RevMexAA (Serie de Conferencias), **7**, 73–80 (1998)

SUPERNOVAE AND THE HUBBLE CONSTANT (OR, BUTTHEAD'S REVENGE)

J. C. Wheeler and P. Höflich

Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA; wheel@astro.as.utexas.edu; pah@astro.as.utexas.edu

RESUMEN

Los modelos físicos de supernovas del Tipo Ia (SN Ia) que no dependen de calibradores secundarios han indicado, durante más de una década, que la Constante de Hubble debe ser $\sim$ 65 km s^{-1} Mpc^{-1} con una incertidumbre que se reduce con la sofisticación de los modelos. Esta estimación concuerda con aquellas que se basan en observaciones del *HST* de Cefeidas variables y con métodos puramente empíricos que se basan en supernovas SN Ia calibradas con Cefeidas. Se revisan las perspectivas de entender la física de la explosión en SN Ia y su aplicación para medir otros parámetros cosmológicos. A pesar de la muy compleja naturaleza de sus atmósferas, las SN Ia pueden dar una estimación más confiable de las distancias que las del Tipo II. Estas últimas dependen de incertidumbres en las átmosferas de dispersión, en la abundancia de helio y en los posibles efectos sistemáticos debidos a distorsiones en la envolvente que no se promedian ni siquiera en una muestra grande.

ABSTRACT

Physical models of Type Ia supernovae (SN Ia) that do not depend on secondary calibrators have indicated that the Hubble Constant must be $\sim$ 65 km s^{-1} Mpc^{-1} for well over a decade with the range of uncertainty shrinking with the sophistication of the models. This estimate is in good agreement with those based on *HST* observations of Cepheid variables and with purely empirical methods based on SN Ia supernovae calibrated with Cepheids. The prospects of progress in understanding the physics of the explosion of SN Ia and of their application to measure other cosmological parameters is reviewed. Despite the rather complex nature of their atmospheres, SN Ia may give a more reliable estimate of distances than Type II. The latter depend on remaining uncertainties in the scattering atmospheres, the helium abundance and possible systematic effects due to distortions of the envelope that will not average out even in a large sample.

Key words: **COSMOLOGY: OBSERVATIONS — DISTANCE SCALE — SUPERNOVAE: GENERAL**

1. INTRODUCTION

In a recent workshop convened in Aspen, Rob Kennicutt gave a striking summary of the convergence of estimates of the Hubble constant and the corresponding shrinking of error bars. One of the most important contributions of the *Hubble Space Telescope* has been, for the first time, accurate estimates of the errors. As Kennicutt pointed to a plot of the value of the Hubble constant versus time since 1990 and the convergence of estimates to a value in the mid to high 60's (in units of km s^{-1} Mpc^{-1}) one of the authors of this paper (JCW) piped up to say, "I knew that", and Kennicutt, without missing a beat, his back to the audience, said "I knew some butthead would claim he knew the right value all along". One purpose of this review is to summarize the arguments that have led theorists studying physical models of Type Ia supernovae (SN Ia) to predict that when the dust settled, the *HST* key project would find the Hubble constant to be $\sim$ 65 km s^{-1} Mpc^{-1}, as has, in fact, been the case. There is some cause for taking this expected but welcome confirmation as proof that we are on the right track in our interpretation of the physical nature of SN Ia and encouragement to employ our growing physical understanding to determine the systematic effects that are expected to dominate the use of SN Ia to determine the deceleration parameter and perhaps even the cosmological constant.

The status of work on SN Ia is given in §2. The use of Type II supernovae (SN II) as a complementary tool to measure the Hubble constant is discussed in §3. A brief summary is given in §4.

2. TYPE IA SUPERNOVAE

The standard model of a SN Ia is a thermonuclear explosion of a carbon/oxygen white dwarf. To first order, models for such an explosion put constraints on the luminosity that in turn constrain the Hubble constant. The reason is that the nuclear energy liberated has two correlated, but independently measurable effects. The energy of the explosion determines the expansion velocity which can be determined from the Doppler shift of spectral features. The energy is supplied by burning carbon and oxygen to intermediate mass and iron-peak elements. The principal iron peak element produced is that having equal numbers of protons and neutrons, as does the fuel, and that is ^{56}Ni . The decay of ^{56}Ni and its daughter product ^{56}Co; however, determine the bolometric luminosity of the explosion with ^{56}Ni dominating near maximum light. Thus, to first order, the amount of ^{56}Ni and hence the luminosity is closely related to the expansion velocity.

