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VOLUME-LIMITED SAMPLES OF SUPERNOVAE

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ABSTRACT

I have constructed two volume-limited samples of supernovae; the first of extragalactic events with a distance modulus less than 29 mag ($H_0 = 75$), and the second of Galactic supernovae from the last millennium within 4 kpc. Out of 33 total events in these samples, a surprising number are either greatly subluminous or possessing highly unusual spectroscopic or photometric properties. My conclusions are as follows. (1) A significant fraction (probably the majority) of Type Ia events are not standard candles, with most being subluminous by from 1 to 6 mag. (2) The luminosity function of Type II events is roughly flat from M_B equal to -18.3 to -15.2 and then rises sharply to lower brightnesses with events as faint as -11.8. (3) Type Ia, Ib, and II events constitute 24%, 14%, and 62% of the samples. (4) One-third of all supernovae cannot be placed in the traditional classification scheme due to unusual properties. (5) A deep supernova search to $M_B = -12$ will discover subluminous events that can serve as well-observed prototypes of new explosion mechanisms.

Subject headings: stars: fundamental parameters — supernovae: general

1. INTRODUCTION

The demographics of supernova eruptions have broad implications throughout modern astrophysics. An excellent review is presented in van den Bergh & Tammann (1991). All previous studies have been (implicitly or explicitly) samples limited by apparent magnitude.

Magnitude-limited samples of supernovae display a simple morphology. Virtually all events fit neatly into the categories of Types Ia, Ib, IIP, and IIL (Doggett & Branch 1985), with the Type Ia events being remarkably good standard candles (Branch & Tammann 1992; Branch & Miller 1993; Rood 1994). In such samples, the Type II events have an average $M_B = -17.2$ ($H_0 = 50$) with an rms scatter of 1.2 mag (Tammann & Schroder 1990, hereafter T&S).

Unfortunately, the use of (apparent) magnitude-limited samples strongly biases the statistics against low-luminosity events. The Asiago and Crimea supernova searches have been active since the 1960s with discovery limiting magnitudes of roughly 16.0 to 17.0 (Cappellara et al. 1993). The visual search of Evans has a completeness limit of 14.5 (van den Bergh, McClure, & Evans 1987). The Palomar 18 inch (46 cm) Schmidt searches by Zwicky have a limiting magnitude of 16.5–17.0 (Filippenko 1988). Serendipitous discovery likely has a brighter limit. These limits must be substantially brighter for events in the galaxy cores or even in bright H II regions (Filippenko 1988).

In this paper, I will report on the demographics of two volume-limited samples for which the effects of discovery thresholds are minimized.

2. NEARBY GALAXIES

2.1. *Sample*

One volume-limited sample can be constructed for supernovae outside our own Milky Way. But what should the limiting distance be? If the cutoff is too close, then few events will be included and the study would be inconclusive for poor statistics. If the cutoff is too far, then the faint end of the luminosity function will be sharply discriminated against in magnitude-limited searches. I have adopted a cutoff distance of 6.3 Mpc (a distance modulus, μ, of 29 mag). This yielded 27 supernovae, a number which is adequate to make broad conclusions. Also, for searches that reach 15 mag, the cutoff distance corresponds to a limiting absolute magnitude -14, which is less luminous than expected for most supernovae.

This volume-limited sample was constructed from supernova lists in Barbon, Cappellaro, & Turatto (1989), van den Bergh (1994b), and from other papers found in literature searches. The procedure was to look up the distance modulus in Tully (1988) for any host galaxy with a radial velocity less than 1000 km s^{-1}. The distances in Tully's Nearby Galaxy Catalog are based on a Hubble constant of 75 km s^{-1} Mpc^{-1}. This volume-limited sample of supernovae is presented in Table 1.

The events are broken into three categories, based on the usual supernova types Ia, Ib, and II. (In § 5, I will argue that these categories are inadequate, although I will still use them since they are generally employed and since I have no better alternative scheme.) Not all type assignments are certain. For example, the type of SN 1939C was apparently based on spectral evidence (Zwicky & Minkowski 1939) but further information is lacking. SN 1954J and SN 1978K are included in with the Type II events since these "Type V" supernovae show hydrogen in their spectra. SN 1969P, SN 1945B, SN 1950B, and SN 1957D are assigned to Type II solely because they appear in late-type spiral galaxies. SN 1885A showed no hydrogen in its spectrum, is associated with an old bulge population, and has a large mass of iron in its remnant (de Vaucouleurs & Corwin 1985; Fesen, Hamilton, & Saken 1989; van den Bergh 1994a), so a strong case can be made that it was a (peculiar) Type Ia event.

Although the sample was selected based on the distance modulus from Tully (1988), four of the events have Cepheid distances measured with the *Hubble Space Telescope*. These improved distances were used for calculating the peak absolute magnitude.

