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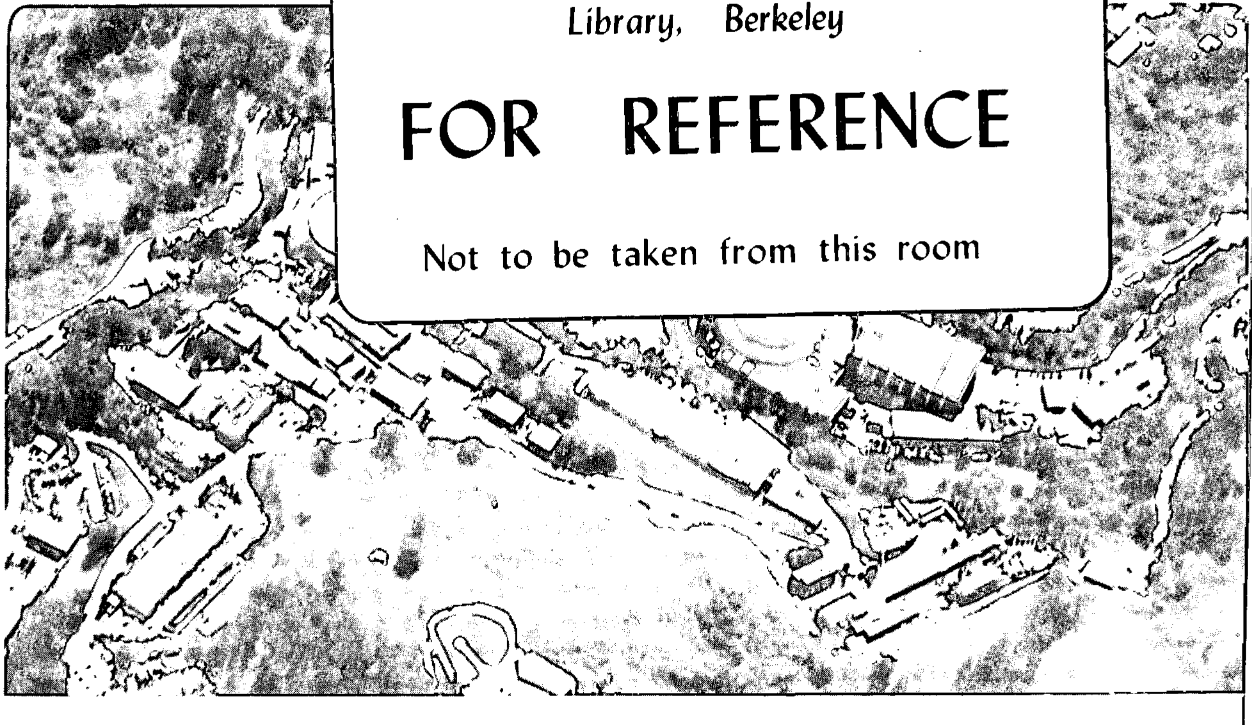

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High Rate for Type Ic Supernovae

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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_{Bsun}, are 0.4 h^2, 1.6 h^2, and 1.1 h^2 per 100 years for SNe type Ia, Ic, and II. 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 years, assuming $h = 0.75$. This high rate has encouraging consequences for future neutrino and gravitational wave observatories.

Subject headings: stars:supernovae--stars:stellar statistics --galaxies:stellar content--instruments

I. Introduction

Supernova rates have been difficult to determine accurately despite the many supernovae that have been discovered in this century, because very few were discovered by searches that kept systematic documentation of the galaxy surveillance times. For a review of supernova searches and rates, see Trimble (1982) or van den Bergh and Tammann (1991). Two recent searches have kept such records: the Asiago search using photographic plates (Cappellaro and Turatto, 1988), and the search of Evans who observes by eye through a small telescope (Evans, van den Bergh and 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' 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 Stirling Colgate (Colgate, Moore, and Carlson, 1975). This system, which for the current prototype stage uses a 76 cm telescope at the Leuschner Observatory (located about 8 km from the Berkeley campus), is designed to fill the gaps of previous searches. We use a CCD camera to achieve greater sensitivity and dynamic range and keep careful documentation of the galaxies searched each night. Our first supernova was discovered in 1986 with semi-automated operation (Kare et al. 1988, Pennypacker et al. 1989a). In January 1988, the supernova search became fully automated, with all observations and analysis results documented in on-line databases (Perlmutter et al. 1988, Pennypacker et al. 1989b, Perlmutter et al. 1989).

