The infrared supernova rate in starburst galaxies

F. Mannucci1, R. Maiolino2,3, G. Cresci4, M. Della Valle5, L. Vanzi5, F. Ghinassi6, V. D. Ivanov5, N. M. Nagar2, and A. Alonso-Herrero7

1 Istituto di Radioastronomia, sezione di Firenze, Largo E. Fermi 5, 50125, Firenze, Italy
2 INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125, Firenze, Italy
3 Dipartimento di Astronomia, Università di Roma, via della vasca navale 86, Roma, Italy
4 Dipartimento di astronomia, Università di Firenze, Largo E. Fermi 5, 50125, Firenze, Italy
5 ESO, Ave. Alonso de Cordova 3107, Casilla 19, Santiago 19001, Chile
6 Telescopio Nazionale Galileo, Aptdo de Correos 565, 38700 Santa Cruz de la Palma, Canary Island, Spain
7 Steward Observatory, Univ. of Arizona, Tucson, AZ85721, USA

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Abstract. We report the results of our ongoing search for extinguished supernovae (SNe) at near-infrared wavelengths. We have monitored at 2.2 μm a sample of 46 Luminous Infrared Galaxies and detected 4 SNe. The number of detections is still small but sufficient to provide the first estimate of supernova rate at near-infrared wavelengths. We measure a SN rate of SNIR = 7.6 ± 3.8 SNe which is an order of magnitude larger than observed in quiescent galaxies. On the other hand, the observed near-infrared rate is still a factor 3−10 smaller than that estimated from the far-infrared luminosity of the galaxies. Among various possibilities, the most likely scenario is that dust extinction is so high (A_V > 30) to obscure most SNe even in the near-IR.

The role of type Ia SNe is also discussed within this context. We derive the type Ia SN rate as a function of the stellar mass of the galaxy and find a sharp increase toward galaxies with higher activity of star formation. This suggests that a significant fraction of type Ia SNe are associated with young stellar populations.

Finally, as a by-product, we give the average K-band light curve of core-collapse SNe based on all the existing data, and review the relation between SN rate and far-infrared luminosity.


1. Introduction

The first report by Maiolino et al. (2002) on a sample of SNe detected in the near-infrared (NIR) has opened a new window for the search of these events. The presence of dust extinction can seriously reduce the measured SN rate in most of the galaxies, especially in starburst systems where dust obscuration is usually larger than in normal galaxies. This explains the puzzling result by Richmond et al. (1998) who found starburst and quiescent galaxies to have the same SN rate. A similar result was obtained by Navasaradyan et al. (2001) who looked for SNe in interacting galaxies, finding no evidence for correlations between SN rate and galaxy properties.

The effects of dust extinction can be vastly reduced by observing in the NIR: at 2 μm the extinction is about a factor of ten lower than in the optical V band, allowing for a much deeper penetration into the dusty star-forming regions. This strategy was originally proposed by van Buren & Norman (1989). The first monitoring campaign was conducted a decade ago and produced the detection of one event, SN 1994bu (van Buren et al. 1994). More recently, Grossan et al. (1999) monitored a large number of galaxies over two years but failed to detect extinguished SNe, probably because of their poor spatial resolution (about 3″). Bregman et al. (2000) used ISO/ISOCAM to look for mid-infrared spectral signatures of recent SNe in the nuclei of 10 nearby galaxies. However they failed to detect any emission from SNe, such as the [NiII] emission line at 6.63 μm which is very bright in SN 1987A (e.g., Arnett et al. 1989). This is probably due to the fact that the number of events expected from the far-IR flux (see Sect. 9) is lower than 0.5. Loridonov et al. (2002) reported the detection, while monitoring another event, of SN 2002cv, a bright type Ia SN showing a high extinction (Meikle & Mattila 2002). A possible SN was also discovered by Mattila et al. (2002) in an archive UKIRT K-band image.

Most SNe in starburst galaxies are expected to be core-collapse events, i.e., to have massive progenitors. The role of type Ia SNe in these galaxies is the subject of an active debate. The progenitors of type Ia SNe are commonly identified with...
old white dwarfs in binary systems, but their rate could be en-
hanced in galaxies with active star formation (see, for example,
Della Valle & Livio 1994, and Della Valle & Panagia 2003), as
discussed in Sect. 8.