The peak *B* magnitude (B_{max}) for each event was found from the original literature. For many of the older supernovae, B_{max} was deduced based on the reasonable assump-

TABLE 1

EXTRAGALACTIC SUPERNOVAE WITH $\mu < 29$

Galaxy	μ[a]	SN	Type[b]	B_{max}	$A(B)$	Reference	M_B[c]	Comments
				Type Ia				
NGC 5253......	27.53 (28.08)	1895B	Ia	8.26 ± 0.11	0.0	1, 2	−19.82	
NGC 5253......	27.53 (28.08)	1972E	Ia	8.4 ± 0.2	0.0	3, 2	−19.68	Slow fading
IC 4182.........	28.22 (28.36)	1937C	Ia	8.71 ± 0.14	0.0	4, 5	−19.65	
Cen A..........	27.71	1986G	Ia	12.45 ± 0.05	3.6	6	−18.86	Fast fading
M31............	24.23	1885A	I	7.1 ± 0.2	1.2	7	−18.33	Very fast fading
NGC 6946......	28.70	1939C	I:	13.7 ± 0.2	small?[d]	8, 9	−15.00*	
NGC 253.......	27.36	1940E	I	14.3 ± 0.3	large?[e]	10	−13.06*	
				Type Ib				
NGC 4214......	27.71	1954A	Ib	9.3 ± 0.2	~0.0	11–13	−18.41	
NGC 5236......	28.35	1983N	Ib	11.7 ± 0.1	2.3	14	−18.95	
				Type II				
NGC 6946......	28.70	1980K	IIL	11.6 ± 0.05	1.2	15	−18.30	
NGC 1313......	27.86	1962M	IIP	11.6 ± 0.2	2.0	16–18	−18.26	
NGC 5236......	28.35	1968L	IIP	11.9 ± 0.2	1.2	19	−17.65	
NGC 5457......	28.65	1970G	IIL	11.5 ± 0.3	0.28	20, 21	−17.43	
M81............	25.67 (27.80)	1993J	II pec	11.35 ± 0.05	0.33	22	−16.78	Two peaks
NGC 6946......	28.70	1978K	V	13.0 ± 1.0	0.7	23	−16.40	"Type V"
NGC 5457......	28.65	1909A	II pec	13.5 ± 0.3	small[f]	24, 25	−15.15*	Long flat peak
NGC 6946......	28.70	1917A	II	13.6 ± 0.3	small?[d]	24–27	−15.10*	
NGC 6946......	28.70	1948B	IIP	13.9 ± 0.3	small[f]	28, 29	−14.80*	
LMC...........	18.50	1987A	II pec	4.58 ± 0.01	0.60	30	−14.52	Two peaks
NGC 6946......	28.70	1969P	...	14.2 ± 0.3	small[f]	31	−14.50*	
NGC 5236......	28.35	1945B	...	13.9 ± 0.2	small[f]	32	−14.45*	
NGC 5236......	28.35	1923A	IIP	14.2 ± 0.1	small[f]	25, 33	−14.15*	
NGC 2403......	28.14	1954J	V	16.3 ± 0.3	0.0	34, 35	−11.84	"Type V"
NGC 6946......	28.70	1968D	II	<13.8	small[f]	36	< −14.90*	
NGC 5236......	28.35	1950B	...	<14.8	small[f]	37	< −13.55*	
NGC 5236......	28.35	1957D	...	<15.0	small[f]	38	< −13.35*	
NGC 5457......	28.65	1951H	II:	<17.5	?	39	< −11.15*	

[a] Distance modulus to host galaxy from Tully 1988. Parenthetical values are from Cepheid distances.
[b] Type assignments are primarily from the Asiago supernova catalog (Barbon et al. 1989).
[c] When the extinction is not known, the tabulated M_B assumes zero extinction, as marked by an asterisk.
[d] The supernova appears outside the core of an open galaxy.
[e] The host galaxy is dusty and nearly edge-on.
[f] The supernova appears far from the center of a face-on galaxy.

REFERENCES.—(1) Schaefer 1995; (2) Saha et al. 1995; (3) Hamuy et al. 1995; (4) Schaefer 1994; (5) Saha et al. 1994; (6) Phillips et al. 1987; (7) de Vaucouleurs & Corwin 1985; (8) Zwicky & Minkowski 1939; (9) Wright & Boyd 1939; (10) Zwicky 1940; (11) Wellmann 1955; (12) Wild 1960; (13) Pietra 1955; (14) Leibundgut et al. 1991; (15) Barbon, Ciatti, & Rosino 1982; (16) Sersic & Carranza 1963; (17) Pratchett & Branch 1972; (18) Hill 1965; (19) Wood & Andrews 1974; (20) Barbon, Ciatti, & Rosino 1973; (21) Winzer 1970; (22) Richmond et al. 1994; (23) Ryder et al. 1993; (24) Baade 1938; (25) Hoffleit 1939; (26) Ritchey 1917; (27) Adams 1917a, b; (28) Nail 1949; (29) Mayall & Sill 1949; (30) Hamuy et al. 1988; (31) Rosino 1971; (32) Liller 1990; (33) Lampland 1936; (34) Kowal et al. 1972; (35) Tammann & Sandage 1968; (36) Wild & Dunlap 1968; (37) Haro 1950; (38) Gates & Carpenter 1958; (39) Barbon et al. 1989.

tion that $B-V = 0.00$ at peak and that B_{max} is 0.3 mag fainter than the peak photographic magnitude. This latter point has been found to be valid for both stars and supernovae with modern plates (Hamuy et al. 1991), old plates (Pierce & Jacoby 1995), and very old plates (Schaefer 1995). The quoted uncertainty in B_{max} will give some indication of how reliably the peak brightness is known. Figures 1–4 present typical light curves for older events, so that the reader may judge the accuracy of the peak magnitude determination in some of the poorest cases. There are only five cases where the uncertainty in B_{max} is greater than 0.3 mag. In four of these cases (SN 1968D, SN 1950B, SN 1957D, and SN 1951H), the date of the peak is unknown and we can put only lower limits on the peak brightness.