The computers at the observatory collect images of galaxies approximately once a minute, and immediately compare each image to a previously observed reference image for evidence of a "new star." If a candidate is present the computer schedules another observation of the same galaxy a few minutes later. If the same candidate appears in this image, a third observation is made an hour later, to eliminate false alarms due to asteroids (which typically would have moved several seconds of arc). 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 January 1990 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.

II. Discoveries

Through 14 June 1991, 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 down-time 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 24 January 1988), 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 23 January 1991. The supernovae found with the Berkeley system through June 1991 are listed in Table 1; the twelve supernova discovered during the three-year fiducial period are listed in italic type.

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 and Filippenko, 1987). Recently a new class has been introduced, a helium-poor Ib called a Ic (Harkness and Wheeler, 1990). Filippenko (in press) 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, all supernovae positively classified as Ic shall keep their 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 designations 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, 1991). 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 results of the current search are the relatively high rate of these type Ic supernovae.

III. 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 magnitude 16.5, 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 of the supernova, and therefore on the class of supernova; we can detect the bright Ia supernovae in distant galaxies (vel $<\approx$ 7000 km/sec), but the dimmer type II supernovae only in nearby galaxies (vel $<\approx$ 3200 km/sec).

To calculate galaxy-years as a function of supernova type we used the light curves in van den Bergh, McClure and Evans (1987), with the updated maximum brightness from Evans, van den Bergh, and McClure (1989), but without their adjustment for a 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 and Branch (1990). These light curves make no distinction between plateau and linear type II supernovae, and assume that the peak magnitude of type Ibc's is brighter than that of type II's, although there is no evidence for bright Ibc's and the findings of this work suggest that they are actually fainter than type II's. However, using these light curves gives us a reasonable estimate of the rates and facilitates direct comparison with those of Evans, van den Bergh, and McClure. The contribution of a galaxy to the galaxy-year integral was normalized to a luminosity of 10^{10} L_{Bsun} (M_{Bsun} = 5.48).

If a supernova of magnitude 16.5 or brighter occurs in our observation period, our efficiency for its detection is high. In our sample of galaxies, 24 supernovae have been discovered since we began operations. Of these, we automatically detected twenty (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 of them were missed because we did not return to the galaxies sufficiently frequently. The other was missed because of a software bug that mis-pointed the telescope, thus giving an image that was automatically identified as an unsuccessful match to the reference image.) The one supernova we truly missed, for which we had an observation that counted in our galaxy-years, was 1989K, which probably reached close to our detection threshold (≈16.5) when at maximum. After this supernova was reported, we found that the reference image was not properly centered in its frame; the supernova was just off the edge. This one example demonstrates that our detection efficiency is less than perfect. However, rather than attempt a correction for this inefficiency, we shall assume the detection efficiency to be 100% for the purpose of calculating supernova rates. This is certainly an overestimation, so the true supernova rates are higher than those we report here.

The galaxies were chosen from the Center for Astrophysics Redshift Catalogue (Zcat) (Huchra et al, in press) based on their redshift, absolute luminosity and morphological type. Our observations were split among ellipticals, early spirals, late spirals, and other galaxies with roughly the following percentages: 20%, 30%, 45%, and 5%. The corresponding (unnormalized) distributions of these types of galaxies in the Shapley-Ames catalogues 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 (Hubble types 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 no supernovae in ellipticals, although if the rate for these galaxies were given by the average Ia rate in all galaxies, we should have seen only 0.8 of them. The number of galaxy years for all galaxies and for late spirals is summarized in Table II below, along with the supernova rates that we calculate from these.

The statistical uncertainties for our data shown in Table 2 were calculated as the one 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 be consistent with $M_{Bsun} = 5.48$; their original values were calculated using $M_{Bsun} = 5.37$. The total supernova rate is $R_{tot} = 1.6 \pm 0.5 \ h^2$ averaging over all galaxies, and $R_{tot} = 3.1 \pm 0.7 \ h^2$ averaging over late spirals. We remind the reader that the true rate is higher since our detection efficiency is less than 100%, and because the systematic uncertainties discussed in the following paragraphs cause an underestimate of the supernova rate.

