sequence.

Photometric observations were carried out using CCD imaging systems on the CTIO 0.91 m, CTIO 4.0 m, Fred Lawrence Whipple Observatory (FLWO) 1.2 m, Lick 1.0 m, and University of New Mexico (Capilla Peak) 0.61 m telescopes. The CCD images were bias subtracted and flatfielded in the usual manner. Some twilight flatfields were obtained using the exposure sequences found in Tyson & Gal (1993). Landolt (1992) standard stars were observed on four photometric nights (two nights using the CTIO 0.91 m telescope, and one night each with the FLWO 1.2 m and Capilla Peak 0.61 m telescopes) to transform our observations to the standard system. First-order transformation coefficients were calculated as described by Harris *et al.* (1981), and were used to calibrate a sequence of seven stars near SN 1992am (Fig. 3, Table 2). Relative photometry between the SN and the sequence of stars was performed by fitting point spread functions to the stars using DOPHOT (Mateo & Schechter 1989). Estimates of the relative photometric errors were derived by placing artificial stars created using DAOPHOT (Stetson 1987)

TABLE 2. Comparison star magnitudes.

Star	*B*	*V*	*R*	*I*
1	17.69(04)	16.62(04)	15.95(04)	15.42(04)
2	18.08(02)	16.91(02)	16.17(04)	15.56(03)
3	15.29(01)	14.88(01)	14.62(04)	14.32(04)
4	17.26(02)	16.52(02)	16.10(04)	15.73(02)
5	18.55(02)	17.08(03)	16.10(05)	15.05(06)
6	18.67(03)	18.09(05)	17.70(08)	17.40(08)
7	18.70(09)	17.78(03)	17.26(06)	16.58(03)

Notes to TABLE 2

Uncertainties in hundreths of magnitudes are listed in parentheses.

TABLE 3. The light curve of SN 1992am.

Date	Julian Date (2440000+)	B	V	I_C	L_{Bol} (erg s^{-1})	Telescope	Observer
1992 Jul 29.4	8832.9	18.87(04)	18.42(03)	–	4.84×10^{42}	CTIO 0.91 m	Tyson
1992 Aug 12.4	8846.9	19.40(06)	18.58(03)	–	4.03×10^{42}	CTIO 0.91 m	Aviles, Hamuy
1992 Aug 13.3	8847.8	19.43(07)	18.56(03)	18.02(03)	4.13×10^{42}	CTIO 0.91 m	Aviles
1992 Aug 14.4	8848.9	19.58(12)	18.62(04)	18.00(04)	3.90×10^{42}	CTIO 0.91 m	Aviles
1992 Sep 4.4	8869.9	–	18.83(04)	18.02(05)	3.68×10^{42}	FLWO 1.2 m	Zucker
1992 Sep 4.5	8870.0	–	18.71(10)	17.95(15)	3.96×10^{42}	Lick 1.0 m	Bolte
1992 Sep 7.3	8872.8	20.05(25)	18.87(05)	18.07(05)	3.52×10^{42}	CTIO 0.91 m	Aviles
1992 Sep 8.2	8873.7	20.17(20)	18.91(10)	18.08(09)	3.47×10^{42}	UNM 0.61 m	Grashuis
1992 Sep 20.4	8885.9	–	18.97(04)	17.96(10)	3.87×10^{42}	CTIO 0.91 m	Aviles
1992 Sep 23.3	8888.8	–	18.96(04)	18.11(03)	3.37×10^{42}	UNM 0.61 m	Grashuis
1992 Sep 25.3	8890.8	20.39(14)	19.05(05)	18.03(04)	3.63×10^{42}	FLWO 1.2 m	Kuijken
1992 Oct 1.1	8896.6	20.47(19)	19.10(05)	18.19(05)	3.13×10^{42}	FLWO 1.2 m	Challis
1992 Oct 3.1	8898.6	20.46(09)	19.13(03)	18.11(04)	3.37×10^{42}	FLWO 1.2 m	Challis
1992 Oct 4.1	8899.7	–	18.94(17)	18.19(13)	3.18×10^{42}	UNM 0.61 m	Grashuis
1992 Oct 10.2	8905.7	–	19.12(11)	18.14(08)	3.28×10^{42}	CTIO 0.91 m	Aviles, Hamuy
1992 Oct 13.2	8908.7	20.51(30)	19.19(10)	18.20(07)	3.10×10^{42}	CTIO 0.91 m	Aviles
1992 Oct 27.1	8922.6	20.88(12)	19.40(04)	18.29(05)	2.88×10^{42}	CTIO 0.91 m	Aviles
1992 Dec 23.1	8979.6	22.50(30)	21.04(12)	19.81(14)	7.97×10^{41}	CTIO 4.0 m	Suntzeff
1992 Dec 26.1	8982.6	–	21.01(23)	19.86(28)	7.82×10^{41}	FLWO 1.2 m	Schmidt

