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TYPE Ia SUPERNOVAE AS STANDARD CANDLES

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1. INTRODUCTION

As extremely luminous point sources, supernovae are attractive indicators of extragalactic distances. On the basis of their optical spectra supernovae are classified as type Ia, Ib, Ic, or II (Harkness & Wheeler 1990, Branch et al 1991). Those of type Ia (SN Ia), the most luminous and homogeneous kind, are the subject of this review.

Observations of SNe Ia and the present understanding of their physics have been reviewed by Wheeler & Harkness (1990). There is a characteristic light-curve shape that can be understood in terms of the trapping and thermalization of the decay products of radioactive ^{56}Ni
Chandrasekhar mass (1.4 $M_{\odot}$) of ejected matter. There also is a characteristic development of the SN Ia optical spectrum. Near the time of maximum light the spectrum contains lines of intermediate-mass elements from oxygen to calcium, ejected at high velocities $\gtrsim$10,000 km s^{-1}. At later times the spectrum becomes dominated by lines of the first several ionization stages of iron, most of which is presumed to have formed by
^{56}Co

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of galaxies, including ellipticals, and they show no obvious preference for regions of current star formation. Thus the initial mass of the SN Ia stellar progenitors must be lower than that of the SNe II and SNe Ib/Ic progenitors. All of this evidence suggests that SNe Ia are the explosions of white dwarfs that accrete matter from binary companions. In numerical simulations, a white dwarf that accretes matter at a rate in the range 10^{-6}–$10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ is found to ignite degenerate carbon at its center. A suitably parameterized nuclear burning front can then propagate outwards through the white dwarf, incinerating an inner fraction of the star to nuclear statistical equilibrium (mainly ^{56}Ni) while ejecting it at low velocity, and burning the outer layers into elements of intermediate mass while ejecting them at high velocity. Such models can account for both the spectra and the light curves. A white dwarf progenitor that accretes matter until it reaches the Chandrasekhar mass also would be consistent with the very impressive observed homogeneity of SNe Ia.

Section 2 reviews the status of the observational homogeneity, and Section 3 is concerned with the calibration of the SN Ia absolute magnitude. A final section discusses the prospects for applications of SNe Ia as distance indicators for cosmology: to provide an independent (but low-resolution) probe of the deviations from a linear expansion law; to measure the Hubble constant, H_0; to test the fundamental premise that the universe is expanding; and to measure the deceleration parameter, q_0.

2. HOMOGENEITY

2.1 *Light Curves*

The similarity of the shapes of the light curves of type I supernovae was pointed out by Pskovskii (1967) and Kowal (1968). Apparent differences in the shape of the blue (*pg* and *B*) light curves, which had been noticed by Schmidt (1957), were accepted as real by Pskovskii (1970, 1977) and expressed by a continuously varying parameter, β, that measures the decline rate. A large body of photometric data was analyzed by Barbon et al (1973) who concluded that SNe I do indeed have remarkably similar blue light curves, but they discussed the possibility of a dichotomy between "fast" and "slow" SNe I (see also Barbon 1980). The variety in the light curves seemed even more significant when correlations between the maximum brightness and the decline rate β were suggested (Rust 1974; de Vaucouleurs & Pence 1976; Pskovskii 1977; Branch 1981, 1982). These differences became less convincing, however, when the analysis was restricted to the best observed SNe I (Tammann 1978, 1982). The infrared light curves also revealed an impressive uniformity (Elias et al 1981). The data available to Cadonau et al (1985) showed that modern B magnitudes scatter significantly less about a mean template light curve than the generally older *pg* magnitudes, and cast doubt upon the distinction between fast and slow SNe I. A compilation of all optical magnitudes of SNe I in the literature (Cadonau & Leibundgut 1990) allowed the construction of template light curves in the *UBV* (Cadonau 1987) and *JHK* bands (Leibundgut 1988, hereafter L88). Four particularly well observed SNe Ia have a mean scatter about the template light curves for the six bands of only $\sigma_m = 0.06$–0.18 mag (Leibundgut 1990). From an atlas of the optical light curves of 75 SNe I (Leibundgut et al 1991a, hereafter LTCC91) it is clear that most SNe I comply with the templates within the photometric errors.

It should be pointed out that the photometry of supernovae is particularly difficult. Photographic photometry requires the setup of an auxiliary local standard sequence. Any zero-point and scale errors in this sequence translate into a magnitude shift and a distortion of the light curve. Photoelectric photometry is sensitive to the background light of the parent galaxy. As the supernova fades the increasing influence of the background distorts the light curve (Boisseau & Wheeler 1991). Even CCD photometry is not above suspicion. The transient phenomenon of a supernova frequently requires the use of nonphotometric nights which do not allow the proper determination of the night's photometric coefficients. Bewildering differences between the photometry of the same supernova by different authors give a vivid illustration of these problems. Deviations from the template in one pass band, for a supernova that appears standard in the other pass bands, are likely to be the result of photometric errors. In general the true deviations from the templates must be smaller than observed.

Because this review is concerned with supernovae of type Ia, we merely note in passing that the recognition of the additional subtypes SN Ib (Wheeler & Levreault 1985, Uomoto & Kirshner 1985, Panagia 1985) and SN Ic (Harkness & Wheeler 1990) had little effect on the discussion of the SN Ia optical templates, because the different subtypes have, at least during the earlier phases, surprisingly similar light curves (Ensman & Woosley 1988, Schlegel & Kirshner 1989, Wheeler & Harkness 1990, Leibundgut & Tammann 1992—hereafter LT92). In the infrared, however, the light curves of SNe Ib and Ic are distinctly different from those of SNe Ia (Elias et al 1985, L88).

The standard *UBVJHK* light curves of SNe I are discussed by LT92, whose main conclusions concerning SNe Ia are as follows. The duration of the rising branch of the light curve is easily underestimated because it is difficult to catch a supernova just after explosion. As Pskovskii (1971) pointed out, the time to reach the blue maximum is longer than 15 days, a value which nevertheless is still frequently used in the literature. Figure 1 shows photometry of the rising light curve. The time scales t_{pg}, t_B, and t_V are counted in days from the *pg*, *B*, and *V* maxima, respectively, and the error bars are determined from the scatter of the post-maximum data of the same authors. SN 1961D was discovered 21 days before *V* maximum (Zwicky 1961) which corresponds to 18.5 before *B* maximum (see below), i.e. $t_B = -18.5$ days. SN 1979B was discovered even earlier, at $t_B = -19.5$ (Rosino 1979, Barbon et al 1982). SN 1971G and SN 1937D were observed at $t_B = -17.5$ (Rosino 1971) and $t_B = -16$ (Hoffleit 1939), respectively. SN 1981D was traced back to $t_B = -15.3$ (Hamuy et al 1991). These are minimum values for the true rise time, although they are affected by errors in the epoch of maximum by about ± 1 day. The conclusion that the typical rise time to *B* maximum lasts at least 19–20 days has been supported recently by SN 1990N (Leibundgut et al 1991b). It may be noted here that Kepler's supernova (to be discussed in Section 3.1) was seen 16 days before the visual maximum, i.e. at $t_B = -13.5$, and its visual light curve agrees reasonably well with the SN Ia template. The agreement becomes even better when allowance is made for the distorting effect of the large, variable extinction, A_V. The value of A_V changes with phase because of the width of the *V* passband and the strong color evolution of supernovae (L88).

Near maximum SNe Ia redden rapidly, which causes them to reach *U*

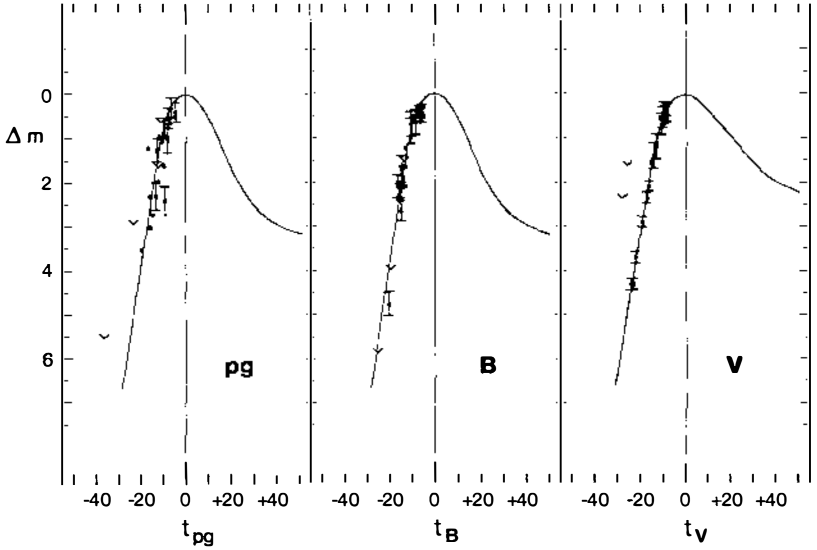

Figure 1 The rising part of SN Ia light curves (adapted from Cadonau 1987).

maximum about 2.8 days before, and V maximum about 2.5 days after, B maximum. The infrared magnitudes, however, do not follow this trend. In the JHK bands SNe Ia have their maxima *before* $t_B = 0$, and they later show secondary maxima around $t_B = 20$ to 30 days (L88). This anomalous behavior in the infrared appears to be caused by a strong unidentified infrared absorption that increases in strength after the time of B maximum (Elias et al 1981, Lynch et al 1990). The high infrared luminosity before B maximum prevents the construction of a reliable bolometric light curve before $t_B = 5$. The mean bolometric light curve for $t_B = 5$ to 110 days was determined by L88 using the $UBVJHK$ light curves. It thus comprises the flux between 3000 Å and 2 μm, which is believed to include practically the entire flux. The bolometric light curve, tabulated by LT92, seems to decline after $t_B = 5$ almost linearly. Extrapolation backwards suggests that the bolometric maximum may occur before $t_B = 0$, perhaps 17–18 days after the explosion.

