The rate of supernovae

II. The selection effects and the frequencies per unit blue luminosity

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Abstract. We present new estimates of the observed rates of SNe determined with the control time method applied to the files of observations of two long term, photographic SN searches carried out at the Asiago and Sternberg Observatories. Our calculations are applied to a galaxy sample extracted from RC3, in which 65 SNe have been discovered. This relatively large number of SNe has been redistributed in the different morphological classes of host galaxies giving the respective SN rates.

The magnitude of two biases, the overexposure of the central part of galaxies and the inclination of the spiral parent galaxies, have been estimated. We show that due to overexposure a increasing fraction of SNe is lost in galaxies of increasing distances. Also, a reduced number of SNe is discovered in inclined galaxies ($i > 30^\circ$): SNIIf and Ib are more affected than Ia, as well as SNe in Sbc-Sd galaxies with respect to other spirals.

We strengthen previous findings that the SN rates is proportional to the galaxy blue luminosity for all SN and Hubble types.

Other sources of errors, besides those due to the statistics of the events, have been investigated. In particular those related to the adopted SN parameters (Cappellaro et al. 1992) and correction factor for overexposure and inclination. Moreover, we show that the frequencies of SNe per unit luminosity vary if different sources for the parameters of the sample galaxies are adopted, thus hampering the comparison of SN rates based on different galaxy samples.

The overall rates per unit blue luminosity are similar to the previous determinations but significant differences show up for individual types. In particular, the rate in ellipticals, 0.11 SNu ($H = 75 km s^{-1} Mpc^{-1}$), is significantly lower than previously reported and better agrees with the predictions of galaxy evolutionary models. Contrary to recent claims, in late spirals the rates of SNIa (0.39 SNu) and Ib (0.27 SNu) are similar. The most frequent SNe in spiral galaxies are SNII (1.48 SNu). Even the possible occurrence of faint SNe similar to SN 1987A ($< 0.5$ SNu in late spirals) does not significantly alter the total rate of SNII.

In the Galaxy, the expected number of SNe is $1.7 \pm 0.9$ per century.

Key words: supernovae and supernova remnants: general – surveys – galaxies: general – galaxies: stellar contents of

1. Introduction

In the past, two different approaches have been followed to estimate the rates of supernovae (SNe) in external galaxies. Such calculation were either based on all the SNe discovered in a given galaxy sample or they were restricted to the SNe discovered in a single search program. In the former case it was necessary to make some assumption on the overall surveillance of the galaxy sample (e.g. Tammann 1982), whereas, in the latter case, it was possible to compute accurately the control time for each individual galaxy from the log of observations of the search (e.g. Cappellaro & Turatto 1988 hereafter CT88).

Regardless of the method used, the comparison between recently published estimates of the SN rates shows general agreement on the gross numbers, but highlights the uncertainty of the rate for a single SN type and/or in a given galaxy type (for a recent review see van den Bergh and Tammann 1993, hereafter vdB&T).

The main purpose of the present work is to reduce the problem of small number statistics by combining two independent SN searches conducted, for almost three decades, at the Asiago Astrophysical Observatory (Italy) and at the Crimean Station of the Sternberg Institute of Moscow (Russia). Also, we improve previous calculations allowing for a more detailed SN taxonomy: SN rates are estimated independently for SN Ia, Ib/c and, when the statistic allows it, for IIP (Plateau) and IIL (Linear). An upper limit is given also for faint SN II similar to 1987A.

In Paper I (Cappellaro et al. 1992) we presented the SN and the galaxy samples on which we base the new estimates. In that paper we also analysed the computational recipe and the errors induced by the uncertainties in the parameters involved. In particular, we stressed the relatively strong influence of the uncertainties in the limiting discovery magnitudes, on the average absolute SN magnitudes and on the light curves shape. The effect due to the dispersion of the absolute SN magnitudes turned out to be negligible. Finally, we emphasized that
in comparing SN rate estimates of different authors one must account for the adoption of a particular galaxy catalogue. In fact, galaxy catalogues differ not only because of their selection criteria, but also in the description of individual galaxies. Particularly important for the SN rates are differences/errors in the galaxy morphological classification and, as we will show in this paper, in the galaxy luminosity.

2. RC3 galaxy sample

After completion of Paper I, the Third Reference Catalogue of Bright Galaxies of de Vaucouleurs et al. ([1991], hereafter RC3) became available. The RC3 is expected to be reasonably complete for galaxies with angular diameter $D_\alpha > 1.0$, total magnitude $B_T < 15.5$ and recession velocity $v < 15000 \, \text{km s}^{-1}$ (∼12000 galaxies). This, combined with the relevant information reported for each galaxy, makes this catalogue particularly suitable for our investigation.

Following the recipe illustrated in Paper I, we first selected the RC3 galaxies which appear in the fields of our surveys (4301 galaxies). We then retained only those galaxies for which the redshift, the morphological type, the axial ratio and the $B_T$ magnitude are available (2461 galaxies). The total control times ($ICT = \sum_{i=1}^{n} t_{ct} i$, where $t_{ct}$ is the total control time of the $i$-th galaxy and $n$ is the number of galaxies) for the different SN types of the RC3 galaxy sample are: $ICT(Ia)=17270$, $ICT(Ib)=11510$, $ICT(IIP)=10820$ and $ICT(III) = 9783$ years (cf. Table 6 of Paper I). In the RC3 galaxy sample, using to the prescription discussed Paper I, we selected 65 SNe (cf. Tab 2 of Paper I).