Notes to TABLE 3

Uncertainties in hundreths of magnitudes are listed in parentheses.

on the galaxy at locations with similar background to the SN, and comparing the output of DOPHOT (Mateo & Schechter 1989) to the brightness of the synthetic stars. Since SN 1992am occurred in the outer reaches of its host galaxy, background contamination by the galaxy is small. Each CCD and filter combination has its own sensitivity function which is not identical to that used by Johnson (1953) or Cousins (1976) when they set up the standard star systems we use today. These differences are particularly large in B (due to the rapid decrease in CCD sensitivities in the blue) where errors can exceed 0.1 mag. Therefore we correct the measured magnitudes of the SN for differences in color between the SN and the standard star sequence using the transformations derived from the standard stars. These results and the corresponding error estimates are presented in Table 3 and Fig. 4.

The spectroscopic evolution of SN 1992am is typical for SNe II as demonstrated in Figs. 1 and 2. Our first spectrum reveals a relatively hot continuum with a prominent Hα P-Cygni profile. Strong absorption features due to Hβ, Hγ, Ca II (H&K), and Fe II (λ4554) are also seen, as well as relatively weak lines produced by Fe II (λ5215, λ5169, and λ5018). These features are typical for SNe II (Branch 1990) and suggest SN 1992am was about two or three weeks past B maximum when discovered. Subsequent spectra show the Ca II IR triplet to be strong 35 days later, and the lines of Sc II λλ5526,5658 to be present approximately two months after discovery. Also seen two months after discovery is a very strong P-Cygni line usually attributed to Na I (λλ5890,5896). However, since this line is usually seen towards the end of the photospheric phase in SNe II, He I (λ5876) could also be contributing; a result of seeing through the nearly transparent hydrogen envelope into the helium-rich layers below. This possibility is given further support by IR spectra of SN 1987A, which show He I λ10830 was very strong 50 days after explosion (Elias *et al.* 1988). Our final two spectra (Fig. 2) show SN 1992am as it makes the transition to the nebular phase. Hα becomes very strong, and the forbidden lines of [O II] λλ7320, 7330 or, more likely, [Ca II] λλ7292, 7324 begin to appear (Kirshner & Kwan 1975; Li & McCray 1993).

SNe II are divided into two subclasses based on the shape of their light curves (Barbon *et al.* 1979; Kirshner 1990): Type II-P(lateau) SNe remain at an approximately constant brightness for about 100 days before fading rapidly to the radioactive tail, whereas Type II-L(inear) SNe decline exponentially in brightness after maximum. SN 1992am's photometric evolution is typical for a SNe II-P. The B, V, and I light curves declined slowly for more than 90 days following discovery, and when observed again 60 days later, had fallen by 1.5 mag to the radioactive tail. At discovery SN 1992am had the color of a relatively young SNe II, $(B-V)=0.45$ mag, and it evolved to the red so that at the end of the plateau, $(B-V)=1.48$ mag. SN 1992am exploded in the outskirts of its host galaxy and lies at high Galactic latitude, so we do not expect it to be highly reddened. We derive the reddening to this SN, using the technique suggested by Schmidt *et al.* (1992), by comparing its $(B-V)$ color evolution to that of SN 1969L (Ciatti *et al.* 1971), which is thought to suffer from very little reddening. Taking explicit account of the color shift of SN 1992am's spectrum due to its large redshift, we estimate this object has a color excess of $E(B-V)=0.1\pm0.1$ mag. Using the galactic reddening law of Whitford (1958), the color excess corresponds to a visual extinction of $A_V=0.3\pm0.3$ mag.

