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HIGH RATE FOR TYPE Ic SUPERNOVAE

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ABSTRACT

Using an automated telescope we have detected 20 supernovae in carefully documented observations of nearby galaxies. The supernova rates for late spiral (Sbc, Sc, Scd, and Sd) galaxies, normalized to a blue luminosity of $10^{10} L_{B\odot}$ are 0.4, 1.6, and 1.1 h^2 per 100 years for Types Ia, Ic, and II supernovae. The rate for Type Ic supernovae is significantly higher than found in previous surveys. The rates are not corrected for detection inefficiencies and do not take into account the indications that the Ic supernovae are fainter on the average than the previous estimates; therefore the true rates are probably higher. The rates are not strongly dependent on the galaxy inclination, in contradiction to previous compilations. If the Milky Way is a late spiral, then the rate of Galactic supernovae is greater than 1 per 30 ± 7 yr, assuming $h = 0.75$. This high rate has encouraging consequences for future neutrino and gravitational wave observatories.

Subject headings: galaxies: stellar content — stars: statistics — supernovae: general — telescopes

1. INTRODUCTION

Supernova rates have been difficult to determine accurately despite the many supernovae that have been discovered in this century, because few were discovered by searches with systematic documentation of galaxy surveillance times. For a review of supernova searches and rates, see Trimble (1982) or van den Bergh & Tammann (1991). Two recent searches have kept such records: the Asiago search using photographic plates (Cappellaro & Turatto 1988), and the search of Evans who observes by eye through a small telescope (Evans, van den Bergh, & McClure 1989). The Asiago search has a limiting magnitude of approximately 16.5, but they must correct their rates for supernovae missed in cores of galaxies and in highly inclined galaxies. Evans's search has a limiting magnitude 14.5–15.4, which makes him less sensitive to the fainter core collapse supernovae (similar to 1987A, for example) at Virgo distances.

In 1980 we began a project to discover supernovae with an automated telescope and analysis system based on an approach similar to that of Colgate et al. (Colgate, Moore, & Carlson 1975). The current system, which uses a 76 cm telescope at the Leuschner Observatory (8 km from Berkeley), is designed to fill the gaps of previous searches. We use a CCD camera to achieve greater sensitivity and dynamic range and to keep careful documentation of the galaxies searched. Our first supernova was discovered in 1986 with semiautomated operation (Kare et al. 1988; Pennypacker et al. 1989a). In 1988 the supernova search became fully automated, with observations and analysis results documented in on-line data bases (Perlmutter et al. 1988, 1989; Pennypacker et al. 1989b).

The computers at the observatory collect images of galaxies approximately once a minute and immediately compare each image to a previously observed reference for evidence of a "new star." If a candidate is present, the computer schedules another observation a few minutes later. If the same candidate appears, a third observation is made an hour later to eliminate false alarms due to asteroids (which typically would have moved several arcseconds). Candidates present in all three images are examined by a scientist the next morning and reported as a new supernova in an IAU telegram that same day. Previous images of the galaxy are checked to see if the supernova was present but below automatic detection threshold on earlier nights. In 1990 January the final stages of observatory automation were completed, and we no longer had an operator at the telescope. The system now observes typically 600 galaxy images on a clear winter night, and 400 on a (shorter) summer night.

2. DISCOVERIES

Through 1991 June 14, the Berkeley system has automatically detected 20 supernovae. Three of these (1989B, 1991G, and 1991T) were discovered earlier by other observers. The system missed four supernovae because of downtime and bugs in the system hardware and software that prevented good images from being taken. No supernovae were falsely reported. We have a completely documented observation record only during the time of fully automated operation (since 1988 January 24), and to avoid bias in the rate calculation we chose in advance to include in this paper's calculation only the supernovae discovered during the three-year period ending 1991 January 23. The supernovae found with the Berkeley system through 1991 June are listed in Table 1; the 12 supernovae discovered during the three-year fiducial period are in italics.