At $t_B = 5$ the B light curve (Figure 2) plunges into a steep decline which reaches 0.12 mag per day at $t_B = 15$ and then flattens again. After 44 days the decline becomes linear at 0.017 mag per day. The linearity of the late blue light curve seems to persist until at least $t_B = 350$ or 400 days. The first plunge in V is slower by a factor of 2, while the plunge in U is slightly steeper and of longer duration, than that in B. The slow linear decline phase of the U and V light curves is reached after 31 and 41 days, respectively, and both are somewhat steeper than in B. Thus at late phases an SN Ia becomes increasingly blue again. It is clear that the shape of the light curve is strongly wavelength dependent.

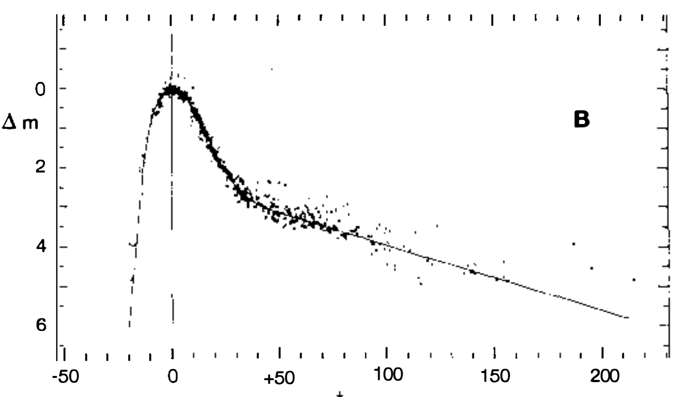

Figure 2 The standard B light curve (adapted from Cadonau 1987), based on observations of 22 SNe Ia.

The significance of the template light and color curves has been greatly increased by two SNe Ia that were discovered after the templates were defined. The photometry of SN 1989B (M. M. Phillips, unpublished) and SN 1990N (Leibundgut et al 1991b) agrees with the templates to within 0.1 mag.

The bolometric light curve (Figure 3) is roughly linear from $t_B = 5$ to 42 days with an average decline of 0.057 mag per day, corresponding to a half-life of 13.2 days. After 42 days the perfectly linear decline rate becomes 0.025 mag per day. The corresponding half-life of 33 days is much shorter than the 77 day half-life of ^{56}Co, indicating that the leakage of γ rays during the late phases is important.

Good definition of the templates in different bands requires, of course, that the color curves also follow a standard behavior. The $(B-V)$ curve, for instance, must simply be the difference between the B and V light curves. The available $(B-V)$ observations of SNe Ia are shown in Figure 4. They follow the expected template quite well up to about $t_B = 40$ days. The much larger scatter at later times may be due to larger observational errors as the supernova becomes fainter.

It should be noted that the zero point of $(B-V)$ in Figure 4 is arbitrary. The individual color curves have been shifted vertically to agree on average with the template. This procedure provides neither a calibration of $(B-V)$ at B maximum nor a proof that all SNe Ia have the same intrinsic color. The observations are consistent with a common intrinsic color evolution, however, and we assume that to be the case.

The value of $(B-V)^{00}$ at $t_B = 0$ can in principle be determined from the

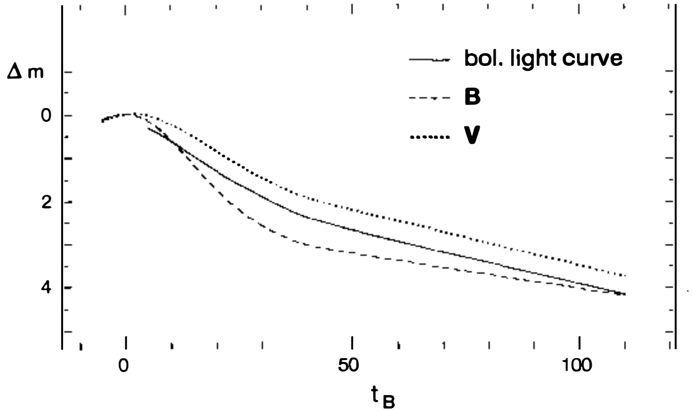

Figure 3 The standard bolometric light curve (adapted from Leibundgut 1988).

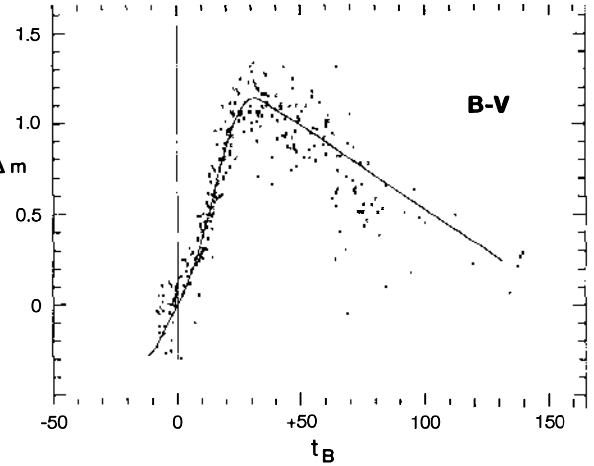

Figure 4 The standard $B-V$ curve. The value of $B-V$ at $t_B = 0$ is arbitrarily plotted at 0.0. The full line is the difference between the standard B and V light curves.

bluest SNe Ia known. [(Here the notation m^0 means that the magnitude has been corrected for Galactic extinction following the precepts of the RSA (Sandage & Tammann 1987), and m^{00} means that the magnitude is also corrected for extinction in the parent galaxy; the analagous notation is used for colors.] Three blue SNe Ia, SN 1970J, SN 1972J, and SN 1974J, all essentially depending on Asiago photometry, give $(B-V)^{00} = -0.2 \pm 0.01$ (LT 92), in good agreement with Pskovskii (1967). However, the value $(B-V)^{00} = -0.15$ found by Barbon et al (1973) has been widely used in the literature, and Hamuy et al (1991) have argued quite convincingly, using SN 1980N and SN 1981D, against a very blue color. We therefore adopt the conventional value of $(B-V)^{00} = -0.15$.

2.2 *Spectra*

Early observers of SNe Ia were justifiably impressed by the spectral homogeneity. Minkowski (1939) presented a long series of photographic spectra of SN 1937C and SN 1937D and stressed the similarity of their spectral evolution. Kirshner et al (1973) presented supernova spectra obtained with a linear detector and emphasized the spectral resemblance of SN 1972E to SN 1937C. Oke & Searle (1974), in their review of all supernova spectra published by that time, found only three SNe I—SN 1954A, SN 1962L, and SN 1964L—to have been significantly peculiar, and all three are now regarded as type Ib or type Ic (Porter & Filippenko 1987, Harkness & Wheeler 1990).

During the early phases near maximum light the SN Ia spectra consist of broad, overlapping P Cygni profiles characteristic of an atmosphere in expansion at velocities on the order of 10,000 km s^{-1}. Identifications are with lines of neutral or singly ionized elements of intermediate mass, e.g. Si II, Ca II, S II, and O I (Pskovskii 1969; Branch et al 1982, 1983). During the first few months after maximum light the spectrum becomes dominated by P Cygni profiles of Fe II (Branch et al 1983), and after hundreds of days it appears to consist mainly of broad overlapping emission lines due to the first few ionization stages of iron (Kirshner & Oke 1975; Meyerott 1978, 1980; Axelrod 1980a, 1980b; Woosley et al 1984). Some direct comparisons of the spectra of a few SNe Ia at the same phase, plotted on a common scale, have been published by Branch (1989), Pearce et al (1988b), Hamuy et al (1991), Ruiz-Lapuente et al (1991), and Filippenko (1991 and Figure 5). The impression one receives is that during the early photospheric phases only minor (but real) differences are present in the strengths of the spectral features. *IUE* observations of a few SNe Ia also show a strong uniformity in the ultraviolet spectra (Panagia & Gilmozzi 1991). Not many spectra obtained during the late nebular phases have been published yet, but inspection of the available data (e.g. Kirshner & Oke 1975 for SN 1972E, Branch 1990 for SN 1981B, de Robertis & Pinto 1985 for SN 1983U) suggests that the early spectral uniformity persists into the late phases. A (nearly) complete bibliography of supernova spectra up to 1988 has been published (Branch 1990) and is being updated (S. Benetti and D. Branch, in preparation). The present list includes some 70 SNe Ia, almost all of which do not noticeably depart from the standard SN Ia spectral evolution.