The extinction has been reliably measured for only about two-thirds of the supernovae. In many cases, the extinction can be estimated only from the colors, for which I assume $B - V = 0.0$ for an unabsorbed event at peak. It is possible that the subluminous events might be redder than assumed (see SN 1991bg and the second peak of SN 1987A), and thus the extinction might be lower, but this could affect only SN 1983N, SN 1962M, and SN 1968L. Often, some indication concerning extinction can be found from the placement of the supernova in the host galaxy.

The peak B absolute magnitude (M_B) is then calculated based on the tabulated B_{max}, μ, and $A(B)$. Cases where the extinction is not known are tabulated for zero extinction and are identified with an asterisk.

2.2. *Uncertainties*

A variety of uncertainties might substantially affect the derived luminosity functions. This section will consider each in turn.

The better observed supernovae have peak magnitudes measured with an accuracy of better than 0.05 mag, while the older events often have accuracies as poor as 0.3 mag. (See Figs. 1–4 for typical old light curves.) Does the inclusion of these old events significantly change the derived lumi-

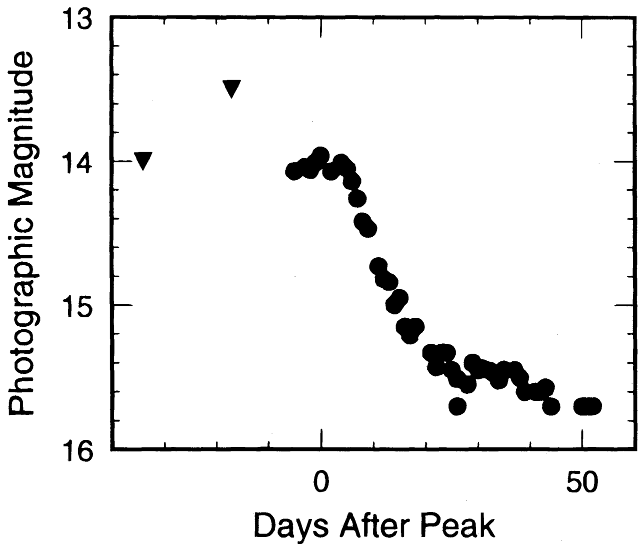

FIG. 1.—Light curve for SN 1923A. The light curve is that of a well-sampled Type II event. The down-pointing triangles are upper limits from the Harvard plate collection. The good coverage around maximum shows a peak photographic magnitude of 13.9 ± 0.1. The peak B magnitude will then be 14.2 ± 0.1.

nosity function? The answer is no, since the uncertainty in even the poorest old events is greatly smaller than the structure in the luminosity function. That is, even if the peak M_B values are arbitrarily moved by the uncertainties, then the deduced luminosity function will remain substantially unchanged. Indeed, my luminosity function will be presented with 1 mag wide bins whereas the poor uncertainties are over a factor of 3 times smaller. Thus the somewhat poorer errors of the older events are no problem.

A more serious uncertainty arises because some of the supernovae do not have a measure of the extinction. Con-

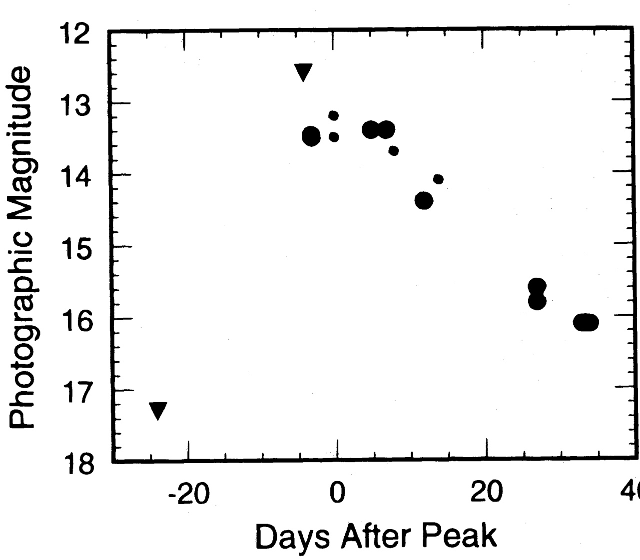

FIG. 2.—Light curve for SN 1939C. The large dots are for observations from Harvard and Palomar. The down-pointing triangles are for upper limits, while the small dots are for points with low accuracy. The light curve shows a typical Type Ia event with a peak photographic magnitude of 13.4 ± 0.2. Then the peak B magnitude will be 13.7 ± 0.2.