Near-infrared monitoring is needed not only to compare the
SN production in quiescent and starburst galaxies, but also to
obtain a complete estimate of the local SN rate to be com-
pared with the rates at high redshift (Madau et al. 1998; Dahlén
& Fransson 1999; Sullivan et al. 2000). Finally, near-infrared
searches are needed to detect a significant number of SNe in
starburst galaxies; these events are expected to have peculiar
properties: the circumstellar medium around them is likely to
be very dense because they occur in molecular clouds and the
mass-loss rates of the progenitor stars are expected to be higher
because of the increased metallicity (Vink et al. 2001). The ef-
ects of this peculiar environment can be studied only when a
significant number of events are discovered (Bressan et al.
2002).

In 1999 we started a program aimed at monitoring a sam-
ple of starburst galaxies, as discussed in Sect. 2. The most im-
portant differences with respect to previous monitoring pro-
grams are the use of 4-m class telescopes with higher spatial
resolution, providing a deeper limiting magnitude especially
for point sources, and the selection of galaxies with higher
star-formation rate in order to have larger expected rates. This
monitoring yielded the detection of 4 SNe, 2 of which were
discovered by our group, SN 2001db (Maiolino et al. 2001)
and SN 1999gw (Cresci et al. 2002). SN 2001db is the first
SN detected in the NIR which has received a spectroscopic
confirmation.

2. The galaxy sample

The SN rate (SNe) is roughly proportional to the star-formation
rate (SFR). The best way to have a galaxy sample selected in
terms of SFR and not biased by extinction is to use the far-
infrared (FIR) luminosity \( L_{\text{FIR}} \) as measured with the IRAS 60
and 100 \( \mu \text{m} \) bands. For all but the most dust-free galaxies
this luminosity is closely proportional to the SFR as measured
from the extinction-corrected optical lines and UV continuum
and from the radio continuum (see, for example, Mannucci &
Beckwith 1995; Schaerer 1999; Cram et al. 1998).

Here we use a definition of FIR luminosity corresponding
to the flux:

\[
L_{\text{FIR}} = 1.26 \times 10^{-14} C (2.58 \cdot f_{60} + f_{100}) \quad \text{(W/m}^2\text{)} \tag{1}
\]

(Heioul 1988), where \( f_{60} \) and \( f_{100} \) are the IRAS fluxes at 60
and 100 \( \mu \text{m} \) in Jy and \( C \) is a numerical constant which depends
on the \( f_{60}/f_{100} \) ratio, and assumes values between 1.4 and 1.8.
For galaxies with dust temperatures between 20 and 80 K and
emissivity between 0 and 2, Eq. (1) is expected to estimate the
total flux between 40 and 120 \( \mu \text{m} \) within 1%.

We selected galaxies from the various catalogs of IRAS
galaxies (Sanders et al. 1995; Soifer et al. 1987; Kim & Sanders
1998) having \( L_{\text{FIR}} > 10^{11} L_\odot \) which corresponds to SN rates
larger than about 0.4 SN/year (see Sect. 9). We chose a limiting
distance modulus of 36.5, corresponding to about 200 Mpc,
in order to have a good detection (signal-to-noise ratio of
about 10) of an average SN (as SN 1980K having \( M_K = -18.8 \)
at peak) with no extinction, given a typical limiting magnitude
of \( K = 18.5 \). Three galaxies with distance modulus up to 37.3
but with very high FIR luminosities were also added to the
sample. In conclusion, half of the sample is at distances be-
low 100 Mpc. At 200 Mpc the spatial scale is 200 pc/arcsec,
allowing for an easy detection of a point source even within the
central kpc of the galaxies.

About a third of the galaxies having a spectroscopic clas-
sification suggesting the presence of a Seyfert nucleus, but in
all cases the far-infrared luminosity seems to be dominated by
star formation (see, for example, Corbett et al. 2002, and Thean
et al. 2001). We excluded from the sample a few galaxies with
low luminosity and large distance, and Mkn 231 as it contains
an AGN whose luminosity outshines the rest of the galaxy.

Table 1 lists the 46 observed galaxies together with coordi-
nates, absolute \( B \) band magnitude, FIR luminosity, redshift and
distance modulus.

3. Observations

The galaxies in Table 1 were observed between October 1999
and October 2001 using three different telescopes: the
Telescopio Nazionale Galileo (TNG) equipped with the NIR
camera ARNICA (Lisi et al. 1993) until September 2001 and
NICS (Baffa et al. 2001) afterward, the ESO NTT telescope
with SOFI (Lidman et al. 2000) and the Kuiper/Steward 61”
infrared telescope (AZ61) on Mount Bigelow, equipped with a
near-IR NICMOS3 camera.

In all cases we used the local realization of the “\( K \) short”
filter (\( K' \)), similar to \( K \) but excluding the thermal part of the
spectrum above 2.3 \( \mu \text{m} \).