A strong indication that SNe Ia do, however, show significant differences in the blueshifts and widths of their spectral features was provided by SN 1984A. The spectrum of SN 1984A (Wegner & McMahan 1987) near maximum light is consistent with a velocity at the photosphere that was 4300 km s^{-1} higher than in the more typical SN 1981B (Branch 1987). Pearce et al (1988a) suggested that the difference in the expansion velocity might merely be due to a mismatch in the phases of the two supernovae, but Branch et al's (1988) plot of the blueshift of the red Si II $\lambda6355$ absorption feature versus phase showed scatter that was too large to be attributed to errors in velocity or phase. Barbon et al (1990) subsequently published a similar diagram supporting the same conclusion (Figure 6). Near maximum light the blueshift of the relatively unblended Si II absorption ranges from about 10,000 km s^{-1} in SN 1986G, SN 1986A, and SN 1989B to at least 15,000 km s^{-1} in SNe 1983G and SN 1984A. Barbon et al (1990) found that a more blended feature in the blue, usually attributed to Mg II $\lambda4481$, shows a smaller scatter in its velocity-phase diagram;

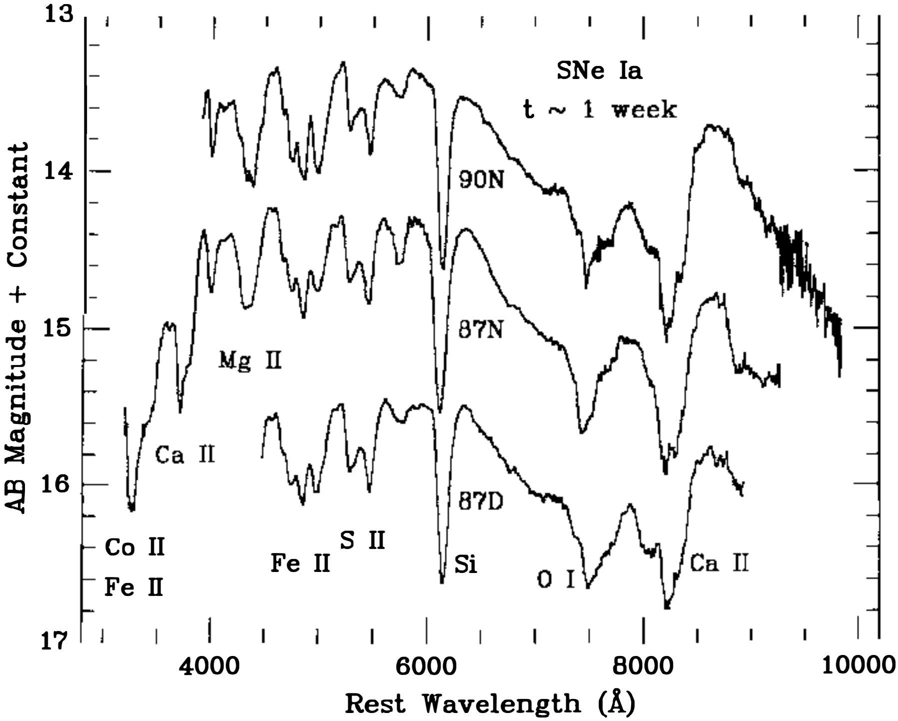

Figure 5 Spectra of three Type Ia supernovae, SN 1987D, SN 1987N, and SN 1990N, about one week after maximum. (Figure courtesy of Alex Filippenko)

whether this is due to smaller intrinsic scatter or to the blending is not yet clear. The physical significance of the velocity differences also is not yet clear. It is possible that SNe Ia arising from white dwarfs that ignite at various central densities might have different expansion velocities but similar absolute magnitudes (Canal et al 1991). Alternatively, the observed differences might be partly due to departures from spherical symmetry—either large-scale shape asymmetries as have been inferred for SN 1987A, or small-scale asymmetries associated with clumping of the ejected matter (Müller & Arnett 1986).

Differences in the velocities may persist into the late nebular phases. Features in the late spectra of SN 1986G appear to be significantly narrower than in SN 1981B (S. Benetti, private communication). As discussed in the next section, however, SN 1986G showed various other peculiarities, so the question of homogeneity in the late phases should be judged on the basis of more well behaved SNe Ia.

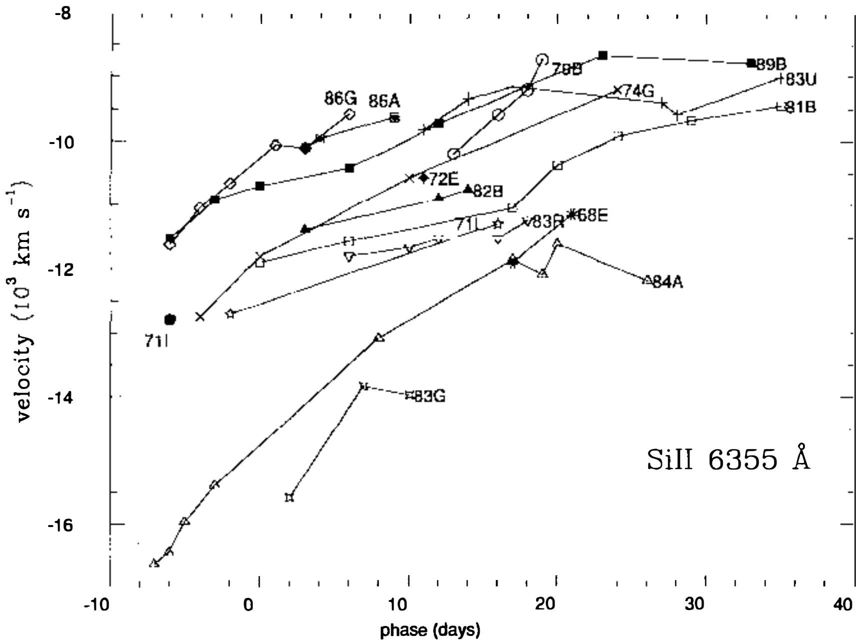

Figure 6 Blueshift of the Si II λ6355 Å absorption feature (expressed as velocity), plotted against time after blue maximum (Barbon et al 1990).

2.3 *Peculiar Supernovae*

With the removal of SN 1954A, SN 1962L, and SN 1964L from the ranks of "peculiar" SNe Ia, only a few with definite peculiarities (other than high or low expansion velocity) remain to be discussed.

SN 1885A in M31 occasionally is listed as a type Ia, but the classification is not established by the assembled descriptions of its optical spectrum or its reconstructed light curve (de Vaucouleurs & Corwin 1985). In fact, the spectrum seems to have lacked the red Si II absorption feature, the light curve too fast for SN Ia, and the color at maximum light was too red. Chevalier & Plait (1988) have proposed that SN 1885A was an off-center detonation of an accreted helium layer on an underlying carbon-oxygen white dwarf. Fesen et al (1989) have rediscovered SN 1885A in an image made with a narrow band filter centered on the wavelength of a strong Fe I absorption line.

SN 1980I, which occurred between NGC 4374, NGC 4387, and NGC 4406 in the Virgo cluster, appeared to have a nearly ordinary type Ia spectrum (Smith 1981) including the usual red Si II absorption, but with an unidentified absorption near 6680Å which has not been reported in the early spectra of any other SN Ia. In the absence of an identification the significance of the extra feature is not at all clear.

SN 1939B is sometimes listed as an SN Ia because it occurred in an elliptical galaxy, but no spectrum is available. Its blue light curve, as published by Minkowski (1964) and attributed to Baade, appears to have decayed extremely quickly (like that of SN 1885A), but it seems that Baade merely passed on to Minkowski the data of Shapley (1939) which were possibly of low quality. The steep rise and fast decline could be due to a single scale error in the photometric standard sequence. Indeed, a recent reanalysis of (some of) the original photographic plates has yielded a B light curve that follows the template fairly well (Leibundgut 1991a).

The optical spectrum of SN 1986G, which appeared in the dust lane of NGC 5128 (Centaurus A), revealed a low expansion velocity but was not otherwise peculiar. The ultraviolet spectrum near maximum light was, however, definitely different from other SNe Ia (Panagia & Gilmozzi 1991). The initial decline of the well observed UBV light curves (Phillips et al 1987) was somewhat fast for SNe Ia, although the later, slower decline had the conventional slope. The JHK light curves (Frogel et al 1987) matched those of neither SN Ia nor SN Ib. In all three infrared bands the somewhat undulant initial decline was too slow. In particular, the fast initial decline and the secondary maximum in the J band were missing. SN 1986G was very faint and red. It was 4 mag fainter than SN 1972E in NGC 5253, which is believed to be in the same group of galaxies, and with $(B-V)=0.96$ it is the reddest SN Ia observed so far. Rich (1987), Phillips et al (1987), and di Serego Alighieri & Pons (1987) have argued for a very high reddening, $E_{(\mathrm{B-V})} = 0.8$. Correcting for extinction with a standard value $R_{\mathrm{B}} = 4$ would make the maximum almost as bright as normal, but if a smaller value of R_{B} is appropriate (Section 2.5) then SN 1986G was intrinsically quite dim.

