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EXPANDING PHOTOSPHERES OF TYPE II SUPERNOVAE AND THE EXTRAGALACTIC DISTANCE SCALE[1]

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ABSTRACT

We use the Expanding Photosphere Method to determine distances to 10 Type II supernovae. The effects of asymmetries, extinction, and flux dilution are explored. Using empirical evidence and time-dependent, spherical models which treat H and He in non–LTE, we show that blackbody corrections caused by flux dilution are small for Type II supernovae in the infrared, and in the optical when their color temperatures are less than 6000 K. The extinction to a Type II-P supernova can be estimated from its light curve: the uncertainty introduced into a distance measurement due to extinction is usually less than 10%. Correcting for extinction and flux dilution, we derive distances to 10 supernovae: SN 1968L, SN 1969L, SN 1970G, SN 1973R, SN 1979C, SN 1980K, SN 1987A, SN 1988A, SN 1990E, and SN 1990ae. The distance measurements span a wide range, 50 kpc to 120 Mpc, which is unique among the methods for establishing the extragalactic distance scale. The distances measured to SN 1970G in M101 and SN 1987A in the LMC are in good agreement with distances determined from Cepheid variable stars. Our distance to the Virgo Cluster, 22 ± 3 Mpc, is larger than recent distance estimates made using surface brightness fluctuations, planetary nebula luminosity functions, and the Tully-Fisher method. Using the distances determined from these Type II supernovae, we derive a value of $H_0 = 60 \pm 10$ km s^{-1} Mpc^{-1}. This value is subject to errors caused by local deviations in the Hubble flow but will soon be improved by applying the Expanding Photosphere Method to several distant Type II supernovae.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

The path to the extragalactic distance scale is long, complex, and pitted with traps for the unwary. Most distance indicators that are useful at the distance of the Virgo Cluster and beyond are calibrated with nearby galaxies whose distances have been measured using Cepheids. This bootstrapping process is far from ideal because the nearby galaxies used for calibration may not represent the distant galaxies where a method is applied. The ideal distance indicator would be independent of distances in the Milky Way or to nearby galaxies and would employ the same method for both local and distant galaxies. Based on a suggestion by Leonard Searle, Kirshner & Kwan (1974) described a method with these desirable properties, the Expanding Photosphere Method (a.k.a. Baade-Wesselink Method), which uses Type II supernovae (SN II's) as "custom yardsticks." The Expanding Photosphere Method (EPM hereafter) is independent of every part of the extragalactic distance ladder and can be used to measure distances to individual SN II's at 50 kpc, as well as 200 Mpc. These attributes make SN II's attractive objects for establishing the extragalactic distance scale. In this paper we show that EPM is accurate, widely applicable, and has the potential to make a significant contribution to the quest for H_0.

[1] Based in part on observations made at the Multiple Mirror Telescope, jointly operated by the Smithsonian Institution and the University of Arizona.

[2] Guest Observer at Kitt Peak National Observatory, operated by AURA, Inc., under contract to the National Science Foundation.

The primitive form of EPM described by Kirshner & Kwan (1974) assumes that a SN II consists of a spherically symmetric expanding photosphere that radiates as a blackbody. If $z \ll 1$,

$$\theta = \frac{R}{D} = \sqrt{\frac{f_\nu}{\zeta^2 \pi B_\nu(T)}}\,, \tag{1}$$

where θ is the angular size, R is the radius of the supernova's photosphere, D is the distance to the supernova, $B_\nu(T)$ is the Planck function, f_ν is the observed flux density of the supernova, and ζ^2 is a correction factor that accounts for the effects of flux dilution; for a blackbody $\zeta^2 = 1$. The stellar envelope undergoes free expansion, and the radius of the photosphere, R, at time t, is just

$$R = v(t - t_0) + R_0\ . \tag{2}$$

The expansion velocity of the material that is instantaneously at the photosphere, v, is determined from absorption minima in the supernova spectra. The radius of the supernova progenitor at t_0, R_0, is usually negligible since typically $R > 10^{15}$ cm and $R_0 \ll 10^{14}$ cm. Supernovae expand freely because their explosion energy is much greater than the gravitational binding energy of the progenitor stars (Sakurai 1960; Grassberg, Imshennik, & Nadyozhin 1971). Deceleration by the interstellar medium and circumstellar gas is small because the mass of matter swept up by the supernova in its first months is much less than the mass ejected for any reasonable density of the circumstellar matter. The photosphere always moves inward in mass coordinates, and its radius is determined by the velocity of the material which is instantaneously at the photosphere. While the photosphere is receding in mass coordinates, and may even be receding in spatial coordinates, it is still being formed in material that is freely expanding outward. Combining equations (1) and (2) we get

$$t = D\left(\frac{\theta}{v}\right) + t_0 . \tag{3}$$

To determine θ, the temperature of the photosphere must be measured either from the spectrophotometry or broad-band filter photometry. This leaves two unknowns, D and t_0. With two or more observations, separated by more than a week, we can determine the distance and time of explosion through a linear regression. If observations do not have sufficient separation, θ/v in equation (3) has a small range, and it is difficult to determine accurately D and t_0 from the regression (Kirshner, Arp, & Dunlap 1976). If t_0 is known, each observation provides an independent measurement of the distance. This provides a useful internal test: if the method is effective, the data will give the same distance to the supernova at all times. EPM has been implemented in this way on several SN II's (SN 1969L and SN 1970G, Kirshner & Kwan 1974; SN 1979C, Branch et al. 1983; SN 1979C and SN 1980K, Kirshner 1985; SN 1987A, Branch 1987, Jeffery & Branch 1990). In addition, Schurmann, Arnett, & Falk (1979) modeled SN II light curves, and by comparing their shape and color to observations, estimated the distance to SN 1959D, SN 1968L, SN 1969L, and SN 1970G.

This simple picture evades some significant challenges to obtaining accurate distances from SN II's. SN II's do not radiate as perfect blackbodies (Wagoner 1981; Shaviv, Wehrse, & Wagoner 1985), and the blackbody correction factors, ζ^2, must be determined. The effect of interstellar reddening and extinction, and the possibility of asymmetric expansion of supernova photospheres also need to be considered. Several groups have modeled SN 1987A's atmosphere to determine blackbody correction factors (Chilukuri & Wagoner 1988; Höflich 1988; Eastman & Kirshner 1989; Schmutz et al. 1990). The distances determined to SN 1987A using these models, $44 \lesssim D_{\rm LMC} \lesssim 50$ kpc, agree with the distance given from Cepheids, 49.4 ± 3.5 kpc (Walker 1987), and give encouragement that SN II's can provide reliable distances to galaxies. In addition, Hauschildt, Shaviv, & Wehrse (1989) have used models of SN II atmospheres to estimate the distances to SN 1980K and SN 1979C.

Here we develop methods for dealing with departures from blackbody emission and with extinction from interstellar dust and then use these results to measure distances to 10 supernovae. Section 2 discusses atmospheric models and blackbody correction factors. Section 3 evaluates the effects of extinction in a distance measurement. Asymmetric supernovae and their role in distance determinations are briefly discussed in § 4. In § 5 we note the advantages of using infrared photometry to measure distances to SN II's. Section 6 contains a short summary of the data for each of the 10 supernovae, and our distance measurements. The distances derived using EPM are compared to distances determined using other methods in § 7. In § 8 we discuss our estimate of H_0.

2. FLUX DILUTION AND MODELS

SN II's have scattering-dominated atmospheres: the flux emerging from their photospheres is smaller than that of a blackbody with the same radius and color temperature (Wagoner 1981; Shaviv et al. 1985). We characterize this dilution of flux by the quantity ζ^2. The actual distance from equation (1), $D_{\rm SN}$, is then a factor of ζ less than the apparent distance measured assuming a SN is a perfect blackbody (i.e., $D_{\rm SN} = \zeta D_{\rm app}$). Random walk arguments show that the radiation field of an atmosphere is thermalized at an optical depth of

$$\tau_{\rm therm} \approx \sqrt{\frac{\sigma + \kappa}{3\kappa}} , \tag{4}$$

where σ is the scattering opacity, and κ is the absorptive opacity. An approximate solution to the radiative diffusion equation for a static plane-parallel atmosphere shows that the emergent flux is

$$F_\nu = \frac{4}{\sqrt{3}}\left(\frac{1}{1 + \sqrt{3}\tau_{\rm therm}}\right)\pi B_\nu(T_{\rm therm}) = \zeta^2 \pi B_\nu(T_{\rm therm}) , \tag{5}$$

where $B_\nu(T_{\rm therm})$ is the Planck function at the temperature where the radiation field is thermalized (Mihalas 1978; Rybicki & Lightman 1979; Hershkowitz, Linder, & Wagoner 1986a). If $\sigma \gg \kappa$, the emergent flux will be much less than $\pi B_\nu(T_{\rm therm})$, and the emission will be that of a dilute blackbody. Figure 1 shows the opacity computed for a 15 $M_\odot$ red supergiant (hereafter RSG) supernova by S. E. Woosley and T. Weaver (personal communication) 10 days after core collapse; σ is 70 times κ, and the flux should be dilute by a factor of 4. Because supernova atmospheres are not plane-parallel, and the ratio of σ to κ varies with optical depth and wavelength, detailed models of supernova atmospheres are essential to get a reliable estimate of ζ.

Motivated by SN 1987A, several groups have recently developed new codes (or adapted existing ones) to model SN II atmospheres which are typically time independent, spherically symmetric, and employ non–LTE equations of statistical equilibrium for hydrogen and helium (Chilukuri & Wagoner 1988; Höflich 1988; Eastman & Kirshner 1989; Schmutz et al. 1990). These models are successful at reproducing the optical spectrum of SN 1987A at several different epochs. In addition, these atmospheric models predict the total emergent flux (and ζ) and can be used to determine the distance to the LMC. The

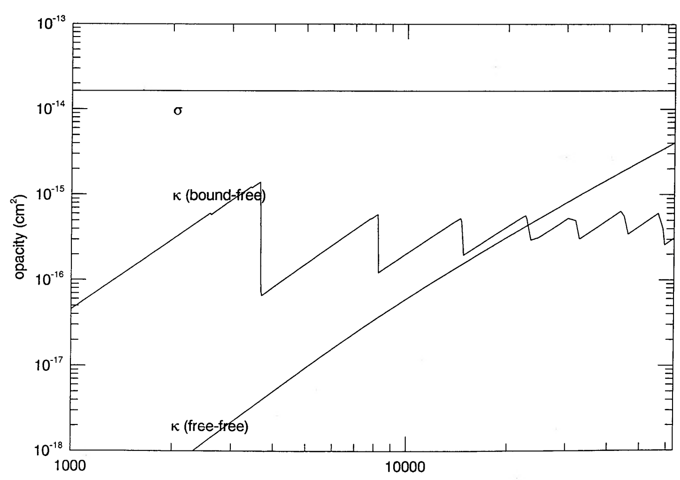

FIG. 1.—Comparison of free-free, bound-free, and electron scattering opacity vs. wavelength from a model of a 15 $M_\odot$ red supergiant 10 days after explosion.

TABLE 1

RECENT DISTANCE ESTIMATES TO THE LMC

Method	Distance (kpc)
Cepheids (Welch *et al.* 1987)	51.8 ± 1.2
Cepheids (Walker 1987)	49.4 ± 3.6
RR Lyrae Stars (Reid and Strungnell 1986)	47.2 ± 3.4
RR Lyrae Stars (Walker and Mack 1988)	48.8 ± 1.1
SN 1987A Circumstellar Ring (Panagia *et al.* 1991)	52.0 ± 2.5
SN 1987A Atmospheric Model (Höflich 1988)	48 ± 4
SN 1987A Atmospheric Model (Eastman and Kirshner 1989)	49 ± 6
SN 1987A Atmospheric Model (Schmutz *et al.* 1990)	45 ± 4
SN 1987A Atmospheric Model (Chilukuri and Wagoner 1991)	45 ± 4[a]
Optical EPM on SN 1987A (Branch 1987)	55 ± 5
Planetary Nebulae (Jacoby, Walker, and Ciardullo 1990)	49 ± 4
IR EPM on SN 1987A (This Work)	49 ± 3

[a] Assuming atmosphere is in the form of eq. (6) with $\gamma = 9$ as determined by Eastman & Kirshner 1989.

distances determined to SN 1987A by these independent groups are consistent to about $\pm 10\%$ and agree remarkably well with Cepheid and RR Lyrae distances for the LMC (Table 1). SN 1987A resulted from the explosion of a B3 star, and models were crafted specifically to fit that event. Taking the next step and determining distances to more distant galaxies requires models for typical SN II's, which likely result from exploding massive stars in the RSG phase.

The code we use to construct model atmospheres is an improved version of that used by Eastman & Kirshner (1989). These models are time-independent, but include the effects of spherical geometry, and treat all relativistic effects which are important in an expanding gas to an accuracy of v/c. The models can employ non–LTE equations of statistical equilibrium for a large number of atoms, but here only H and He are treated in this manner. The excitation and ionization of all other elements is computed from the Saha-Boltzmann equation. These populations are used to approximate the opacity from 63,000 transitions in heavy elements, most of which lie in the UV and which have a major effect on the UV radiation transport (Karp et al. 1977).

For each model the lower and upper boundary conditions must be specified, as well as the velocity and density structure. The upper boundary condition is given by the assumption that there is no radiation striking the atmosphere from above. The lower boundary condition is usually given as the total luminosity at the lower boundary of the atmosphere. The first assumption could be in error if there is a significant amount of circumstellar material. This material, however, produces a noticeable effect on the SN spectrum (see § 6.5, SN 1979C) and should not generally be an undetected problem. The velocity and density structure are generally supplied from hydrodynamic calculations (e.g., Woosley 1988), but for convenience are sometimes parameterized in the form of a power law where the density structure is

$$\rho(v, t) = \rho_0 \left(\frac{v}{v_0}\right)^{-\gamma} \left(\frac{t}{t_0}\right)^{-3} . \qquad (6)$$

This parameterization of the supernova atmosphere agrees with the hydrodynamic calculations, and allows for easy experimentation with density structures.