To estimate the systematic uncertainties in our results, we have recalculated the galaxy-years and supernova rates assuming different limiting magnitudes for supernova detection in our search, different template light curves, and different relationships between Type II peak luminosities and host galaxy luminosity. The detection limit of our search varies from night to night, and even hour to hour, as a function of atmospheric seeing and transmission, but is generally between R = 16 and 17. The estimated supernova rate varies by approximately 10% for type Ia supernovae and about 30% for type Ic's and II's if we vary the average detection limit 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's have a peak luminosity that ranges over four magnitudes (Miller and Branch, 1990). Since SNe type Ib are presumed to be similar explosions to type II's (Filippenko, 1988), it is possible that as more information becomes known, their light curves may likewise show a large non-uniformity. Due to observational biases, we would expect the average peak magnitude to be revised fainter. In Section IV, we give some preliminary evidence that these supernovae are in fact fainter. If the peak magnitude of type Ibc's were actually one magnitude fainter on average than the Evans, van den Bergh, and McClure 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 Poisson statistical error, the rates could be significantly larger. In the future we will try to decrease the systematic errors, by measuring our 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, especially for the sparsely observed type Ibc's would also be particularly useful. As we find more supernovae and the statistical errors become smaller we expect to reduce these sources of systematic error correspondingly.

IV. Comparison with Previous Results

One can see from Table 2 that our rates for SNe Ia are generally in agreement with those of Evans, van den Bergh, and McClure (1989) except that we find significantly higher rates of type Ibc's. Furthermore, if we include the same adjustment for dependence of type II luminosity on that of the parent galaxy as used by Evans, van den Bergh, and McClure, our type II rate nearly doubles. The higher rates are particularly apparent in the Ibc rate of late spirals, where we find a rate four 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 5 events or more is 1%. The higher rate we see 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 type Ic supernovae, 1990B, had its magnitude, B = 17.7, measured photometrically by Suntzeff (1990) at Cerro Tololo about one 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 magnitudes 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, and Turatto, 1990). If we are in fact finding a group of supernovae that are dimmer—whether or not this is due to extinction—than the Evans, van den Bergh, and McClure Ibc light curves indicate, then the Ibc rates are significantly higher, as discussed above in Section III.

For the Asiago photographic search, Cappellaro and 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 depends on the luminosity of the supernova type considered. Even for the type II supernovae, Cappellaro and Turatto adopted a different peak luminosity than that used in our calculations or those of van den Bergh et al. 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 type I's and II's differently, it is probably not useful to compare even the relative rates of type I's and type II's.

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 degrees 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 our supernova 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 June 1991.) 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 used in most previous searches 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, McClure, and Evans, 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.

V. 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 years. (We take the Milky Way luminosity to be $1.9 \times 10^{10}\ L_{Bsun}$ [Gilmore, King, and 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 by other detection inefficiencies. The rate would also be higher if it is confirmed that the supernovae Ibc's we discover are fainter than previous estimates for Ib's.

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 and Thorne 1980.) If the sensitivity of the detectors is extended to reach galaxies within 5 Mpc, then one supernova would be detected every 5 years (for h = 0.75). This estimate is based on a total luminosity of 13 x 10^{10} L_{Bsun} 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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Table 1

Supernovae Detected by Berkeley Search through June 1991

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, beginning with 1988H, shown in italics were discovered during the fiducial three-year time period used for the rate calculations in this paper.

[b] Galaxy type is from Huchra et al (in press).

[c] IAU is the International Astronomical Union circular in which the discovery of the supernova was announced.

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

[e] Cos(i) is the cosine of the galaxy inclination angle, from de Vaucouleurs and de Vaucouleurs (1964) and the NASA/IPAC Extragalactic Database (NED), operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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

Table 2

Supernova rates for the period January 1988-January 1991

All galaxies

	Ia	**Ibc**	**II**
# supernovae	3	5	4
Galaxy yrs*	1447	747	587
Avg rate*	$\mathbf{0.21^{+0.12}_{-0.07}}$	$\mathbf{0.67^{+0.25}_{-0.17}}$	$\mathbf{0.68^{+0.31}_{-0.20}}$
Evans et al. rate*	0.25 ± 0.09	0.24 ± 0.14	0.94 ± 0.27

Late spiral galaxies†

	Ia	**Ibc**	**II**
# supernovae	2	5	3
Galaxy yrs*	546	319	265
Avg rate*	$\mathbf{0.37^{+0.29}_{-0.16}}$	$\mathbf{1.57^{+0.59}_{-0.39}}$	$\mathbf{1.13^{+0.62}_{-0.38}}$
Evans et al. rate*	0.2	0.4	1.2

*The rates are in supernovae per 10^{10} L_{Bsun} 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. were adjusted to be consistent with $M_{sun} = 5.48$

†Galaxies of types Sbc, Sc, Scd, and Sd.

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