The sampling time was chosen in order to maximize the
number of detections. At the limiting distance of our sample,
200 Mpc, an average SN remains above the detection limit for
about 40 days, increasing to 110 days at 100 Mpc. To be con-
servative and concentrate the observations around nights with
a full moon, we chose to observe the sample every 30 days.
The final sampling is not very uniform as the atmospheric con-
tions and the actual scheduling on the three telescopes in-
troduced some distortions on the original plan. We collected
234 observations, with an average number of 5.1 observations
per galaxy (see Table 7).

The typical on-source integration times were
about 20–30 min for NTT and TNG and 45–60 min for AZ61.
Typical values of the seeing FWHM were 1.2 arcsec at TNG,
1.0 arcsec at NTT and 1.5 arcsec at AZ61. The photometric
 calibration was achieved by using the Hunt et al. (1998) and
Persson et al. (1998) standard stars.

4. SN detection method, limiting magnitudes,
and the SNe detections

The comparison of the images of the same galaxies
was performed with ISIS, a tool developed by Alard &
Lupton (1998), refined by Alard (2000) and available at
http://www.iap.fr/users/alard/package.html. First,
all the images of a galaxy were aligned by using field stars
or the galaxy nucleus. Second, the image with the best point-
spread-function (PSF) was identified and used as reference for
the comparison with the other images. In order to minimize
the residuals without losing spatial resolution, the PSF of the
reference image was convolved with an appropriate kernel de-
termined, for each image pair, by a linear fit. ISIS was found to
give better results than other similar tasks, such as the IRAF
task “immatch”. Finally, the images were normalized to the
same total flux and subtracted.

On average ISIS is able to subtract 97% of the total
galaxy flux, with a mode of 98%. The residuals were usually
concentrated at the position of the galactic nuclei, where the
emission has a strong radial gradient. Non circular structures
such as the diffraction spikes on the spider arms are not re-
produced by the ISIS kernel. The presence of these residuals
makes the detection of nuclear SNe much more difficult, as
discussed below.

Outside the nuclear regions, i.e., about 1 arcsec away from
the galaxy center, the SN detection limit was estimated through
simulations by adding point sources to the subtracted image
and trying to recover them. The detection was performed by
using SExtractor (Bertin & Arnouts 1996) with parameters set
Table 2. SN detection limits.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>5σ limit K’ mag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>off-nucleus</td>
</tr>
<tr>
<td>NTT/SOFI</td>
<td>19.3 ± 0.4</td>
</tr>
<tr>
<td>TNG/NICS</td>
<td>18.8 ± 0.5</td>
</tr>
<tr>
<td>TNG/ARNICA</td>
<td>18.2 ± 0.3</td>
</tr>
<tr>
<td>AZ61</td>
<td>17.2 ± 0.2</td>
</tr>
</tbody>
</table>

Fig. 1. Histogram of the nuclear residuals in the TNG/NICS images. The residuals are plotted in counts/sec and the scale near the top shows the corresponding magnitudes. The Gaussian fit and the 5σ limit of K’ = 16.6 are also shown.

to have secure detections of point sources (2.5σ per pixel over an area of 6 pixels, corresponding to about a 6σ detection). The limiting magnitudes, defined at a completeness level of 50%, are listed in Table 2 for each telescope, together with their spread because of variable seeing, transparency and integration time. These values are in good agreement (within 0.1 mag) with the expectation from the parameters of the detector and of the exposures.

In the central arcsec, the presence of the PSF subtraction residuals makes it possible to detect only brighter SNe. To estimate this limit we measured the residuals inside a 1.5 arcsec aperture on each subtracted image, as shown in Fig 1. The magnitude corresponding to 5σ positive counts is taken as the detection limit. This is actually an upper limit to the real sensitivity as in doing this we assume than the measured residuals are instrumental and no SNe are actually present.

The analysis of the data revealed 4 SNe, listed in Table 3. Two objects, SN 1999gd and SN 2000bg, were independently detected by us but they had been already discovered by optical searches a few days before. Their K-band magnitudes are listed in Table 4. The other two SNe, discovered in our images, are presented in Maiolino et al. (2002). All the SNe were discovered out of the galactic nuclei; the event closest to the nucleus of its host galaxy is SN 1999gw at 3.5″ distance. As discussed in Maiolino et al. (2002), SN 2001db is highly extincted (A_V ~ 5.6), while the available data do not allow to constrain the extinction of the other SNe.