This correlation was pointed out by Sutherland & Wheeler (1984) and its direct implications for the Hubble constant were summarized by Arnett, Branch, & Wheeler (1985). It was not possible at that time to put precise limits on the Hubble constant because of simplifications and some uncertainties in the radiative transfer, but some limits were clear. If the amount of nuclear burning were too low, then the white dwarf could not be unbound, never mind give the requisite expansion velocity of $\sim$ 10 000 km s^{-1}. This meant that this class of model could not be consistent with a Hubble constant of 100 km s^{-1} Mpc^{-1} and even 70 km s^{-1} Mpc^{-1} caused some discomfort. At the other extreme, such a model could not produce more than its entire mass, a Chandrasekhar mass, of ^{56}Ni . This constraint and the observation that rise times of SNe Ia are at least 2 weeks, put an absolute upper limit on the brightness and a lower limit on H_0 of 40 km s^{-1} Mpc^{-1}. This is clearly an unphysical lower limit because we know from the spectrum that a substantial portion of the outer layers of the ejecta of an SN Ia are not iron peak, but intermediate mass elements. Exactly how outrageous this lower limit was could not be assessed precisely at the time, but a model with about 0.6 $M_\odot$ of nickel (model W7 of Nomoto, Thielemann, & Yokoi 1984) gave a reasonable light curve and, even more importantly, spectrum (Harkness 1986, 1991). The luminosity of this model applied to normalize the Hubble diagram of SN Ia implied that a preferred value of the Hubble constant was $\sim$ 60 km s^{-1} Mpc^{-1}. Subsequent work has made crucial refinements in both the physics of the explosion and the sophistication of the radiative transfer that allows one to go from the bolometric luminosity given by radioactive decay to the observed multi-color light curves. This work brought a recent critical advance in understanding that kept pace with important observational developments.

On the observational side, the long suspected inhomogeneity of SNe Ia (Pskovskii 1977) has been confirmed (Phillips 1993; Hamuy et al. 1993). There is no longer any basis for assuming they are intrinsically ideal "standard candles". Rather, this inhomogeneity gives an opportunity for a deeper understanding of the underlying evolutionary and physical processes. This diversity must also be taken into account in using SNe Ia to determine cosmological distance scales. This can be done to some extent by empirical methods (Riess, Press, & Kirshner 1996), but a physical understanding is both intrinsically preferable and necessary to fully integrate the changing properties of SNe Ia with the structure and evolution of their host galaxies. Of particular interest is the light curve brightness/decline relation. Observations show that dimmer SNe Ia decline more rapidly than brighter events (Phillips 1993; Hamuy et al. 1996). A one-parameter version of this relation has been used to empirically calibrate SNe Ia in the context of estimates of the Hubble constant (Riess et al. 1996) and the deceleration parameter (Kim et al. 1997), but one expects and observes scatter around the mean brightness/decline relation that must be understood and incorporated in further work.

On the physical side, there have been important breakthroughs in understanding the possible nature of the thermonuclear combustion of SN Ia. There is now strong reason to believe that the explosion proceeds from a phase driven by a subsonic turbulent combustion, a deflagration, followed by a transition to a shock-driven, supersonic detonation phase (Khokhlov 1991). Spherically symmetric models that treated the density at which this deflagration to detonation transition occurred as a free parameter revealed a new effect. The nuclear energy that gave rise to the expansion velocity could be provided by burning predominantly to intermediate mass elements, especially silicon. The critical nuclear energy to unbind the white dwarf and provide the expansion velocity is thus proportional to the sum of the Si peak material and Ni (Höflich, Khokhlov, & Wheeler 1995). Depending on the value of the transition density, however, more or less ^{56}Ni would be produced which would in turn produce different values of the luminosity. This class of models, while generically closely related to earlier ones, broke the tight relation between the mass of ^{56}Ni and the expansion velocity. Models with less ^{56}Ni (but with substantial total thermonuclear energy release, $\sim 10^{51}$ ergs) were not only dimmer, but also cooler. The lower temperatures resulted in lower opacity and faster rates of decline. These models account qualitatively and even quantitatively for the observed brightness-decline rate relation (Höflich et al. 1995; Höflich et al. 1996b).