SNe II show a large dispersion in absolute magnitude at maximum (Young & Branch 1989; Schmidt *et al.* 1992). Using the distance derived in Sec. 4, we find SN 1992am to be more luminous than average. $M_V^{\max}<-18.2-5\log(D/180$ Mpc). Furthermore, SN 1992am is also very luminous on the

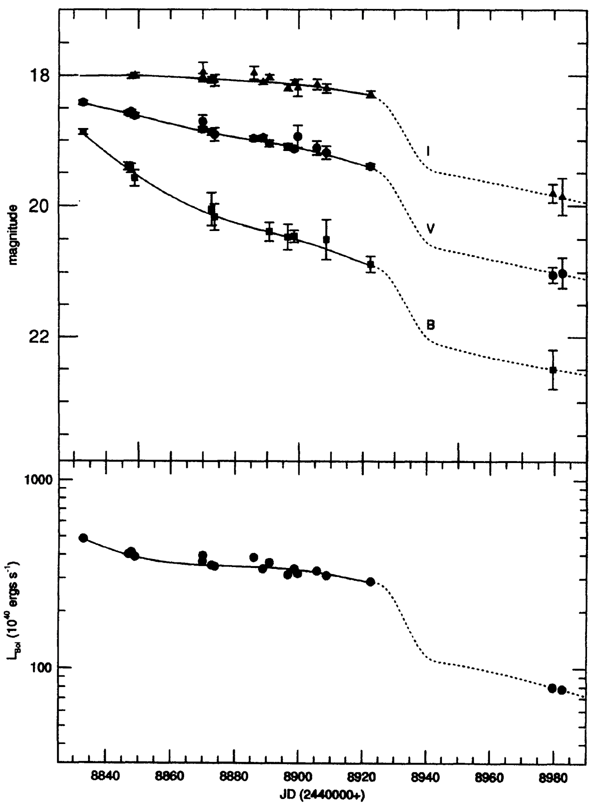

FIG. 4. The *BVI* and bolometric light curves of SN 1992am. A fit to the data is drawn over each light curve. A dashed line of the likely evolution of the SN is included at late times.

radioactive tail where SNe II appear to be more uniform in brightness (Phillips *et al.* 1990). We use our *BVI* photometry and the bolometric corrections derived by Schmidt *et al.* (1993b) to estimate SN 1992am's bolometric light curve (the total energy output by the SN excluding γ rays). These results, displayed in Table 3 and Fig. 4, assume a visual extinction of $A_V=0.3$ mag and a distance to the SN of 180 Mpc.

In the first seconds that follow the core collapse of a massive star, the outgoing shock wave heats the material at the star's center to sufficiently high temperatures that the material is cooked to nuclear statistical equilibrium (Arnett *et al.* 1989). Although the amount of ^{56}Ni (the principal product of this cooking) produced in the explosion is not difficult to calculate, a significant fraction of the newly synthesized material falls back onto the newly formed neutron star. Modeling of this fall-back of material onto the neutron star is very demanding, and empirical estimates of the amount of ejected ^{56}Ni are needed to help guide the theorists. SNe II, after becoming optically thin, are powered by the decay of ^{56}Co (the daughter nucleus of ^{56}Ni) to ^{56}Fe. In a SN II, if there is enough mass, the majority of the gamma rays produced by this β-decay are thermalized in the expanding ejecta, producing a light curve that decays with the *e*-folding time of ^{56}Co, 111.3 days. Under these conditions we can easily use this portion of the SN II light curve to estimate the count of ^{56}Ni ejected by the SN. A decay time near to 111.3 days has been seen at late times in many well observed SNe II such as SN 1969L (Ciatti *et al.* 1971), SN 1987A (Suntzeff & Bouchet 1990; Whitelock *et al.* 1988), and SN 1990E (Schmidt *et al.* 1993a).