Note that while the number of galaxies in the RC3 sample is about 50% larger than it was for the RC2 sample it yielded the same number of SNe. The main reason is that the RC3 sample contains a significant fraction of distant galaxies with small control times, each of which gives a small contribution to the SN statistics. In fact the ICTs of the RC3 are only ∼15% larger than for RC2 sample.

The reader is reminded that RC2 included all SN parent galaxies, known at the time of publication. Therefore it cannot be considered an unbiased collection of galaxies for SN statistics. In principle this is also reflected in RC3, since it includes all RC2 galaxies. However, a quick investigation shows that only one of the parent galaxies of our selection (NGC 4525) fails the limits of completeness of the RC3, because of its small diameter. Therefore, we can safely assume that the RC3 galaxy sample is not biased in favour of SNe producers.

3. Selection effects on the SN discovery

The control time of a galaxy is the time during which a given SN stays above the detection threshold. Sometimes a SN may be lost, even if brighter than the assumed limiting discovery magnitude $m_{\text{lim}}$, because of various random or systematic effects. Random effects include plate defects, poor weather conditions, errors of the hunter, etc. We showed in Paper I that, because of the oversampling of our combined survey, this kind of errors has only a minor impact on the calculated SN rates (<3%).

Systematic effects such as the discovery of SNe in the brightest regions of galaxies and in inclined galaxies result more severe bias. Overexposure, in particular, is expected to change with the scale of the telescope, the exposure time, etc. Hence it is expected that the correction factor will depend on the different types of instrumentation. In the following, because of the similarity of the Asiago and Crimean searches (both based on wide field telescopes and photographic plates and reaching similar limiting magnitude), we will analyse these effects on the combined surveys.

3.1. Overexposure of the nuclear regions of galaxies

It has been shown by Shaw ([1979]) that, in SN searches, a number of SNe in the central regions of the galaxies is lost. This effect was found to be dependent on the distance of the host galaxy and is relatively strong in photographic surveys. This is so because the central regions of such galaxies are overexposed due to the low dynamic range of the plates (Bartunov et al. [1991]). Visual and CCD surveys appear less affected by this effect.

To evaluate the size of this effect, we compared the radial distribution of SNe discovered in our combined search with that of the SNe discovered visually by Evans (Evans et al. [1984] and by the CCD Berkeley automated supernova search (hereafter BASS, Muller et al. [1992]) considered together. For each SN the projected relative distance from the nucleus was calculated using the relation:

$$r = 2 \times (d_a^2 + d_b^2)^{1/2}/D_\alpha$$

where $d_a$ and $d_b$ are the measured offset of the SN from the nucleus and $D_\alpha$ is the apparent diameter of the parent galaxy.

Since here we are interested only to the locations of SNe within the host galaxies (not in the rates), we can use all SNe in Tab. 2 of Paper I whose parent galaxy distances are known. The radial distribution of SNe in galaxies at different recession velocities are listed in Table I.

First of all let us compare the radial distributions in the two groups of searches (the Asiago+Crimea versus the Evans+BASS) for SNe that exploded in nearby galaxies ($v < 2000 \, \text{km s}^{-1}$). Normalizing the two distributions to the outer regions ($r > 0.25$) in the photographic surveys results in a deficiency of SNe in the inner regions. Assuming that the visual/CCD searches did not miss SNe in the central regions of nearby galaxies we find that our searches lost ∼18% of all SNe.

We then compared the radial distributions of SNe in galaxies of increasing redshift in order to test the finding by Shaw ([1979]) that increasing the distance the effect is larger. It turns out that for parent galaxies in the range 2000 to 4000 $\text{km s}^{-1}$, our photographic searches lost ∼23% of the SNe, whereas for the more distant galaxies ($v > 4000 \, \text{km s}^{-1}$) we lost about 35% of SNe (relative to the nearby Evans+BASS sample). Finally we note that, contrary to previous claims, even the combined Evans+BASS sample is affected by this bias for the more distant galaxies (Tab. I). They lost ∼22% of all SNe in parent galaxies in the range 2000 to 4000 $\text{km s}^{-1}$ (where the BASS contribution is dominant).

At first sight, the effect appears significantly smaller than that derived by Shaw ([1979], Fig. 3). However, this is mainly due to the different units adopted for the radial distances of SNe. If we carry out the same exercise using for each SN the absolute radial distance (in kpc) instead of the relative distance as in Tab. I, we find that 36% of the SNe in galaxies between 2000 and 4000 $\text{km s}^{-1}$ were lost, whereas for $v > 4000 \, \text{km s}^{-1}$ this percentage is 49%. These numbers are in excellent agreement with Shaw ([1979]). However, one must keep in mind that, at large distance, the galaxy sample is biased in
favour of intrinsically bright and large galaxies. Therefore SNe in distant galaxies are expected to have (in absolute units) a less peaked radial distribution. This is not an observational selection effect, but rather it results from the intrinsic properties of the galaxy selection. We prefer, therefore, to use the correction factors derived from the relative radial distributions.