A striking example of a peculiar SN Ia is the very recent SN 1991T (Filippenko et al 1992a, Ruiz-Lapuente et al 1992, Jeffery et al 1992, Phillips et al 1992). The premaximum optical spectrum, which did not resemble that of any previous supernova, was dominated by lines of iron-group elements. Si II and Ca II features appeared near maximum light, but much more weakly than in ordinary SNe Ia. Only during the later phases, when the spectrum developed strong Fe II lines, did SN 1991T begin to closely resemble ordinary SNe Ia. In addition, SN 1991T may have been overluminous, although the issue is somewhat clouded by strong extinction as indicated by the strengths of the interstellar sodium lines and by the uncertain membership of the host galaxy, NGC 4527, to the Virgo cluster. Binggeli et al (1985) do not list NGC 4527 as a certain cluster member. For a Virgocentric model (Kraan-Korteweg 1985) the redshift of NGC 4527 formally puts it either in the cluster or at a distance 1.7 times farther, but the possibility that it is a foreground galaxy falling into the Virgo cluster cannot be ruled out. The blue maximum of SN 1991T occurred near April 29, with $m_B = 11.65$, brighter by 1.3σ than the mean in Table 2. The value of $(B-V)^0$ is 0.15. Assuming $(B-V)^{00} = -0.15$ and $R_B = 1.5$ (Section 2.5), then $m_B{}^{00}$ becomes 11.20, 3.2σ brighter than the mean. The spectroscopy and the possible overluminosity appear to be consistent with the hypothesis that the explosion of SN 1991T incinerated more of the ejected matter to nuclear statistical equilibrium than do ordinary SNe Ia.

SN 1991bg also failed to conform to the standard behavior of an SN Ia (Filippenko et al 1992b). It was intrinsically red and intrinsically subluminous. Its maximum-light and post-maximum spectra were perhaps more like those of SN Ia than like those of other types, but very peculiar. SN 1991bg is the first outburst in an elliptical galaxy to show definite peculiarities.

None of the peculiar supernovae discussed in this section necessarily pose serious challenges to the uniformity of SNe Ia. It is not yet clear whether they really represent variations on the standard SN Ia theme, or are the first examples of what will become recognized as distinct subclasses. In any case, with reliable data it is possible to weed them out.

2.4 *Absolute Magnitudes*

In this section we discuss only the uniformity of the absolute magnitudes, and defer the calibration to Section 3. We first discuss the absolute magnitude scatter without making any allowance for extinction in the parent galaxies.

In a Hubble diagram for SNe Ia, i.e. in a plot of log v_0 versus apparent magnitude, the scatter is due not only to intrinsic scatter in absolute magnitude but also to peculiar motions, to extinction in the parent galaxy, and to observational magnitude errors. Tammann & Leibundgut (1990) have considered a sample of 35 SNe Ia with reasonably well determined apparent magnitudes in galaxies with recession velocities larger than $v_{220} = 1000$ km s^{-1}. (The v_{220} values are corrected for a self-consistent Virgocentric velocity model having an infall velocity at the Local Group of 220 km s^{-1}.) The velocity limit is imposed to guard against strong influences of peculiar motions. The observed magnitude scatter about the Hubble line is $\sigma_B = 0.53$ mag. With reasonable assumptions about the influence of peculiar motions and observational errors, it was concluded that the true intrinsic scatter of the blue absolute magnitudes is less than $\sigma_B = 0.25$ mag.

Another way to check the absolute magnitude scatter is provided by galaxies that have produced *two* confirmed SNe Ia. The few such galaxies and their supernovae are listed in Table 1. The maximum magnitudes are taken from Hamuy et al (1991) and LTCC91. With no allowance for differences in parent-galaxy extinction, the mean magnitude differences of 0.43 and 0.08 mag must be considered as upper limits.

A third way to estimate the absolute magnitude scatter is provided by the nonpeculiar events that have occurred in the Virgo cluster (Tammann 1988, Capaccioli et al 1990). Table 2 lists the six SNe Ia that have sufficiently well determined B maxima (from LTCC91) and have occurred in certain member galaxies of the Virgo cluster [for a discussion of membership see Binggeli et al (1985) and Leibundgut & Tammann (1990)]. As Table 2 shows, the scatter of maximum magnitudes is $\sigma_{\rm B} = 0.36$ and $\sigma_{\rm V} = 0.29$ mag. Again, these values should be upper limits to the intrinsic scatter. It is worth noting that the least certain cluster member in Table 2 is NGC 4639, whose SN Ia was the faintest in the sample. A self-consistent Virgocentric model (Kraan-Korteweg 1985) allows the possibility that NGC 4639 ($v_0 = 864$ km s^{-1}) is at 1.25 times the Virgo distance, falling in from behind. If so, SN 1990N should be 0.48 mag fainter than the true Virgo SNe Ia, in agreement with observation. If NGC 4639 indeed is in the background, the scatter in Table 2 would be further reduced.

So far no corrections for parent-galaxy extinction have been applied, but there is reason and indeed good evidence that SNe Ia do suffer extinction in their parent (spiral) galaxies. Miller & Branch (1990, hereafter MB90) have

Table 1. Galaxies with two SNe Ia

Galaxy (1)	SN (2)	$m_{\rm B}^{0}$ (3)	$m_{\rm V}^{0}$ (4)	$(B-V)^{0}$ (5)	position (6)	$E(B-V)$ (7)	$A_{\rm B}$ (8)	$m_{\rm B}^{00}$ (9)	$m_{\rm V}^{0\bullet}$ (10)
NGC 1316	**1980N**	**12.49B**	**12.44V**	**0.05**	**outer**	**0.20**	**0.30**	**12.19**	**12.34**
	1981D	**12.59B**	**12.40V**	**0.19**	**inner**	**0.34**	**0.51**	**12.08**	**12.23**
NGC 3913	**1963J**	**13.1pg**	**12.5pv**	**0.6**	**inner**	**0.75**	**1.13**	**11.97**	**12.12**
	1979B	**12.5pg**	**12.4V**	**0.1**	**outer**	**0.25**	**0.38**	**12.12**	**12.27**
NGC 4753	**1965I**	**12.5B**	**12.7V**	**−0.2**	**outer**	**0**	**0**	**12.50**	**12.70**
	1983G	**13.1B**	**12.8V**	**0.3**	**inner**	**0.45**	**0.68**	**12.42**	**12.57**
	$\overline{\Delta m^{0}}$:	0.43	0.08					0.11	0.13

Table 2. SNe Ia in the Virgo Cluster

SN (1)	Galaxy (2)	m_B^o (3)	m_V^o (4)	$(B-V)^o$ (5)	$E(B-V)$ (6)	A_B (7)	m_B^{oo} (8)	m_V^{oo} (9)
1957B*	**N4374**	**11.7**	**11.8**	**-0.1**	**0.05**	**0.08**	**11.62**	**11.77**
1960F	**N4496**	**11.7**						
1961H*	**N4564**	**12.0**						
1981B	**N4536**	**12.0**	**12.0**	**0.0**	**0.15**	**0.23**	**11.77**	**11.92**
1984A	**N4419**	**12.45**	**12.30**	**0.15**	**0.30**	**0.45**	**12.00**	**12.15**
1990N	**N4639**	**12.65**	**12.57**	**0.08**	**0.23**	**0.35**	**12.30**	**12.45**
	mean:	12.08	12.17				11.92	12.07
	σ:	0.36	0.29				0.26	0.26

* Assumed to be type Ia because occurred in E galaxy.

shown that some SNe Ia in highly inclined spiral galaxies are exceptionally faint. They assume that the faint SNe Ia lie on the far side of the spiral and are strongly extinguished. After correcting these faint supernovae by $A_B = 0.8\sec(i)$ mag, they find an absolute magnitude scatter of $\sigma_B = 0.39$ mag. Excluding five objects that occurred in Am (or I0) galaxies for which the extinction correction cannot be applied, they obtain $\sigma_B = 0.27$ mag, which can be entirely explained by apparent magnitude, distance, and Galactic extinction errors.

SNe Ia in spiral galaxies tend on the whole to be fainter and redder than their counterparts in elliptical galaxies, where the effect of extinction is expected to be smaller (Tammann 1982). This trend is confirmed by the data in Tables 1 and 2. Of the three pairs of SNe Ia that occurred in one galaxy, the fainter supernova always lies closer to the center of the galaxy and is redder (cf Table 1, columns 3–6). The SNe Ia in Virgo ellipticals are brighter by 0.35 mag than those in Virgo spirals, and there is a rather clear dependence between luminosity and color (Table 2, columns 3–5). The fact that the scatter is larger in B than in V (Table 1, columns 3 and 4, and Table 2, columns 3 and 4) also is characteristic of the effect of extinction.