We assume SN 1992am traps all of the gamma rays produced in the decay of ^{56}Co to ^{56}Fe, and use the bolometric light curve to estimate a lower bound to the amount of radioactive nickel ejected by the explosion to be $\mathscr{M}(^{56}\mathrm{Ni})=0.30\mathscr{M}_\odot(D/180\ \mathrm{Mpc})^2$. This amount is approximately four times that produced by SN 1969L. SN 1983K (Phillips *et al.* 1990), SN 1987A (Suntzeff & Bouchet 1989), SN 1990E (Schmidt *et al.* 1993a), and SN 1993J (Schmidt *et al.* 1993c; Nomoto *et al.* 1993). While our estimate assumes that SNe II trap all of their gamma rays, and is sensitive to errors in the extinction and distance, this interesting result withstands these uncertainties. If only some fraction of the gamma rays are captured, we would underestimate the amount of nickel produced in the explosion. We also assume very little extinction to SN 1992am; increasing the amount of extinction would increase the estimated amount of ejected nickel (and would also affect the EPM distance determination to a lesser extent). Finally, we have used the EPM distance to SN 1992am that corresponds to $H_0=81$ km s^{-1} Mpc^{-1}. If a smaller Hubble constant is really correct, this would also increase the amount of nickel. Unless we have overestimated the distance by a factor of two (when we expect an error of 15%), it appears SN 1992am ejected significantly more nickel compared to SN 1969L, SN 1983K, SN 1987A, SN 1990E, and SN 1993J.

3. APPLYING EPM AT LARGE REDSHIFTS

Factors of $(1+z)$ affect EPM distances for objects at large redshifts. For SN 1992am, at $z=0.0487$, these effects need to be included to avoid significant errors in the distance. Wagoner (1977) expanded on the initial work of Kirshner & Kwan (1974) and derived the effect on EPM if it is assumed that SNe II are perfect blackbodies. However, work in the past 15 years has shown that SNe II have significant deviations from blackbodies, which require correction using atmospheric models (Wagoner 1981; Chilkuri & Wagoner 1988; Höflich 1988; Eastman & Kirshner 1989; Schmutz *et al.* 1990). The details of these corrections are not easily implemented in the elegant procedure developed by Wagoner (1977), so we take a different approach. We modify EPM as discussed by Schmidt *et al.* (1992) so that it can be applied to SNe II regardless of their redshift. The resulting distances obey the "luminosity distance" formula as given by Matting (1958),

$$d_L=\frac{1}{H_0q_0^2}\left[q_0z+(q_0-1)(\sqrt{1+2q_0z}-1)\right]. \qquad (1)$$

Schmidt *et al.* (1992) showed that SNe II could be approximated as dilute blackbodies so that if $z\ll 1$ their angular radius, θ, is given by

$$\theta=\frac{R}{D}=\sqrt{\frac{f_\lambda}{\zeta_\lambda^2\pi B_\lambda(T)}}, \qquad (2)$$

where R is the radius of the SN photosphere, D is the distance to the SN, $B_\lambda(T)$ is the Planck function at temperature, T, and ζ_λ is a distance correction factor determined from models. Additionally, SNe II freely expand so that at any time, t, the radius of the photosphere is given by

$$R=R_0+v(t-t_0), \tag{3}$$

where R_0 is the initial radius of the progenitor, v is velocity of the material in which the photosphere is being formed, and t_0 is the time of the explosion. R_0 is usually negligible, and combining (2) and (3) yields

$$t=D\left(\frac{\theta}{v}\right)+t_0. \tag{4}$$

For EPM to produce luminosity distances, we must correct (2) and (4) for the effects of redshift. Our strategy is to correct the observed quantities so they are equivalent to the observations made of objects with zero redshift. Equation (4) is easily corrected, time dilation being the only relevant effect. The ticks of a rapidly receding clock are spread out in time as seen by the observer, and therefore the light curve of a distant SN II appears protracted relative to its stationary counterpart. Equation (4) becomes