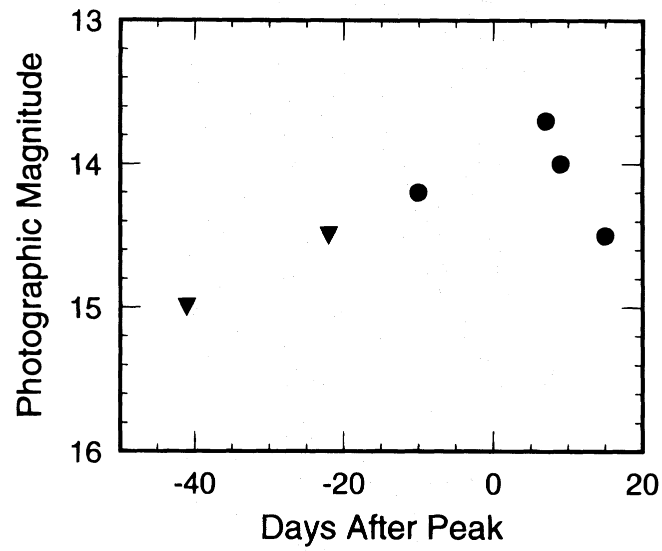

FIG. 3.—Light curve for SN 1945B. The dots are for positive detections, while the down-pointing triangles are for upper limits. This light curve is very sparse, yet is nevertheless adequate to yield a reasonable peak magnitude. The first positive observation is substantially fainter than the second positive observation, and so must be on the rising branch of the light curve. The light curve passes through 14.2 mag on days −10 and +10. The mean light curve for a Type IIL event is 0.6 mag below peak at times −10 and +10 days (Doggett & Branch 1985), so the peak photographic magnitude of SN 1945B is 13.6 ± 0.2 while the peak B magnitude is 13.9 ± 0.2. If SN 1945B were actually as bright as $M_B = -17.2$ (the center of the T&S Type II luminosity function), then it should have a peak photographic magnitude of 10.85. Thus, even the old light curve of SN 1945B established the existence of Type II supernovae as faint as SN 1987A.

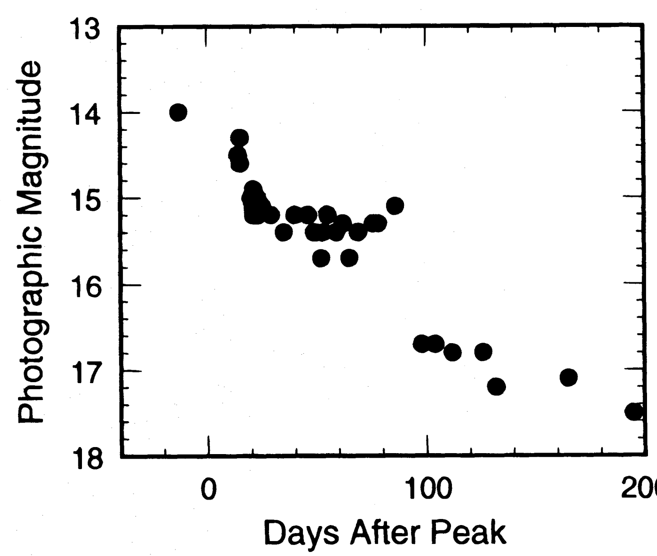

FIG. 4.—Light curve for SN 1948B. The light curve is well sampled soon after maximum and shows a typical Type IIP event. The date of maximum is set to within several days by a spectrum on the discovery date. The Harvard plates contained several prediscovery plates and one premaximum plate. The supernova was at 14.0 mag on day −13, and a short extrapolation of the postmaximum points shows the supernova to also be at 14.0 mag on day +12. The mean light curve for a Type IIP event has a width of 25 days when it is 0.4 mag below peak (Doggett & Branch 1985). Thus the peak photographic magnitude is 13.6 ± 0.3 and the peak B magnitude is 13.9 ± 0.3. If SN 1948B were actually at $M_B = -17.2$ (the center of the T&S Type II luminosity function), then its peak photographic magnitude would have to be 11.2, which is greatly outside any error region. The point of Figs. 1–4 is that even the older light curves are more than adequate for establishing the shape of a luminosity function which is over 6 mag wide and for which the bins are 1 mag wide (see Fig. 5).

ceivably, these events could all have large extinction such that their intrinsic luminosity is that of a bright standard candle. But this is unlikely, since all but one appear outside the core of an open galaxy, while all but three appear far from the center of a face-on galaxy.

An uncertainty arises since four events have not been classified by type, while I have presumed them to be Type II. Could the luminosity function significantly change if my presumption is in error? The peak around $M_B = -14$ in the Type II luminosity function would be somewhat diminished, but there would nevertheless remain a majority of "faint" events. Any such effort to explain away the Type II faint events would only then create an even more lopsided luminosity function for Type I supernovae. Thus, any arbitrary assignment of type for these four events will not change the predominance of faint supernovae for either Type I or Type II.

A similar uncertainty relates to the handling of the Type V events (SN 1978K and SN 1954J). I have included them with the Type II supernovae because they are extremely luminous stellar explosions which have hydrogen lines in their spectra, that is, they fit the relevant definition. Some researchers might prefer to reject these two events from my list for purely definitional reasons. If so, then the shape of the Type II luminosity function is not substantially changed since both a bright and faint event are eliminated.