To correct the data in Tables 1 and 2 for parent-galaxy extinction, the intrinsic color $(B-V)^{00}$ at maximum and the value of R are needed. ($R_B = A_B/E_{B-V}$ and $R_V = R_B - 1$.) A value of $(B-V)^{00} = -0.15$ has been adopted in Section 2.1. Arguments for a best, although unconventional, value of $R_B = 1.5$ will be given in Section 2.5. With these choices the calculation of $m^{00}{}_B$ and $m_V{}^{00}$ in Tables 1 and 2 is straightforward. The resulting values of the magnitude scatter are $\sigma_B = \sigma_V = 0.26$ mag for the Virgo data, and for the small sample of SNe Ia pairs one finds a very low value of $\sigma_B \simeq \sigma_V = 0.12$ mag!

It is, of course, also appropriate to repeat the analysis of the SNe Ia Hubble diagram by including the extinction corrections. For this the $(B-V)^0$ color at maximum is needed. These are available for only 14 (out of 35) SNe Ia. The inclusion of the extinction correction reduces the scatter about the Hubble line from $\sigma_B = 0.53$ to 0.38 mag (LT92).

The independent ways to estimate the scatter, after extinction corrections, give values of $\sigma_B \simeq \sigma_V = 0.12$–$0.39$ mag. It must be stressed again that these values still contain effects of peculiar motions on the distances and the full observational errors of the magnitudes at maximum, which in most cases had to be interpolated or more frequently even extrapolated back in time by means of the adopted template light curves. In addition the adopted extinction corrections are anything but perfect.

From the above it appears unlikely that the true intrinsic luminosity scatter at B and V maxima could be larger than 0.25 mag. This makes SNe Ia the best standard candles known so far. If SNe Ia are such good standard candles at maximum light, and if, as argued in Section 2.1, they closely follow standard light and color curves, then they are standard candles at any given phase. This implies that their bolometric light curves are nearly identical and that their total energy output is the same to within 20%.

2.5 *Reddening and Extinction*

In principle the determination of $R = A/E_{B-V}$ requires the knowledge of the extinction and the color excess. Using cluster galaxies, Sandage (1976) has illustrated how standard candles can be used to determine R. Depending on the dust properties the value of R can change arbitrarily, but within the Galaxy variations of R appear to be marginal. Because of the width of the B and V passbands, R changes somewhat with spectral type. For example, if $R_B = 4.2$ for an O-type star, then $R_B = 4.9$ for an M-type star (Buser 1978). R. Buser (private communication) has calculated R_B from the well observed maximum-light spectrum of the type Ia SN 1981B (Branch et al 1983) on the assumption of a $1/\lambda$ extinction law and has found that R_B would be nearly the same as for a late O-type star.

In spite of this expectation there are clear indications that R is surprisingly small for SNe Ia (Joeever 1982; Tammann 1982, 1987; Capaccioli et al 1990). For instance, the observed color range of SNe Ia at maximum is at least 0.8 mag, which with $R_B = 4$ corresponds to a range in A_B of 3.2

mag, which is clearly not the case. The generally small effect of extinction can also be seen by comparing Equations 1 and 2 below.

As an illustration one may use the SNe Ia in the Virgo cluster (Table 2), two of which are in elliptical galaxies and four in spirals. The latter are on average 0.18 mag redder and 0.35 mag fainter. These admittedly incomplete data thus suggest $R_B = 2$. The three galaxies with two SNe Ia (Table 1) are all of spiral type. The fainter supernova in each galaxy is 0.35 mag redder and only 0.43 mag fainter on average than its bright counterpart. This suggests $R_B = 1.2$.

A more solid test for R is provided by the Hubble diagram for SNe Ia. A value of $R_B = 4$ would drastically increase the scatter about the Hubble line. Using 14 field SNe Ia with color information, LT92 have found from a least-squares solution $R = 0.7 \pm 0.1$ (which is unphysical), whereas the 17 SNe Ia with colors from the sample of MB90 give $R = 1.3 \pm 0.2$.

A powerful test for R is in principle provided by a plot of $(B-V)$ versus $(B-H)$ (LT92). While $(B-V)$ measures the color excess, $(B-H)$ measures essentially the extinction A_B, because A_H is small ($A_H = 0.11\ A_B$ (Elias et al 1985). So far only four SNe Ia have measured values of $(B-H)$ at $t_B = 0$ (L88), but they already require a low value of R. While these objects have a range in $(B-V)$ of 0.35 mag, the range in $(B-H)$ is only 0.16 mag, implying a range in A_B of 0.18 and $R = 0.5$.

The large extinction corrections one would obtain with $R_B = 4$ could be avoided by assuming a redder color $(B-V)$ for SNe Ia at maximum, i.e. $(B-V) = 0.0$ or 0.1 instead of -0.15. There are, however, too many SNe Ia observed with negative $(B-V)$ for this solution to be acceptable. The available observations strongly indicate a low value of R for SNe Ia. As a compromise value we adopt throughout this paper $R_B = 1.5$ and $R_V = 0.5$.

Why is R for SNe Ia so small? One might think of the following possibilities.

1. The dust in spiral galaxies could be drastically different from the Galactic dust—but the assumption that our galaxy is exceptional is unattractive.
2. Most of the extinction might be caused by circumstellar dust with very particular optical properties—but SNe Ia in elliptical galaxies tend to be blue and bright, which would mean that SNe Ia in spirals have dust shells while those in E galaxies do not.
3. The observed spread of $(B-V)$ at maximum might be inflated by observational errors—but if, in fact, $R_B = 4$, the consequence would be that the observed color range of about 0.8 mag would have to be compressed to 0.3 mag or less. Although observed supernova colors, particularly the older ones, are notoriously unreliable, they are probably not this bad.

4. The assumption of a unique intrinsic $(B-V)$ for all SNe Ia could be invalid—but if the observed color differences are intrinsic the absolute magnitude scatter would be expected to be even larger than if the color range was due to extinction with $R_B = 4$. Temperature and absolute magnitude changes in a blackbody having $T \gtrsim 10^4$ K mimic a value $R_B \gtrsim 6$.

The very small value of R required by the available SN Ia data remains a mystery awaiting future resolution.

Van den Bergh & Pazder (1992), Della Valle & Panagia (1992), and van den Bergh & Pierce (1992) recently have investigated the dispersion in the SN Ia absolute magnitudes on the assumptions of 1. a unique SN Ia color at maximum, 2. error-free observed colors, and 3. a unique value of R. The large extinction corrections applied by these authors produce a larger dispersion in absolute magnitude than we have found here. However, the large extinction corrections also have the dubious property of producing superluminous SNe Ia, while none were present before extinction corrections were applied. Rather than putting all of the "blame" on the absolute-magnitude dispersion, one should consider simultaneously the possibilities of a range in intrinsic color, errors in the colors, and a range in the value of R.

3. ABSOLUTE MAGNITUDE

3.1 *Historical Galactic Supernovae*

Among the historical Galactic supernovae, four candidate type Ia events (and their remnants) are SN 185 (RCW 86), SN 1006 (PKS 1459-41), Tycho's supernova of 1572 (3C 10), and Kepler's of 1604 (3C 358). To determine their absolute magnitudes we need to know distances, apparent magnitudes, and the interstellar extinction. Distances can be inferred only from the remnants, and apparent magnitudes only from contemporary records of the supernova brightness. The interstellar extinction can be estimated either from the remnants, from the extinction of field stars in the directions of the remnants, or from contemporary descriptions of the supernova colors.

Strom (1988) attempted to put the distances to the four remnants on a self-consistent absolute scale. The known ages and measured angular diameters of the remnants, together with the assumption that they are in the adiabatic phase of their evolution, were first used to determine relative distances to 10% accuracy, and then the scale was fixed to within 20% by considering various determinations of the absolute distances to individual remnants. In Table 3 we list Strom's estimates of the distances and their uncertainties. Distance determinations not considered by Strom (1988) tend to suggest that the remnant distance scale may need to be *increased*, making the absolute magnitude brighter than in Table 3. Westerlund (1969) determined a distance of 2.5 kpc for the OB association near RCW 86 [but no distance estimates for SN 185 have any basis *if*, as suggested by Huang & Moriarty-Schieven (1987), RCW 86 is not the remnant of SN 185]. From a new proper-motion study of PKS 1459-41 Long et al (1988) derive a most probable distance range for SN 1006 of 2.1–2.7 kpc, Fesen et al (1989) find a range of 1.5–3.3 kpc on the basis of the background Schweizer-Middleditch star, and Smith et al (1991) obtain 1.4–2.8 kpc from a comparison of proper motions and the shock velocity from the Hα emission line, all to be compared to 1.4 kpc in Table 3. Smith et al (1991) also obtain a range of 1.5–3.1 kpc for Tycho. From a bow shock model Bandiera (1987) estimates 4.5 ± 1.0 kpc for Kepler, but Blair et al (1991) estimate 2.9 ± 0.4 kpc from the shock emission method. Van den Bergh & Tammann (1991) note that the surprisingly high local supernova frequency that is implied by the historical events could be reduced by increasing the remnant distance scale, again making the absolute magnitudes in Table 3, and their mean, brighter.