$$\frac{t}{(1+z)}=D\left(\frac{\theta}{v}\right)+\frac{t_0}{(1+z)}. \tag{5}$$

At large z, θ must be corrected by what amounts to a K-correction (Oke & Sandage 1968) as a result of two effects. First, observers see light from shorter wavelengths shifted by a factor of $(1+z)$ into their bandpasses. Second, each part of the spectrum has been spread out so that it now lies in a wavelength interval a factor $(1+z)$ larger as seen by the observer. The decrease in each photon's energy by a factor of $(1+z)$, and the decrease in the number of photons arriving per unit time interval (the two other effects of redshift), are included in Eq. (1) where the luminosity distance is formulated. Equation (2) then becomes

$$\theta=\frac{R}{D}=\sqrt{\frac{f_\lambda(1+z)}{\zeta_{\lambda'}^2\pi B_{\lambda'}(T)}}, \tag{6}$$

where $\lambda'=\lambda/(1+z)$. Note that θ, as defined in Eq. (6), does not obey the "angular size distance" relation as Wagoner (1977) derived for EPM.

Since the calibrated flux of SNe II is almost always determined using broadband filter functions, θ is actually determined from

$$\theta=\frac{\sqrt{(1+z)}}{\zeta_{\lambda'}}\,10^{-(1/5)C}, \tag{7}$$

where C, the ratio of the flux seen by the observer to the flux at the surface of a blackbody expressed in magnitudes, is found by minimizing the difference between the magnitudes of a blackbody, $M_i^{\rm BB}$, and those observed, $m_i^{\rm obs}$:

$$\min_{C,T}\left(\sum_{B,V\ldots} m_i^{\rm obs}-M_i^{\rm BB}(T)+C\right). \tag{8}$$

The magnitudes of a blackbody (corrected for redshift) are determined by integrating over the sensitivity functions, S_i, for each filter, and shifting the spectrum to the blue by a factor of $(1+z)$,

$$M_i^{\rm BB}(T)=-2.5\log\left[\frac{\int\lambda S_i(\lambda)\pi B_{\lambda'}(T)d\lambda}{\int\lambda S_i(\lambda)d\lambda}\right]-A_i. \tag{9}$$

Here A_i is a zero point for each filter determined by integrating the absolute spectrophotometry of Vega (e.g., Hayes *et al.* 1975) and comparing the result to the broadband photometry of Vega (e.g., Johnson & Morgan 1953). An extra factor of λ has been included in both the numerator and denominator of (9) because photometry is gathered with photon counters, not energy meters.

Although Eqs. (6) through (9) correct for the effects of redshift in determining T and θ for distant SNe, the quantities have been determined using bandpasses which have been effectively shifted to the blue. SNe II spectra are not perfect Planck functions, and the derived values of T and θ (and hence ζ_λ) depend on which parts of the spectrum are used in their determination, an effect which must also be considered for nearby SNe. We take this effect into account by determining the distance correction factors with respect to the shifted bandpasses.

The distance correction factor, $\zeta_{\lambda'}$, is simply the ratio of the distance determined to a SN II assuming it radiates as a blackbody, and the SN's actual distance. These factors can be calculated from atmospheric models of SNe II as the ratio of the synthesized spectrum's blackbody photospheric radius, $R_{\lambda'}$, and the physical position of the photosphere (defined to be at τ=2/3),

$$\zeta=\frac{R_{\lambda'}}{R(\tau=2/3)}. \tag{10}$$

The blackbody photospheric radius is found with respect to the filter functions. In this case we minimize the dispersion in the photometric radii, R_i, as a function of the temperature, T,

$$\min_T\left(\sum_{B,V\ldots}(\bar{R}-R_i)^2\right). \tag{11}$$

Here $\bar{R}$ is the mean of the R_i values which are determined by integrating the luminosity per unit wavelength of the models shifted by a factor of $(1+z)$, $L_{\lambda'}$, with the appropriate filter sensitivity functions, and comparing this to the surface flux of a blackbody (and a factor of 4π) shifted by the same amount:

$$R_i=\sqrt{\frac{\int\lambda L_{\lambda'}S_i(\lambda)d\lambda}{4\pi\int\lambda S_i(\lambda)\pi B_{\lambda'}(T')d\lambda}}. \tag{12}$$