The distances in Tully (1988) are based on galaxy redshifts (for $H_0 = 75$), whereas nearby galaxies can have significant peculiar velocities which can lead to substantial distance errors. So there is no virtue in blindly following the Tully values when reliable distances (independent of the peculiar velocities) are available. Thus in this paper I have used the Cepheid distances when possible.

This volume-limited sample is likely to be incomplete for the faintest absolute magnitudes. Thus, an $M_B < -13$ event at $\mu = 29$ would be missed by many surveys and an $M_B < -15$ event at $\mu = 29$ would be missed by many surveys if it appeared in the galaxy core. Should this residual incompleteness be corrected, the resultant luminosity function will only be more dominated by fainter events than is deduced in § 4.

In summary, there are no uncertainties that are likely to significantly alter the luminosity function derived in § 4.

3. SUPERNOVAE IN THE MILKY WAY

3.1. *The Sample*

Supernovae is our Milky Way over the last millennium within 4 kpc of Earth constitute a second volume-limited sample. Out to this distance, the probability of detection is uniform and high, as can be seen from Figure 1 of Dawson & Johnson (1994). Past this distance, the probability of detection drops sharply. Thus the apparent brightness of a standard event in the Galactic plane at 8 kpc is 9.1 mag fainter than the same event at 4 kpc. (This assumes 1.9 mag kpc^{-1} of extinction in the plane.)

The Galactic supernovae that are in this volume-limited sample are listed in Table 2 in chronological order. These events are SN 1006, SN 1054 (the Crab supernova), SN 1181, SN 1572 (Tycho's supernova), SN 1604 (Kepler's supernova), and SN 1680 (Cassiopeia A).

3.2. *Event Types*

The type of each event is somewhat uncertain. So care must be taken in the type assignment for each of the six Galactic events.

Recently, two of the most prominent arguments concerning supernova type assignments have been found to be ambiguous: (1) Until the mid-1980s, the main rationale for identifying SN 1006, SN 1572, and SN 1604 as Type Ia events was their light curve. But this rationale was eliminated when Doggett & Branch (1985) and Panagia (1985) showed that the observed light curves could arise from Type IIL and Ib events. (2) A "highly tentative classification scheme" has been advanced to relate the event type with the remnant morphology (van den Bergh 1988; Weiler & Sramek 1988). However, substantial evidence contradicts this scheme (e.g., Bandiera 1987) and a subsequent review by van den Bergh (van den Bergh & Tammann 1991) no longer holds by this idea.

What is the type of SN 1006? The large measured mass of iron in the remnant (Wu et al. 1983; Hamilton & Fesen 1988), the thin medium into which the remnant is expanding (Hamilton & Fesen 1988; Moffett, Goss, & Reynolds 1993), the large distance from the Galactic plane, and the lack of any phenomena associated with a neutron star all indicate a Type Ia event.

What is the type of SN 1054? The existence of the Crab pulsar, the hydrogen in the nebula, as well as detailed comparisons with models (e.g., Chevalier 1977; Nomoto 1987) imply that SN 1054 was a Type II eruption (van den Bergh 1988).

What is the type of SN 1181? The similarity of the remnant's plerionic structure with the Crab Nebula provides strong evidence that SN 1181 was a Type II event (e.g., Weiler & Sramek 1988; van den Bergh 1988). Although this analogy is strong, it is still only an analogy, so I will follow van den Bergh & Tammann (1991) and call it a probable Type II supernova.

What is the type of SN 1572? Here the evidence is not decisive. The small ejecta mass (Strom 1988), the unionized nature of the surrounding gas (Raymond 1984), and the

TABLE 2

GALACTIC SUPERNOVAE WITHIN FOUR KILOPARSECS

SN	μ	Type	V_{max}	$A(V)$	Reference	$M_V \sim M_B$	Comments
1006......	11.39	Ia	-4.9 ± 0.5	0.32	1	-16.61	Subluminous
1054......	11.50	II	-4.8 ± 0.5	1.1	2	-17.4	Plerion
1181......	12.08	II?	0.7 ± 1.0	1.3	2–4	-12.68	Plerion, subluminous
1572......	11.86	Ib?	-4.15 ± 0.10	2.25	1	-18.26	
1604......	12.66	Ib or II	-2.62 ± 0.09	3.5	1	-18.78	
1680......	12.23	Ib	3.5 ± 2.5	4.3	5, 6	-13.03	Subluminous?[a]

[a] If SN 1680 was as bright as $V_{max} = 0$ (van den Berg & Tammann 1991), then it need not be subluminous.

REFERENCES.—(1) Schaefer 1996; (2) Pskovskii 1978b; (3) Green & Gull 1983; (4) Fesen 1983; (5) Ashworth 1980; (6) Searle 1971.

development of the observed colors (Pskovkii 1978a; Schaefer 1996) all argue against a Type II origin. The proximity of the remnant to the Galactic plane suggests a young population progenitor, so that a Type Ib event is to be preferred.