Ideally, to determine the distance to a supernova, the distance correction factor, ζ, is calculated from models. First, we fit the synthetic spectrum's color temperature. The temperature is derived by comparing the broad-band colors of the calculated spectrum ($B-V$, $V-R$, etc.) determined using analytic filter functions (described in § 6) to those of a blackbody. In equation (5) $\tau_{\rm therm}$ and $T_{\rm therm}$ may be dependent on wavelength, and this will cause supernova spectra to deviate from a Planck function. Therefore, determining the temperature of a supernova over a broad range of wavelength (e.g., V to H) should be avoided. We determine ζ from the ratio of the modeled luminosity of the supernova in a given wavelength range to the luminosity of a blackbody with radius equal to that of the photosphere at the fit temperature.

Eastman & Kirshner (1989) modeled SN 1987A at five different epochs (1.85, 2.5, 5.5, 7.7, and 10.0 days). Figure 2 shows ζ, calculated from models for both the optical (4000–6000 Å) and infrared (1.2–2.2 μm), as a function of color temperature. The optical distance correction factors are large at early times when the supernova is hot ($T_{\rm opt} \approx 10{,}000$ K), but become less important as the supernova cools to $T_{\rm opt} \lesssim 6000$ K. The corrections are much less important in the infrared, where the color temperature of the IR continuum is smaller than that of the optical.

We have calculated ζ for models of 15 and 25 $M_\odot$ RSG supernovae whose structures were calculated by S. E. Woosley and T. Weaver (personal communication). These models show that the evolution of ζ as a function of temperature is similar to SN 1987A. It would be a great simplification if the atmospheres of SN II's are sufficiently similar that ζ depends only on the temperature of the photosphere. When the observations of a SN II constrain the value of t_0, it is possible to make empirical estimates of ζ. In this situation each observation provides an independent measure of the distance to the SN, and if ζ changes, so will the computed distance (Branch 1987). Equation (1) gives

$$\zeta_{\rm emp}(T_{\rm opt}) = \frac{D_{\rm SN}}{D_{\rm app}(T_{\rm opt})} , \qquad (7)$$

where $D_{\rm SN}$ is the actual distance to the SN, and $D_{\rm app}(T_{\rm opt})$ is the distance determined to the SN at the optical color temperature assuming $\zeta = 1$. If we take the distance to the LMC to be 50 kpc, and the explosion time from the observation of neutrinos (Bionta et al. 1987; Hirata et al. 1987), we can derive ζ from the

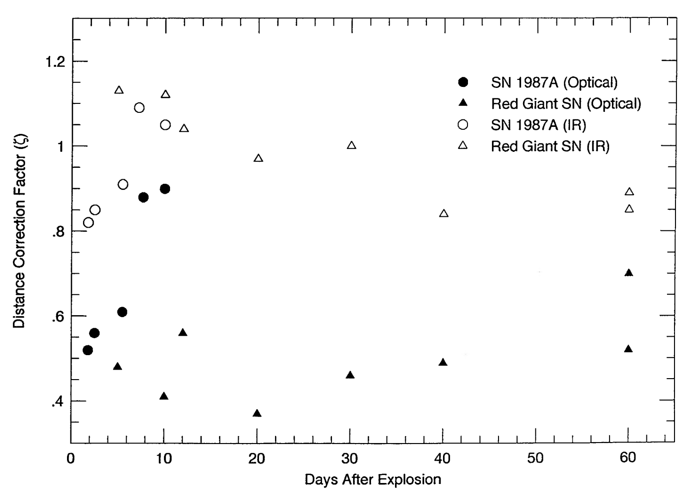

FIG. 2.—The time variation of distance correction factors derived from fitting optical and infrared photometry to models of SN 1987A, and 15 $M_\odot$ and 25 $M_\odot$ red supergiant supernovae.

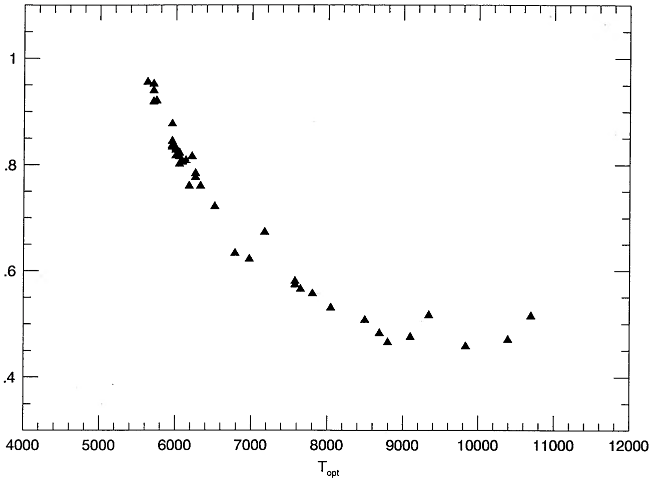

FIG. 3.—Distance correction factors, $\zeta_{\rm emp}$, empirically derived from SN 1987A, shown as a function of the optical color temperature.

application of EPM on SN 1987A (see § 6 for discussion of observations). Figure 3 shows $\zeta(T_{\rm opt})$ as measured from SN 1987A and suggests that $\zeta \approx 1$ when $T_{\rm opt} \approx 5500$ K. Our models also show that ζ approaches 1 when $T_{\rm opt} \approx 6000$ K for SN II's, however, we have not yet made models with $T_{\rm opt} <$ 6000 K. As the gas temperature at the photosphere decreases, the ratio of absorptive to scattering opacity at optical wavelengths increases. The optical scattering opacity is mainly electron scattering, and is independent of temperature above the recombination temperature of hydrogen. The most important absorptive opacity source is photoionization out of hydrogen $n = 3$, which is a sensitive function of T. As the temperature decreases, the fraction of H atoms in $n = 3$ goes up, and consequently, ζ increases. A rough first-order analysis suggests the distance correction factor should vary with gas density as $\rho^{1/4}$. The already low sensitivity of ζ to ρ might be softened somewhat further by other factors, such as the effect which varying ρ has on the temperature structure and departure from thermal equilibrium. The details of this relationship will be explored more thoroughly in a future paper. At any given color temperature, the models and, presumably, the supernovae shown in Figure 4, span a range of values for the gas density at the photosphere, which probably accounts for much of the scatter in the figure. For the model calculations shown in Figure 4, the density at the photosphere at all times varied by less than a factor of 10. Apparently, over the range of densities present at the photospheres of SN II's, ζ is most sensitive to temperature.

As the photospheric temperature approaches the hydrogen recombination temperature, $T_{\rm rec}$, a recombination wave begins moving inward through the envelope. In this phase, the photosphere is always at the place where hydrogen is recombining. The thermalization depth reaches a minimum near $T_{\rm rec}$, and the distance correction factor approaches unity.

If we assume that $\zeta = 1$ when $T_{\rm opt} < 5500$ K, ζ can be estimated for other SN II's whose times of explosion are roughly known, but whose distances are not. Figure 4 shows $\zeta(T_{\rm opt})$ as computed from our models, and measured empirically from SN 1987A and four other SN II's. The agreement is remarkable, especially considering the errors are at least $\pm$(10–20)% for the empirically derived factors, and around ± 10% for the factors derived from the models. The agreement also supports the assumption that SN II's are good blackbodies at 5500 K (if they were not, the correction factors derived empirically and using models would be offset from each other). The evidence that ζ depends uniformly on temperature is persuasive, but incomplete, and in the future we will model the atmospheres of many more SN II's to further test this hypothesis. In the meantime we apply the results of Figure 4 to several historical supernovae (about as old as the youngest author) and a few more recent ones.

3. EXTINCTION

As the light from a supernova travels to Earth, it passes though dust both in the parent galaxy and in the Milky Way. Dust reddens the light and diminishes its intensity, and we expect these effects to cause some uncertainty in applying EPM. Extinction in the Milky Way has been well studied (Burstein & Heiles 1982, 1984). However, there are still sizable uncertainties in the extinction at low Galactic latitude. Extinction from dust within a supernova's host galaxy is much harder to quantify. SN II's always occur in galaxies rich with dust, and the total extinction to a supernova may have large uncertainties, especially if the galaxy is a highly inclined spiral. Problems with extinction are minimized when a supernova occurs at high Galactic latitude and in the outer regions of a face-on spiral. In these instances the total extinction is expected to be small and should not pose a significant problem.

A direct method of determining the extinction to a supernova is to measure the equivalent width of Na and Ca interstellar absorption against the continuum source provided by the supernova. Although the observations are difficult and the interpretation is uncertain because of the unknown dust-to-gas ratio, the measurement gives a direct measure of the column density of gas, and we expect this to be proportional to the extinction. This method has been applied to several supernovae; e.g., Penston & Blades (1980) for SN 1979C, Pettini et al. (1982) for SN 1980K, Blades et al. (1988) for SN 1987A, and Steidel, Rich, & McCarthy (1990) for SN 1989M.

Light curves of SN II's are subdivided into two classes based on their shape; linear (II-L), and plateau (II-P). SN II-L's, after maximum, decline exponentially in brightness (linear in magnitudes), whereas SN II-P's, 25 days after maximum, maintain a nearly constant brightness for several weeks (Barbon,

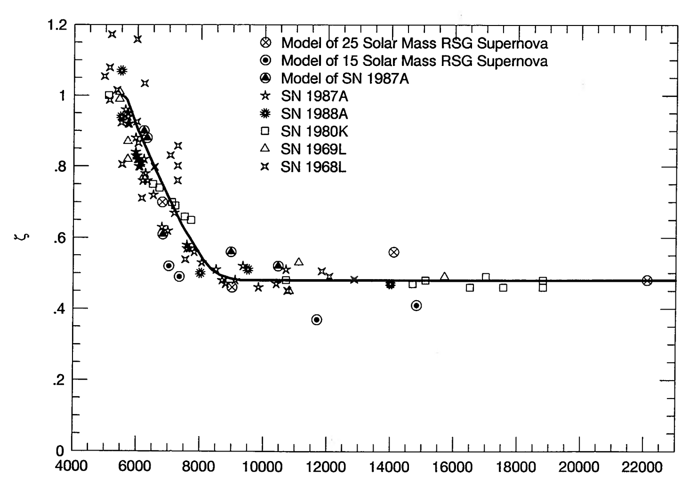

FIG. 4.—Optical distance correction factors plotted as a function of color temperature derived empirically, and from models of SN 1987A, and 15 $M_{\odot}$ and 25 $M_{\odot}$ red supergiant supernovae. The line of best fit is also plotted.

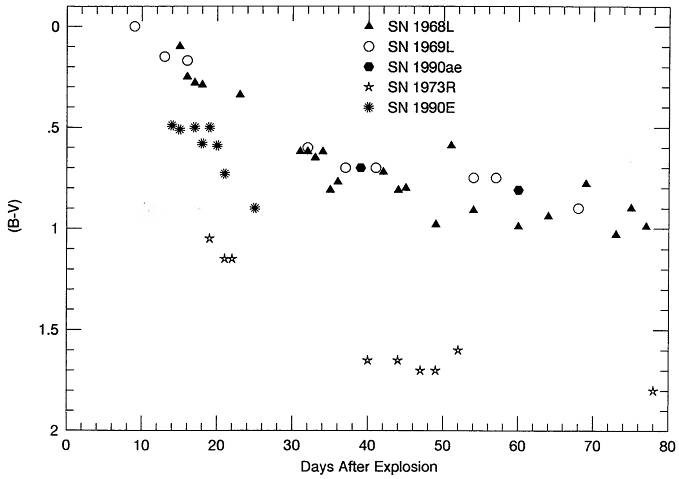

FIG. 5.—$(B-V)$ color evolution of five SN II-P's. The unreddened supernovae; SN 1968L, SN 1969L, and SN 1990ae all show a uniform evolution. SN 1973R and SN 1990E are reddened and show a $(B-V)$ color excess.

Ciatti, & Rosino 1979; Kirshner 1990). A less direct method of determining the extinction for a SN II-P is to examine its color evolution. SN II-P's start out hotter than 10,000 K ($B-V \lesssim 0.2$) and cool to the recombination temperature of hydrogen (5500 K) during the plateau phase. During the plateau phase, which lasts for several weeks, the supernova has a constant color of $(B-V) = 0.75 \pm 0.1$ as shown below. The evolution tightly constrains the amount of reddening present in a SN II-P. This recombination temperature of hydrogen is relatively insensitive to density and metallicity and should be nearly the same for all SN II-P's. This insensitivity of the recombination temperature to density and metallicity can be demonstrated by using Saha's equation to determine when hydrogen ionizes, over the range of densities indicated by hydrodynamic calculations of SN 1987A (Woosley 1988) and 15 and 25 $M_\odot$ RSG supernovae. The calculation, simple as it may be, yields a recombination temperature (5500 ± 500 K) which is consistent with SN 1987A (Table 8), when corrected for $A_V = 0.6$ as determined by Blanco et al. (1987). It is also consistent with SN 1968L (Table 2b), SN 1969L (Table 3b), and SN 1990ae (Table 11b). All of these supernovae occurred at high Galactic latitude; in addition, SN 1968L occurred in a face-on galaxy, and SN 1969L and SN 1990ae occurred in the outer regions of their parent galaxy, where we expect the total reddening is small. Figure 5 shows the $(B-V)$ evolution for SN 1968L, SN 1969L, and SN 1990ae. Two supernovae in highly inclined spirals, SN 1973R and SN 1990E, are also plotted. All of the supernovae have evolved in a similar manner, except that SN 1973R and SN 1990E are shifted by a constant $(B-V)$. This shift represents the color excess, $E(B-V)$, and indicates the amount of extinction. Using $A_V = 3E(B-V)$ (Whitford 1958) to determine the visual extinction suggests that if the $(B-V)$ color excess can be determined to ± 0.1 mag, the extinction to SN II-P's can be estimated to ± 0.3 mag.