In Eq. (12), instead of shifting the bandpasses to the blue, we have made the equivalent adjustment by shifting both the model spectrum and the Planck function to the red. These changes to EPM allow us to calculate distances to high redshift objects in the same way as we do the nearby objects; the only difference is we shift the photometric bandpasses for distant objects to the blue by a factor of $(1+z)$. The effects of redshift are especially pronounced when B photometry is used to determine T and θ. After maximum, SNe II suffer from line blanketing in the UV [as seen for SN 1993J by

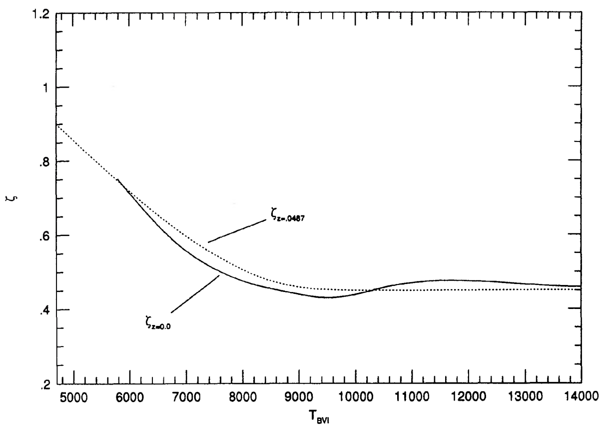

FIG. 5. The value of the ζ, the distance correction factor, as a function of temperature as determined from the models of Eastman *et al.* (1993). Lines are drawn for ζ determined for SNe II at zero redshift, and for SNe II at the recession velocity of SN 1992am, z=0.0487.

TABLE 4. Derived quantities for EPM.

Julian Date (2440000+)	$t^a/(1+z)$ (Days)	T_{BVI} (K)	$\zeta_{BVI}{}^b$	θ_{BVI} 10^{15} cm Mpc^{-1}	v km s^{-1}
8833	0.0	9340	0.44	0.0140	8300
8837	3.8	8260	0.50	0.0147	7400
8842	8.6	7450	0.56	0.0151	7000
8847	13.4	6860	0.62	0.0155	6700
8852	18.1	6350	0.67	0.0160	6400
8857	22.9	6010	0.72	0.0165	6100
8862	27.7	5770	0.75	0.0169	5900
8867	32.4	5550	0.78	0.0174	5600
8872	37.2	5380	0.80	0.0177	5300
8877	42.0	5270	0.82	0.0179	5050
8882	46.7	5150	0.84	0.0181	4800
8887	51.5	5070	0.85	0.0184	4500
8892	56.3	4970	0.86	0.0187	4200
8897	61.0	4890	0.87	0.0188	3900

[a]JD 2448833 is $t=0$.
[b]ζ_{BVI} is calculated for cz=14 600 km s^{-1}.

HST (Jeffery *et al.* 1993)], and SNe II observed at large distances have a substantial loss of flux in the B band. The corrections become significant for objects at redshifts greater than 10 000 km s^{-1}, and should be incorporated into all EPM distances of objects beyond this redshift.

Because EPM is applied to SNe II which are intrinsically bright objects, and should not suffer from redshift-dependent effects such as Malmquist Bias, aperture corrections, and evolution, it may be of use in measuring the deceleration parameter, q_0. The corrections to EPM at large redshifts are done only to the models, which have no observational uncertainties (unlike K-corrections for SNe Ia and galaxies), and are limited by the accuracy of the SNe II atmospheric models. Although intrinsically bright, SNe II will be very faint at the redshifts needed to determine q_0: at a redshift of z=0.5, SN 1992am would have $m_R \approx 23$ mag at maximum. At this redshift, the difference between q_0=0.05 and q_0=0.5 is only 12% in distance, yet note that the uncertainty associated with the SN 1992am distance is about 15%. Clearly, many supernovae will have to be observed in order to determine q_0 accurately.