Unfortunately, given the small numbers, it was not possible to check the possible variations of this bias for the different SN types and galaxy morphological types. In principle such a dependence is expected because of the different surface brightness profile of the various galaxy types and because of the different stellar populations to which various SN types belong.

The net result of overexposure is an underestimate of the SN rates. We account for it by simply multiplying the control time of each individual galaxy by an average factor, \( f_v \), which is function of the galaxy distance as shown in the last row of Table 1.

### 3.2. Inclination of spiral galaxies

The probability of discovering SNe in spiral galaxies depends on the inclination of the disk relative to the line of sight; SNe in more inclined galaxies being more difficult to find. At least for photographic surveys, this effect has been verified by several authors, even if different correction factors were found in different samples (Tammann 1977, CT88, Guthrie 1990, van den Bergh & McClure 1990). Usually it is assumed that the cause of this bias is the presence of absorbing layers close to the disks of spiral galaxies, that probably have been hollowed out by multiple SN explosions (van den Bergh & McClure 1990). Alternatively, it has been suggested that the higher surface brightness of inclined spirals cause the overexposure of disks on photographic plates. This would explain why this selection effect is found not to be so important for visual (vdB&T) or CCD (Muller et al. 1992) surveys.

Regardless of the causes, we try to estimate the size of this bias in our searches for the galaxies of the RC3 sample. First, we computed the inclination angle \( i \) along the line of sight, from the isophotal axial ratio \( d/D \), and through the relation (it is assumed that an edge–on system would be measured to have the axial ratio \( d/D = 0.2 \)):

\[
i = \cos^{-1} \left\{ \left( \frac{d}{D} \right)^2 - 0.2^2 \right\}^{1/2} \]

Then, the whole spiral galaxy sample was divided in three inclination bins and the SN rates per average galaxy were calculated in each bin. Note that for this purpose the control times have been corrected for the overexposure effect as determined in Sect. 3.1. The results for the different types of SNe and galaxies are shown in Fig. 1.

Even if the statistics are relatively poor, especially when considering only a particular type of SNe, a number of useful indications can be obtained from Fig. 2.

1. The inclination bias is important: in the whole sample the rate of SNe shows a sharp peak in face–on galaxies; the observed SN rate in inclined galaxies (\( i > 30^\circ \)) being about 3 times smaller. A similar result was found by van den Bergh and McClure (1990), who argued in favour of chimney like structures in the absorbing layers.

2. The bias is more severe in the late than in the early spirals, as found also by van den Bergh and McClure (1990) and by Guthrie (1994). Whereas in the inclined early spirals (S0a-Sb) the factor is only \( \sim 2 \), in the late spirals (Sbc-Sd) the rate of SNe is depressed by a factor \( \sim 4 \) (possibly only due to SNeI).

3. The bias appears dependent on the type of SNe considered: it is stronger for Ib and II (factor \( \sim 4 \)), smaller for Ia (\( \sim 1.5 \)). Among SNeII, it appears stronger for IIP than for IIL, but, due to the poor statistics, we will neglect this tentative result.

For Sdm-Sm galaxies, the statistics are very poor since only two SNe in our sample belong to parent galaxies of this type. To gain some indication, in analogy to van den Bergh & McClure (1990), we compared the distribution of the inclinations of all Sdm-Sm parent galaxies listed in the Asiago SN Catalogue (Barbon et al. 1983) with that of the RC3 galaxies of this type. It appears that the effect in Sdm-Sm is not so strong as for Sbc-Sd and, therefore, we applied to Sdm-Sm the same factors as for S0a-Sb.

In order to correct for this selection effect, the control time of each inclined (\( i > 30^\circ \)) galaxy has been multiplied by a factor \( f_{\text{inc}} \) as reported in Tab. 4.

### Table 2. Correction factors, \( f_{\text{inc}} \), for inclined (\( i > 30^\circ \)) spiral galaxies

| galaxy type | Ia | Ib | II |
|-------------|----|----|----|
| S0a-Sb      | 1  | 0.50 | 0.50 |
| Sbc-Sd      | 0.50 | 0.25 | 0.25 |
| Sdm-Sm      | 1  | 0.50 | 0.50 |

It is clear that the correction factors for inclination will significantly change the final SN rates, especially in Sbc-Sd galaxies. Therefore, the uncertainty on the correction factors is a major source of errors, as it will be discussed in Sect. 7.4.

It is worth noting that there is no general agreement on the values of the inclination factors since they depend on the

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Table 1. Radial distribution of SNe in galaxies at different distances

| \( r/R \) | \( v \leq 2000 \) | \( 2000 < v \leq 4000 \) | \( v > 4000 \) | \( v \leq 2000 \) | \( 2000 < v \leq 4000 \) | \( v > 4000 \) |
|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| \( \leq 0.25 \) | 12 | 4 | 2 | 12 | 4 | |
| 0.25 to 0.75 | 24 | 11 | 15 | 14 | 10 | |
| > 0.75 | 6 | 2 | 3 | 3 | 2 | |
| Lost SNe | 18% | 23% | 35% | ** | 22% | **

** Adopted reference distribution.
survey type. For instance, the visual search of Evans is less affected (vdB&T). The present values are similar (although not identical) to those adopted in the past for the Asiago search (CT88); we verified that the differences is in a different grouping of galaxy and SN types. Finally, we note that the values of Tab. 2 resemble the dependence on galaxy and on SN type adopted in vdB&T.