Surprisingly, even a moderately large extinction does not produce a large effect in the estimated distance. EPM is affected in two ways by extinction. A supernova appears dimmer, and hence we overestimate its distance. However, a supernova also appears redder and cooler, and therefore we underestimate the distance. In addition, because the supernova appears cooler, the distance correction factors (ζ) from Figure 4 are closer to unity, and we overestimate the distance. These effects can cancel each other to a remarkable extent. The effect of extinction on the distance determination has been calculated for several individual supernovae (Figs. 6*a* and 6*b*). The uncertainty in distance due to extinction is $<10\%$ in most cases, even though the uncertainty in the extinction is ± 0.3 mag. The

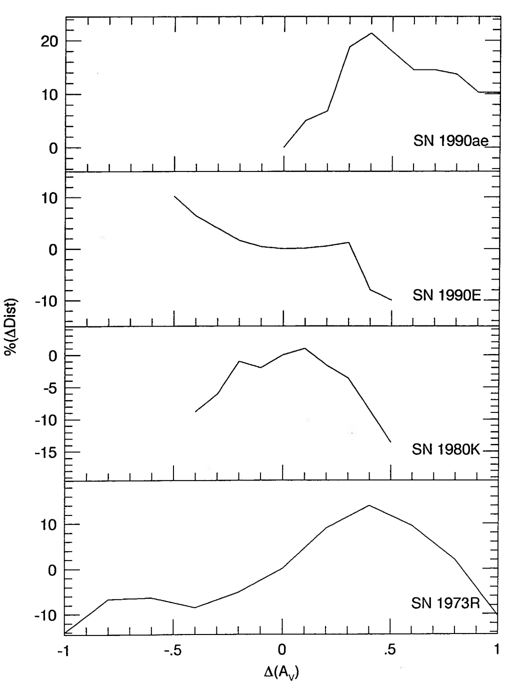

FIG. 6*a*

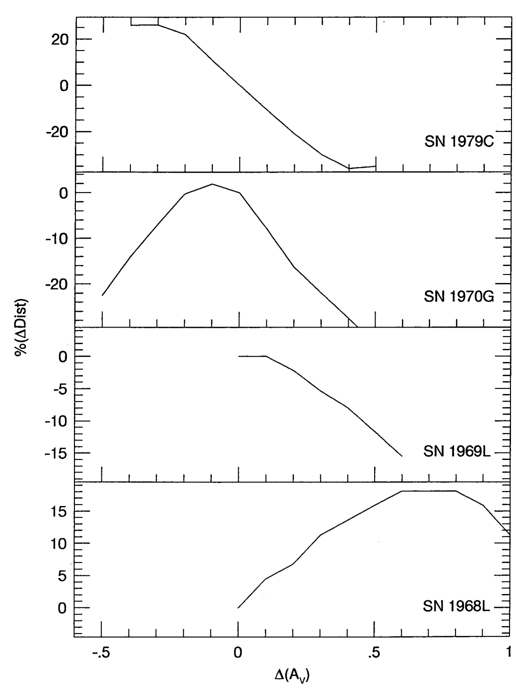

FIG. 6*b*

FIG. 6.—(*a*) The percent change in distance as a function of visual extinction for SN 1968L, SN 1969L, SN 1970G, and SN 1979C. (*b*) The percent change in distance as a function of visual extinction for SN 1973R, SN 1980K, SN 1990E, and SN 1990ae.

uncertainties, however, can be much larger in cases where the supernova is not observed continuously over a long period of time. Extinction has a much smaller effect in the infrared. If infrared photometry (*JHK*) is used to measure a distance, the distance is systematically underestimated by less than 10% for a full magnitude of unaccounted visual extinction.

4. ASYMMETRIES

Polarization (Cropper et al. 1988), speckle observations (Papaliolios et al. 1989) and *HST* observations of the circumstellar shell (Jakobsen et al. 1991) give indications for some degree of asymmetry in SN 1987A. Although an asymmetric photosphere could affect the individual distance determinations, there are several reasons to believe it is not a serious problem for EPM. The polarization measurements may indicate moderate asymmetries (20%) at early times in SN 1987A. However, these determinations are hampered by uncertainties in the polarization due to the interstellar medium which are as large as the observed polarization in SN 1987A (Jeffery 1989). If the inferred asymmetry for SN 1987A were correct, it would produce a 10% uncertainty in the derived distance to the supernova (Wagoner 1991). The speckle observations indicate large asymmetries in SN 1987A, but only several months after the explosion. These observations are looking at material substantially deeper inside the supernova than the gas that formed the photosphere during the first 50 days of SN 1987A.

Chevalier & Soker (1989) have shown that a supernova arising from the explosion of a RSG, which we identify with a typical SN II-P, is likely to have asymmetries much smaller than found in SN 1987A. The flatter density profile of the RSG reduces the asymmetry of the propagating shock relative to SN 1987A. Additionally, because a RSG is more extended, rotationally induced asymmetries will be smaller than for compact progenitors. Most bright SN II models require extended RSG progenitors (Chevalier 1976) and should have smaller uncertainties from asymmetries than SN 1987A.

Wagoner (1991) estimated the effect of asymmetries on the determined distance of a SN II. He showed that although the individual effects can be large for highly flattened systems, the average distance determined, when summed over all viewing angles, is within 1% of the correct distance. Large asymmetries could cause substantial errors in individual distance determinations, but they would not bias the derived global distance scale to smaller or larger distances.

5. USING THE INFRARED

With the advent of infrared arrays, it is now possible to obtain infrared photometry (*JHK*) of relatively faint supernovae. The infrared has several advantages over optical observations for applying EPM. First, as shown in § 3, the uncertainty in a distance measurement due to extinction is less than half that incurred when optical photometry is used. Second, the early spectra of SN 1987A (Elias et al. 1988) show few spectral features in the *J*, and especially the *H* and *K* bands, making it easier to determine the temperature from the broad-band colors. Finally, as discussed previously, the flux dilution in the infrared is much smaller.

Flux dilution depends on the ratio of the scattering opacity to the absorptive opacity (eqs. [4] and [5]). In the infrared, free-free absorption begins to dominate the bound-free process and is the major source of the absorptive opacity. The opacity due to free-free transitions is proportional to λ^3. Thus, we expect SN II's to better approximate blackbodies at longer wavelengths. This prediction is borne out in our models, which show the blackbody correction factors near unity for near infrared wavelengths (Fig. 2). This result is not consistent with the models of Hershkowitz, Linder, & Wagoner (1986b) and Hershkowitz & Wagoner (1987), whose plane-parallel models, which treat hydrogen (six levels) in non–LTE, show that at $T_{\rm EFF} > 6000$ K, the emergent flux in the infrared is dilute for any reasonable density of the supernova photosphere. The effective temperature of a supernova photosphere is typically larger than the color temperature, and this may account for the discrepancy.

Measuring the color temperature of a supernova in the infrared is more difficult than in the optical because the spectrum is close to Rayleigh-Jeans. Infrared photometry is generally of lower accuracy than optical, and this accentuates the problem. Fortunately, in the Rayleigh-Jeans regime, the flux and temperature are linearly related, and therefore the distance depends on $T^{1/2}$. If the error in the *J*, *H*, and *K* photometry is ± 0.05 mag, the uncertainty in the distance for a single measurement is 7% at 5500 K and is 12% at 10,000 K. SN II-P's cool to $T_{\rm IR} < 5500$ K very quickly and remain at that temperature while on the plateau phase. Therefore, determining the color temperature from (*JHK*) will not cause significant errors except at the earliest stages in a supernova's evolution.

6. OBSERVATIONS AND DISTANCE DETERMINATIONS

We present a summary of the observational data and its implementation in making distance determinations to 10 SN II's. The temperatures of the supernovae are determined in one of two ways. In most cases the color temperature is fitted from the photometry using analytic filter functions. For *B* and *V* the functions of Ažusienis & Straižys (1969) are used. The filter functions of Bessel (1983) are used for R_C and I_C, but are shifted 23 Å to the blue and 50 Å to the red, respectively, as suggested by Taylor (1986). The filter functions of Johnson (1965) are convolved with the transmission through a model terrestrial atmosphere (Selby & McClatchey 1972) for the *J*, *H*, *K*, and *L* bands. The analytic filter functions have been checked by determining the broad band colors of the spectrophotometric standards of Oke & Gunn (1983), and they agree in *B* and *V* to ± 0.03 mag. Integrating blackbodies with these filter functions yields the relation between color temperature and $(B-V)$ color:

$$\frac{10^4\ \mathrm{K}}{T} = 1.605(B-V) + 0.67\ . \tag{9}$$

In other cases where photometry is not available, but flux-calibrated spectra are, the temperatures are fitted directly from the spectra by comparing the continuum to a blackbody. The two methods generally agree to 10% in temperature (Fig. 7), however temperatures measured from spectra are systematically $\approx 5\%$ smaller than those measured from the $(B-V)$ color. Systematic effects of this size have a minor effect on a distance determination (5%–10%, depending on the temperature). In cases where both spectra and photometry are available, we have used photometry. In addition, all distances derived from optical photometry are corrected for flux dilution using the solid line in Figure 4. The velocity of a supernova's photosphere is usually derived from the absorption minimum of the Fe II lines λ5169, λ5018, and λ4924 as suggested by the calculations of Eastman & Kirshner (1989) and Schmutz et al. (1990). These lines are narrow and are formed at small optical depth for the first several weeks in a supernova's evolution. In

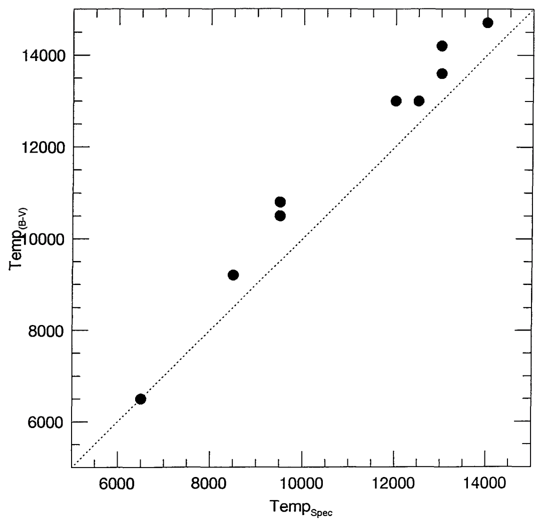

FIG. 7.—Comparison of the temperature of the supernova continuum as derived from the $(B-V)$ color and optical spectrum. The dotted line is $T_{B-V} = T_{\rm Spec}$.

a few instances, at early times, these lines are not easily visible, and the velocities are derived from the Balmer lines. Models, if they were available, could be used to estimate the photospheric velocity from the Balmer lines. In practice, however, the velocities measured from the hydrogen lines are corrected by the ratio of the velocities of the hydrogen and iron lines when the iron lines are first visible. If there are periods where photometry is available, and spectra are not, velocities are estimated through linear interpolation or extrapolation. In all cases the internal scatter of the distance measurements is less than 10%. Our estimates of the total error, which range from 5% to 30% also include uncertainties in blackbody correction factors and reddening.

6.1. *SN1968L*

NGC 5236 has been the site of six supernovae this century. The fifth, SN 1968L, was discovered on 1968 July 16 near the nucleus by J. C. Bennett. Photographic spectra and photometric observations were made by Wood & Andrews (1974), and further photoelectric photometry (*BV*) was obtained by Wamsteker (1972). Wamsteker's data were corrected for the brightness of the galaxy background by Wood & Andrews (1974). The data cover the first 2 months of the supernova's evolution quite thoroughly and show it had a plateau light curve, but the quality of both the spectra and photomentry is poor. The RMS errors in the velocities measured from spectra by Wood & Andrews (1974) are around 20%, and the RMS error in the corrected *BV* photoelectric photometry is approximately 0.2 mag (Table 2A).

To determine the temperature from the $(B-V)$ light curve, we have corrected for the foreground Galactic extinction, $A_V = 0.11$ (Burstein & Heiles 1984). NGC 5236 is nearly face-on, and we see no evidence for significant reddening of the supernova from the $(B-V)$ color of the plateau. Because the individual spectra are poor, a mean velocity curve is used, instead of determining the velocities at each time. Table 2B and Figure 8*a* show the results of the distance determination. We find a distance for NGC 5236 of $4.8^{+1.3}_{-0.7}$ Mpc.

6.2. *SN 1969L*

SN 1969L was discovered on 1969 December 2 in the outer regions of NGC 1058 as a $m_B = 13$ object. Photographic spectra and photometry (*BV*) were published by Ciatti, Rosino, & Bertola (1971). In addition Kirshner & Kwan (1974) published photographic and photoelectric spectra of the supernova. The data, which are reasonably extensive and of good quality, show that SN 1969L was a Type II-P and was discovered near maximum (Table 3A).

The data are corrected for a foreground extinction of $A_V = 0.17$ (Burstein & Heiles 1984), and the temperature is calculated from the *BV* photometry. SN 1969L should be free from significant extinction in the parent galaxy, as it occurred 227″ from the nucleus in the nearly face-on galaxy. A distance of $11.2^{+1.0}_{-2.0}$ Mpc for SN 1969L is derived from the data (Table 3B and Figure 8*a*).

6.3. *SN 1970G*

SN 1970G was discovered in M101 (NGC 5457) on 1970 July 30. Photoelectric photometry (*UBV*) was published by Winzer (1974) and showed SN 1970G to be a Type II-L. Both photoelectric and photographic spectra were published by Kirshner & Kwan (1974). The early spectroscopic and photometric coverage of SN 1970G extends to only 30 days after discovery, but it is of good quality (Table 4A).

There is little foreground extinction to M101 (Burstein & Heiles 1984). However, the supernova occurred in an H II region studied by Searle (1971), who estimated the total internal extinction to be $A_V = 0.44$. Since SN 1970G did not have a plateau phase, we cannot estimate the extinction from its color evolution, and we adopt $A_V = 0.44$ as the extinction to the supernova. The temperatures are derived from the *BV* photo-

TABLE 2A

OBSERVATIONS OF SN 1968L

t^a			V^b (km sec^{-1})				
(days)	B	V	H_β	H_γ	FeII λ5169	FeII λ5018	FeII λ4924
14	12.00	11.90	8270	7949	...	...	...
15	12.10	11.85	7653	8433	...	...	...
16	12.24	11.96	...	...	...	...	...
17	12.12	11.83	7653	7051	...	...	...
19	...	...	6727	8433	...	...	...
20	...	...	7653	...	...	6935	...
22	12.24	11.90	...	...	...	...	...
30	12.50	11.88	5925	6290	4933	4962	5118
31	12.58	11.96	...	...	...	...	...
32	12.64	11.99	...	...	...	...	...
33	12.61	11.99	3333	...	4527	...	...
34	12.71	11.90	...	...	...	...	...
35	12.67	11.90	...	...	...	...	...
41	12.71	11.99	...	...	...	...	...
43	12.80	11.99	...	...	...	...	...
44	12.87	12.07	6110	7396	4527	4843	...
48	13.14	12.16	...	...	...	...	...
50	12.66	12.07	...	...	...	...	...
53	13.14	12.23	...	...	...	...	...
59	13.06	12.07	...	...	...	...	...
62	...	...	3024	...	...	2750	2864
63	12.87	11.93	...	...	...	...	...
67	...	...	3888	...	...	...	...
68	12.74	11.96	...	...	...	...	...
71	...	...	4876	...	3366	3946	...
72	13.19	12.16	...	...	...	...	...
74	13.06	12.16	...	...	...	...	...
76	13.06	12.07	...	...	...	...	...