What is the type of SN 1604? The runaway velocity of the progenitor (van den Bergh & Kamper 1977), the preexisting circumstellar shell (White & Long 1983; Hughes & Helfand 1985; Dennefeld 1982; van den Bergh & Kamper 1977), the small mass of iron in the remnant (Hatsukade et al. 1990), and the large deduced mass for the progenitor (Hughes & Helfand 1985) all deny the possibility of a Type Ia origin (Bandiera 1987). Unfortunately, there are no valid grounds for choosing between a Type Ib and a Type II event.

What is the type of SN 1680? The complex distribution of elemental abundances in the remnant imply a massive progenitor that had shed its hydrogen-helium envelope prior to the supernova event (Peimbert & van den Bergh 1971; Chevalier 1976; Lamb 1978), which is to say that SN 1680 is Type Ib.

For these reasons, I conclude that the types are as listed in Table 2. The review by van den Bergh & Tammann (1991) reached identical conclusions.

3.3. *Uncertainties*

We should consider the various sources of uncertainty and examine their potential effect on the deduced luminosity function.

Four of the historical supernovae have uncertainties in their peak magnitudes ranging from 0.5 to 2.5 mag. Nevertheless, this relatively large uncertainty will not affect any conclusions. SN 1006 has a quantitatively measured uncertainty of 0.5 mag (from the heliacal rise method, Schaefer 1996), while the peak is ~3.0 mag less luminous than the Type Ia standard candles. Thus, for any reasonable Hubble constant and brightness measurement error, SN 1006 is certainly greatly subluminous. SN 1054 has an estimated measurement error of 0.5 mag, which is too small to affect the Type II luminosity function. SN 1181 has a measurement error of ~1.0 mag, which is still too small to affect the conclusion that SN 1181 is greatly less luminous than even SN 1987A. SN 1680 has the huge uncertainty of ~2.5 mag, but this is irrelevant to either the Type Ia or II luminosity functions since SN 1680 is typed as a Ib event.

The distance moduli and extinctions are all deduced by multiple methods, as specified in the references. SN 1006, SN 1054, SN 1572, and SN 1604 all have a combined distance/extinction error of roughly one-third of a magnitude, while SN 1181 and SN 1680 can be in error by ~1 mag. The derived peak V absolute magnitudes (M_V) should be close to M_B since $B-V$ is close to zero for all types of events. (Type Ib events are somewhat redder, but this will not significantly affect the discussion since other uncertainties are larger for the relevant cases.) M_V is independent of the Hubble constant for these Galactic supernovae, and so a small shift of up to perhaps half a magnitude may be needed to combine the two volume-limited samples. In all cases, these uncertainties cannot affect the conclusions.

Can the uncertainty in the type classification for the Galactic events affect the deduced luminosity function? The types for SN 1006 and SN 1054 are very secure. In the unlikely case that SN 1181 was not a Type II event, then the deletion of one event would only slightly change the derived luminosity function. SN 1572, SN 1604, and SN 1680 are classed as probable Type Ib events, and so will not be used for the construction of either the Type Ia or Type II luminosity functions.

In summary, there are no uncertainties that will substantially change the luminosity functions or conclusions of the next section.

4. LUMINOSITY FUNCTIONS

4.1. *Type Ia*

In a magnitude-limited sample of Type Ia supernovae, roughly 89% have a constant standard candle luminosity (Branch, Fisher, & Nugent 1993; Vaughan et al. 1995). In contrast, the extragalactic and Galactic volume-limited samples have 43% and 0% that are near this standard candle luminosity. That is, five out of eight Type Ia events in the two samples are significantly subluminous. These are faint by 0.8, 1.4, 4.7, 6.6, and 3.1 mag. While five out of eight is not large number statistics, it is inconsistent with an 11% abnormality rate at the 0.9993 probability level. Thus it appears that the majority of Type Ia events are subluminous by ~1–7 mag.

This conclusion is not unprecedented in the literature: Branch et al. (1993) end their paper with a note that "events like SNe 1986G and 1991bg would be underrepresented by factors of 3.3 and 11" in a magnitude-limited sample. Similar isolated comments have been made by Branch (1985), Branch & Miller (1993), and S. van den Bergh (1995, private communication). Nevertheless, other than these few sentences, the results from the volume-limited sample will surprise most researchers.

So it is worthwhile trying to find flaws in the analysis. The most prominent potential problem is the lack of a measured extinction to SN 1939C and SN 1940E. It might be possible that SN 1940E had 6.6 mag of extinction since its host galaxy is dusty and near edge-on. But that SN 1939C has 4.7 mag of extinction is implausible since it appeared far out in an armless region of a face-on galaxy. Another potential problem is that SN 1939C might not be a Type Ia event. SN 1939C is known only as a Type I event apparently from spectral evidence (Zwicky & Minkowski 1939), but modern checks are lacking. (For the case of SN 1940E, A. H. Joy explicitly states that the "spectrum taken by Humason is of the type of the supernova observed in I. C. 4182 rather than that of N. G. C. 4725" [Zwicky 1940].) I judge that the chances are small that both problem cases are not counterexamples to the standard candle hypothesis. Nevertheless, the most conservative line of reasoning is to reject these two events. But then we are left with three out of six (SN 1986G, SN 1885A, and SN 1006) of the Type Ia events in the two samples as distinctly subluminous. Thus, even after we post facto reject the contrary data, we are still left with 50% of Type Ia events as greatly subluminous. At this point, the statistics of small numbers becomes worrisome, although the hypothesis of 89% normality is still rejected at the 0.98 probability level. In summary, my conclusion that the majority of Type Ia events are not standard candles is persuasive but not final.