4. Dependence on the galaxy luminosity

It was first pointed out by Tammann (1974) that the SN rate in Sc galaxies is proportional to the galaxy B luminosity. A similar relation has also been proved for S0 (CT88).

To test this effect, we calculated the absolute luminosity $L_B$, for each galaxy of the RC3 sample, from the total $B_T$ magnitude corrected for galactic and internal absorption (adopting $M_B = 5.48$ and $H = 75\, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$). The blue luminosity was used as reference because $B$ magnitudes have been measured for a larger number of galaxies. However, it must be stressed that the near and the far infrared luminosities are better indicators of star formation than the blue luminosities (Gallagher et al., 1984) and may be physically more closely related to the rate of SNe with massive progenitors (II, Ib).

After correcting for the overexposure and inclination biases, as described in previous sections, we derived the SN rates for the different SN and galaxy types binned according to the galaxy luminosity. The results are summarized in Fig. 2, where indicative error bars are also reported.

The figure clearly shows that the SN rate is proportional to the B luminosity. This is true for all SN types (even if we could not test for type Ib due to the small statistics) and along the Hubble sequence of galaxy morphological types.

These results confirm previous findings and make it possible to compute SN rates in the so-called SN units, i.e. \( 1 \, \text{SNu} = 1 \, \text{SN} \, (100 \, \text{yr})^{-1} \, (10^{10} \, L_{\odot})^{-1} \). We remind the reader that SN rates expressed in SNu depend on the adopted distance scale, i.e. in our case they scale as $(H/75)^2$.

5. Dependence on galaxy catalogue parameters

Using the galaxies in common between three different catalogues we showed in Sect.8 of Paper I that discrepant morphological classifications induce significant differences in the SN rates computed for specific galaxy types. In particular, the rate of SNe in a galaxy type critically depends on the morphological classification of the few SN host galaxies, rather than...
Fig. 2. Dependence of the SN rate on the galaxy B luminosity. In the upper panels the overall SN rate and the rates of Ia and II, divided in three luminosity bins are shown. In the lower panels data for different morphological types of galaxies are plotted. Due to the poor statistics they are split only into two luminosity bins. In all figures the line passing through the origin and the barycentre of the points is drawn. In brackets are the numbers of SNe in each sample. Indicative error bars are computed assuming Poisson statistics for the SN events.

Table 3. Dependence of SN rate on galaxy catalogue parameters.

| $< L_B^{10} >$ [10$^{10}$ $L_\odot$] | SN rates | SNu |
|-------------------------------|---------|-----|
|                               | E-S0    | S0a-Sb | Sbc-Sd | All  |
| Tully                        | 1.69    | 0.13  | 0.83  | 3.00 | 0.95 |
| RSA                          | 2.83    | 0.12  | 0.42  | 1.80 | 0.66 |
| RC3                          | 2.11    | 0.11  | 0.60  | 2.17 | 0.75 |

on the existing systematic differences between the catalogues. Once the frequency is computed for groups of morphological types or for a catalogue in full, the differences on the SN rates are washed out.

We now want to test the effects due to the discrepancies in the magnitudes and absorption corrections reported by different catalogues. With this aim in mind we calculated the SN rates in SNu for the galaxies in the Tully (1988), RSA (Sandage & Tammann 1981) and RC3 (instead of RC2 as in Paper I) catalogues. The common sample contains 456 galaxies with 39 SNe. To compute the SN rates we used for each galaxy the distance, morphological type, magnitude, galactic and internal absorption, taken from each of the three catalogues. We note that while some quantities do not change significantly passing from one catalogue to another, e.g. apparent magnitude and distance, important systematic differences do occur for the internal and galactic extinctions. The results are reported in Tab. 3. From the analysis of the common galaxy sample, we reached the following conclusions:

1. There is a systematic difference among the corrected luminosity $L_B^{10}$ reported in the three catalogues, mostly due to the different corrections adopted for the Galactic and internal absorptions (col. 2 of Tab. 3). In particular, the average RC3 luminosity is $\sim 1.25$ times that of Tully and $\sim 0.75$ times that of the RSA. This reflects directly on the SN rates measured in SNu (cols. 3-6) and must be kept in mind when comparing results of authors using different source catalogues.

2. Random errors and/or systematic differences in the morphological types reported by the catalogues cause some variations in the relative rates of SNe. Obviously, the uncertainty is, more severe when a single morphological class is considered. For instance, we have verified that the SN rate in Sc galaxies of Tully is $\sim 4$ times the average value computed for all morphological types, while the same ratio is only $\sim 2.7$ if data are taken from RSA. Some effects
6. SN rates per unit luminosity

In Table 4 and Fig. 3 we report the SN rate per unit blue luminosity for the different types of galaxies and SNe (based on the RC3 sample). Because of the small numbers, IIP and IIL have been lumped together and unclassified SNe (cf. Table 2 of Paper I) have been distributed among different subtypes with the following prescriptions: a) only Ia are allowed in E-S0 or I0 galaxies (Barbon et al. 1989); b) the average ratio of discovery of our searches among the different SN subclasses is $I_a = 4 \times I_b$, IIP=IIL and $I = 0.6 \times I_{All}$. In Table 4, the numbers of galaxies are listed in col. 2, the numbers of SNe in cols. 3–5, while the rates for the different SN types are in cols. 6–8. In the last column are reported the total SN rates and the errors due only to the statistic of these events.