Supernovae are broadly divided into two categories: Type I that lack strong hydrogen lines, and Type II that have them. Type I have been subclassified into types Ia and Ib based on spectral differences that suggest different origins for the two types (Porter & Filippenko 1987). Recently a new class has been introduced, a helium-poor Ib called a Ic (Harkness & Wheeler 1990). Filippenko (1991) has suggested that most (but not all) previously described Type Ib supernovae were really Ic; they were misclassified because the distinction between Ib and Ic had not yet been recognized, or because they were caught late or had their epoch misidentified. For the remainder of the paper, supernovae positively classified as Ic shall keep that designation. However, since we used what was previously referred to as a Ib light curve to calculate survey times (in galaxy years) and we compare our rates with the rates of others who did not distinguish Ib from Ic events, all desig-

TABLE 1

SUPERNOVAE DETECTED BY BERKELEY SEARCH THROUGH 1991 JUNE

SN[a]	Galaxy	Type[b]	IAU[c]	Type	m_{CCD}[d]	cos (i)[e]
1986I	N4254	Sc	4219	II	14	0.91
1986N	N1667	Sc	4287	Ia	15	0.75
1986O	N2227	Scd	4298	Ia	14	0.73
1987K	N4651	Sc	4426	II, Ic	15	0.68
1988H	N5878	Sb	4560	II	15.5	0.42
1988L	N5480	Sc	4590	Ic	16.5	0.78
1989A	N3687	Sbc	4721	Ia	15.3	1.00
1989B[f]	N3627	Sb	4726[f]	Ia	12	0.47
1989L	N7339	Sbc	4791	II	16	0.24
1990B	N4568	Sbc	4949	Ic	16	0.42
1990E	N1035	Sc	4965	II	16.7	0.36
1990H	N3294	Sc	4992	II	16	0.52
1990U	N7479	Sc	5063	Ic	16	0.75
1990aa	U540	Sc	5087	Ic	17	0.5
1991A	U6872	Sc	5153	Ic	17	0.53
1991B	N5426	Sc	5163	Ia	16	0.56
1991G[f]	N4088	Sbc	5188[f]	II	17	0.41
1991M	I1151	Sc	5207	Ia	15	0.28
1991N	N3310	Sbc	5227	Ibc	15	0.92
1991T[f]	N4527	Sbc	5239[f]	Ia	11.5	0.34

[a] The 12 supernovae (in italics) starting with 1988H were discovered during the three year time period used for the rate calculations in this paper.

[b] Galaxy type is from Huchra et al. 1990.

[c] International Astronomical Union circular.

[d] Our magnitudes were measured on a CCD imaging detector, sensitive primarily in yellow and red. The CCD magnitudes were at time of discovery and are uncertain by about a magnitude.

[e] Cosine of the galaxy inclination angle, from de Vaucouleurs & de Vaucouleurs 1964 and the NASA/IPAC Extragalactic Database (NED), operated by the Jet Propulsion Laboratory, Cal Tech.

[f] Supernovae 1989B, 1991G, and 1991T were discovered first by other observers, but were detected by the Berkeley search independently.

nations relating to the galaxy years or rates will be made as Ibc.

One of the Berkeley supernovae (1987K) was observed by Filippenko (1988) to make a transition from a Type II to a Type Ic, thus establishing a link between these types. He reported additional hints of a link in the spectra of 1991A (Filippenko 1992). He suggests that Type II and Type Ic may form a continuous sequence in which the mass of the star's hydrogen envelope is the main variable. The most surprising result of the current search is the relatively high rate of these Type Ic supernovae.

3. SUPERNOVA RATE FOR THIS SEARCH

To derive the supernova rate we need the integral of the galaxy observations over time; this is given in units of galaxy years. Our threshold for automatic detection is approximately 16.5 mag, although the sensitivity on any given night depends on the atmospheric absorption and seeing. Since supernovae can remain visible above this threshold for many days, it is not necessary to view the galaxies every night. However, our search returns to nearby galaxies more frequently than necessary in order to find supernovae early. In calculating survey times in galaxy years, we credit to a single observation either the period since the previous observation or the days that a supernova in that galaxy would have remained visible, whichever is less. Thus the number of galaxy years depends on the light curve and therefore on the class of supernova; we can detect bright Ia supernovae in distant galaxies (vel $< \approx 7000$ km s^{-1}), but dimmer Type II supernovae only in nearby galaxies (vel $< \approx 3200$ km s^{-1}).