These new developments were applied to the determination of the Hubble constant by Höflich & Khokhlov (1996). This paper presented a large variety of models computed with different assumptions concerning the

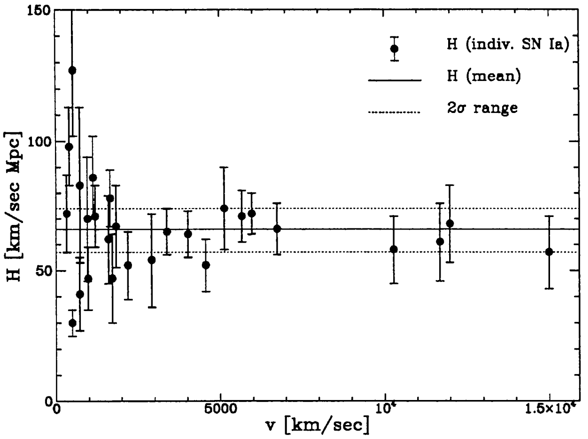


Fig. 1. Values for H_0 with 2 σ error ranges are shown based on individual distances to SN1937C, 70J, 71G, 72E, 72J, 73N, 74G, 75N, 81B, 83G, 84A, 86G, 88U, 89B, 90N, 90T, 90Y, 90af 91M, 91T, 91bg 92G, 92K, 92bc 92bo, and 94D. SN1988U at v=91500 km s^{-1} gives $H_0 = 64 \pm 10$ km s^{-1} Mpc^{-1}.

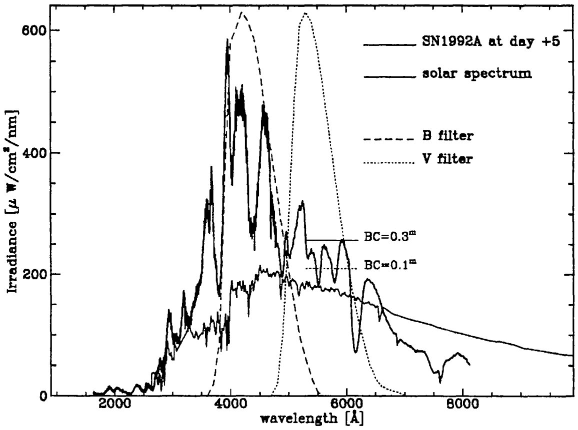
combustion physics, for each of which multi-color light curves were computed. The result was an ensemble of models from which one could chose the ones that best matched the observations, or, more precisely, one could reject models that clearly failed to match the observations. Models that provided reasonable fits to the light curves around maximum in a wide variety of photometric bands constrain the luminosity rather tightly. Thus one can estimate the brightness (as well as reddening) of each individual supernova and determine a corresponding point on the Hubble diagram. The result is the currently best guess for the Hubble constant using only physical models and observations of individual supernovae with no reference to local calibrators. The result obtained by Höflich & Khokhlov is 67±9 km s^{-1} Mpc^{-1} (Figure 1). The error is a "2 σ" value (i.e., the 95 % probability limit for a non-Gaussian error distribution) obtained by assessing the probability that a given range of models fit a given supernova. The value and error estimate are in excellent accord with recent estimates of H_0 based on distances to Cepheid variables. From *HST* observations of δ-Cephei stars in IC 4182, NGC 5253, and NGC 4536 distance moduli have been found to be 28.47 ± 0.08, 28.10 ± 0.07, and 31.17 ± 0.20 mag, respectively (Freedman et al. 1994; Sandage et al. 1994; Tammann 1996) which also compare well with the estimates of Höflich & Khokhlov of 28.3 ± 0.25, 28.0 ± 0.15, and 31.17 ± 0.20 mag, respectively. The spread for nearby SNe Ia in Fig. 1 is consistent with the COBE dipole field. Höflich & Khokhlov were also able to show (based on one very distant supernova, SN 1988U) that H_o does not vary significantly from redshift of 0.1 to 0.5 and to put rough limits on the deceleration parameter, q_0 = 0.7±1.

The bolometric luminosity in the models basically depends on the decay energies which are well known. The translation between total luminosity and brightness in a given band may be a point of concern. The bolometric correction, defined to be the conversion factor between the total luminosity and that in the V band, can be tested with observed spectra in a model-independent way because it depends only on the flux distribution. Figure 2 gives the spectrum of SN 1992A and that of the Sun normalized to give the same total flux. Models give a bolometric correction of $\sim 0.1^m$, consistent with the normalized observed SN spectrum in the V band. A BC of 0.3^m would clearly be too large to be consistent with the flux in the observed supernova spectrum in the V band. The models reproduce the empirical constraints on BC to within $\pm$ 0.1^m, implying a systematic error of less than 10 % (Höflich & Khokhlov 1996).

This work strongly suggests that the physical and radiative transfer models of SN Ia are on the right track and can be used with some confidence in the next exciting phase as one attempts to use high redshift supernovae (Perlmutter et al. 1995; Kim et al. 1997; Schmidt 1997) to determine q_0 and Λ_0. With the great productivity of the distant supernova searches, internal errors due to small number statistics will soon become of vanishing significance. The critical issue will be to determine the systematic effects as one looks back to earlier eras when metallicities, progenitor evolution, even galaxy evolution may be significantly different.