From Table 4 and Fig. 3 it is clearly seen that the SN rate is strongly dependent on Hubble type, with late–spirals (Sbc-Sd) being about 15 times more prolific than early–type galaxies (E-S0). This is mainly due to the contribution of type II and Ib SNe. However, it is important to note that SN Ia are also about 3 times more frequent in late spirals than they are in ellipticals.

For Ib/c the statistics are very poor, and, consequently, the uncertainty in the supernova rates is large. The ratio of the rate of Ib and Ia supernovae in late spirals is $\nu(I_b)/\nu(I_a) = 0.7$. Even allowing for the severe uncertainties in the adopted absolute magnitude and light curve of Ib (discussed in Paper I), the above ratio reaches, in the most unfavourable case (cf. Tab. 7), the value of 2. Our result is in good agreement with the same conclusion by Evans et al. (1989) and vdB&T, but significantly different from $\nu(I_b)/\nu(I_a) \sim 4$ found by Muller et al. (1993) (cf. Sect. 8).

Some concerns may arise because in Table 4 we redistributed unclassified SNe among the known subtypes using an empirical rule. To verify the relative ratio between different subtypes (without considering the absolute values of the frequencies), we report in the relative rates of occurrence of SNe in late spirals that were computed using only classified SNe. We confirm that, within the errors, Ia and Ib have similar rates whereas SNII occur at a significantly higher rate. Moreover, we show that the rates of IIP and IIL SNe are very similar.

Table 5. Relative rates $[\nu = \nu(SN \text{ type})/\nu(all)]$ of SNe in late spirals (Sbc-Sd) computed only with classified SNe

| SNe   | Ia | Ib | IIP | IIL |
|-------|----|----|-----|-----|
| num.  | 8  | 2  | 7   | 6   |
| $\nu'$ | 0.15 ± 0.05 | 0.10 ± 0.07 | 0.39 ± 0.15 | 0.36 ± 0.15 |

6.1. The rate of SNe similar to 1987A

After the discovery of the unusual SN 1987A in the LMC it has been claimed that this kind of faint SNII may be the most common SN event; the discovery of this type of SNe being strongly biased by low intrinsic luminosity (Schmitz & Gaskell 1989). It has also been proposed that some of the faint (M$\sim -14$) SNII discovered in the past are similar to SN 1987A. In particular SN 1973R (in the Sb galaxy NGC3627) and 1982F (in the Sd galaxy NGC4490) have been mentioned (van den Bergh & McClure 1989).

In analogy to what was done for the other SN types, we computed the integral control time of 1987A-like SNe for each galaxy type. Because SN 1987A is not in our SN sample, our derived rate for this SN subtype is $\nu = 0$. If we admit that the two afore mentioned SNe (belonging to our SN sample) were similar to SN 1987A, we can derive the rates of 1987A-like SNe $\nu(S0a - Sb) = 0.35$ and $\nu(Sbc - Sd) = 0.48$ SNe, consistent with the average value of van den Bergh & McClure (1989). In this case, the two SNe have to be removed from the sample of other SNII and the frequencies of SNII (Plateau +Linear) in spirals become 0.77 SNe, which is almost twice the estimate for 1987A-like SNe (0.40 SNe).

It must be noted, however, that the light curves of the two SNe were rather normal plateau type while the color indices were very red (Patat et al. 1992). It is, therefore, likely that...
Table 4. SN rate per unit blue luminosity in different types of RC3 galaxies \((H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1})\)

| galaxy | SNe | SN rate [SNU] |
|---|---|---|
| type | num. | Ia | Ib | II | Ia | Ib | II | All |
| E  | 263 | 3.0 | 0.11 | 0.11±0.06 |
| S0 | 437 | 4.0 | 0.15 | 0.15±0.08 |
| S0a, Sa | 274 | 5.2 | 0.8 | 3.8 | 0.30 | 0.15 | 0.19 | 0.64±0.24 |
| Sab, Sb | 432 | 5.0 | 1.2 | 3.8 | 0.12 | 0.12 | 0.36 | 0.60±0.19 |
| Sbc | 202 | 2.8 | 0.4 | 4.8 | 0.22 | 0.10 | 1.19 | 1.51±0.53 |
| Sc | 173 | 5.9 | 2.7 | 6.4 | 0.50 | 0.54 | 1.45 | 2.49±0.64 |
| Sbc, Sd | 351 | 5.3 | 0.3 | 6.4 | 0.48 | 0.09 | 1.87 | 2.43±0.70 |
| Scd, Sd | 304 | 1.5 | 1.1 | 1.4 | 0.20 | 0.30 | 0.40 | 0.90±0.45 |
| E, S0 | 700 | 7.0 | 0.13 | 0.13±0.05 |
| S0a-Sb | 706 | 10.2 | 2.0 | 4.8 | 0.17 | 0.13 | 0.30 | 0.60±0.15 |
| Sbc-Sd | 726 | 14.0 | 3.4 | 17.6 | 0.39 | 0.27 | 1.48 | 2.14±0.36 |
| All(∗) | 2461 | 34.6 | 6.6 | 23.8 | 0.22 | 0.11 | 0.41 | 0.74±0.09 |

(∗) including 8 I0 with 1 SNIa and 17 Pec with 1 SNIa.

they suffered a heavy reddening and that they were intrinsically different from SN 1987A. Therefore, the reported faint SNII rate has to be considered an upper limits.