[a] $t_0 = 1968$ Jul 2.
[b] Corrected for $v_{rec} = 506$ km s^{-1}.

TABLE 2B

DERIVED QUANTITIES FOR SN 1968L

t^a (days)	v_{used} (km sec^{-1})	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
14	7550	0.081	0.91	11800	11.3	0.48	5.4
15	7350	0.118	0.95	9100	8.1	0.48	3.9
16	7000	0.120	0.97	8700	8.1	0.49	4.0
17	7000	0.130	1.03	8600	7.9	0.49	3.9
22	6800	0.140	1.29	8100	9.2	0.54	5.0
30	5000	0.255	1.30	6000	5.1	0.91	4.6
31	5000	0.246	1.34	6000	5.5	0.91	5.0
32	4900	0.257	1.35	5800	5.3	0.95	5.0
33	4900	0.242	1.40	6000	5.8	0.91	5.2
34	4850	0.372	1.42	5100	3.8	1.00	3.8
35	4850	0.345	1.47	5200	4.2	1.00	4.2
41	4650	0.299	1.65	5500	5.5	1.00	5.5
43	4650	0.357	1.73	5100	4.8	1.00	4.8
44	4600	0.338	1.75	5100	5.2	1.00	5.2
48	4300	0.471	1.78	4500	3.8	1.00	3.8
50	4200	0.220	1.81	6200	8.3	0.88	7.2
53	4150	0.392	1.90	4700	4.8	1.00	4.8
59	4100	0.495	2.09	4500	4.2	1.00	4.2
63	3900	0.478	2.12	4600	4.4	1.00	4.4
68	3700	0.343	2.17	5200	6.3	1.00	6.3
72	3600	0.523	2.24	4300	4.3	1.00	4.3
74	3500	0.400	2.24	4700	5.6	1.00	5.6
76	3500	0.495	2.30	4500	4.6	1.00	4.6

[a] t_0 = 1968 Jul 2.
[b] Corrected for $A_V = 0.11$ mag.

metry, except for days 35 and 70. In these cases the temperature and flux are taken from spectrophotometry published by Kirshner & Kwan (1974). The temperature measured from the spectrophotometry is consistent (within the expected errors) with those measurements made from the photometry. Our distance determination to M101 is $7.6^{+1.0}_{-2.2}$ Mpc (Table 4B and Fig. 8*a*).

6.4. *SN 1973R*

SN 1973R was discovered in NGC 3627 on 1973 December 19. Ciatti & Rosino (1977) published photographic photometry (*BV*) and spectroscopy of the supernova, and Kirshner & Kwan (1975) published photoelectric spectrophotometry. The photometric coverage is quite good and showed SN 1973R to

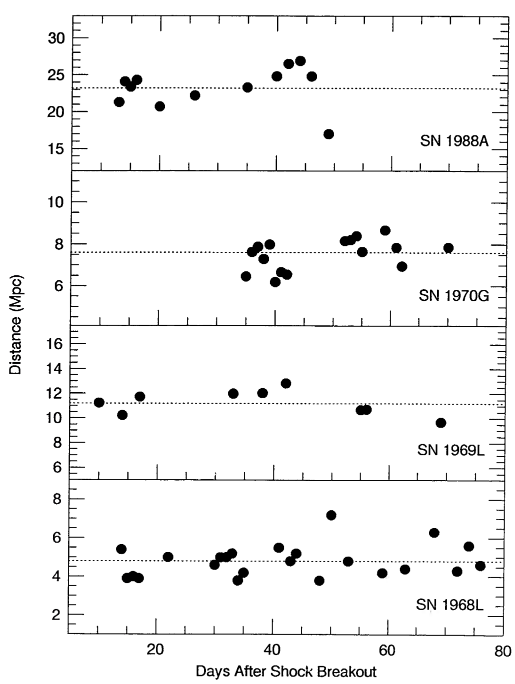

FIG. 8*a*

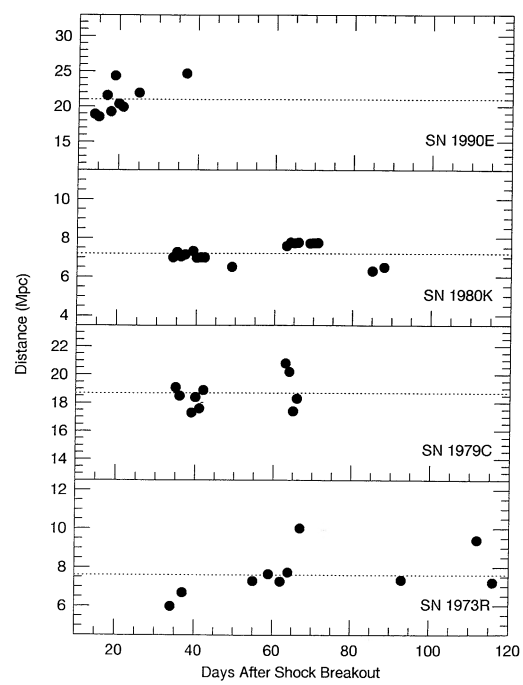

FIG. 8*b*

FIG. 8.—(*a*) Distance as a function of time for SN 1968L, SN 1969L, SN 1970G, and SN 1988A. (*b*) Distance as a function of time for SN 1973R, SN 1979C, SN 1980K, and SN 1990E.

TABLE 3A

OBSERVATIONS OF SN 1969L

t^a			V^b (km $\sec^{-1}$)						
(days)	B	V	H_α	H_β	H_γ	H_δ	FeII λ5169	FeII λ5018	FeII λ4924
10	13.20	13.20	12300	9800	9500	9000	...	...	...
14	13.40	13.25	10200	9200	9100	...	...	...	...
17	13.42	13.25	...	9600	9400	8400	...	...	...
33	13.95	13.35	10000	7900	7400	6400	6000	...	...
38	14.05	13.35	...	7200	6600	6200	...	5600	...
42	14.05	13.35	9300	7300	6700	5700	5400	...	...
55	14.10	13.35	6800	5800	5950	4900	3900	3700	3400
56	14.10	13.35	6700	5800	5400	5500	3500	...	...
69	14.25	13.35	7200	5200	5900	4950	4200	...	...

[a] t_0 = 1969 Nov 25.
[b] Corrected for $v_{rec} = 519$ km s^{-1}.

TABLE 3B

DERIVED QUANTITIES FOR SN 1969L

t^a (days)	v_{used} (km $\sec^{-1}$)	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
10	9000	0.033	0.78	15667	23.4	0.48	11.2
14	8500	0.048	1.03	11160	21.3	0.48	10.2
17	8400	0.051	1.23	10767	24.4	0.48	11.7
33	6000	0.123	1.71	6224	13.9	0.86	12.0
38	5600	0.150	1.84	5683	12.2	0.99	12.0
42	5400	0.150	1.96	5683	13.0	0.99	12.8
55	3750	0.167	1.78	5441	10.7	1.00	10.7
56	3700	0.167	1.79	5441	10.7	1.00	10.7
69	3700	0.228	2.21	4824	9.7	1.00	9.7

[a] t_0 = 1969 Nov 25.
[b] Corrected for $A_V = 0.17$ mag.

be a highly reddened Type II-P supernova. The spectral coverage of SN 1973R is limited to only three epochs, but data are of good quality (Table 5A).

NGC 3627 suffers from only a small amount of extinction from the Milky Way (Burstein & Heiles 1984); however, NGC 3627 is a very dusty spiral that is inclined. During the plateau phase, SN 1973R had $(B-V) = 1.65$, which gives a color excess of 0.9 ± 0.1 mag, and implies that $A_V = 2.7 \pm 0.3$ mag. The temperature and photometric angular size are determined from the BV photometry. The results are given in Table 5B and in Figure 8*b*, and give the distance to SN 1973R as $7.6^{+2.2}_{-1.5}$ Mpc.

TABLE 4A

OBSERVATIONS OF SN 1970G

t^a			V^b (km $\sec^{-1}$)				
(days)	B	V	H_α	H_β	FeII λ5169	FeII λ5018	FeII λ4924
35	...	...	7800	8400	6400	6500	6200
36	11.94	11.65	...	...	...	...	...
37	11.95	11.66	...	...	...	...	...
38	12.00	11.67	...	...	...	...	...
39	12.08	11.76	...	...	...	...	...
40	12.14	11.67	8000		6200	5800	...
41	12.21	11.78	...	...	...	...	...
42	12.22	11.75	...	...	6200	...	...
52	12.86	12.15	...	...	...	...	...
53	12.89	12.17	...	...	...	...	...
54	12.83	12.16	...	...	...	...	...
55	12.95	12.14	...	...	...	...	...
59	12.96	12.26	...	...	...	...	...
61	12.96	12.18	...	...	...	...	...
62	13.05	12.18	...	...	...	...	...
70	...	...	...	...	3700	...	...

[a] t_0 = 1970 Jul 1.
[b] Corrected for $v_{rec} = 266$ km s^{-1}.

6.5. *SN 1979C*

SN 1979C was discovered in M100 (NGC 4321) on 1979 April 19. Spectrophotometry is available from Branch et al. (1983) and R. P. Kirshner (unpublished), and there is photographic spectroscopy from Panagia et al. (1980). Photoelectric photometry was published by de Vaucouleurs et al. (1979), and Barnes et al. (1979). Additional photographic photometry was published by Ciatti et al. (1979a, b). The spectral coverage of this supernova is very good, and the photometric coverage is relatively good (Table 6A). SN 1979C was an unusual SN II-L and was also observed extensively in the UV, radio, and X-ray (Panagia et al 1980). Fransson (1982) has shown that the radio and UV observations suggest SN 1979C has a significant amount of circumstellar matter.

The extinction to SN 1979C was estimated by Penston & Blades (1980) and Branch (1983) using interstellar lines, and we adopt their value of $A_V = 0.45$. The temperatures are derived from the BV photoelectric photometry, and a distance of 19 ± 5 Mpc is determined for M100 (Table 6B and Figure 8*b*). The large uncertainty is primarily due to reddening (Fig. 6*a*). This distance implies that SN 1979C was extremely luminous, $M_B \approx -20.4$ (Table 12).

6.6. *SN 1980K*

SN 1980K was discovered in NGC 6946 on 1980 October 29 and is the most recent of the six observed supernovae in this galaxy. Extensive photographic (UBV) and photoelectric (UBV) photometry were carried out by Barbon et al. (1982) and Buta (1982), respectively. In addition, infrared photometry ($JHKL$) was published by Dwek et al. (1983). Extensive spectrophotometry is also available from Uomoto & Kirshner (1986). The data for SN 1980K are exceptionally good in cover-

TABLE 4B

DERIVED QUANTITIES FOR SN 1970G

t^a (days)	v_{used} (km sec^{-1})	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
35	6400	0.144	1.99	9500	13.8	0.48	6.5
36	6400	0.125	2.05	10800	16.3	0.48	7.6
37	6400	0.125	2.10	10800	16.9	0.48	7.9
38	6300	0.136	2.12	10100	15.6	0.48	7.3
39	6300	0.128	2.18	10300	17.0	0.48	8.0
40	6200	0.172	2.20	8600	12.7	0.50	6.2
41	6200	0.162	2.25	8700	13.9	0.49	6.7
42	6200	0.180	2.30	8200	12.8	0.52	6.5
52	5307	0.247	2.43	6300	9.8	0.85	8.2
53	5218	0.250	2.43	6200	9.7	0.86	8.2
54	5129	0.227	2.44	6500	10.7	0.80	8.4
55	5039	0.304	2.44	5800	8.0	0.97	7.6
59	4682	0.231	2.43	6400	10.5	0.84	8.7
61	4504	0.283	2.41	5900	8.5	0.94	7.8
63	4414	0.341	2.40	5440	7.1	1.00	6.9
70	3700	0.285	2.27	5000	8.0	1.00	7.9

[a] t_0 = 1970 Jul 1.
[b] Corrected for $A_V = 0.44$ mag.

age and quality and show the supernova to the Type II-L (Table 7A). SN 1980K was also observed in the UV (Panagia 1980), in the radio (Sramek, van der Hulst, & Weiler 1980), and is still observable (Leibundgut et al. 1991b). In addition, a deep plate was taken of NGC 6946 49 days before the discovery of the supernova. From this plate Thompson (1982) was able to place an apparent magnitude limit of $m_F \gtrsim 21.7$ for the progenitor of SN 1980K.

NGC 6946 lies at low Galactic latitude and has a foreground extinction of $A_V = 1.2$ (Burstein & Heiles 1984). NGC 6946 is nearly face-on, and SN 1980K occurred in the outer regions of the galaxy, so it is unlikely that the supernova was reddened substantially from the parent galaxy. The photometric angular size was determined using both the infrared ($JHKL$) and the optical (BV) photometry. A distance of 8.1 ± 1.5 Mpc is

TABLE 5A

OBSERVATIONS OF SN 1973R

t^a			V^b (km sec^{-1})			
(days)	B	V	H_α	H_β	FeII λ5169	FeII λ5018
34	15.40	14.25	...	...	...	...
37	15.50	14.35	8200	8100	5800	6070
55	16.35	14.60	6920	6250	5220	...
59	16.30	14.65	...	...	...	...
62	16.40	14.70	...	...	...	...
64	16.50	14.80	...	...	...	...
67	16.50	14.90	...	...	...	...
93	16.60	14.80	...	...	...	...
112	17.70	14.80	...	...	...	...
116	17.65	15.65	6005	4270	3130	...

[a] t_0 = 1973 Nov 22.
[b] Corrected for $v_{rec} = 697$ km s^{-1}.