4. THE DISTANCE TO SN 1992am AND H_0

We have applied EPM to SN 1992am using the technique outlined above. The individual photometric measurements have substantial errors, and we estimate SN 1992am's *BVI* magnitudes at five-day intervals by fitting the observations with a spline. From these smoothed measurements the color temperature (T_{BVI}) and θ_{BVI} are determined using Eqs. (7) through (9). The velocity of the photosphere is determined from spectra using the absorption minima of Fe II lines as discussed by Eastman & Kirshner (1989) from Schmutz *et al.* (1990). On dates that fall between observations, we estimate the velocity of the photosphere through linear interpolation. We use the grid of models calculated by Eastman *et al.* (1993) to determine ζ as a function of temperature corrected for the $(1+z)$ shift as prescribed in Eqs. (10) through (12) (Fig. 5). These models were calculated using the atmospheric code developed by Eastman & Kirshner (1989) and Eastman & Pinto (1993). They include the effects of spherical geometry, treat all relativistic effects which are important in an expanding gas to v/c, and employ non-LTE equations of statistical equilibrium for several atoms, including H I, He I, Fe II. These ingredients for EPM on SN 1992am are given in Table 4, and the relevant parameters [θ/v and $t/(1+z)$] are plotted against each other in Fig. 6. The data are well represented by a straight line—a crucial test of the method—from which we derive a distance of $D=180^{+30}_{-25}$ Mpc and a time of explosion approximately 31 days before discovery. 25^{+8}_{-10} June 1992. The uncertainty of this measurement may be reduced in the future by creating custom models to match SN 1992am's spectra, and would be smaller had the SN been discovered closer to the time of explosion. SN 1992am is more luminous than most SNe II (but is still a magnitude fainter than SNe II such as SN 1979C and SN 1983K). However, EPM distances should not depend on luminosity, and therefore, it is not a concern that this SN II was brighter than average; in fact, it has made the SN easier to observe.

SN 1992am lies in a group of galaxies, seven of which have redshifts from the CfA redshift survey (Geller & Huchra 1989). The mean recession velocity of these galaxies is 14 500 km s^{-1} with a dispersion of 250 km s^{-1}. Using this value for the recession velocity (including a 600 km s^{-1} uncertainty to allow for perturbations in the pure Hubble flow), and the distance to SN 1992am determined above, we derive a Hubble ratio of $H_0=81^{+17}_{-15}$ km s^{-1} Mpc^{-1}. Schmidt *et al.* (1992) determined the distances to 10 SNe II using EPM, and these distances have been redetermined by Eastman *et al.* (1993) using correction factors calculated from a much more complete grid of models. The distances derived by Eastman *et al.* (1993) are 10% larger on average than those determined by Schmidt *et al.* (1992). The value of H_0 derived from the 10 SNe by Eastman *et al.* (1993), $H_0=67\pm12$ km s^{-1} Mpc^{-1}, is consistent with that implied by the EPM distance to SN 1992am. The SNe II in the sample of Eastman *et al.* (1993) are nearby (only one has a redshift greater than 1500 km s^{-1}), and are subject to peculiar motions which are

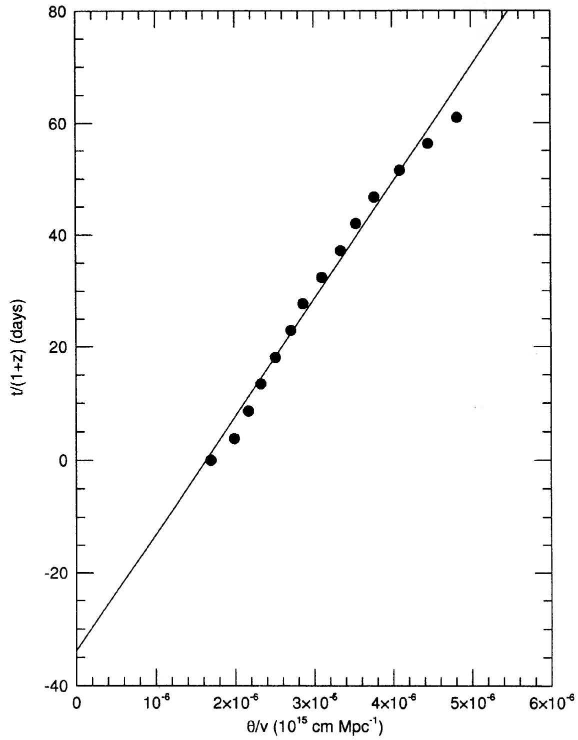

FIG. 6. The parameters needed to determine the distance to SN 1992am. θ/v and $t/(1+z)$ are plotted against each other. The first day of observations, 1992 Jul 29, is defined as $t=0$. The line of best fit determined using least squares is also plotted, the slope of which yields a distance of 180 Mpc for the SN. The y intercept of the line gives the date of explosion date to be 31 days before discovery, 1992 June 25.