To calculate galaxy years we used the light curves in van den Bergh, McClure, & Evans (1987), with the updated maximum brightness from Evans et al. (1989), but without their adjustment for dependence of Type II luminosity on the luminosity of the parent galaxy. The possibility that this last adjustment was made in error due to an observational bias has been suggested by Miller & Branch (1990). These light curves make no distinction between plateau and linear Type II supernovae and assume that the peak magnitude of Type Ibc supernovae is brighter than that of Type IIs, although there is no evidence for bright Ibc supernovae and the findings of this work suggest that they are actually fainter than Type IIs. However, using these light curves gives us a reasonable estimate of the rates and facilitates direct comparison with those of Evans et al. The contribution of a galaxy to the galaxy-year integral was normalized to a luminosity of $10^{10}\ L_{B\odot}$ ($M_{B\odot} = 5.48$).

Our detection efficiency is high for any supernova of magnitude 16.5 or brighter occurring in our observation period. In our sample of galaxies, 24 supernovae have been discovered since we began operations. Of these, we automatically detected 20 (three of these were discovered first by others), and missed four. However three of the four we missed did not contribute to our integral of galaxy years (two because we did not return to the galaxies sufficiently frequently; one because of a software bug that mispointed the telescope, giving an image automatically identified as an unsuccessful match to the reference). The one supernova we truly missed, for which we had an observation that counted in our galaxy years, was 1989K, which was probably close to our detection threshold (16.5) at maximum. After this supernova was reported, we found that the reference image was not properly centered; the supernova was just off the edge of the frame. This example demonstrates that our detection efficiency is not perfect. However, rather than attempt a correction, we shall assume the efficiency to be 100% for the purpose of calculating supernova rates. This is certainly an overestimation, so the true rates are higher than those we report here.

The galaxies were chosen from the Zcat catalog (Huchra et al. 1990) based on redshift, absolute luminosity, and morphological type. Our observations were split among ellipticals, early spirals, late spirals, and other galaxies with roughly the percentages 20%, 30%, 45%, and 5%. The corresponding (unnormalized) distributions of these types in the Shapley-Ames catalog is 11%, 43%, 40%, and 5%. It has been known for some time that the rate of supernovae is high in late-type spiral galaxies (Sbc through Sd). Although only 45% of our observations were of such galaxies, all but two of our supernovae (both in Sb spirals) were found in late spirals. We discovered none in ellipticals, although if the rate for ellipticals were given by the average Ia rate in all galaxies, we should have seen only 0.8. The galaxy years for all galaxies and for late spirals is summarized in Table 2, along with the supernova rates calculated from them.

The statistical uncertainties for our data shown in Table 2 were calculated as the 1 standard deviation Poisson error (rather than by using the $\sqrt{N}$ rule). Also shown in the table are the rates of Evans et al. (1989), adjusted to $M_{B\odot} = 5.48$; their original values were calculated using $M_{B\odot} = 5.37$. The total supernova rate is $R_{\mathrm{tot}} = 1.6 \pm 0.5\ h^2$ for all galaxies, and $R_{\mathrm{tot}} = 3.1 \pm 0.7\ h^2$ for late spirals. We remind the reader that the true rate is higher since our detection efficiency is less than

TABLE 2

SUPERNOVA RATES FOR THE PERIOD 1988 JANUARY–1991 JANUARY

Parameters	Ia	Ibc	II
All Galaxies			
Number of supernovae	3	5	4
Galaxy years[a]	1447	747	587
Average rate[a]	$0.21^{+0.12}_{-0.07}$	$0.67^{+0.25}_{-0.17}$	$0.68^{+0.31}_{-0.20}$
Evans et al. rate[a]	0.25 ± 0.09	0.24 ± 0.14	0.94 ± 0.27
Late Spiral Galaxies[b]			
Number of supernovae	2	5	3
Galaxy years[a]	546	319	265
Average rate[a]	$0.37^{+0.29}_{-0.16}$	$1.57^{+0.59}_{-0.39}$	$1.13^{+0.62}_{-0.38}$
Evans et al. rate[a]	0.2	0.4	1.2

[a] The rates are in supernovae per 10^{10} $L_{B\odot}$ per 100 years (called "SNU"—supernova units—elsewhere in the literature). All galaxy years should have a factor h^{-2}, and all rates should have a factor h^2. The rates of Evans et al. 1989 were adjusted to be consistent with $M_\odot = 5.48$.

[b] Galaxies of types Sbc, Sc, Scd, and Sd.

100%, and because the systematic uncertainties discussed in the following paragraphs cause an underestimate of the rate.