TABLE 6A

OBSERVATIONS OF SN 1979C

t^a			V^b (km sec^{-1})				
(days)	B	V	H_β	H_γ	FeII λ5169	FeII λ5018	FeII λ4924
33	...	...	9900	...	9700	...	...
35	12.37	12.19	...	...	...	...	...
36	12.30	12.11	...	...	...	...	...
37	...	...	...	...	10600	...	...
39	12.61	12.34	...	...	...	...	...
30	12.62	12.36	...	...	...	...	...
41	12.66	12.37	...	...	...	...	...
42	12.64	12.37	...	...	...	...	...
54	...	...	10000	...	8300	8600	...
57	...	...	10100	...	8800	8700	8900
59	...	...	10600	...	8800	8600	9100
61	...	...	9100	...	7100	7000	7100
63	13.59	12.96	8800	...	7250	7400	...
64	13.60	12.96	8200	...	7000	7100	...
67	13.64	12.97	7810	...	5930	5650	...
68	13.76	13.07	...	...	...	...	...

[a] t_0 = 1979 Mar 19.
[b] Corrected for $v_{rec} = 1568$ km s^{-1}.

TABLE 5B

DERIVED QUANTITIES FOR SN 1973R

t^a (days)	v_{used} (km sec^{-1})	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
34	5900	0.139	1.73	9538	12.5	0.48	6.0
37	5800	0.133	1.85	9538	13.9	0.48	6.7
55	5220	0.340	2.48	5473	7.3	1.00	7.3
59	5000	0.333	2.55	5473	7.7	1.00	7.7
62	4900	0.361	2.62	5244	7.3	1.00	7.3
64	4830	0.345	2.67	5244	7.7	1.00	7.7
67	4750	0.269	2.75	5704	10.2	0.98	9.9
93	3850	0.421	3.09	4858	7.3	1.00	7.3
112	3200	0.329	3.10	4506	9.4	1.00	9.4
116	3130	0.435	3.14	4203	7.2	1.00	7.2

[a] t_0 = 1973 Nov 22.
[b] Corrected for $A_V = 2.70$ mag.

TABLE 6B

DERIVED QUANTITIES FOR SN 1979C

t^a (days)	v_{used} (km sec^{-1})	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
35	10000	0.076	3.02	13009	39.9	0.48	19.1
36	10000	0.080	3.10	12726	38.5	0.48	18.5
39	9500	0.088	3.19	10872	36.0	0.48	17.3
40	9500	0.085	3.27	11073	38.3	0.48	18.4
41	9500	0.091	3.36	10496	36.8	0.48	17.6
42	9500	0.087	3.44	10872	39.4	0.48	18.9
63	7300	0.146	3.97	6716	27.2	0.76	20.8
64	7000	0.149	3.86	6648	25.9	0.78	20.2
65	6000	0.158	3.36	6449	21.2	0.82	17.4
66	6000	0.157	3.42	6324	21.8	0.84	18.3

[a] t_0 = 1979 Mar 19.
[b] Corrected for $A_V = 0.45$ mag.

derived from the infrared observations alone, and the optical data give an independent measure of $7.2^{+0.7}_{-1.0}$ Mpc for the distance to NGC 6946 (Table 7B and Figure 8*b*). This distance implies SN 1980K was also quite luminous, $M_B \approx -19.3$.

6.7. *SN 1987A*

SN 1987A was discovered in the LMC on 1987 February 23. It is one of the most extensively observed extragalactic objects in the history of astronomy—being observed in wavelengths from the radio to gamma rays (Arnett et al. 1989). This paper uses the photoelectric photometry (*UBVRIJHKLM*) published by Hamuy et al. (1988) and Catchpole et al. (1987), and the spectral observations of Phillips et al. (1988) (Table 8A). In addition, the detection of neutrinos (Bionta et al. 1987; Hirata et al. 1987) establishes the time of explosion, and this is extremely useful as it eliminates one of the two free parameters when applying EPM. The knowledge of the explosion date also acts as a test of the method if t_0 is left as a free parameter.

The total extinction to SN 1987A is determined to be $A_V = 0.6$ (Blanco et al. 1987). Eastman & Kirshner (1989) have used specific models of SN 1987A during its first 10 days to determine a distance of 49 ± 6 kpc to the LMC. Individual models do not yet exist for other SN II's, so here we will apply EPM to SN 1987A in a manner consistent with the nine other supernovae. We have used both optical (VI_C and infrared (JHK) photometry to determine θ for the first 50 days of SN 1987A. Line blanketing in the *B* band, which is easily observable in spectra, makes the determination of the color temperature

TABLE 7A

OBSERVATIONS OF SN 1980K

t^a							V^b (km sec^{-1})					
(days)	B	V	J	H	K	L	H_β	H_γ	FeII λ5169	FeII λ5018	FeII λ4924	FeII λ5215
29	...	...	...	...	...	...	9504	...	...	...	...	...
30	...	...	...	...	...	...	8950	...	...	...	...	...
32	...	...	10.46	10.23	10.07	...	...	...	...	...	...	...
33	...	...	10.49	10.40	10.18	9.92	...	...	...	...	...	...
34	11.79	11.39	...	...	...	...	7500	6900	7100	6800	6900	6800
35	11.81	11.41	10.40	10.28	10.10	9.88	6900	6200	7100	6700	...	7100
36	11.85	11.43	...	...	...	...	...	...	...	...	...	...
37	11.89	11.46	...	...	...	...	7700	6700	6700	...	...	7200
39	11.99	11.55	10.58	10.43	10.24	9.97	6700	7100	6100	6000	...	...
40	12.06	11.59	10.55	10.42	10.22	9.89	...	...	...	...	...	...
41	12.11	11.63	...	...	...	...	...	...	...	...	...	...
42	12.18	11.68	...	...	...	...	...	...	...	...	...	...
45	...	...	10.71	10.56	10.35	10.05	7700	...	7100	6900	...	...
46	...	...	10.60	10.53	10.33	10.00	...	...	...	...	...	...
47	...	...	10.78	10.64	10.40	10.14	7400	6200	6400	6000	5500	...
48	...	...	...	...	...	...	6500	...	6500	5750	...	...
49	12.66	12.03	...	...	...	...	...	...	...	...	...	...
50	...	...	...	...	...	...	6800	5800	6400	5700	...	6000
63	13.46	12.60	11.13	10.93	10.64	10.35	...	...	...	...	...	...
64	13.51	12.63	...	...	...	...	...	...	...	...	...	...
65	13.59	12.67	...	...	...	...	...	...	...	...	...	...
66	13.64	12.71	...	...	...	...	...	...	...	...	...	...
69	13.80	12.82	...	...	...	...	4600	4600	4000	4000	3600	4000
70	13.83	12.84	...	...	...	...	...	...	...	...	...	...
71	13.88	12.87	...	...	...	...	...	...	...	...	...	...
72	...	...	...	...	...	...	4700	4800	3900	3800	3900	3900
79	...	...	11.48	11.30	10.97	10.55	...	...	...	...	...	...
85	14.70	13.41	...	...	...	...	...	...	...	...	...	...
88	14.79	13.50	...	...	...	...	...	...	...	...	...	...
94	...	...	...	...	...	...	3800	3900	2700	2800	2700	2700

[a] t_0 = 1980 Oct 2.
[b] Corrected for $v_{rec} = 46$ km s^{-1}.

TABLE 7B

DERIVED QUANTITIES FOR SN 1980K

t^a (days)	v_{used} (km sec^{-1})	R (10^{15}cm)	θ^b_{Opt} (10^{15}cm Mpc^{-1})	Temp$^b_{Opt}$ (K)	D (Mpc)	Corr	D_{corr} (Mpc)	θ^b_{IR} (10^{15}cm Mpc^{-1})	Temp$^b_{IR}$ (K)	D_{IR} (Mpc)
32	7400	2.05	...	...	...	...	...	0.285	6856	7.2
33	7200	2.05	...	...	...	...	...	0.292	6428	7.0
34	7100	2.09	0.143	14200	14.6	0.48	7.0	...	...	...
35	7100	2.15	0.142	14200	15.1	0.48	7.3	0.289	6814	7.4
36	7000	2.18	0.149	13500	14.7	0.48	7.0	...	...	...
37	7000	2.24	0.150	13200	14.9	0.48	7.1	...	...	...
39	6700	2.26	0.148	12900	15.3	0.48	7.3	0.293	6233	7.7
40	6600	2.28	0.157	12100	14.5	0.48	7.0	0.309	5968	7.4
41	6500	2.30	0.158	11900	14.6	0.48	7.0	...	...	...
42	6500	2.36	0.162	11400	14.6	0.48	7.0	...	...	...
45	6300	2.45	...	...	...	...	...	0.290	5934	8.4
46	6200	2.46	...	...	...	...	...	0.281	6310	8.8
47	6200	2.52	...	...	...	...	...	0.279	5968	9.0
48	6100	2.53	...	...	...	...	...	...	...	...
49	6000	2.54	0.187	9200	13.6	0.48	6.5	...	...	...
50	5900	2.55	...	...	...	...	...	...	...	...
63	4500	2.45	0.236	6900	10.4	0.73	7.6	0.278	5267	8.8
64	4500	2.49	0.243	6700	10.2	0.76	7.8	...	...	...
65	4400	2.47	0.258	6500	9.6	0.81	7.7	...	...	...
66	4300	2.45	0.260	6400	9.4	0.82	7.8	...	...	...
69	4000	2.38	0.272	6100	8.8	0.88	7.7	...	...	...
70	3950	2.39	0.276	6100	8.7	0.89	7.7	...	...	...
71	3900	2.39	0.284	5900	8.4	0.92	7.7	...	...	...
79	3700	2.53	...	...	...	...	...	0.268	4730	9.4
85	3400	2.50	0.396	4700	6.3	1.00	6.3	...	...	...
88	3250	2.47	0.380	4700	6.5	1.00	6.5	...	...	...

[a] t_0 = 1980 Oct 2.
[b] Corrected for A_V = 1.20 mag.

from $(B-V)$ unrealistic for SN 1987A, and therefore we use the temperatures derived from $(V-I_C)$ when determining θ from the optical photometry. For most SN II's $(V-I_C)$ gives color temperatures which are systematically $\approx$500 K higher than $(B-V)$; however, for SN 1987A the difference is $>$2000 K. For the infrared, we calculate the color temperature directly from the *JHK* photometry. With the IR data we assume that $\zeta = 1$ at all times (as the models suggest) and measure a distance to the LMC of 49 ± 3 kpc (Table 8B and Fig. 9). If t_0 is left as a free parameter, the time of the explosion using the IR data is derived to be 0.7 ± 0.7 days after the neutrino event, so it appears that EPM has performed well. The optical data, corrected for flux dilution using Figure 4, yield a distance to the LMC of 53 ± 4 kpc. This distance is shown for comparison; it is not an independent determination of the distance because Figure 4 is partially determined using data for SN 1987A and assuming a distance of 50 kpc to the LMC.

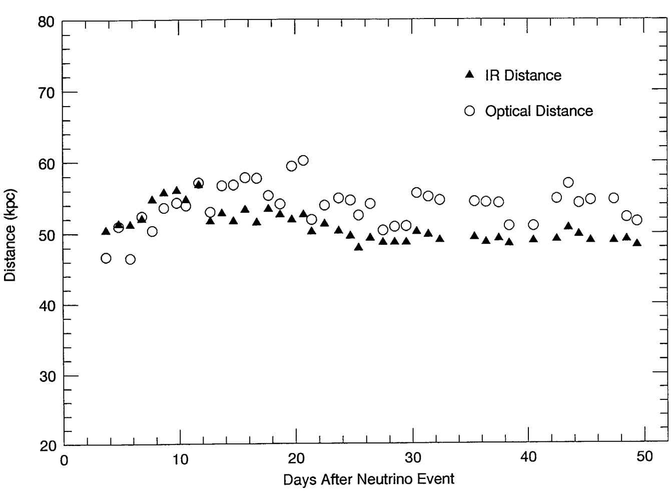

FIG. 9.—Distance as a function of time for SN 1987A using infrared and optical photometry.

6.8. *SN 1988A*

SN 1988A was discovered in M58 (NGC 4579) on 1988 January 15 near maximum light. Visual, photographic, and photoelectric photometry (V) is published by Ruiz-Lapuente et al. (1990) and Ruiz-Lapuente et al. (1991). In addition there is photographic and CCD color photometry from Benetti, Cappellaro, & Turatto (1991), and IAU circulars (Kidger 1988a, b; Binzel 1988; and Sadler & Simkin 1988). Spectrophotometry is available from Ruiz-Lapuente et al. (1990), R. Stathakis & E. M. Sadler (in preparation), and E. M. Schlegel and R. P. Kirshner (in preparation) (Table 9A). The photometric coverage is good but of marginal quality and shows SN 1988A to be Type II-P. The spectral coverage is limited, but of good quality.

M58 has little foreground Galactic extinction (Burstein & Heiles 1984; Steidel et al. 1990), and there is no evidence that there is a substantial amount of reddening from the parent galaxy. The temperature evolution of SN 1988A is determined by *BV* photometry, when available, and from spectra otherwise. The data give a distance to M58 of 23 ± 4 Mpc (Table 9B and Fig. 8*a*).

6.9. *SN 1990E*

SN 1990E was discovered near maximum light by the Berkeley Automated Supernova Search on 1990 February 15. In addition, it was not present down to $m_V = 19$ on an image taken on 1990 February 10 (Pennypacker & Perlmutter 1990). We have reduced CCD photometry (*BVRI*) taken with the 24 inch (0.61 m) telescope at FLWO by R. Schild as well as IR (*JH*) photometry on the same telescope by R. Peletier and S.