In Table 3 we list apparent magnitudes and associated uncertainties from Clark & Stephenson (1977, 1982). Quite discordant estimates can be found in the literature for SN 185 ($m_v = -6$; Huang & Moriarty-Schieven 1987) and for SN 1006 ($m_v = -6$; Pskovskii 1978). Other estimates for SN 1572 include $m_v = -4.5 \pm 0.2$ (Pskovskii 1978) and $m_v = -4.1 \pm 0.15$

Table 3. Possible SNe I a in the Galaxy

SN	D (kpc)	μ_o	m_V	A_V	m_V^o
185	1.2±0.2	10.4±0.4	−8±2	1.8±0.3	−20.2±2.1
1006	1.4±0.3	10.7±0.4	−9±1	0.3±0.3	−20.0±1.1
1572	2.5±0.5	12.0±0.4	−4.0±0.3	2.0±0.3 (Ia)	−18.0±0.6 (Ia)
				0.5±0.3 (Ib)	−16.5±0.6 (Ib)
1604	4.2±0.8	13.1±0.4	−3.0±0.3	3.6±0.3 (Ia)	−19.7±0.6 (Ia)
				2.1±0.3 (Ib)	−18.2±0.6 (Ib)
				Adopted:	−19.7±0.6 (Ia)

(de Vaucouleurs 1985), and for SN 1604 $m_v = -3.5 \pm 0.2$ (Pskovskii 1978) and $m_v = -2.5$ (L88).

For the extinction of SN 185 we use $A_v = 1.8 \pm 0.3$. Leibowitz & Danziger (1983) derived $A_v = 1.7$ from the Balmer decrement in the RCW 86 remnant and Westerlund (1969) found $A_v = 2.0$ for the OB association. For SN 1006 we use $A_v = 0.3 \pm 0.3$ on the basis of $A_v = 0.46$ from the Balmer decrement in the remnant (Lasker 1981) and $A_v = 0.28$ for the total Galactic extinction in that direction (Burstein & Heiles 1978). The extinction of SN 1572 and SN 1604 can be estimated from their colors, but the result depends on whether they are assumed to have been intrinsically blue like types Ia and II–linear (II–L), with an intrinsic $B-V \simeq 0.0$ at maximum light, or redder like type Ib and Ic. The SN 1572 and SN 1604 light-curve shapes are consistent with all three types (Doggett & Branch 1985). For the intrinsically blue case, we use $A_v = 2.0 \pm 0.3$ for SN 1572 [de Vaucouleurs (1985) derived $A_v = 1.95 \pm 0.1$] and $A_v = 3.6 \pm 0.5$ for SN 1604 [Pskovskii (1978) found $A_v = 3.81 \pm 0.12$, Bandiera & van den Bergh (1991) prefer $A_v = 3.4 \pm 0.9$]. If SN 1572 and/or SN 1604 were intrinsically as red as SNe Ib/Ic, which typically are 0.5 mag redder in $B-V$ than SNe Ia (L88, Wheeler & Harkness 1990), then the visual extinction derived from their colors would be about 1.5 mag lower, as indicated in Table 3. Both the high and low values of extinction from the colors of SN 1604 are within the range of independent estimates [e.g. $A_v = 2.2$ by van den Bergh & Kamper (1977) from foreground field stars, $A_v = 3.5$ by Danziger & Goss (1980), and $A_v = 2.7 \pm 0.3$ by Blair et al (1991) from the Balmer decrement in the remnant]. Field stars in the direction of SN 1572 suggest that, for a distance of 2.5 kpc, A_v may be in the range 1–3 mag (Brodskaya & Grigor'eva 1962), which favors the higher extinction value for SN 1572.

Our tentative interpretation of the absolute magnitudes in Table 3 is that SN 1572 was either a type Ib (Green 1986, Strom 1988), a type II–L, or some other kind of event that is fainter than type Ia; and that SN 185, SN 1006, and SN 1604 were type Ia. The only absolute magnitude that can possibly be considered to be quantitatively reliable is that of Kepler, $M_v^{00} = -19.7 \pm 0.6$, and this relies on Kepler having been a highly extinguished type Ia.

3.2 *SNe Ia in Nearby Galaxies*

No supernova known to be of type Ia has been observed in a galaxy in which cepheids have been reached, but four SNe Ia have appeared in galaxies within just a few megaparsecs. SN 1937C in IC 4182 and SN 1895B and SN 1972E in NGC 5253 were observationally normal and only slightly extinguished, and are suitable calibrators provided their distances can be established. SN 1986G in NGC 5128 was both observationally peculiar and highly reddened (Section 2.3), and cannot be trusted as a calibrator (Section 2.3).

In Table 4 we adopt a distance modulus $\mu_0 = 28.2 \pm 0.3$ (4.4 ± 0.6 Mpc) for IC 4182, as determined by Sandage & Tammann (1982) on the assumption that its three brightest red stars have a mean value of $M_v^{00} = -7.72$. The spiral features and associations of IC 4182 made the identification of its member stars quite straightforward and photometry of the brightest stars was particularly easy because the surface brightness of the background disk of IC 4182 is low. The main uncertainty regarding the distance determination is whether the red-star luminosity function in IC 4182 is filled. Sandage & Tammann also determined the distance to NGC 4214, the parent galaxy of SN 1954A, but this supernova is now regarded to have been of type Ib (Branch 1990). A shorter distance to IC 4182 has been derived by Pierce et al (1992) from *I*- and *K*-band photometry of its brightest red stars. Observations of cepheids in IC 4182 by Sandage and others with the Hubble Space Telescope will clarify the discrepancy.

Van den Bergh (1989) reviews the distance to the NGC 5128/5236 group, which he takes to include NGC 5253. Based on the planetary nebula distance to NGC 5128 relative to M31 (Jacoby et al 1988), van den Bergh recommends $\mu_0 = 27.95 \pm 0.13$ (3.9 ± 0.2 Mpc) for NGC 5128 itself, and he concludes that most of the group members have distances in the range 3.2–4.6 Mpc. We adopt this recommendation and use 3.9 ± 0.7 Mpc for NGC 5253 in Table 4.

Supernova apparent magnitudes, corrected for Galactic extinction, are taken from LTCC91. For SN 1937C and SN 1895B we have converted from m_{pg} to B magnitudes using $B = m_{pg} + 0.26$ (Leibundgut & Tammann 1990).

Our interpretation of the absolute magnitudes in Table 4 is that all three supernovae were normal SN Ia. The excessively high brightness of SN

Table 4. SNe Ia in nearby galaxies

SN	Galaxy	D (Mpc)	μ_o	m_B^o	M_B^o	A_B	M_B^{oo}
1937C	**IC 4182**	**4.4±0.6**	**28.2±0.3**	**8.76±0.2**	**−19.4±0.4**	**0.54**	**−19.9**
1895B	**NGC 5253**	**3.9±0.7**	**27.95±0.4**	**7.17±0.5**	**−19.8±0.5**	**?**	**−20.:**
1972E	**NGC 5253**	**3.9±0.7**	**27.95±0.4**	**8.45±0.2**	**−19.5±0.5**	**0.15**	**−19.7**

Adopted: -19.8 ± 0.3

1895B is probably due to the ancient photometry (cf Cadonau & Leibundgut 1990) and should be given low weight. We therefore adopt $M_B{}^0 = -19.6 \pm 0.3$. This value may still be affected by some extinction in the parent galaxies. From the precepts set out in Section 2.5 and the colors given by LTCC91 we have estimated the parent-galaxy extinction in Table 4. No colors are available for SN 1895B. The fully corrected absolute magnitudes $M_B{}^{00}$ are given in Table 4. From them we adopt as the best value $M_B{}^{00} = -19.8 \pm 0.3$.

3.3 *SNe Ia in the Virgo Cluster*

The distance to the Virgo cluster has been reviewed recently by van den Bergh (1989), who recommends $D = 20.1 \pm 1.5$ Mpc, by Sandage & Tammann (1990), who give 21.9 ± 0.9 Mpc, and by Jacoby et al (1992), who find a weighted average of seven methods of 16.0 ± 1.7 Mpc and an unweighted average of 17.6 ± 2.2 Mpc. In these reviews the distance depends to some extent on SNe Ia. From six determinations of the Virgo distance that are independent of SNe Ia—based on globular clusters, novae, type II supernovae, the $D_n - \sigma$ relation, galactic diameters, and the Tully-Fisher method—Leibundgut & Tammann (1990) find 21.9 ± 0.9 Mpc. Here we will use 20.0 ± 3 Mpc ($\mu_0 = 31.51 \pm 0.33$). Combined with a well determined mean $m_B{}^{00} = 11.92 \pm 0.11$ for six SNe Ia in the Virgo cluster (Table 2), the adopted distance gives an extinction-corrected value $M_B{}^{00} = -19.6 \pm 0.4$.