Riess et al. (1996) have shown the power of correcting for the brightness/decline relation. By so doing, the scatter around the Hubble flow line is reduced from $\sim 0.4^m$ if SN Ia are assumed to be standard candles to $\sim 0.2^m$ if their multi-color techniques are used to determine peak luminosity. Some reservation about this empirical technique has been expressed by noting that some of the nearest SN Ia are the brightest, a distinctly counter-intuitive result. This needs to be better understood, but it is probably the result of low number statistics for nearby supernovae and the fact that spiral galaxies have, in the mean, somewhat brighter supernovae. The local sample is dominated by spiral galaxies. Another aspect of this issue was recently uncovered by Wang,

Fig. 2. Comparison of the standard solar flux distribution (thin line, Kohl, Parkinson, & Kurucz 1992; Avrett 1992), with the observations of SN1992A at about 5 days past maximum light (thick line, Kirshner et al. 1993). Both spectra are normalized to the bolometric irradiance of the Sun measured in $\mu W/\mathrm{cm}^2/\mathrm{nm}$. Also shown are the B and V filter functions of Bessell (1990). The horizontal lines at about 5500 Å give the mean flux level in V which would be required for a BC of 0.1^m (dots), the mean value for models of SNe Ia, and 0.30^m (dashed dotted).



Höflich, & Wheeler (1997). They examined the radial distribution of supernovae in galaxies. Using the well-calibrated Calán-Tololo sample of SN Ia, they showed that at galactocentric radii less than ~ 7 kpc, SN Ia show the full dispersion of peak luminosity reflected in the brightness/decline relation. Beyond ~ 7 kpc, however, the dispersion in peak brightness drops dramatically. The intrinsic dispersion with no correction whatever for the brightness/decline relation is $\sigma \sim 0.2^m$, comparable to that obtained after correction by Riess et al. The reason for this remarkable change in the properties of SN Ia demands explanation in terms of progenitor evolution, metallicity, etc. It suggests that their may yet be a way of picking a sample of SN Ia which do represent nearly "standard candles", but it remains abundantly clear that this is not the case for the full sample of SN Ia.

Future work, both on understanding the progenitor evolution and physics of SN Ia and on purely empirical calibration methods must focus on departures from a one-parameter light curve brightness/decline relation. The observational data, for instance from the Calán-Tololo survey, already show a dispersion that cannot be fit by a one parameter curve (Hamuy et al. 1996; Höflich et al. 1996b). SN 1994D is a particular case in point. It is too bright and blue for its light curve shape (Höflich 1995a). There are also abundant theoretical reasons to think that there should be a scatter in properties in terms of initial metallicity, rotation, and mass accretion rate. Even if the progenitor evolution is identical, the randomness associated with the site of ignition of carbon many points and with subsequent turbulent burning is sure to impose some dispersion of final properties.

Current work on the physics of SN Ia promises deeper understanding of these issues. The carbon runaway will grow out of a preliminary phase of quasi-static convective carbon burning. The resulting dynamical runaway may start in the center or off center in one or many points (so called "spotty ignition") as determined by the temperature distribution on the convective phase. The first full 3-D calculations of the deflagration of a carbon/oxygen white dwarf have been done by Khokhlov (1995). These calculations show that the expansion and freezing of the flow is important and seems to be consistent with models in which expansion quenches the subsonic deflagration, thus allowing a turbulent mixing of warm ash and cold fuel. Subsequent recompression is likely to trigger a detonation. This problem of deflagration to detonation transition is currently under intense study (Khokhlov, Oran, & Wheeler 1997a,b; Niemeyer & Woosley 1997). Future 3-D calculations will use adaptive mesh techniques to extend the resolution of the turbulent flame to the scale where turbulence disrupts the laminar flame (the "Gibson" scale) to provide a more accurate model of the turbulent burning phase and a natural transition to detonation. These models should go a long way to removing the current free parameter of the transition density from deflagration to detonation and leave the progenitor evolution as the major unknown.