TABLE 8A

OBSERVATIONS OF SN 1987A

t^a									V^b (km sec^{-1})				
(days)	B	V	R	I	J	H	K	L	H_α	H_β	H_γ	FeII λ5169	FeII λ5018
3.7	4.83	4.45	4.08	4.01	3.61	3.44	3.21	2.92	16504	14051	13113	11375	...
4.8	4.97	4.46	4.04	4.00	3.47	3.29	3.05	2.70	16101	13280	12152	9930	...
5.8	5.18	4.50	4.03	3.96	3.40	3.21	2.97	2.66	15080	12516	11489	8447	8694
6.8	5.28	4.45	4.04	3.95	3.35	3.14	2.90	2.61	14419	11773	10694	7860	7778
7.7	5.38	4.48	4.01	3.92	3.28	3.07	2.85	2.57	13838	11052	10029	7332	7388
8.7	5.46	4.45	3.96	3.83	3.23	3.01	2.79	2.54	13204	10464	9562	6820	7021
9.8	5.51	4.41	3.94	3.82	3.18	2.94	2.73	2.48	...	...	...	...	...
10.6	5.55	4.38	3.91	3.78	3.13	2.88	2.68	2.44	12082	9290	8473	5843	6038
11.7	5.60	4.35	3.89	3.62	3.09	2.83	2.64	2.38	11939	8979	7919	5649	5787
12.7	5.63	4.34	3.84	3.55	3.04	2.77	2.57	2.33	11327	8466	7856	4940	5154
13.7	5.66	4.30	3.80	3.63	2.97	2.70	2.51	2.21	10871	8148	7604	4871	4961
14.7	5.66	4.27	3.74	3.57	2.94	2.66	2.46	2.18	11342	7889	7528	4574	4755
15.7	5.70	4.26	3.73	3.54	2.87	2.60	2.41	2.12	10202	7747	7482	4436	4532
16.7	5.72	4.22	3.70	3.49	2.82	2.53	2.34	2.05	10490	7664	7528	4244	4368
17.7	5.69	4.23	3.68	3.33	2.79	2.50	2.30	2.01	10372	7747	7283	4361	4230
18.7	5.68	4.22	3.65	3.27	2.73	2.44	2.25	1.92	10093	7851	7337	4132	4047
19.7	5.73	4.20	3.61	3.38	2.68	2.41	2.19	1.89	9840	7835	7247	4012	3913
20.7	5.74	4.20	3.59	3.35	2.64	2.36	2.15	1.85	8936	7869	7093	4003	3808
21.4	5.69	4.18	3.56	3.16	2.60	2.31	2.12	1.81	8535	7889	7152	3561	3709
22.5	5.68	4.16	3.53	3.14	2.56	2.27	2.08	1.78	8217	7854	7024	3700	3547
23.7	5.70	4.13	3.48	3.19	2.52	2.23	2.04	1.76	8264	7744	6649	3432	3354
24.7	5.69	4.11	3.45	3.16	2.48	2.19	2.00	1.68	8152	7596	6387	3298	3273
25.4	5.68	4.09	3.42	3.13	2.45	2.17	1.97	1.69	8064	7453	6183	3138	3103
26.4	5.68	4.08	3.39	3.10	2.42	2.12	1.94	1.62	8152	7487	6268	3151	3120
27.5	5.64	4.06	3.39	2.98	2.37	2.09	1.89	1.59	7623	7282	5988	2911	3156
28.5	5.61	4.05	3.35	2.95	2.35	2.06	1.86	1.57	...	...	...	...	...
29.5	5.59	4.02	3.31	2.92	2.33	2.03	1.83	1.52	...	...	...	...	...
30.4	5.61	3.99	3.28	2.99	2.28	2.01	1.80	1.49	7604	6885	5974	2653	2682
31.4	5.56	3.97	3.27	2.87	2.25	1.97	1.77	1.46	7556	6770	5803	2887	2697
32.4	5.54	3.94	3.23	2.84	2.22	1.94	1.73	1.44	7596	6457	6023	2817	2802
35.4	5.50	3.87	3.14	2.85	2.15	1.87	1.67	1.35	7370	6478	5876	2749	2567
36.4	5.45	3.82	3.11	2.75	2.12	1.84	1.63	1.33	...	...	...	...	...
37.5	5.40	3.79	3.08	2.70	2.09	1.81	1.61	1.29	...	...	...	...	...
38.4	5.39	3.76	3.04	2.68	2.07	1.79	1.58	1.25	7152	6229	5822	2589	2461
40.5	5.32	3.71	2.98	2.61	2.01	1.72	1.51	1.18	6766	6281	5694	2612	2372
42.5	5.29	3.64	2.92	2.65	1.95	1.67	1.46	1.11	6902	5938	5663	2530	2335
43.5	5.22	3.59	3.59	2.53	1.91	1.63	1.42	1.11	6884	...	5904	2626	2342
44.4	5.22	3.58	2.88	2.50	1.89	1.62	1.41	1.06	6396	5849	5712	2409	2405
45.4	5.19	3.54	2.85	2.48	1.86	1.58	1.37	1.05	6419	5985	5843	2424	2328
47.4	5.13	3.50	2.80	2.42	1.81	1.54	1.32	0.98	6727	6010	5907	2395	2270
48.5	5.09	3.47	2.77	2.40	1.81	1.52	1.31	0.96	6319	6235	5781	2347	2267
49.4	5.07	3.43	2.74	2.38	1.76	1.49	1.27	0.93	6661	...	5904	2312	2194

[a] t_0 = 1987 Feb 23.
[b] Corrected for $v_{rec} = 285$ km s^{-1}.

Willner. In addition we have used spectra reduced by B. Leibundgut and taken by J. Peters, E. Horine, and A. Zabludoff on the 1.5 m telescope at FLWO, as well as spectra taken at the MMT. The details of the data will be discussed in a future paper on SN 1990E. The spectral coverage of SN 1990E is very good, but the data are of mediocre quality. The optical photometry is of good quality, but the coverage is rather sparse. The IR photometry coverage is sparse and of poor quality (0.25 mag RMS). The data show SN 1990E is a typical Type II-P supernova (Table 10A).

NGC 1035 lies at high Galactic latitude, and there is little foreground extinction (Burstein & Heiles 1984); however, NGC 1035 is a highly inclined spiral, and therefore we expect SN 1990E to be reddened. Comparing the $(B-V)$ color of SN 1990E with other Type II-P supernova, the extinction to SN 1990E is estimated as $A_V = 1.0 \pm 0.3$ (Fig. 5). The optical temperature evolution for the supernova is determined from the *BV* photometry except for day 37, where it is determined from a spectrum. The IR temperature cannot be determined with the *JH* photometry due to the poor quality of the data, and the temperature measured from the optical spectrum is used. Our models indicate that this could overestimate the IR temperature by 15%. At these temperatures, however, the flux in the infrared is directly proportional to the temperature (Rayleigh-Jeans regime), and the distance from this approximation is overestimated by less than 11%. The *BV* photometry gives a distance for the supernova of 21^{+3}_{-3} Mpc, and this is consistent with the distance derived from *JH* photometry of 22 ± 6 Mpc (Table 10B and Fig. 8*b*).

6.10. *SN 1990ae*

SN 1990ae was discovered well after maximum on 1990 October 15 in an anonymous galaxy. We have two spectra (Fig. 10) of SN 1990ae. The first was taken on 1990 October by A. Zabludoff with the LMT blue channel spectrograph and reduced by B. Leibundgut. The second spectrum was obtained and reduced by R. C. Smith on 1990 November 12 with the MMT red channel spectrograph. We also have CCD photometry taken with the KPNO 2.1 m by A. Porter and B. Leibundgut on 1990 October 23, and 1990 November 9. These

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TABLE 8B

DERIVED QUANTITIES FOR SN 1987A

t^a (days)	v_{used} (km sec^{-1})	R (10^{15}cm)	θ^b_{Opt} (10^{15}cm Mpc^{-1})	Temp$^b_{Opt}$ (K)	Corr	D_{corr} (Mpc)	θ^b_{IR} (10^{15}cm Mpc^{-1})	Temp$^b_{IR}$ (K)	D_{IR} (Mpc)
3.7	11375	0.36	3.74	10697	0.48	46.7	7.21	5989	50.4
4.8	9930	0.41	3.87	10393	0.48	51.0	8.02	5763	51.3
5.8	8571	0.43	4.44	9343	0.48	46.5	8.38	5719	51.2
6.8	7819	0.46	4.21	9832	0.48	52.4	8.84	5587	52.0
7.7	7360	0.49	4.66	9097	0.48	50.7	8.95	5678	54.7
8.7	6921	0.52	5.28	8496	0.50	49.4	9.34	5582	55.7
9.8	6431	0.54	5.07	8797	0.49	52.5	9.73	5509	56.0
10.6	5941	0.54	5.25	8688	0.49	51.0	9.95	5527	54.7
11.7	5718	0.58	6.71	7574	0.61	52.8	10.17	5509	56.8
12.7	5047	0.55	7.46	7174	0.68	50.5	10.72	5381	51.7
13.7	4916	0.58	6.18	8044	0.54	51.3	11.02	5403	52.8
14.7	4665	0.59	6.61	7803	0.58	52.0	11.45	5298	51.7
15.7	4484	0.61	6.88	7646	0.60	53.3	11.40	5469	53.3
16.7	4306	0.62	7.13	7574	0.61	53.4	12.07	5320	51.5
17.7	4296	0.66	9.48	6517	0.80	55.6	12.30	5308	53.4
18.7	4090	0.66	10.35	6262	0.85	54.5	12.57	5329	52.6
19.7	3963	0.67	8.39	6973	0.72	57.7	12.98	5271	51.9
20.7	3906	0.70	8.85	6785	0.75	59.4	13.28	5259	52.6
21.4	3635	0.67	11.79	5952	0.92	52.4	13.40	5298	50.2
22.5	3624	0.70	11.90	5952	0.92	54.4	13.72	5281	51.3
23.7	3393	0.69	10.56	6329	0.84	55.3	13.82	5329	50.3
24.7	3286	0.70	10.89	6262	0.85	55.0	14.14	5308	49.6
25.4	3121	0.68	11.17	6215	0.86	53.0	14.30	5320	47.9
26.4	3136	0.72	11.55	6135	0.88	54.5	14.51	5329	49.3
27.5	3034	0.72	13.72	5705	0.98	51.5	14.80	5329	48.7
28.5	3023	0.74	14.25	5625	0.99	51.9	15.28	5230	48.7
29.5	2966	0.76	14.44	5625	0.99	52.0	15.52	5220	48.7
30.4	2950	0.77	12.42	6049	0.90	56.0	15.43	5320	50.2
31.4	2877	0.78	12.75	6001	0.91	55.5	15.67	5320	49.8
32.4	2810	0.79	13.10	5952	0.92	55.2	16.06	5271	49.0
35.4	2658	0.81	13.60	5952	0.92	55.0	16.46	5308	49.4
36.4	2612	0.82	13.60	6001	0.91	54.8	16.86	5259	48.7
37.5	2556	0.83	13.61	6049	0.90	54.6	16.82	5329	49.2
38.4	2525	0.84	15.76	5705	0.98	52.1	17.29	5259	48.5
40.5	2492	0.87	16.66	5625	0.99	52.0	17.85	5249	48.9
42.5	2433	0.89	14.38	6087	0.89	55.3	18.21	5271	49.1
43.5	2484	0.93	14.18	6179	0.87	57.3	18.43	5298	50.7
44.4	2407	0.92	15.33	6001	0.91	54.6	18.54	5298	49.8
45.4	2376	0.93	15.20	6049	0.90	55.0	19.06	5249	48.9
47.4	2333	0.96	15.41	6087	0.89	55.1	19.54	5230	48.9
48.5	2307	0.97	17.76	5705	0.98	53.4	19.67	5220	49.1
49.4	2253	0.96	17.72	5745	0.97	52.7	19.92	5249	48.3

[a] t_0 = 1987 Feb 23.
[b] Corrected for $A_V = 0.60$ mag.

TABLE 9A

OBSERVATIONS OF SN 1988A

t^a (days)	B	V	V^b (km sec^{-1}) H_α	H_β	H_γ	FeII λ5169	FeII λ5018	FeII λ4924
13	14.40	...	...	...	...	...	...	...
14	14.40	14.40	10100	8900	...	...	...	...
15	14.43	14.40	8000	7000	...	...	...	...
16	14.55	14.50	7820	8500	7900	...	...	...
20	...	14.70	7700	7800	...	7400	7800	...
25	...	...	7800	7800	...	7200	6700	...
26	...	14.80	...	...	...	...	...	...
35	...	14.80	6400	5900	...	5150	5200	5450
40	15.55	14.90	...	...	...	...	...	...
41	...	...	6300	5300	...	5450	5000	5370
42	15.60	15.00	...	...	...	...	...	...
44	15.75	15.10	...	...	...	...	...	...
46	15.60	14.95	...	...	...	...	...	...
49	15.93	15.06	...	...	...	...	...	...

[a] t_0 = 1988 Jan 8.
[b] Corrected for $v_{rec} = 1567 \text{ km s}^{-1}$.

TABLE 9B

DERIVED QUANTITIES FOR SN 1988A

t^a (days)	v_{used} (km sec^{-1})	θ^b (10^{15}cm Mpc^{-1})	R (10^{15}cm)	Temp^b (K)	D (Mpc)	Corr	D_{corr} (Mpc)
13	8400	0.021	0.93	14000	44.0	0.48	21.1
14	8300	0.020	0.99	14700	50.2	0.48	24.1
15	8150	0.021	1.04	13600	48.7	0.48	23.4
16	8000	0.022	1.09	13000	50.6	0.48	24.3
20	7550	0.030	1.29	9500	43.2	0.48	20.7
26	6800	0.038	1.52	8000	40.3	0.55	22.2
35	5680	0.066	1.71	6000	25.9	0.90	23.3
40	5100	0.067	1.75	5800	26.1	0.95	24.8
42	4810	0.058	1.75	6100	30.1	0.88	26.5
44	4560	0.061	1.73	5800	28.3	0.95	26.9
46	4300	0.066	1.71	5800	26.0	0.95	24.8
48	3950	0.098	1.67	4850	17.0	1.00	17.0

[a] t_0 = 1988 Jan 8.
[b] Corrected for $A_V = 0.00$ mag.

TABLE 10A

OBSERVATIONS OF SN 1990E

t^a (days)	B	V	J	H	V^b (km sec^{-1}) Hβ	Fe II λ5169	Fe II λ5018
7	...	...	14.55	14.30	8903	...	...
8	...	...	...	...	10075	...	...
11	...	...	...	...	10569	...	...
13	...	...	...	...	10075	8679	...
14	16.10	15.62	...	...	10075	...	7767
15	16.10	15.59	...	...	10507	8737	7707
17	16.12	15.62	...	...	10384	...	...
18	16.21	15.63	...	...	10075	9027	...
19	16.17	15.67	...	...	...	...	...
20	16.22	15.63	...	...	...	...	...
21	16.31	15.58	...	...	9335	8331	7886
25	16.47	15.57	...	...	...	...	...
30	...	...	13.60	13.44	...	...	...
37	...	15.81	...	...	7668	6183	6332

[a] t_0 = 1990 Feb 10.
[b] Corrected for $v_{rec} = 1240$ km s^{-1}.

data were reduced with IRAF using standard procedures. The quality of the data is superb (Table 11A).