3.4 *Thermal Emission*

The recognition around 1970 that supernovae near maximum light emit a thermal spectrum from a photosphere (Branch 1990 and references therein) opened up a new way to estimate extragalactic distances that is independent of all intermediate distance calibrations. The observed flux from a supernova is compared to an absolute flux that is calculated on the basis of the radius and temperature of the photosphere. The radius is the product of the instantaneous velocity at the photosphere, inferred from blueshifts of spectral features, and the time elapsed sincc the explosion. The explosion time can be derived, in the spirit of Baade's (1926) method for variable stars, by considering more than one time of observation (Branch & Patchett 1973) or more directly from an extrapolation of the observed premaximum light curve (Arnett 1982a).

A thorough examination of the broadband photometry of SNe Ia (L88) reveals that although the energy distribution of SNe Ia is distinctly non-Planckian during most phases of their evolution, at about 25 days after maximum light the energy distribution from the U band (0.36 μ) to the K band (2.1 μ) resembles that of a blackbody having a temperature of 5500 ± 500 K. At that phase most SNe Ia exhibit a blueshift of the red Si

II absorption feature within the range 9500 ± 500 km s^{-1} (Branch et al 1988, Barbon et al 1990), which we take to be the velocity at the photosphere. With a rise time to maximum light of 19 ± 2 days, the time since the explosion is 44 days and the radius becomes $3.6 \pm 0.4 \times 10^{15}$ cm. On the assumption of blackbody emissivity at 5500 ± 500 K, the absolute blue magnitude is then $M_B = -17.9 \pm 0.7$. The blue light curve drops by 2.2 mag during the first 25 days after maximum light (L88), so the corresponding absolute magnitude at maximum is $M_B = -20.1 \pm 0.7$. This very simple estimate constitutes an appeal to equilibrium and makes no allowance for the effects of the extension of the atmosphere and the nongrey, scattering-dominated nature of the opacity. Jeffery et al (1992) recently have used a more detailed form of the thermal expansion approach to estimate a peak $M_B = -19.8$ for SN 1990N. Until detailed model atmospheres based on accurate opacities are developed and applied to SNe Ia, however, the external error in the thermal-emission estimate will not be known.

3.5 *Nickel-Cobalt Radioactivity*

The recognition around 1980 that SN Ia light curves are powered by the radioactive decay of ^{56}Ni and ^{56}Co (Woosley & Weaver 1986 and references therein) presented another new opportunity to derive distances to SNe Ia. An approximate but useful early rule was provided by Arnett (1982b), who predicted on the basis of an analytical model and reasonable asumptions that the SN Ia maximum luminosity is equal to the instantaneous decay luminosity of the nickel and cobalt. In this case the maximum luminosity can be expressed in terms of just the ejected nickel mass and the rise time to maximum light. Owing to uncertainties in the physics of the nuclear burning front that explodes the white dwarf (e.g. Woosley 1990) the ejected nickel mass cannot yet be predicted accurately by theory. As outlined by Sutherland & Wheeler (1984) and Arnett et al (1985), however, limits to the nickel mass can be inferred from the SN Ia spectra and light curves. Doppler shifts in the spectrum and the decay rate of the light curve constrain the explosion kinetic energy. Assuming that the white dwarf disrupts completely, the nuclear fusion energy must be the sum of the kinetic energy and the net binding energy of the immediate preexplosion white dwarf. Taking into account the fraction of the nuclear energy that comes from the synthesis of isotopes other than ^{56}Ni, Arnett et al (1985) used this line of reasoning to argue that the nickel mass must be in the range 0.4–1.4 $M_{\odot}$, with a most likely value of 0.6 $M_{\odot}$.

The effect of recent observational and theoretical developments on the radioactivity method have been reviewed by Branch (1992). On the assumptions that SNe Ia are the complete disruptions of carbon-oxygen white dwarfs near the Chandrasekhar mass, that their light curves are powered entirely by nickel-cobalt radioactivity, and that scatter in their maximum luminosities can be disregarded, the absolute blue magnitude is estimated. Combining a rise time to maximum blue and bolometric light of 19 ± 2 days, an ejected nickel mass $M_{Ni} = 0.6(+0.2, -0.1)$ $M_{\odot}$, a ratio of maximum bolometric luminosity to instantaneous radioactivity luminosity of 1.2 ± 0.2, as found in light-curve calculations with realistic opacities (Harkness 1991, Höflich et al 1991), and a bolometric correction $M_B - M_{bol} = -0.28$ obtained from an observed maximum-light flux distribution, gives $M_B = -19.4 \pm 0.3$. Possibilities of external error include the ejection of less than a Chandrsekhar mass (Shigeyama et al 1992) and effects associated with shape asymmetries such as have been detected in SN 1987A or with small-scale clumping of ejected matter (Müller & Arnett 1986).

3.6 *Summary of Calibrations*

The adopted values of M_B^{00} from the various calibration methods are listed together in Table 5. Not one of the individual values can be regarded to be free of the possibility of serious external error, but the mutual consistency of these independent estimates is encouraging. Assigning double weight to the absolute magnitudes obtained from the Virgo cluster SNe Ia and from the radioactivity method, and disregarding the thermal emission estimate on the grounds that the external error is unknown but may be large, we obtain as the best current estimate $M_B^{00} = -19.6 \pm 0.2$.

4. PROSPECTS FOR COSMOLOGY

With an absolute-magnitude scatter of no more than 0.25 mag, SNe Ia can be expected to play an increasingly important role in cosmology. A shadow may be cast upon them because of the need to apply an extinction

Table 5. Summary of SN Ia absolute magnitude calibrations

Method	M_B^{00}	Weight
Historical Galactic supernovae	-19.7 ± 0.6	1
SNe Ia in nearby galaxies	-19.8 ± 0.3	1
SNe Ia in the Virgo Cluster	-19.6 ± 0.4	2
Thermal emission	-20.1 ± 0.7	0
Nickel–Cobalt Radioactivity	-19.4 ± 0.4	2
Adopted:	-19.6 ± 0.2	

correction that is unusual and not understood (Section 2.5), but this is not a fundamental problem because their average extinction is apparently quite modest, and even without extinction corrections their scatter is less than 0.3 mag. Moreover, at large distances the highly extinguished SNe Ia will be discriminated against observationally. The selection against underluminous supernovae is easy to see in the Asiago Supernova Catalogue (Barbon et al 89); almost all classified supernova well outside the local supercluster are SNe Ia. For this reason, the contamination of type Ia samples by types II, Ib, and Ic can be controlled. SNe Ib, SNe Ic, and almost all SNe II are considerably less luminous than SNe Ia; SNe Ib and SNe Ic are considerably redder; and of course all are distinguishable spectroscopically. Likewise, unusual supernovae such as SN 1885A, SN 1991bg, and SN 1986G tend to be underluminous and can be controlled. Overluminous supernovae such as SN 1991T (if in or behind the Virgo cluster) may pose more of a problem, because even if rare their frequency will be artificially increased in flux-limited samples. Spectroscopic information may be needed to weed them out.

One way to protect remote SN Ia samples against interlopers and extinction may be to concentrate on elliptical galaxies. So far, all classified supernovae in elliptical galaxies except SN 1991bg (and possibly, but not probably, SN 1939B; Section 2.3) have been ordinary SNe Ia. The disadvantage that elliptical galaxies are slow supernova producers (Tammann 1991a) may be offset by the fact that supernova searches at high redshift will be conducted in very rich clusters of galaxies where the fraction of galaxies that are elliptical is exceptionally high.

The future role of SNe Ia in cosmology will be illustrated here by four examples.

4.1 *Peculiar Velocities and Streaming Motions*

The detailed mapping of the cosmic velocity field and the reliable measurement of deviations from a pure Hubble flow are prerequisites for our understanding of the large-scale structure of the universe. The determination of peculiar velocities requires only *relative* distances. The absolute peculiar velocity (in the radial direction as seen by the observer) between any two standard candles can be determined from their apparent magnitudes and recession velocities. The error of the resulting peculiar velocities depends only on how good the standard candles are. If SNe Ia have a luminosity scatter of only 0.2 mag, peculiar velocities can be measured to 10% of the recession velocity. For instance, at 2000 km s^{-1} the error in the peculiar motion will amount to 200 km s^{-1}. If n SNe Ia are available in a galaxy or cluster the error will decrease by $n^{1/2}$.

A first attempt to test the reality of large-scale streaming motions using

SNe Ia has been made by Miller & Branch (1992). They find that the adoption of a Virgocentric infall model strikingly reduces the luminosity scatter of their sample of SNe Ia in field galaxies from $\sigma_B = 0.63$ to 0.32 mag. Additional allowance for the influence of a Great Attractor or *IRAS* clusters does not give a smaller scatter. This is not surprising because the photometry, especially of the older SNe Ia, is too inaccurate and because the sample of 34 SNe Ia has a median velocity of only 1500 km s^{-1}—too low to be sensitive to streaming motions beyond the Virgo complex. The result is in accordance with that of Jerjen & Tammann (1992), who did not find the local microwave dipole motion to be reflected in the data of an independently defined sample of SNe Ia. Again, the photometry is insufficient and the sample is too near to provide a sensitive test.

These mainly negative results will drastically change, no doubt, when several dozen well observed SNe Ia with recession velocities in the range 4000–6000 km s^{-1} become available.