The explosion will inevitably be a function of the redshift and hence age of the host galaxy, the mass accretion rate, metallicity, rotation and other factors. An example of how the metallicity could alter the resulting spectrum is given in Figure 3 from Höflich et al. (1997). In this calculation, the metallicity of the progenitor white dwarf is varied from solar to 1/3 solar. It is important to note that this variation must be imposed on the progenitor, not added after the explosion, because it changes the nucleosynthesis during the explosion. The principal effect is to alter the iron peak abundances and these in turn primarily affect the spectrum in the blue. One result of this is substantially different colors, say $B - V$, as the small differences in the rest frame U band spectra are redshifted to B and then to V. Figure 4 shows that the differences in $B - V$ can be up to 0.2^m. Some groups doing supernova searches at large redshifts (Perlmutter et al. 1995) search only in the CCD band and clearly will have to account for such variations. Other groups (Schmidt 1997), employ

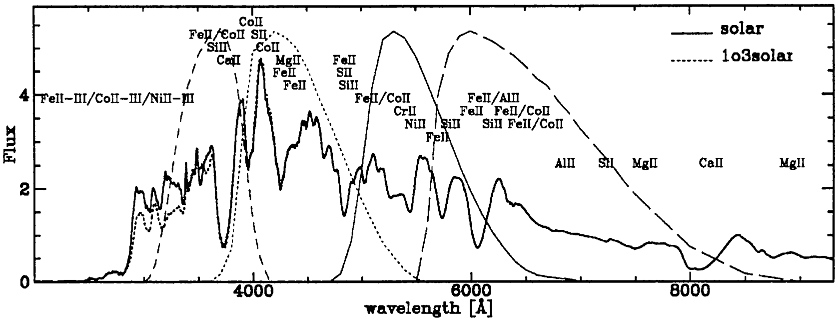


Fig. 3. Comparison of synthetic spectra for deflagration/detonation model DD200c at maximum light assuming initial compositions of solar and 1/3 of solar, respectively.

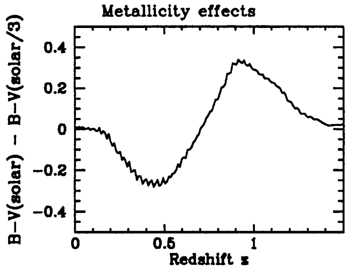


Fig. 4. Effect of a change in the initial metallicity (solar vs. 1/3 solar) (cf., Fig. 3) on $B - V$ for deflagration/detonation model DD200c as a function of the redshift Z.

specially constructed filters so that they are effectively always looking at the rest frame V band. Even with this technique, care must be taken that the red-shifted filter matches the standard V-band filter (whatever standard one chooses) and that the match remains precise over the observed redshift range.

3. TYPE II SUPERNOVAE

SN II represent an important complement to SN Ia as a technique to measure cosmological distances. In principle, the distance to each individual SN II can be measured by the "Baade-Wesslink" or "Expanding Photosphere" Method (note the photosphere actually retreats in mass with time) in which the ratio of the observed apparent flux to the intrinsic absolute flux gives the anglular size and the velocity and elapsed time give the radius. The critical aspect of this method is to determine the intrinsic flux of the atmosphere where scattering effects are important. In simple terms, scattering results in a "dilute black body" and this dilution factor which is, in general, a function of frequency and time, must be determined.

Schmidt et al. (1994) have computed the behavior of this dilution factor over a range of temperatures and for a variety of models and have compared their results to SN 1987A and other SN II. Their dilution factor is unity at low temperatures, drops rather rapidly by a factor of about 4 by 9000 K, and then remains constant at higher temperatures. This dilution factor has been used to determine the distances to a number of SN II and to derive an estimate of the Hubble constant, $H_0 = 73$ km s^{-1} Mpc^{-1}. There are a number of reasons to think that this issue can benefit from further examination.

The power of this method was illustrated by SN1987A where many groups agreed within 10% in distance (42± 5 kpc, Chilukuri & Wagoner 1988; 48± 4 kpc, Höflich 1987, 1988; 46± 4 kpc, Schmutz et al. 1990; 49± 5 kpc, Eastman & Kirshner 1989). This was, however, by far the best observed SN with good time coverage and knowledge of the time of the explosion. For the Baade-Wesselink method, exact knowledge of the time of the explosion can be important. The error in the distance scales as $\delta t/t$. Typically, the time of the explosions of other supernovae are only known to within a few days at best, implying an error of $\approx$ 20% in the first few weeks. Later on, when this source of error becomes small, the photospheres of SN II tend to be about 5000 K in the recombination phase of the plateau which puts the dilution factor on the steeply declining part of the function. This clearly calls for especially careful treatment, by fitting individual supernovae. Although all groups (Höflich 1991; Schmidt et al. 1994; Baron et al. 1995) agree on the general relation between dilution factor and photospheric temperature including the change of the dilution factor during the recombination phase, Höflich (1991) and Baron et al. (1994) found a value of the dilution factor for high temperatures (i.e., $\sim$ 9000 K) that was higher by about 30 and 50%, respectively, than that of Schmidt et al. (1994). The estimate of Baron et al. was in the context of SN 1993J, not a standard SN II, but their models were rather generic. Moreover, depending on the model parameters, both Höflich and Baron et al. found larger scatter around the mean, even at large temperatures, than Schmidt et al. 1994, Clocchiatti et al. (1995) found that in the early stages of the expansion of the fireball of SN 1993J, the atmosphere was hot, $\sim$ 10 000 K, but the dilution factor was essentially unity, in sharp contrast with the asymptotic value of Schmidt et al. The difference can be attributed to the apparent steep density profile of the atmosphere of SN 1993J (brick walls radiate like black bodies), but this result suggests another cause for caution. The range of estimates of the dilution factor by Schmidt et al., Höflich, and Baron et al., might be regarded as the intrinsic range in uncertainty. At the very least the source of these discrepancies should be understood.