To estimate the systematic uncertainties, we recalculated the galaxy years and rates assuming different limiting magnitudes for supernova detection, different template light curves, and different relationships between Type II peak luminosities and host galaxy luminosity. Our detection threshold is generally between $r = 16$ and 17; it depends on atmospheric seeing and transmission, and these vary from night to night, and sometimes even hour to hour. The estimated supernova rate changes by approximately 10% for Type Ia supernovae and about 30% for Types Ic and II if we change the average detection threshold by half a magnitude from the value of 16.5 used in Table 2.

An additional source of error comes from the uncertainty in the light curves. Currently there are two recognized light-curve shapes for supernovae of Type II (Wheeler 1990). In addition, type II supernovae have a peak luminosity that ranges over 4 mag (Miller & Branch 1990). Since Type Ib supernovae are presumed to be similar to those of Type II (Filippenko 1988), it is possible that as more information becomes known, their light curves may likewise show a large nonuniformity. Due to observational biases, we would expect the average peak magnitude to be revised fainter. In § 4 we give some preliminary evidence that these supernovae are in fact fainter. If the peak magnitude of type Ibc supernovae were actually 1 mag fainter on average than the Evans et al. (1989) light curves used to calculate Table 2, then we would have observed only 419 normalized Ibc galaxy years, or 193 in late spirals, in our three-year fiducial period, resulting in a Ibc rate of 1.19 (about 80% higher), or 2.59 in late spirals (65% higher). This would increase our overall supernova rate by 33% and make Ibc supernovae the most common type. It is possible that a similar effect applies to Type II supernovae; we know from SN 1987A that there are also subluminous versions of this type.

While not all of our systematic errors necessarily increase the supernova rate, we have tried to err on the side of low rates. Since the systematic error is comparable to the statistical error, the rates could be significantly higher. In the future the systematic errors can be reduced by measuring the nightly limiting magnitude and estimating the detection threshold as a function of galaxy brightness, morphology, and supernova position on the galaxy. Better characterizations of the supernova light curves would also be particularly useful, especially for those of type Ibc. As we find more supernovae and the statistical errors become smaller, we expect to reduce these sources of systematic error correspondingly.

4. COMPARISON WITH PREVIOUS RESULTS

One can see from Table 2 that our rates for Type Ia supernovae are generally in agreement with those of Evans et al. (1989) except that we find significantly higher rates of Type Ibc. Furthermore, if we include the same adjustment for dependence of Type II luminosity on that of the parent galaxy as used by Evans et al., our Type II rate nearly doubles. The higher rates are particularly apparent in the Ibc rate of late spirals, where we find a rate 4 times higher. Based on Evans et al.'s value of 0.4 for Ibc supernovae in late spirals, we should have seen 1.3 events. The probability of finding the observed five events or more, given their rate, is 1%. Our higher rate is probably due to our more sensitive limiting magnitude.

It would be helpful to use the magnitudes listed in Table 1 to test the suggestion that we are seeing Type Ibc supernovae that are dimmer (on average) than those previously reported. Unfortunately few of our supernovae have had photometric magnitudes taken; our telescope is at a poor site, and automated calibration of our photometry is not yet operational; the CCD magnitudes reported are uncertain to about a magnitude. However one of our Ic supernovae, 1990B, had its magnitude, $B = 17.7$, measured photometrically by Suntzeff (1990) at Cerro Tololo about 1 week past maximum. Using the distance 16.8 Mpc (Tully 1987) for $h = 0.75$, the absolute magnitude of this supernova was $M_B = -13.4$, uncorrected for extinction. This is 3.3 mag dimmer than the dimmest of the eight well-studied Type Ib supernovae reviewed by Miller & Branch (1990). Spectral measurements indicate that SN 1990B was strongly obscured by dust in the parent galaxy (Benetti, Cappellaro, & Turatto 1990). If we are in fact finding supernovae that are dimmer than previous Ibc light curves indicate, regardless of whether or not this is due to extinction, then the Ibc rates are significantly higher, as discussed above in § 3.

For the Asiago photographic search, Cappellaro & Turatto

(1988) report a limiting magnitude 16–17 (similar to ours), and thus they would be expected to find a similarly higher rate. Unfortunately it is difficult to compare with the rates reported in this reference for several reasons. First, this search found most of its supernovae before the distinction between Ia and Ibc supernovae was established, and the galaxy years used in the rate calculation depend on the luminosity of the supernova type considered. Even for the Type II supernovae, Cappellaro & Turatto adopted a different peak luminosity than that used in our calculations or those of van den Bergh et al. (1991). Their rates have also been corrected for the tendency of photographic searches to miss supernovae in the saturated core of galaxies, and in spiral galaxies that are seen close to edge-on. (This "inclination effect" is discussed below.) Since these corrections appear to affect Types I and II differently, it is probably not useful to compare even the relative rates of Type I and Type II supernovae.