There is little foreground extinction to SN 1990ae (Burstein & Heiles 1982), and the supernova occurred in the outer regions of its parent galaxy (Fig. 11). Therefore we adopt $A_V = 0.0$. The temperature and photometric angular size at both times were determined from the BV photometry. The distance derived is 117^{+25}_{-15} Mpc as given in Table 11B.

7. DISCUSSION OF DISTANCES

Several of the galaxies that contain SN II's for which we have determined distances have had their distances measured by other methods. Most notable of these are the LMC and M101 for which Cepheid distances are available and which contained SN 1987A and SN 1970G, respectively.

Cepheid and RR Lyrae stars have long been studied in the LMC (e.g., Leavitt 1912), and its distance is well established.

TABLE 10B

DERIVED QUANTITIES FOR SN 1990E

t^a (days)	v_{used} (km sec^{-1})	R (10^{15}cm)	θ^b_{Opt} (10^{15}cm Mpc^{-1})	Temp$^b_{Opt}$ (K)	D (Mpc)	Corr	D_{corr} (Mpc)	θ^b_{IR} (10^{15}cm Mpc^{-1})	Temp$^b_{IR}$ (K)	D_{IR} (Mpc)
7	9000	0.54	...	...	...	...	...	0.0300	10000	18.1
14	8700	1.05	0.0267	10550	39.4	0.48	18.9	...	...	...
15	8700	1.13	0.0292	10000	38.6	0.48	18.5	...	...	...
17	8600	1.26	0.0281	10200	45.0	0.48	21.6	...	...	...
18	8600	1.34	0.0336	9000	39.8	0.48	19.3	...	...	...
19	8500	1.40	0.0275	10200	50.7	0.48	24.4	...	...	...
20	8300	1.43	0.0343	8900	41.8	0.49	20.4	...	...	...
21	8200	1.49	0.0473	7400	31.5	0.63	19.9	...	...	...
25	8000	1.73	0.0682	6200	25.3	0.87	21.9	...	...	...
30	6800	1.76	...	5500	...	...	...	0.0770	5500	22.9
37	6200	1.98	0.0803	5500	24.7	1.00	24.7	...	...	...

[a] t_0 = 1990 Feb 10.
[b] Corrected for $A_V = 1.00$ mag.

TABLE 11A

OBSERVATIONS OF SN 1990ae

t^a (days)	B	V	V^b (km s^{-1}) Hα	Hβ	Fe II λ5169	Fe II λ5018	Fe II λ4924
24.........	...	...	5600	5000	3790	4080	...
28.........	20.60	19.90	...	...	...	...	...
45.........	20.52	19.71	...	...	...	...	...
48.........	...	...	4940	3730	2805	3010	2880

[a] t_0 = 1990 Sep 25.
[b] Corrected for $v_{rec} = 7680$ km s^{-1}.

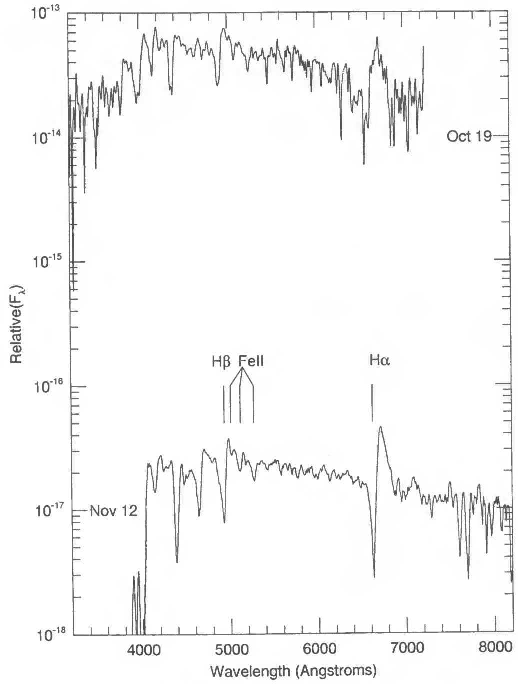

FIG. 10.—Spectrum of SN 1990ae from the MMT blue channel on 1990 October 19, and MMT red channel on 1990 November 12.

Our determination of the distance to the LMC of 49 ± 3 kpc using EPM with infrared photometry, and 53 ± 4 kpc using VI_C photometry, is in excellent accord with the distance to the LMC derived recently by Walker & Mack (1988) with RR Lyrae Stars, 48.8 kpc, and Walker (1987) with Cepheids, 49.4 kpc. It is also consistent with other determinations of the distance to the LMC which use detailed models of SN 1987A to determine the flux dilution (Chilukuri & Wagoner 1988; Höflich 1988; Eastman & Kirshner 1989; Schmutz et al. 1990). A novel method of determining the distance to SN 1987A which exploits the geometry of the circumstellar ring observed with the *Hubble Space Telescope* (Panagia et al. 1991) gives a distance of 51 ± 3 kpc which is also consistent with our results.

Cook, Aaronson, & Illingworth (1986) found two Cepheids in M101 at $m_R > 23$. These are the most distant Cepheids yet discovered and give a distance of 7.1 ± 0.3 Mpc for M101. The distance to M101 determined from SN 1970G, $7.6^{+1.0}_{-2.2}$ Mpc, is in excellent accord with this Cepheid distance. SN 1970G and SN 1987A are radically different from each other, with different light curves, and different absolute magnitudes (Table 12), yet EPM has given a distance consistent with Cepheid distances in both instances. We believe this agreement with Cepheid distances gives strong support to the distances measured with EPM to other supernovae.

We can compare our results to several other methods of measuring extragalactic distances. The 21 cm line width–luminosity method of distance determination for spirals pioneered by Tully & Fisher (1977) has been widely used in the past 15 years (Aaronson, Huchra, & Mould 1979; Aaronson et al. 1982; Aaronson et al. 1986; Pierce & Tully 1988; Fouqué et al. 1990). The method has been calibrated using M31, M33, and NGC 2403, and has been applied to hundreds of spiral galaxies. The method works to relatively large distances ($cz \approx 7000$ km s^{-1}), but gives distances with typical errors

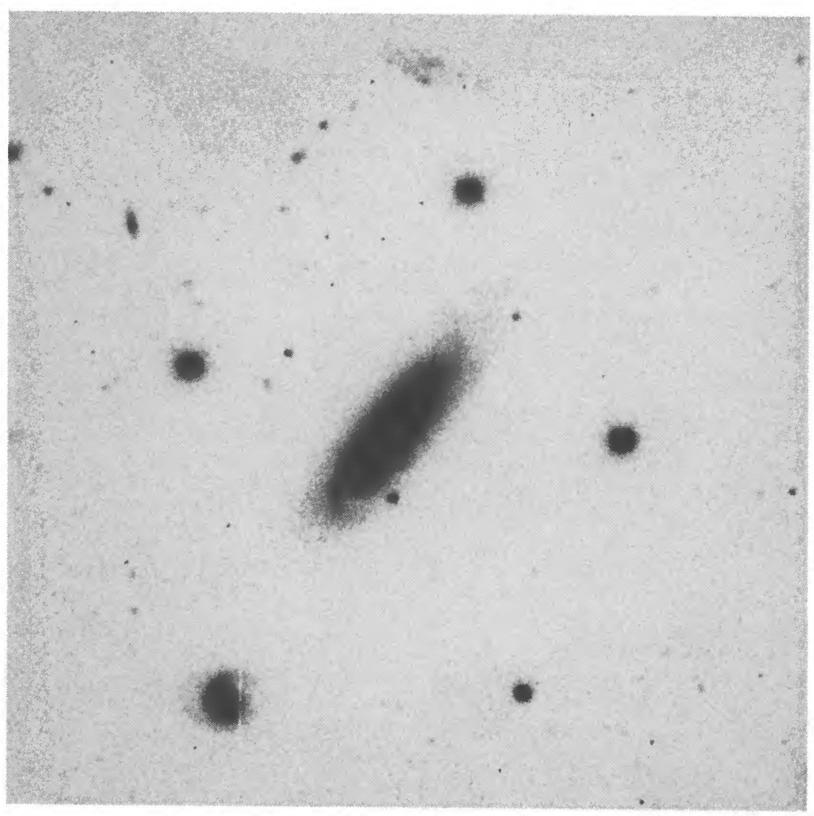

FIG. 11.—A 10 minute exposure in *R* at the KPNO 2.1 m telescope showing SN 1990ae in its anonymous parent galaxy on 1990 October 23

TABLE 11B

Derived Quantities for SN 1990ae

t^{a} (days)	v_{used} (km s^{-1})	θ^{b} (10^{15} cm Mpc^{-1})	R (10^{15} cm)	Temperature[b] (K)	D (Mpc)	Correction	D_{corr} (Mpc)
28.........	3640	0.0075	0.89	5561	118	0.99	117
45.........	3030	0.0101	1.18	5092	117	1.00	117

[a] t_0 = 1990 Sep 25.
[b] Corrected for $A_V = 0.00$ mag.

greater than 15%. Recently, two additional methods of extragalactic distance determination have been introduced which show great promise. The first uses the planetary nebula luminosity function as a standard candle (Jacoby & Ciardullo 1988; Jacoby 1989; Jacoby et al. 1989; Ciardullo, Jacoby, & Ford 1989a; Ciardullo et al. 1989b; Jacoby, Ciardullo, & Ford 1990a). By cataloging planetary nebulae in early-type galaxies, a luminosity function for planetary nebulae in a galaxy is constructed. The luminosity function is calibrated with M31 and its distance using Cepheids. This method appears to have high internal precision for relative distances. The method has been applied to the LMC and M81, and the derived distances agree with the Cepheid distances to both these galaxies. It is worth noting that M31, M81, and the LMC are *not* early-type galaxies, and that this method provides only distances relative to the calibrator, M31. Recently, however, Ciardullo, Jacoby, & Harris (1991) have given evidence that planetary nebulae luminosity functions may be insensitive to the age of the stellar population and galaxy Hubble type. A second method uses the surface brightness fluctuations of early-type galaxies as a distance indicator (Tonry & Schneider 1988; Tonry & Schechter 1990; Tonry, Ajhar, & Luppino 1990, Tonry 1991). The fluctuations are inversely proportional to distance, and relative distances can be derived by taking the ratio of the surface brightness fluctuations of two galaxies. Absolute distances are measured by determining the fluctuations of a galaxy whose distance is known by other methods—in this case, the Cepheid distances of M31 and M32. Tonry (1991) has shown that there is a color effect due to different stellar populations in different galaxies. This calibration is not yet complete and could be a source of error when using surface brightness fluctuations to measure relative distances. The initial results, however, also show excellent internal consistency.

NGC 5236, which is considered part of the Centaurus A group, has very few measures of its own distance. However, Centaurus A (NGC 5128) and the group itself are well studied. By fitting planetary nebula luminosity functions, Jacoby et al (1988) have determined the distance to the NGC 5128 as $3.8^{+0.1}_{-0.2}$ Mpc. Surface brightness fluctuations (Tonry & Schechter 1990) give a somewhat smaller distance of 3.1 ± 0.1 Mpc. When comparing the distances to Centaurus A derived using the two above methods with the distance determined using SN 1968L in NGC 5236 of $4.8^{+1.3}_{-0.7}$ Mpc, one must take into account that the cluster depth may be a sizable fraction of the distance to the cluster. In this case it appears EPM is consistent with the planetary nebulae distance but is not consistent with the surface brightness fluctuation distance.

SN 1988A (NGC 4579) and SN 1979C (NGC 4321) both occurred in galaxies that are associated with the Virgo Cluster. The Virgo Cluster is a good place to compare the results of EPM with other methods. Jacoby et al. (1990a), using the planetary luminosity functions of six cluster members, have determined a distance of 14.7 ± 1 Mpc. Tonry (1991), using surface brightness fluctuations, derives a distance of 15.9 ± 0.9 Mpc. Applying the Tully-Fisher method to several galaxies of the Virgo Cluster has typically given distances near 15 Mpc (Aaronson et al. 1986; Pierce & Tully 1988); however, distances over 19 Mpc have been determined by other groups (Fouqué et al. 1990; Sandage & Tammann 1984). Sandage & Tammann (1990), using the mean of six independent distance indicators (globular clusters, novae, Type Ia supernovae, D_n-σ, Tully-Fisher, disk sizes of Virgo spirals) derive a distance of 21.9 ± 0.9 Mpc. Bartel (1991), using VLBI observations to measure the angular radius of SN 1979C's radiosphere, measured the distance to M100 to be 22^{+7}_{-6} Mpc. EPM using SN 1988A (23 ± 4 Mpc) and SN 1979C (19 ± 5 Mpc), gives a distance of 22 ± 3 Mpc. Since the depth of the Virgo Cluster is small compared to the discrepancies, there appears to be a signficant difference between the two distance scales. If a distance of 15 Mpc were correct, it would require that $\zeta < 0.7$ for SN 1988A at all times we apply EPM. We believe $\zeta = 0.9 \pm 0.1$ when $T_{opt} \lesssim 6000$ K. We have not yet matched individual

TABLE 12

Recession Velocities and Supernova Absolute Magnitudes

SN	Galaxy	v_{obs} (km sec^{-1})	Model 1[a] v_{corr} (km sec^{-1})	Model 2[b] v_{corr} (km sec^{-1})	m_B at max	Dist (Mpc)	A_B	M_B
SN 1968L	NGC 5236	506	330	317	12.00	4.8	0.15	-16.6
SN 1969L	NGC 1058	519	660	666	13.30	11.2	0.23	-17.2
SN 1970G	NGC 5457	266	442	419	11.70	7.6	0.59	-18.3
SN 1973R	NGC 3627	697	431	413	15.00	7.6	3.60	-18.0
SN 1979C	NGC 4321	1568	1100	1600	11.60	19	0.60	-20.4
SN 1980K	NGC 6946	46	394	422	11.60	7.2	1.62	-19.3
SN 1987A	LMC	270	0	0	4.50	0.049	0.80	-14.8
SN 1988A	NGC 4579	1567	1100	1600	13.80	23	0.00	-18.0
SN 1990E	NGC 1035	1260	1151	1094	16.10	21	1.33	-16.8
SN 1990ae	ann0020+06	7680	7920	7962	...	117	0.00	...