If the majority of Type Ia events are not standard candles, then can they still be used for distance determinations? I think that the key lies with the fact that there is a significant fraction of events that do appear to be good standard candles (Branch & Tammann 1992; Hamuy et al. 1995). Magnitude-limited samples are strongly biased against the inclusion of subluminous events (Branch et al.

1993), so Hubble diagrams constructed from distant events will have a ridge line well defined by standard candles from the mode of the luminosity function. For nearby events used as calibrators, the selection of standard candles can be confidently made by selecting spectroscopically and photometrically normal cases. Thus the subluminous tail can be rejected either by observational biases or by their unusual properties, depending on the application.

4.2. *Type II*

The history of the luminosity function for Type II supernovae can be divided up into two phases. In the first phase, a researcher would collect available light curves and average the peak absolute magnitude. Barbon, Ciatti, & Rosino (1979) collect many previous such results as well as derive one of their own. They find the mean M_B equals -17.07 (for $H_0 = 75$) with an rms scatter of 0.78 mag. The basic problem with these studies is that they use magnitude-limited samples, so that subluminous events are greatly underrepresented and the luminosity function is greatly biased.

The second phase came after SN 1987A showed that extremely subluminous Type II events existed. Filippenko (1988) explained how events like SN 1987A have been missed by previous supernova searches. Tammann (1994) comments that subluminous events must be rare or else variable star searches of nearby galaxies would have turned up examples, but even in the extreme case where a dozen galaxies are intensely monitored for a decade the odds would be against the detection of any subluminous events even if they dominate the luminosity function. Van den Bergh & McClure (1989) used the magnitude-limited survey of Rev. R. Evans to place limits on the luminosity function and found that the faint events cannot dominate. Young & Branch (1989) advanced the qualitative suggestion that faint events might dominate the luminosity function. Schmitz & Gaskell (1988) and Miller & Branch (1990) show that a simplistic correction for completeness in a magnitude-limited sample yields a luminosity function totally dominated by faint events, although this can only set an extreme limit since galaxies are not observed with a uniform distance distribution (Miller & Branch 1990; T&S).

The two volume-limited samples in Tables 1 and 2 contain 20 Type II events. The resulting luminosity function (for $H_0 = 75$) is displayed in the bottom half of Figure 5. The range of M_B is from -11.1 to -18.3. If the events with limits are ignored (they are all very faint limits), then the M_B has a median of -15.1, an average of -15.5, and an rms scatter of 1.9 mag. The luminosity function is fairly flat from -18.3 to -15.2 and rises dramatically for fainter explosions. A low-luminosity cutoff at around -14 could be caused by either an intrinsic limit for Type II events or residual magnitude threshold effects. The near coincidence of the observed cutoff with that expected from known discovery thresholds suggests that the luminosity function continues strong to fainter levels.

Recently, T&S found a Gaussian luminosity function (see top panel of Fig. 5) centered at M_B equals -17.2 (for $H_0 = 50$) with an rms scatter of 1.2 mag. The two luminosity functions in Figure 5 are greatly different. One source of this difference is simply that T&S use $H_0 = 50$, so that most of their events should be made 0.88 mag fainter to match my adopted $H_0 = 75$. Nevertheless, there is a remaining systematic difference in both the average and shape of the

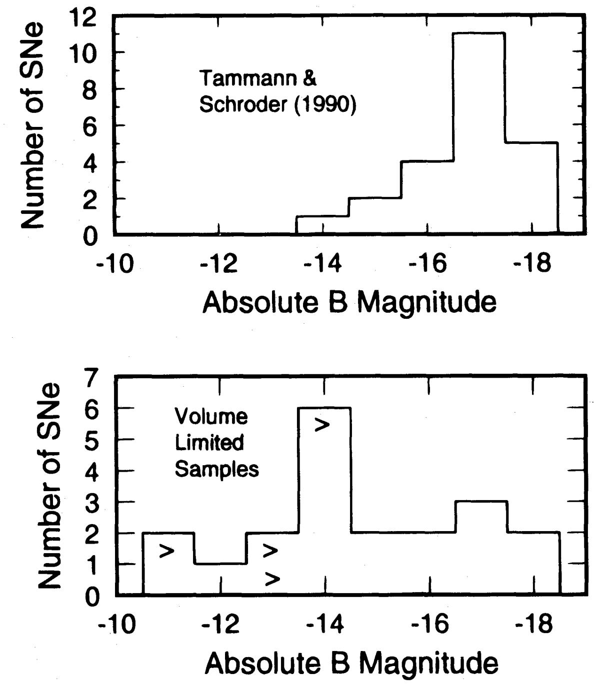

FIG. 5.—Luminosity function for Type II supernovae. The bottom panel shows the Type II luminosity function derived from my two volume-limited samples (with $H_0 = 75$). The graph shows a very broad range of luminosities which starts rising at the faint end. The cutoff around $M_B = -14$ is consistent with the cutoff due to discovery thresholds. In other words, the majority of Type II are significantly subluminous and there are likely to be many events with $M_B \sim -13$ or fainter. The top panel shows the luminosity function from T&S (with $H_0 = 50$) for comparison.