The ability of polarimetry of supernovae to give unique information about intrinsic asymmetries has long been discussed (Shapiro & Sutherland 1982; McCall et al. 1984). SN 1987A also represented a breakthrough in this area by providing the first detailed record of the spectropolarimetric evolution (Mendez et al. 1988; Cropper et al. 1988). SN 1993J also provided a wealth of data which is still being analyzed (Trammell, Hines, & Wheeler 1993; Höflich 1995b; Doroshenko et al. 1995; Höflich et al. 1996a; Tran et al. 1997). More recently we have begun a program at McDonald Observatory to attempt to get routine spectropolarimetry on all accessible supernovae. This program has nearly doubled the number of supernovae for which polarimetry is available. The early qualitative conclusion was that all Type II are polarized at about the 1 percent level and that Type Ia are much less polarized, less than 0.1 – 0.2 percent. (Wang et al. 1996). That trend continues without exception.

There are a number of ways in which the emission from supernovae could be polarized. There could be asymmetries associated with the circumstellar medium, especially aided by the large scattering cross section of dust (Wang & Wheeler 1996). There could be asymmetries in the ejecta that reflect initial distortions in the outer envelope due to rotation, filling a Roche lobe, or other influences (Höflich 1991; Jeffery 1991). A symmetric explosion in an envelope distorted by rotation or by filling a Roche lobe can give a prolate envelope and an oblate core (Steinmetz & Höflich 1992). The reason is that shocks first propagate up the axis where the density gradient is steeper, but then sideways to the equatorial axis where they meet and eject matter in the equatorial plane giving a prolate, pancake-like geometry. Pressure waves are then sent into the core by momentum conservation, compressing the core along the equatorial plane. This tends to yield an oblate, cigar-shaped core. Both a distortion of the envelope and dust scattering may have played a role in SN 1987A. If the source of illumination is off-center even in an otherwise spherically symmetric density distribution, the emergent light will be polarized (Höflich 1995b). This type of asymmetry is also established in other ways in SN 1987A and, to a certain extent, in SN 1993J. Finally, and perhaps most importantly, the intrinsic explosion process, core collapse or thermonuclear explosion, may impose asymmetry. The polarization of SN Ic 1997X, a bare, non-degenerate carbon/oxygen core, may give strong indication of this effect. Polarimetry may thus provide a unique ability to determine the asymmetry of the explosion mechanism and hence special constraints on the physics of the explosion independent of any subsequent instabilities or other symmetry-breaking phenomena.

The first several SN II events with confirmed polarization, SN 1987A, SN 1993J, SN 1994Y (a narrow emission line event), were odd in some way, so there was some question of whether the trend identified by Wang et al. (1996) that all SN II were substantially polarized was due to a sample that was unrepresentative of normal SN II. Observations of SN 1996W help to remove that concern. SN 1996W was a perfectly normal Type II plateau event. It was observed shortly after the first "hump" in the visual at the very early stage of the plateau at the beginning of the recombination wave phase. SN 1996W, like the other SN II, was polarized at about the 1 percent level. Because SN IIP are bright red supergiants with very large envelopes, rotational distortion of the envelope seems unlikely and any dust-scattered light should be rather dilute. The envelope should be very optically thick at the observed phase, so it is unlikely that any effect of off-center nickel blobs would be manifest. This may mean that the polarization observed in SN 1996W was due to some asymmetry associated with the explosion process.