7. Errors

7.1. Influence of the correction factors

We already noted that the correction factors discussed in Sect.3 have a major influence on the final SN rates and that the uncertainties on their values affect not only the absolute values of the frequencies, but also the relative ratios among the SN types and among galaxy types. For instance, it may be argued that the peak of the SN rate in Sbc-Sd galaxies, \(\sim 4\) times than in S0a-Sb, is not intrinsic but due to an overestimate of the adopted correction factor for the late spirals (cf. Sect. 3.2).

For the sake of comparison, we show in Table 6 the SN rates computed without correction factors (cols. 2–5) and with the factors adopted in Sect. 3 (cols. 6–9). The corrections increase the SN rates by about 40% for E-S0, \(\sim 88\%\) for S0a-Sb, \(\sim 210\%\) for Sbc-Sd and the overall SN rates by \(\sim 85\%\). We also tested on the RC3 sample the correction factors used in CT88 and found SN rates \(\sim 7\%\) larger than those derived with the new factors.

Table 6. Influence of the correction factors on SN rates

| galaxy type | plain | corrected | SN rate [SNU] |
|---|---|---|---|
| E-S0 | 0.09 | 0.00 | 0.00 | 0.09 | 0.13 | 0.00 | 0.00 | 0.13±0.00 |
| S0a-Sb | 0.13 | 0.06 | 0.13 | 0.32 | 0.17 | 0.13 | 0.30 | 0.60±0.19 |
| Sbc-Sd | 0.18 | 0.08 | 0.43 | 0.69 | 0.39 | 0.27 | 1.48 | 2.14±0.36 |
| All | 0.14 | 0.06 | 0.20 | 0.40 | 0.22 | 0.11 | 0.41 | 0.74±0.09 |

To estimate the errors induced by these factors, we computed the SN rates considering a 50% uncertainty on the number of SNe lost by overexposure and by inclination. The resulting errors are reported in cols. 11–13 of Tab. 6, along with the errors from other sources as described in the next section.

It is clear that this source of error is very important for all galaxies except E-S0, for which no inclination is involved.

7.2. Cumulative errors

Following the above discussion and the tests performed in Paper I, we can now give reasonable estimates of the total errors on SN rates. In Tab. 6 we list, along with the SN rates (cols. 2–4), the contributions of the different sources of error: in cols. 5–7 those derived assuming Poisson statistics for the SN events, in cols. 8–10 those related to the uncertainties in the input parameters (cf. Tab. 4 of Paper I), in cols. 11-13 those due to the uncertainties on the correction factors described in the previous section. Finally in cols. 14–16 are reported the cumulative errors obtained adding, in quadrature, the various terms. While not formally correct, given the different meaning of the individual items, we think that this numbers is a reasonable estimates of the total uncertainties of SN rates.

Of course, when considering a particular SN type in a given type of galaxy, the determinations of the SN rates are based on small numbers of SNe and, therefore, the errors associated with the statistics of the events dominate. However, if we bin the galaxies in wider morphological classes, as in Tab. 6, then the contribution of the statistics to the total error is reduced. The uncertainties in input parameters, discussed in Paper I, hence in all cases a small contributions. Instead, for spirals the uncertainty due to the correction factors, in particular the contribution of the inclination along the line of sight, is dominant. Ellipticals do not have such term, so that statistical errors prevail. Hence, the actual total errors of the SN rates are significantly larger than those due to the statistics alone, which dominate only when the SN sample is small.
Table 7. Different contributions to the errors of the SN rates [SNu]

| galaxy type | SN rate | SN statistics | input parameters | correction factors | total errors |
|-------------|---------|---------------|------------------|--------------------|-------------|
|             | Ia      | Ib | II | Ia | Ib | II | Ia | Ib | II | Ia | Ib | II | Ia | Ib | II |
| E-S0        | 0.13    | 0.05 | 0.14 | 0.02 | 0.03 | 0.05 | 0.05 | 0.05 | 0.12 | 0.07 | 0.11 | 0.19 | 0.06 |
| S0a-Sb      | 0.17    | 0.05 | 0.09 | 0.14 | 0.02 | 0.03 | 0.05 | 0.05 | 0.26 | 0.15 | 0.09 | 0.48 | 0.19 | 0.11 | 0.19 |
| Sbc-Sd      | 0.39    | 0.10 | 0.27 | 1.48 | 0.05 | 0.05 | 0.26 | 0.15 | 0.09 | 0.48 | 0.19 | 0.18 | 0.65 |

8. Discussion

In a recent paper vdB&T carefully reviewed the determinations of the SN rates published by Tammann (1982), Evans et al (1989), and CT88. Applying normalization factors to each set of statistics, they derived their best estimates of the SN rates (cf. their Tab. 8).