luminosity function. This difference arises for four reasons: T&S adopted a distance limit of $\mu = 31.1$ ($H_0 = 75$) which is sufficiently far as to have discovery thresholds cut deeply into the faint end of the luminosity function, the majority of events discovered after T&S compiled their list (SN 1945B, SN 1978K, and SN 1993J) are subluminous, one-third of their sample has photographic magnitudes which will correspond to B peaks 0.3 mag fainter, and T&S did not use events with types " V " or " pec," or unlisted. (With regard to the last mentioned difference, the faint events will preferentially not be typed, so that the demand for a Type II assignment immediately cuts off the derived luminosity function. Alternatively, identifying these events as not being Type II raises serious problems for the luminosity functions of Type I events.) The combination of these four effects serves to brighten and artificially cut off the T&S luminosity function.

Even though the differences with T&S are easily understood, we should still seek weaknesses with the volume-limited luminosity function. The most obvious weakness is the inclusion of four events with only limits on their peak brightness (boxes containing a " > ") in Figure 5. But these were excluded from the above quantitative analysis. The next most obvious weakness is that six events have no real measure of the extinction, so conceivably a correction for this could greatly boost the average luminosity. However, in all but one case, the supernovae appeared far out in the galaxy where small extinction is expected. Another worry is that the photometry of the old events might be significantly in error. However, the typical errors in old photographic data of supernovae is a few tenths of a magnitude (Schaefer 1989, 1994, 1996; also see Figs. 1–4). Yet this problem tends to increase the brightness, so the relative inaccuracy of old photometry is unlikely to brighten the luminosity function. In summary, I do not see any weakness that will significantly change the luminosity function.

The change in the Type II luminosity function will force a revision in the rate of such events. That is, the rate calculations (e.g., van den Bergh et al. 1987; Evans, van den Bergh, & McClure 1989; van den Bergh & McClure 1994) are based on magnitude-limited samples which miss the faint events, as the calculators caution the reader (e.g., van den Bergh & Tammann 1991). The missing tail comprises a number roughly equal to the bright events. Thus the rate of Type II supernovae must be roughly doubled. This will also force a small lowering of the minimum progenitor mass that will core-collapse to form Type II explosions.

5. DISCUSSION

The two volume-limited samples provide a measure of the relative frequency of the various types of supernovae. In the extragalactic sample, the percentages of Types Ia, Ib, and II are 26%, 7%, and 67%, respectively. Of the 18 Type II events, 11% were of "Type V." In the Galactic sample, the percentages of Types Ia, Ib, and II are 16%, 42%, and 42%, respectively. (Here, SN 1604 was given half weight as Type Ib and II each.) In both samples, the percentages of Types Ia, Ib, and II are 24%, 14%, and 62%, respectively.

In stark contrast to the comprehensive simplicity of the traditional morphological scheme, volume-limited samples show a complex situation. Consider the nearby supernovae with $\mu_{\rm Tully} < 27$, where *all* the events are highly unusual. These include SN 1987A with *two* peaks in its light curve and a very subluminous maximum, SN 1885A with its *extremely* fast light curve and its subluminous maximum, and SN 1993J with *two* peaks in its light curve. Three out of the three nearest supernovae are so weird that they cannot be accommodated in the classical morphology categories. Alternatively, consider the events with $27 < \mu_{\rm Tully} < 29$, where we find such weird events as SN 1986G (a spectroscopically unusual and photometrically fast Type Ia event), SN 1939C (a Type I event with $M_B = -15.0$), SN 1940E (a Type I event with $M_B = -13.1$), SN 1978K (a "Type V" event with extraordinarily high X-ray and radio luminosity), SN 1909A (with a subluminous peak that was nearly constant for over 70 days), and SN 1954J (a "Type V" event visible for decades with wild fluctuations). A full third of the events in the extragalactic volume-limited sample are too weird to be fit into the simple classification scheme.

The weird events are generally faint. So if we wish to push the frontiers of supernova knowledge, then we must discover these low-luminosity events. For example, the faint Type II events could come from "fizzled" core collapses, so their study might tell us much about explosion physics. To have a supernova search reach to $M_B = -12$ out to a distance modulus of 29 mag, the discovery threshold would have to be 17 mag. Such a threshold is easy on midsize telescopes with CCD cameras. Tully (1988) lists just over 150 galaxies inside this volume for a total *B* luminosity of $4 \times 10^{11}\ L_\odot$. With the rates from van den Bergh & Tammann (1991), we could expect of order 100 normal events per century plus perhaps an additional 40 subluminous Type II events per century. So a 5 yr deep survey of nearby galaxies might net a few subluminous supernovae. Alternatively, a 5 yr deep search to 19 mag of 100 galaxies in the Virgo Cluster might net a half-dozen subluminous events. Such surveys would be long and tedious, but the scientific return from well-studied supernovae with extreme properties or with new classes of explosion mechanisms will be worth the effort.

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