The observations of SN 1996W imply that polarization of SN II is ubiquitous. This conclusion may have implications for use of SN II to measure the distance scale. To generate the observed polarizations, envelope distortions of 10 – 50 percent are required (Höflich 1995b), although this may not be necessary in dust scattering models. For such distortions, the luminosity can be strongly asymmetric with differences of up to a factor two along the polar and equatorial directions. If the asymmetric luminosity were distributed in the same way as orientation on the sky, this would have no affect on a large sample of supernovae, because the effect would average out. The luminosity is not, however, a linear function of the inclination angle. Therefore, the distribution of luminosity could have a net systematic bias which will affect the use of SN II to make distance estimates. Further study of the polarization of supernovae is thus warranted in this regard.

4. SUMMARY

The most recent estimate for the value of the Hubble constant by the Hubble Key Project (Freedman et al. 1997) is 67±5(internal)±8(systematic) km s^{-1} Mpc^{-1}. In this work, local distances based on Cepheid variables are extrapolated out to the Hubble flow using the Tully-Fisher relation, the surface brightness fluctuation method or SN Ia, all of which provide the same relative distances. The issue has been the absolute calibration, which the Cepheids are now providing. Note that it is somewhat circular to use empirical determinations of SN Ia as one means of extrapolation when this technique is itself dependent on the Cepheids to determine the absolute scale. In any case, the two methods agree. Riess, Press, & Kirshner get H_0 = 67±8 km s^{-1} Mpc^{-1}. In an important complementary study, Sandage et al. (1996) have determined the distances to Cepheid variables that have specifically been host to SN Ia. They have obtained H_0 = 56±4(internal) km s^{-1} Mpc^{-1} based on *B* magnitudes, and H_0 = 58±4(internal) km s^{-1} Mpc^{-1} based on *V* magnitudes for the SN Ia. This analysis assumes that SN Ia are standard candles, which is not valid. A correction for the brightness/decline relation would give a value that is quite consistent with those quoted above.

The current empirical values for the Hubble constant based on SN Ia and Cepheids are consistent with the value obtained by direct comparison of models with observations of SN Ia with no reference to local calibrators, H_0 = 67±9 km s^{-1} Mpc^{-1} (Höflich & Khokhlov 1996). Further work on the physics of the explosion and the use of spectral, rather than broad band, evolution should be able to reduce the error in this method. Using SN II, Schmidt et al. (1994) obtain H_0 = 73±6(internal)±7(systematic) km s^{-1} Mpc^{-1}. This is consistent, within the errors, with estimates based on SN Ia. If, however, the dilution factor of Baron et al. (1994) were used at face value, this estimate would drop to $H_0 \sim 50$ km s^{-1} Mpc^{-1} and with that of Höflich (1991), the value would be $H_0 \sim 65$ km s^{-1} Mpc^{-1}. Some improvement could probably be made in the estimates based on SN II, including possible systematic effects of asymmetries.

Improvements are still necessary, but discussion of the Hubble constant concerns uncertainties of 10 – 20 percent, no longer a factor of two. Recent developments show that things are still somewhat in a state of flux on the observational side. There is a rumor that Hipparchos will recalibrate the distances to Cepheids and increase the distance scale by ~10 percent; however, Kochanek (1997) has examined the color effects of the Cepheid period/luminosity relation and deduced that the distance scale must be decreased by ~ 10 percent. These effects may prove to cancel, or one or the other may be otherwise qualified. A colleague recently remarked that the theoretically-based methods using either SN Ia or SN II are doing quite well and if the observations threaten to depart from those results, one should question the observations. This is no time for the theorists to lose heart!

The value of the Hubble constant is 65.73. You heard it here first.

We thank our colleagues at Rice for the opportunity to summarize these issues and numerous colleagues who work on the distance scale for stimulating discussions over many years. This work was supported in part by NSF Grant AST9528110, NASA Grant NAG52888 and a grant from the Texas Advanced Research Program.

REFERENCES

Arnett, W. D., Branch, D., & Wheeler, J. C. 1985, Nature, 314, 337

Avrett, E. H. 1992, in Solar Electromagnetic Radiation, ed. R.F. Donnelly (NOAA ERL), 20

Baron, E., et al. 1995, ApJ, 441, 170

Bessell, M. S. 1990, PASP, 102, 1181

Chilukuri, M., & Wagoner, R. V. 1988. Lect. Notes in Physics, 305, 295

Clocchiatti, A., Wheeler, J. C., Barker, E. S., Filippenko, A. U., Matheson, T., & Liebert, J. W. 1995, ApJ, 446, 167

Cropper, M., Bailey, J., McCowage, J., Cannon, R. D., Couch, W. J., Walsh, J. R., Strade, J. O., & Freeman, F. 1988, MNRAS, 231, 695

Doroshenko, V. T., Efimov, Y. S., & Shakhovskoi, N. M. 1995, Astron. Lett., 21, 513