A direct comparison between the result of that paper and our new estimates is not straightforward, because they refer to $L_B$ luminosities not corrected for (large) internal absorption or for inclination, whereas we used corrected $L_B^0$ luminosities. A test on our sample of late spirals shows that the SN rate expressed in SNu decreases by a factor 2 if one uses $L_B^0$ instead of the uncorrected luminosities. Moreover, because the luminosities of E-S0 change less (being not affected by internal absorption) this also alters the relative SN rates between early and late Hubble types. Keeping this in mind, we compare our revised SN rates with those of vdB&T, scaling the results to our adopted value of the Hubble constant.

First of all, our rate of SN Ia in E-S0 galaxies, $\nu_{Ia} = 0.13 \pm 0.06$ SNu, is a factor 4 smaller than that in vdB&T. Moreover, our $\nu_{Ia}$ in E-S0 is 1/3 of that in late spirals, while is $\nu_{Ia}(E-S0) \approx 2 \times \nu_{Ia}(Sbc-Sd)$ in vdB&T, who assumed the rate of SNIa constant from early to late spirals. Such large discrepancies may be partially due to the different sources of the galaxy parameters, in particular, the luminosity and the internal absorption, and to the poor statistics in this type of galaxies.

Alternatively, the adoption of different corrections for selection effects can play a role. In principle, we might have overestimated the selection effects in spirals and simultaneously neglected possible selection effects in E-S0 galaxies. For instance, the shading of SNe in the nuclear region of galaxies might be more severe in E than in Sc galaxies. However, if the rates of SN Ia of vdB&T are correct then our searches must have missed almost 75% of the SNe in E galaxies, which is hard to believe. However, our total rates of SNe in late spirals are in fair agreement with the corresponding value of vdB&T, after accounting for the difference in luminosity scale.

The relative frequency of type II to Ia supernovae in late spirals is $\approx 4$ according to our estimates, and $\approx 8$ according to vdB&T. Again, this is probably related to their a priori assumption of a uniform $\nu_{Ia}$ in all spirals.

We already mentioned in Sect. 8 that our results contradict the finding by Muller et al. (1992) of a very high rate of SN Ib/c. As a possible explanation of this disagreement, one may recall that SN Ib/c have been clearly separated from SNIa only after 1985. Since our searches have produced most of the discoveries earlier, one might think that there is a bias in the subclassification within our SNI sample. Whereas this cannot be completely ruled out, we remind the reader that published spectra have been examined by Branch (1990) to assign, when possible, each SNI to the appropriate subtype. In fact, in our SN sample only $\approx 30\%$ of SNI could not be better classified, excluding SNe in E-S0 galaxies that, safely, can be assumed to be of type Ia. Moreover, from an updated version of the Asiago SN catalogue (Barbon et al. 1989), we found that the percentage of SNIb among the classified SNI is $\approx 20\%$. This is so if we consider the SNe discovered in the most active period of our searches (1960-1988), but also during the following 4 years.

On the other side, whereas the Berkeley CCD search independently discovered $\approx 15\%$ of all SNe announced after 1986 (Muller et al. 1992), they found $\approx 45\%$ of all SNe classified Ib/c in that period. This can probably be understood considering that CCDs have a very high red sensitivity, compared with normal photographic plates, and that at maximum SN Ib are significantly redder ($\langle B-V \rangle_0 \approx 1$ and $\langle V-R \rangle_0 \approx 0.5$) than SN Ia and II ($\langle B-V \rangle_0 \approx 0$ and $\langle V-R \rangle_0 \approx 0$). Instead, the SN maximum luminosities adopted by Muller et al. (1992) for their frequency computations are more suited for blue sensitive detectors. This is not a serious problem for Ia and II, given their average colors, but make a big difference for Ib’s that can be as luminous as SNeIa in the yellow–red spectral region. If this is true, the SNIb rate of Muller et al. (1992) should be reduced by a factor $\approx 2$ (cf. Paper I). This also reduces the disagreement with our Ib rate.

8.1. The local SN rate

From the values reported in Tab. 4, we can determine the expected SN rates in our Galaxy and compare them with values obtained from other sources. We assume the Galaxy to be of type Sb of $L_B \approx 0.5$ and to have a total luminosity $L_B \approx 2.0 \pm 0.6 \times 10^{10} L_\odot$ (van der Kruit 1987). In order to reduce statistical uncertainties, we use the average SN rates for the galaxy types Sab-Sbc. With these assumptions, the Galaxy is expected to produce $3 \pm 2$ Ia, $2 \pm 2$ Ib, and $12 \pm 2$ II, i.e. $17 \pm 9$ SNe per millennium (considering only the uncertainties due to SN statistics and to the luminosity of the Galaxy).