Tammann (1977) and Cappellaro & Turatto (1988) report that the number of supernovae they observe in Sc galaxies is strongly dependent on the inclination of the parent galaxy. To account for this effect, they correct the number of supernovae found in galaxies with inclination over 30° by factors of 5.5 and 5, respectively. Van den Bergh (1990) has argued that high supernova rates in late spiral galaxies have been hidden from observers by dust. He points out that 45 out of 95 supernovae in Sc galaxies which have multiple supernovae were in the 17% of galaxies that were closest to face-on, with the cosine of their inclination angle greater than 0.88. (Van den Bergh's correction factor is ~ 3.)

Our supernovae, in contrast, show no strong inclination effect; the cosines of the inclination angles of the parent galaxies are given in Table 1, and their distribution is essentially flat for Sc galaxies as well as for all galaxies. Only 1 out of the 11 supernovae in Sc galaxies, or 3 out of all 20 supernovae, have $\cos(i) > 0.88$. (These counts include the supernovae discovered through 1991 June.) The inclination effect previously seen in the Sc galaxies may be due to a bias in prior searches that made it more likely that a supernova would be discovered in a face-on galaxy. For example, the low dynamic range of photographic plates can cause supernovae to be lost in the high surface brightness of edge-on galaxies. This explanation is consistent with the fact that the supernovae found by Evans in his visual search likewise show no inclination effect (van den Bergh et al. 1987). Note that the combined supernovae of the Evans search and our search give a statistical sample showing no inclination effect that is almost half as large as the sample from well-documented photographic searches which do show the effect.

5. DISCUSSION

High supernova rates for the Milky Way have been claimed using many methods, including extrapolation from the seven observed in the last 1000 years, from pulsar birth rates, and from rates of nucleosynthesis; for a review see Wheeler (1990), who also discusses problems with high rates. However, there has been reason to be skeptical of these rates because of the many correction factors that have to be estimated to obtain them. Direct searches for supernovae, in particular, have required large corrections (e.g., for the inclination effect) to get large rates. Based on our measured rate of $3.1 \pm 0.7\ h^2$ for late spirals, we calculate an average period between supernovae in the Milky Way of 30 ± 7 yr. (We take the Milky Way luminosity to be $1.9 \times 10^{10}\ L_{B\odot}$—Gilmore, King, & van der Kruit 1990—and use $h = 0.75$.) This confirms the previous claims of relatively high rates, but *without* using complicated correction factors. This rate, of course, does not include supernovae below our detection threshold or those missed due to other detection inefficiencies. The rate would also be higher if it is confirmed that our Type Ibc supernovae are fainter than previous ones of Type Ib.

These higher rates for core-collapse supernovae have interesting implications for the detection of neutrinos and gravitational waves from nearby supernovae. (For descriptions of detectors, see Norman 1989; Thorne 1980.) If the sensitivity of the detectors is extended to reach galaxies within 5 Mpc, then one supernova would be detected every 5 yr (for $h = 0.75$). This estimate is based on a total luminosity of $13 \times 10^{10}\ L_{B\odot}$ for late spiral galaxies within this region (calculated from Tully 1987) and our rate of $2.7\ h^2$ for core-collapse supernovae (assumed to be Type Ibc as well as Type II) in late spiral galaxies.

Most of the Berkeley Type Ic and Type II supernovae are near the limit of our present sensitivity; this suggests that there may be many more supernovae discovered with a better system. An improved automatic telescope to be located at a better site is under development at Berkeley. This system will extend the sensitivity of automated discovery to 19th magnitude and beyond.

In summary, we have found a high rate of supernovae in late spiral galaxies. Although only 45% of our observations were in such galaxies, they accounted for 18 of our 20 supernovae. Type Ic supernovae, previously considered rare, are the most abundant type in late spirals. Further studies will show whether there are even more supernovae at dimmer magnitudes. These Ic supernovae are apparently the most common supernovae in galaxies similar to the Milky Way, and yet they are the least well studied and understood.

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