Eastman, R. G., & Kirshner, R. P. 1989, ApJ, 347, 771

Freedman, W. L., et al. 1994, ApJ, 427, 628

Freedman, W. L., et al 1997, in preparation and private communication

Harkness, R. P. 1986, in Radiation Hydrodynamics in Stars and Compact Objects, ed. D. Mihalas & K.-H. A. Winkler, (Berlin: Springer Press), 166

__________. 1991, in SN 1987A and Other Supernovae, ed. J. Danziger & K. Kjär, (Garching: ESO), 447

Hamuy, M., et al. 1993, AJ, 106, 2392
Hamuy, M., et al. 1996, AJ, 112, 2408
Höflich P. 1987, in SN 1987A, ed. I. J. Danziger, (Garching: ESO), 449
_________. 1988, Pub. Ast. Soc. Aus., 7, 434
_________. 1991, in Supernovae, ed. S. E. Woosley, (New York: Springer-Verlag), 415
_________. 1995a, ApJ, 443, 89
_________. 1995b, ApJ, 440, 821
Höflich, P., & Khokhlov, A. 1996, ApJ, 457, 500
Höflich, P., Khokhlov, A., & Wheeler, J. C. 1995, ApJ, 444, 831
Höflich, P., Wheeler, J. C., Hines, D. C., & Trammell, S. T. 1996a, ApJ, 459, 307
Höflich, P., Khokhlov, A., Wheeler, J. C., Phillips, M. M, Suntzeff, N. B., & Hamuy, M. 1996b, ApJ, 472, 81
Höflich, P., et al. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Canal, & J. Isern, (Dordrecht: Kluwer), 659
Jeffery, D. J. 1991, ApJS, 77, 405
Khokhlov, A. 1991, A&A, 245, 114
_________. 1995, ApJ, 449, 695
Khokhlov, A., Oran, E. S., & Wheeler, J. C. 1997a, Combustion & Flame, 108, 503
_________. 1997b, ApJ, 478, 678
Kim, A., et al. 1997, ApJ, 476, L63
Kirshner, R. P., et al. 1993, ApJ, 415, 589
Kochanek, C. S. 1997, ApJ, in press
Kohl, J. L., Parkinson, W. H., & Kurucz, R. L. 1992, in Center to Limb Solar Spectrum, NBS
McCall, M. L., Reid, N., Bessell, M. S., & Wickramasinghe, D. 1984, MNRAS, 210, 839
Mendez, M., Clocchiatti, A., Benvenuto, O. G., Feinstein, C., & Marraco, H. G. 1988, ApJ, 334, 295
Niemeyer, J. C., & Woosley, S. E. 1997, ApJ ,475, 740
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, 268, 644
Perlmutter S., et al. 1995, ApJ, 440, L41
Phillips, M. M. 1993, ApJ, 413, L108
Pskovskii, Yu. P. 1977, Sov. Astr., 21, 675
Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 588
Sandage, A., Saha, A., Tammann, G. A., Labhardt, L., Schwengeler, H., Panagia, N., & Macchetto, F. D. 1994, ApJ, 423, L13
Sandage, A., Saha, A., Tammann, G. A., Labhardt, L., Panagia, N., & Macchetto, F. D. 1996, ApJ, 460, L15
Schmidt, B. P. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Canal, & J. Isern, (Dordrecht: Kluwer), 765
Schmidt, B. P., Kirshner, R. P., Eastman, R. G., Phillips, M. M., Suntzeff, N. B., Hamuy, M., Maza, J., & Avilés, R. 1994, ApJ, 432, 42
Schmutz, W., Abbott, D. C., Russell, R. S., Hamann, W.-R., & Wessolowski, U. 1990, ApJ, 355, 255
Shapiro P. R., & Sutherland, P. G. 1982, ApJ, 263 902
Steinmetz, M., & Höflich P. 1992, A&A, 257, 641
Sutherland, P., & Wheeler, J. C. 1984, ApJ, 280, 282
Tammann, G. 1996, PASP, 108, 1083
Trammell, S. R., Hines, D. C., & Wheeler, J. C. 1993, ApJ, 414, L21
Tran, H., Filippenko, A. V., Schmidt, G. D., Bjorman, K. S., Jannuzi, B. T., & Smith, P. S. 1997, PASP, 109, 489
Wang, L., & Wheeler J. C. 1996, ApJ, 462, L27
Wang, L., Höflich, P., & Wheeler, J. C. 1997, ApJ, in press
Wang, L., Wheeler, J. C., Li, Z. W., & Clocchiatti, A. 1996, ApJ, 467, 435