Six historical supernovae are known to have exploded in the Milky Way in the last millennium, but many more have been lost due to the heavy absorption in the galactic disk. The evaluation of the percentage of obscured SNe is not straightforward, however different authors (cf. vdB&T) agree in giving galactic SN rates ($> 50$ SNe per millennium) larger than the results discussed above. The disagreement may be reduced if the Galaxy has in fact a higher luminosity or if one adopts a later Galactic type.
The SN rate in the Galaxy can also be derived from the observed distribution of radio SN remnants. The result is $3.4 \pm 2.0$ SNe per century (vdBB&T). Within the errors this is consistent with our estimate ($1.7 \pm 0.9$). Also note that our value is in very good agreement with the best estimate of the galactic rate of $\sim 2$ SNe per century derived by van den Bergh (1990), analysing galactic SNR’s, historical SNe, and novae in M31 and M33.

Finally, it is interesting to compute the total expected number of SNe per century in the galaxies of the Local Group, where it is reasonable to assume that no SN has been missed during the last century. Using the SN rates (in SNe) of Table 3 and using for each local galaxy the morphological type and luminosity reported in the RC3, we expect 2.9 SNe per century (excluding our own Galaxy). This number is in good agreement with the observed number of 2 SN in the last century (1885A in M31 and 1878A in LMC).

8.2. Comparison with theoretical predictions

Theoretical estimates of the SN rates have been derived from models for stellar and galaxy evolution. There are, in principle, many different explosion mechanisms that can lead to a SN event, either from massive single star progenitors or from binaries. Tutukov et al. (1992) proposed, depending on different properties of binary systems, two dozen possible kinds of SNe, many of which still remain without an observed counterpart. Using a numerical program they calculated the expected numbers per century of different SN types in the Galaxy. The results can be lumped in the two major types as follows: 1.0 to 1.9 SNe per century for type I and 1.96 to 3.35 for type II. These numbers are consistent with our observed estimates for the Galaxy, the lower values being favored.

SN explosions release large amounts of energy and of heavy elements, synthesized during the evolution of the progenitors and in the explosions, in the interstellar medium. Therefore, they play a major role in the chemical and dynamical evolution of galaxies. Tornabè & Matteucci (1987) derived the present rate of SNIa in ellipticals from an evolutionary model. With the present work, the discrepancy between their predicted value, 0.04 SNe, and the observations is reduced. Moreover, they found that the expected rates of SNIa and SNIb in the Galaxy are almost identical (assuming that SNIb progenitors are in binary systems consisting of a degenerate dwarf and a non-degenerate He-star).

More recently, Ferrini and Poggianti (1992) presented a multiphase model of the evolution of elliptical galaxies that includes the chemical galactic enrichment and gas removal due to SN explosions. Their rate of SN Ia in E is in the range 0.01 to 0.10 SNe, consistent with the observed rate of Tab. [1]. Models of the chemical evolution for the solar neighbourhood and the whole disk, including detailed nucleosynthesis from SNe, have been computed by Matteucci & François (1989). They predict for our Galaxy 0.4 SNIa per century, 0.4 SNIb and 1.1 SNII, in remarkable agreement with our estimates.

9. Conclusions

A significant enlargement of the galaxy and of the SN samples used for the determination of the frequency of SNe with the so-called control time method, was obtained by including in a common database the observations of two long term SN search programmes. This allowed us to estimate the rates of SNe of various subtypes in different morphological classes of the parent galaxies. In particular, SNe Ia and Ib were considered separately as were SNe IIP and IIL in late spirals. Also an upper limit to the frequency of SNII similar to SN 1987A was computed.

We discussed the importance in our combined searches of two major selection effects, which bias our samples, against the discovery of SNe due to plate overexposure and galaxy inclination. The overexposure effect increases with the recession velocity of the parent galaxies and is stronger in our photographic searches than in visual and CCD surveys. Nevertheless, contrary to previous claims, even the latter surveys are affected when more distant galaxies are considered. The effect of galaxy inclination is large and depends on the galaxy morphology and SN type (cf. Tab. [3]).

The rates of SNe in different galaxy types (cf. Tab. [1]) have been computed in $SN = 1 S(100 yr)^{-1} 10^{10} L_{B}^{-1}$, after proving that the rates of occurrence of all SN types is proportional to the luminosity of the host galaxies. The derived rate of SNIa in E galaxies is smaller than in other galaxy types and is considerably reduced with respect to previous determinations (e.g. vdBB&T). The rate of SNIb in spirals is found to be similar to that of SNe Ia while II are the most frequent SN type.

A particular effort has been devoted to a reliable determination of the errors of the SN rates originating from the input assumptions on the SN parameters (Paper I) and from the correction factors discussed in Sect. [2]. While the errors of the SN rate in ellipticals is still dominated by the SN statistics, in spirals the uncertainties in the correction factors is dominant. In general, we show that the total errors of the SN rates are larger than those usually reported in the literature. We also tested the effect on the final SN rates of the parameters of the sample galaxies reported in three different catalogues and found that the adoption of a different correction for galactic and internal absorption will modify the SN rates (in SNe) and makes it hard to compare supernova rate determinations based on different source catalogues.

Accounting for all the sources of uncertainties our best estimates of the absolute SN rates are in the following ranges: 0.05 to 0.2 in E-S0, 0.2 to 1 in S0a-Sb and 1 to 3.5 SNe in Sbc-Sd.

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