a significant fraction of their observed recession velocity. This nearby sample of galaxies is useful, however, for establishing that EPM gives nearly the same distance to galaxies measured with other methods such as Cepheids (Schmidt *et al.* 1992) and the Tully–Fisher relation (Pierce 1994). In the near future we can expect to develop a moderate sized sample of distances to SNe that lie well beyond the Virgo cluster. These objects will enable us to establish a statistically robust estimate of H_0, free from the pitfalls of peculiarities in the local Hubble flow and poor footing on the nearby rungs of the cosmic distance ladder.

5. CONCLUSIONS

SN 1992am is the first well studied SN II at $cz>10\,000$ km s^{-1}. We have presented low resolution spectra and *BVRI* photometry for the first five months of its evolution. Our observations show SN 1992am had spectral and photometric properties typical of SNe II-P. Using broadband photometry we estimate SN 1992am's bolometric light curve, and find that the supernova was unusually luminous for SNe II-P both on the plateau and on the radioactive tail. We determine SN 1992am ejected approximately $0.30\mathcal{M}_\odot$ of ^{56}Ni, four times the amount inferred for other well studied SNe II.

Although studying SNe II at large distances is difficult, there are some rewards. Perturbations in the smooth Hubble flow beyond $cz=10\,000$ km s^{-1} are expected to be small relative to an object's recession velocity, and the Hubble law can give relative distances with an accuracy of better than 10% at these distances. Therefore SNe at these distances can be compared with one another without the normal uncertainties in the object's relative distances. The accuracy of the Hubble law also makes these distant SNe II good targets for measuring H_0 using the Expanding Photosphere Method. Using the data presented in this paper, we find the distance to SN 1992am to be $D=180^{+30}_{-25}$ Mpc. This distance, combined with the host galaxy's redshift yields a Hubble ratio of $H_0=81^{+17}_{-14}$ km s^{-1} Mpc^{-1}, which is consistent with the value of the Hubble constant derived using EPM on a relatively nearby sample of galaxies. Because SN 1992am's host galaxy belongs to a group of galaxies with a wide variety of Hubble types, it may be possible to compare the distance measured here to distances determined with other methods. The Luminosity Line-Width relation (Tully & Fisher 1977) can be applied to increasingly large distances using velocity widths measured optically from Hα. In addition, a Surface Brightness Fluctuation (Tonry & Schneider 1988) distance to several cluster members could be measured if observations were made with a refurbished *Hubble Space Telescope.* These comparisons would be useful in evaluating the effectiveness of all three methods at large distances.

The number of EPM distances beyond the Virgo cluster is still very small, and there is plenty of room to improve the value of H_0 derived from SNe II. Although SN 1992am was a distant object, the observations needed to determine its distance were not especially demanding, and could be done each year for many SNe II at comparable distances. Most of the photometry was gathered using telescopes with apertures smaller than one meter, and all the spectra gathered with larger telescopes took less than half a night in total integration time. Furthermore, because the uncertainty in relating the observed absorption line velocities to the photospheric velocities in much larger than the measurement errors, these spectral observations could have had lower signal-to-noise ratios without sacrificing any precision in the distance determination.

Although SN 1992am was not discovered when it was particularly young (which would have helped constrain the distance further), the error in its distance determination is sufficiently small that, had it been discovered at $z=0.5$, it would have been possible to differentiate between $q_0=0.05$ and $q_0=0.5$ at the 1σ level. As several telescopes larger than six meters are commissioned over the next five years, it is not unreasonable to plan to gather data sets (which have the quality of those we have presented for SN 1992am) on SNe II at redshifts up to $z=0.5$. Finding these SNe and then measuring q_0 will not be easy, but the Expanding Photosphere Method, which does not depend on any standard candle assumption, may prove to be a very useful method for measuring the global geometry of the Universe.

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