[a] Model parameters: $\gamma = 2$, $\delta\rho/\rho = 3$, $V_{infall} = 200$ km s^{-1}, $V_{Virgo} = 900$ km s^{-1}.
[b] Model parameters: $\gamma = 2$, $\delta\rho/\rho = 3$, $V_{infall} = 375$ km s^{-1}, $V_{Virgo} = 1225$ km s^{-1}.

models to the spectra of SN 1988A, so we cannot conclusively rule out the possibility that ζ remains much less than unity even when the supernova cools to below 6000 K, but it would be a very surprising result.

SN 1990E occurred in NGC 1035, a highly inclined spiral for which Aaronson et al. (1982) have determined a distance relative to the Virgo Cluster using the infrared Tully-Fisher relation. Their distance, D(NGC 1035)/D(Virgo) = 0.88, is consistent with our determination of 21^{+3}_{-3} Mpc [D(NGC 1035)/D(Virgo) = 0.95, comparing SN 1990E to SN 1988A and SN 1979C].

The agreement between EPM and other methods is not yet satisfactory. Although they generally agree nearby (e.g., the LMC), they most certainly do not agree on the distance to the Virgo Cluster. More cases need to be studied to sort out the discrepancies. High-quality infrared data of future SN II-P's in the Virgo Cluster will allow EPM to give a firmer distance estimate to the cluster.

8. DETERMINING H_0

The primary goal of determining the extragalactic distance scale is to calculate H_0. This is a difficult task even if local distances are known exactly, due to local and large scale pertubations in the Hubble flow (e.g., Aaronson et al. 1982; Lynden-Bell et al. 1988). EPM has the potential for circumventing this problem because it works to large distances where perturbations are expected to be small compared to the Hubble flow. Unfortunately, distant SN II's ($cz > 5000$ km s^{-1}), which are relatively faint ($m_V > 18.0$), but still easy to study with large telescopes, have not been considered interesting objects in the past, and few data have been garnered on them. In the future we plan to concentrate our observational efforts on SN II's that occur beyond the Virgo Cluster. The current sample permits us to estimate H_0 from one distant supernova (SN 1990ae), and eight supernovae which have occurred in nearby galaxies.

Determining H_0 from SN 1990ae is straightforward as its velocity of recession, 7680 km s^{-1}, is sufficient so that velocity perturbations should be less than a 10% effect. Derived from this single galaxy, ignoring all peculiar motions, $H_0 = 66^{+9}_{-12}$ km s^{-1} Mpc^{-1}.

It is possible to use nearby galaxies to measure H_0 by comparing our distances with velocities corrected for infall into Virgo and the rotation of our Galaxy (assumed to be 300 km s^{-1}). We have created a Virgo infall model using the equations set out by Schechter (1980) and Kraan-Korteweg (1986). This model has four free parameters, $V_{\rm Virgo}$, $V_{\rm infall}$, γ, and $\delta\rho/\rho$. Here, $V_{\rm Virgo}$ is the observed velocity of recession for the Virgo Cluster corrected for the motion of our Galaxy, $V_{\rm infall}$ is the rate that the Local Group is falling into the Virgo Cluster, γ is the power-law index to the virgocentric density profile [i.e., $\rho(r) = \rho_0 r^{-\gamma}$), and $\delta\rho/\rho$ is the overdensity at the Local Group relative to the background density. The values of these parameters are not well agreed upon, and we choose ranges for these parameters from a review by Huchra (1988) and from Sandage & Tammann (1990). These values are $900 < V_{\rm Virgo} < 1225$ km s^{-1}, $200 < V_{\rm infall} < 375$ km s^{-1}, $2 < \gamma < 3$, and $2 < \delta\rho/\rho < 4$.

The use of a Virgocentric infall model significantly reduces the scatter when trying to determine H_0. Fortunately, the exact choice of parameter values input into the model has a surprisingly small effect on the determination of H_0 (Table 12). Figures 12 and 13 show distance versus recession velocity, corrected for Virgo infall, in the manner of the original Hubble diagram (Hubble 1929). From Figure 12, which does not include SN 1990ae, we derive $H_0 = 58 \pm 10$ km s^{-1} Mpc^{-1}. From Figure 13, which includes SN 1990ae, we derive $H_0 = 60 \pm 10$ km s^{-1} Mpc^{-1}. This figure clearly demonstrates the linearity of the Hubble flow over a factor of 25 in distance.

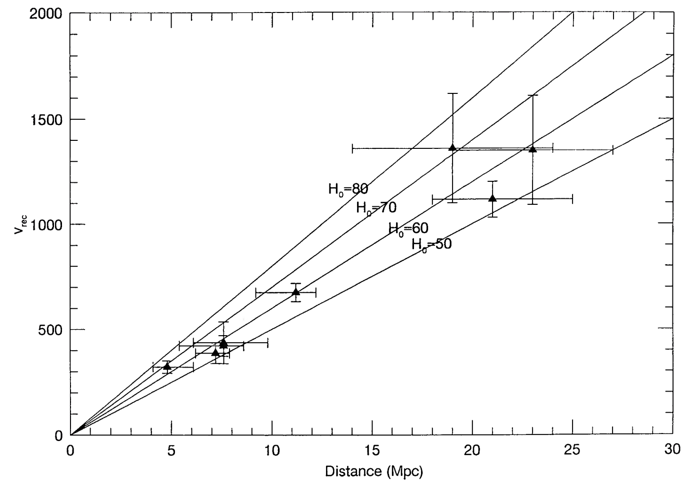

FIG. 12.—The Virgo-corrected velocities for eight galaxies with SN II's (SN 1990ae is excluded) are plotted against their distances derived using the Expanding Photosphere Method. Lines for Hubble constants ranging from 50 to 80 km s^{-1} Mpc^{-1} are shown.

A less direct method of determining the Hubble constant is to calibrate the absolute magnitude of Type Ia supernovae. There is evidence that Type Ia supernovae are standard candles at maximum (Hamuy et al. 1991; Miller & Branch 1990; Leibundgut 1991). A Hubble diagram can be constructed from these standard candles which is relatively free from local perturbations in the Hubble flow because SN Ia's have been observed in all directions, and to large distances, $cz \approx 6000$ km s^{-1} (e.g., Tammann & Leibundgut 1990). If the absolute magnitude of Type Ia supernovae were known, then H_0 could be determined. Although this is not strictly an independent method of determining H_0, it is a method to circumvent uncertainties caused by local deviations of the Hubble flow.

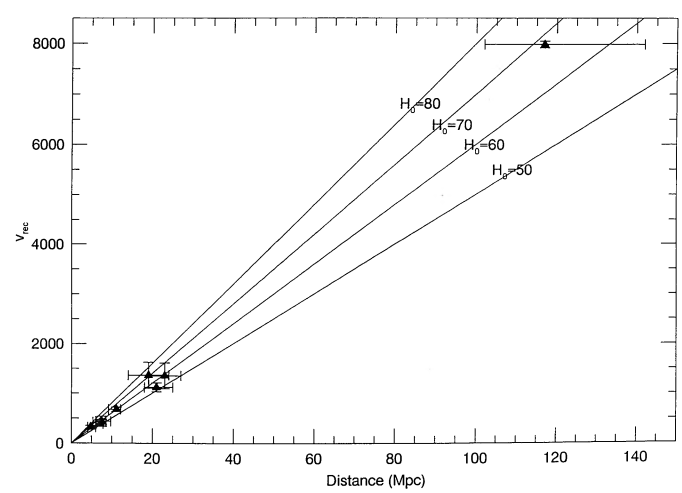

FIG. 13.—The Virgo-corrected velocities for nine galaxies with SN II's are plotted against their distances derived using the Expanding Photosphere Method. Lines for Hubble constants ranging from 50 to 80 km s^{-1} Mpc^{-1} are shown.

Two of the galaxies for which we have measured the distance using EPM have also had a well-observed SN Ia. SN 1989B, a SN Ia, occurred in NGC 3627 16 years after SN 1973R. Both supernovae were highly reddened, but the reddening to both can be estimated. Barbon et al. (1990) determined that SN 1989B reached $m_B = 12.5$ at maximum. They also estimated the extinction to be $A_B = 3.24$ by comparing the $(B-V)$ evolution of SN 1989B to a standard color curve for SN I's by Cappellaro (1982). Wells et al. (1992) determine $M_B^{\max} = 12.36$ for SN 1989B. They derive $A_B = 1.28$ by comparing the *BVRIJHK* colors of SN 1989B to those of SN 1980N (Hamuy et al. 1990). We favor the determination of the reddening of Wells et al. because the standard color curve by Capellaro is based on photographic photometry of a few SN I's, and is much bluer than indicated by recent photoelectric and CCD SN photometry (e.g., 1980N and 1981D, Hamuy et al. 1990; 1990N, Leibundgut et al. 1991a; 1991T, Phillips et al. 1992). Our distance of 7.6 Mpc to SN 1973R, combined with the photometry and reddening estimate from Wells et al., implies an absolute maximum for SN 1989B of $M_B^{\max} = -18.3$. The associated error due to reddening is too large to allow calibration of SN Ia's from SN 1989B. Uncertainty in extinction causes equal uncertainties in distance measurements when employing standard candles; however, this is not the case with EPM.

SN 1989M, similarly, was found less then 2 years after SN 1988A in NGC 4579. SN 1989M reached a maximum of $m_B = 12.2$ (Kharadze & Pskovsky 1989). Steidel et al. (1990) used SN 1989M to study the ISM of NGC 4579 and measured very little extinction to the supernova. Using our distance of 23 Mpc derived from SN 1988A, an absolute magnitude at maximum for SN 1989M is determined to be $M_B^{\max} = -19.6 \pm 0.6$. Combining a Hubble diagram, constructed by Tammann & Leibundgut (1990) using 35 Type Ia supernovae at distances extending to the Coma Cluster, with our calibration of the absolute magnitude of Type Ia supernovae ($M_B^{\max} = -19.6 \pm 0.6$), yields $H_0 = 51^{+19}_{-14}$ km s^{-1} Mpc^{-1}.

Clearly these methods of determining H_0 are not perfected, even if the distances derived using EPM were exactly correct. However, there are many distant SN II's discovered each year (eight in 1990 with $v_{\rm rec} > 1500$ km s^{-1}), for which it should be possible to determine distances. In the next few years, as we concentrate on gathering data for faint SN II's a global measurement of H_0 free from uncertainties due to local perturbations in the Hubble flow should be feasible. The ability to measure accurate individual distances of galaxies well beyond the Virgo Cluster is an inherent advantage of EPM. Planetary nebulae and surface brightness fluctuations are limited to galaxies closer than 40 Mpc. These two methods, however, do have outstanding internal consistency and can be applied at will to many nearby galaxies. A more satisfactory agreement with these methods may result from further development of all three.

9. CONCLUSIONS

We have explored the principal sources of systematic errors that might occur when applying EPM. We have presented distance correction factors based on radiative transfer in a scattering atmosphere from models of SN 1987A and have shown that these corrections are substantial. We have also found that the correction factors are substantially less important at longer wavelengths, and as the supernova cools. Modeling individual supernovae is very difficult, but is the ideal method of determining the distances to SN II's. However, preliminary models for generic 25 and 15 $M_\odot$ RSG supernovae show the same evolution of correction factors as SN 1987A and suggest that blackbody correction factors for most SN II's are dependent only on temperature, not on the details of the individual progenitor. Additional empirical evidence further supports this relation. This relation in its current form (Fig. 4) is very useful, but models need to be calculated for a wide variety of progentiors to improve our understanding of the correction factors. The uniform evolution of $(B-V)$ (i.e., their constant temperature on the plateau) in SN II-P's permits a simple estimate of the total reddening to this type of supernova. We have also explored the effect of extinction on distance determinations and have shown that due to canceling effects, extinction has a surprisingly small effect (less than 10% for 0.3 mag uncertainty in A_V) on the distance measurements. Typical SN II's should not be prone to large asymmetries at early times. Even if asymmetries do exist in individual SN II's, the derived distance scale, on average, is not biased to small or large values. Much of the uncertainty with EPM can be circumvented by working in the near-infrared. Our modeling indicates that effects of extinction and flux dilution cause only small uncertainties at wavelengths longer than 1 μm.

We have applied blackbody correction factors derived empirically and from our models to 10 supernovae and have determined their distances. In addition, we have used infrared photometry to determine independent distances to three of these supernovae. Of these supernovae, SN 1987A and SN 1970G lie in galaxies with Cepheid distances. In both cases the derived distances agree with the Cepheid distances within the errors. In general, EPM gives slightly smaller distances (15%) than those proposed by Sandage & Tammann (1990) to other galaxies and gives larger distances ($\approx 50\%$) than those derived using Tully-Fisher, planetary nebulae luminosity functions, and surface brightness fluctuations.

The distances derived in this paper, spanning the range from 50 kpc to 120 Mpc, are used to estimate H_0. Using the distant SN II, SN 1990ae, we find $H_0 = 66^{+9}_{-12}$ km s^{-1} Mpc^{-1}. A Virgo infall model combined with the distances of the 10 supernovae gives $H_0 = 60 \pm 10$ km s^{-1} Mpc^{-1}. Finally, we determine the absolute magnitude of Type Ia supernovae from two galaxies that have had both a well-observed Type Ia and Type II supernova. These calculations yield $M_B^{\max} = -19.6 \pm 0.6$ for Type Ia supernovae. This result, when combined with a Hubble diagram of distant Type Ia supernovae at maximum, yields $H_0 = 51^{+19}_{-14}$ km s^{-1} Mpc^{-1}.

Obtaining data for SN II's is difficult because telescope time is scheduled in advance, and supernovae are not. Spectra need be taken only once a week, because the velocity of the SN photosphere does not evolve rapidly, except at early times. U and R photometry are *not* as useful as B, V, I, J, H, K, and L photometry because the continuum is strongly contaminated by absorption and emission in these two bands. Special emphasis should be placed on obtaining infrared photometry because of the reduced uncertainty from extinction and flux dilution. The observations should span from discovery until the supernova leaves the plateau phase for SN II-P's, or about 50 to 100 days after maximum for SN II-L's. After this time the photosphere is no longer formed within the hydrogen envelope and loses all semblance to a blackbody. Observations while a supernova is young constrain t_0 and are therefore especially valuable.

Applying EPM to supernovae is already a very useful method of measuring extragalactic distances. In the future, by obtaining high quality data of the many SN II's discovered each year, it will be possible to derive independent distances to many supernovae, most of which will be well in the Hubble flow. In this way we believe that Type II supernovae will become central to determining the extragalactic distance scale.

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