4.2 *The Hubble Constant*

From the Hubble diagram for their sample of 35 SNe Ia, Tammann & Leibundgut (1990) inferred

$$M_B = -18.13 \pm 0.09 + 5 \log h, \qquad 1.$$

while from a sample of 40 SNe Ia MB90 found

$$M_B = -18.36 \pm 0.04 + 5 \log h, \qquad 2.$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The difference is primarily due to the fact that Tammann & Leibundgut did not apply any corrections for parent-galaxy extinction while MB90 did apply a simple inclination dependent correction procedure to the apparently faint SNe Ia in disk galaxies. For nine SNe Ia in elliptical galaxies MB90 found

$$M_B = -18.33 \pm 0.11 + 5 \log h. \qquad 3.$$

With $M_B{}^{00} = -19.6 \pm 0.2$ (Section 3.6), Equation 3 gives $H_0 = 56 \pm 6$ km s^{-1} Mpc^{-1}. This result does not depend on parent-galaxy extinction, but it does depend on the absolute-magnitude calibration, and because the nine SNe Ia are in galaxies having a median recessional velocity of only about 4000 km s^{-1} the result is not guaranteed to be free of local streaming motions.

SNe Ia also can be used to obtain a solution for the cosmic (>4000 km s^{-1}) value of H_0, however, through the Virgo cluster. The cosmic velocity of the cluster, i.e. the velocity freed of all local effects, can be inferred from much more distant clusters whose distance relative to the Virgo cluster is known (Sandage & Tammann 1990). It can be shown that the distant clusters with a median velocity of 6400 km s^{-1} do not partake of the local microwave dipole motion and that they therefore constitute, to a good approximation, a Machian frame (Jerjen & Tammann 1992). Within this cosmic frame the Virgo recession velocity becomes 1182 ± 19 km s^{-1}. Now excluding (to avoid circularity) the Virgo-cluster calibration of SNe Ia in Section 3.6, we have $M_B = -19.6 \pm 0.3$. With $m_B^{00} = 11.92 \pm 0.09$ for six Virgo SNe Ia (Table 2), we have a Virgo distance modulus $\mu_0 = 31.54 \pm 0.31$, a Virgo distance of 20.3 ± 2.9 Mpc, and a cosmic value of $H_0 = 58 \pm 8$ km s^{-1} Mpc^{-1}. This result for the Virgo distance is independently supported by globular clusters, novae, the $D_n - \sigma$ and Tully-Fisher relations, and the requirement that our Galaxy and M31 not be oversized. These methods give a Virgo distance modulus of 31.64 ± 0.09 (Tammann 1991b) which, if taken at face value, suggest that 1. the low extinction of SNe Ia adopted in Section 2.5 cannot be increased without increasing the difference between the Virgo distances from SNe Ia and from other evidence, and 2. the formal difference of -0.10 ± 0.32 between the Virgo moduli from SNe Ia and from external evidence represents an external error to the SN Ia luminosity calibration of $M = -19.6$ adopted in Section 3.6. The agreement within the errors between H_0 at $\sim$4000 km s^{-1} and its cosmic value is very satisfactory, and is consistent with the linearity of the expansion over a wide range of scales (Sandage 1992).

It should perhaps be noted that the determination of distances at *large* redshift would not yield the present value of the expansion rate, H_0, but the value H_t at the time of emission, which is a function of H_0 and q_0. The determination of q_0 from SNe Ia, independent of H_0, will be discussed in Section 4.4.

The prospects for firmly establishing the value of H_0 from SNe Ia are excellent. The historical Galactic supernovae may never be more than an interesting consistency check, but the calibration via IC 4182 and eventually the Virgo cluster can be checked by means of cepheids. Advances in both observation and modeling of SNe Ia will allow the thermal emission and radioactivity methods to fuse into one complete physical picture that will demand a particular maximum luminosity for each event. The accuracy may then be limited primarily by uncertainties associated with departures from spherical symmetry.

4.3 *Testing the Nature of the Redshift*

The extragalactic redshift generally is assumed to be caused by a universal expansion, but direct tests are few in number and difficult to execute. Hubble (1953) himself kept open the possibility that the universe does not expand. Two tests are known, one of which is best performed with SNe Ia.

1. The Tolman test. In an expanding universe, surface brightness varies as $(1+z)^{-4}$(Tolman 1930, 1934; Kristian & Sachs 1966). This holds for galaxies, provided that surface brightness within a metric diameter is used. Sandage & Perelmuter (1991) recently have applied the test using surface photometry and Petrosian diameters (Petrosian 1976) for the several brightest galaxies in 56 nearby clusters and groups of galaxies. After the application of reduction procedures to remove observational biases, the data appear to support the reality of the expansion, but Sandage & Perelmuter give reasons to view this result with caution.
2. The time dilation test. In an expanding universe the observed rate of a distant clock is slowed down by a factor of $(1+z)$. The standard light curves of SNe Ia therefore are broadened by this factor (Wilson 1939, Rust 1974, de Vaucouleurs & Pence 1976). This provides, at least in principle, a very simple test for the nature of the redshifts of SNe Ia and their parent galaxies. At a redshift $z = 0.3$, for instance, the inflection point of the B light curve at $t_B = 44$ days should be delayed by 13 days.

A practical complication is the wavelength dependence of the standard light curves. It has been proposed, therefore, to measure the light curve of the supernova at the rest wavelength of the B band in the frame of the parent galaxy (Tammann 1979). An alternative solution is to use a K-correction to predict the shape of the standard light curve in, for instance, the V band, at a redshift z. Because of the pronounced color evolution of SNe Ia (Figure 4) the K-correction is strongly variable, resulting in a deformation of the light curve. Using information on the SN Ia spectral energy distribution at various phases, Leibundgut (1990) has calculated the expected standard light curves in the V band for discrete values of z.

Heroic search efforts have so far provided one supernova that may be suitable for the test: SN 1988U at $z = 0.28$ (Hansen et al 1989, Nørgaard-Nielsen et al 1989). The somewhat fragmentary V photometry of SN 1988U (not certain to be of Type Ia) indicates an initial decline rate of 0.10 mag per day, which is nearer to the rate of 0.12 mag per day that is predicted when the $(1+z)$ factor is included than to the rate of 0.15 mag per day predicted for a stationary universe (Leibundgut 1991b).

A few confirmed SNe Ia with good photometry at $z \simeq 0.3$ should provide a definitive test of the time dilation in the near future.

4.4 *The Deceleration Parameter*

For the greatest problem of observational cosmology during the coming decades—the determination of the deceleration parameter, q_0,—SNe Ia will play an important and perhaps decisive role. The route to q_0 has been mapped out by Sandage (1961). At that time he proposed first-ranked cluster galaxies as standard candles. They have the advantage of extremely high luminosity but they suffer from luminosity and dynamical evolution. SNe Ia are about 3.7 mag fainter in V than first-ranked cluster galaxies (at $z = 0$), but they are expected to be much less subject to evolutionary effects. They also offer the important advantages of being point sources, thus greatly facilitating the photometry, and of being very good standard candles with little luminosity scatter at maximum.

A strategy to determine q_0 from SNe Ia as standard candles has been outlined by Tammann (1979). Including a K-correction, Leibundgut (1990) has calculated m_v for SNe Ia as a function of z for the cases $q_0 = 0$ and $q_0 = 1/2$. At redshifts of $z = 0.3$ and 0.5 the SNe Ia will be brighter in a critical universe than in an empty one by 0.2 and 0.3 mag, respectively. Even if the intrinsic scatter of SNe Ia is as large as 0.25 mag, ten SNe Ia at $z = 0.3$ (and $m_v \simeq 21.4$) would distinguish the two cases at the 3.2σ level (cf Burns et al 1990). At $z = 0.5$ the distinction between the two cases would be even easier, but here the SNe Ia would be fainter by about 1.7 mag. This is because the K-correction in the V band is negative for $z = 0.3$ but then increases rapidly with increasing z. Thus, if q_0 is to be determined at higher redshifts, SNe Ia should be observed redwards of the V band.

A determination of q_0, or a combination of q_0 and Λ if the cosmological constant is permitted to be nonzero (Sandage & Tammann 1984), by means of SNe Ia appears to be feasible. In any case, among the methods proposed so far, SNe Ia offer the best hope.

5. CONCLUSIONS

SNe Ia appear to be photometrically quite homogeneous, generally following standard light-curve shapes to within 0.1 mag and having an absolute magnitude scatter of no more than 0.25 mag. The available data favors a low value of the ratio of extinction to color excess, $R_B \simeq 1.5$, which is unexpected and not understood. The spectral features closely follow a standard pattern of evolution, but real differences in the blueshifts of spectral features occur and their physical significance is not yet clear.

With advances in observation and modeling, SNe Ia are certain to become increasingly valuable as extragalactic distance indicators. Relatively nearby SNe Ia ($z \lesssim 0.1$) will be used to probe departures from pure Hubble flow and to measure the value of the Hubble constant. More remote SNe Ia ($z \lesssim 1$) will be used to test the reality of the universal expansion and measure the deceleration parameter.

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