5. Computing the infrared SN rate

This paper is devoted to computing the near-IR SN rate in starburst galaxies by comparing the number of detections with the number of expected events. To do this we need a few ingredients which will be the subject of the following sections:

- The computation of the expected number of detections is based on the estimate of the control time, i.e., the amount of time that a SN in a given galaxy remains above the detection limit (as defined by Zwicky 1938). Therefore it is critical to have a good knowledge of the NIR light curve, as discussed in Sect. 6.
- The expected number of exploding core-collapse SNe is also related to the total SFR and therefore is expected to be proportional to the FIR luminosity of the target galaxies. This proportionality is discussed in Sect. 7.
- Type Ia SNe are usually assumed to have old progenitors and therefore to be more related to the total mass in stars of the galaxies than to the current or recent SFR. This might not be true for all types of Ia SNe as discussed by several authors. In Sect. 8 we discuss the relation between type Ia SN rate and stellar mass along the Hubble morphological types sequence. We will discuss the effect of including the type Ia SNe on the infrared SN rate.
- Very different detection limits apply to nuclei and to the rest of the galaxies; as a consequence, the SN rates depend of the fraction of starburst activity contained in the inner few arcsec of the galaxies. In Appendix A we discuss the existing FIR data, concluding that they do not really constrain

Table 3. Detected SNe.

<table>
<thead>
<tr>
<th>SN</th>
<th>Type</th>
<th>Galaxy</th>
<th>Discovery</th>
<th>Date</th>
<th>Band</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999gd</td>
<td>Ia</td>
<td>NGC 2623</td>
<td>1999 Nov. 24</td>
<td>Opt. 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999gw</td>
<td>II</td>
<td>UGC 4881</td>
<td>1999 Dec. 16</td>
<td>K’ 3.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000bg</td>
<td>IIn</td>
<td>NGC 6240</td>
<td>2000 Apr. 01</td>
<td>Opt. 5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001db</td>
<td>II</td>
<td>NGC 3256</td>
<td>2001 Jan. 09</td>
<td>K’ 3.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References. 1: Li (1999); 2: Filippenko & Garnavich (1999); 3: Cresci et al. (2002); 4: Maiolino et al. (2002); 5: Sato & Li (2000); 6: Jha & Brown (2000); 7: Maiolino et al. (2001);


<table>
<thead>
<tr>
<th>Date</th>
<th>K’</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1999gd</td>
<td></td>
</tr>
<tr>
<td>1999 Dec. 15</td>
<td>16.0 ± 0.2</td>
</tr>
<tr>
<td>2000 Jan. 25</td>
<td>17.4 ± 0.2</td>
</tr>
<tr>
<td>2000 Feb. 11</td>
<td>&gt;18.0</td>
</tr>
<tr>
<td>SN 2000bg</td>
<td></td>
</tr>
<tr>
<td>2000 Mar. 14</td>
<td>&gt;17.0</td>
</tr>
<tr>
<td>2000 Apr. 10</td>
<td>16.0 ± 0.3</td>
</tr>
<tr>
<td>2000 May 12</td>
<td>16.0 ± 0.3</td>
</tr>
</tbody>
</table>
the size of the starbursts, even if in many cases most of the star formation activity is concentrated in the nuclear region.

Section 9 contains the actual computation of the SN rate. This is done considering three scenarios for the spatial dimension of the starbursts: we consider the two limiting cases that the fraction of starburst in the central 2 arcsec is (a) negligible, and (b) dominant, and an intermediate case in which 80% of the starburst is contained in the nucleus. The rates are also computed both by considering the core-collapse SNe only and also by including the type Ia SNe.

6. The K-band light curve of the core-collapse SN

The evolution of the K band luminosity of the core-collapse SN is currently not very well constrained. Mattila & Meikle (2001) made a compilation of the 12 curves available at that time in the K band to derive the average light curve. The small number of available measures is due to the fact that NIR observations are not available for all the SNe and that only events with a well known epoch of the optical maximum are considered. They divided the core-collapse supernovae in two classes, the “ordinary events” showing decline rate similar to the optical band, and the “slow declining events” with NIR luminosity almost constant for hundreds of days after the optical maximum. We have added 9 new light curves for a total number of more than 200 NIR observations (see Table 5 and references therein). We have also included SN 1987A which, in the near-IR, has a less peculiar behavior than in the optical.

The resulting sample is not complete, so it should not be used for statistics. Nevertheless the fraction of the slow declining events appears to be not negligible: 7 out of 22 SNe show a peculiar behavior at some point of their evolution, and 5 of them are classified as type IIn SNe from the optical spectra. The fraction is even higher, 7 out of 12, if only the SN with observations after 4 months from the maximum are considered. Such a high fraction is certainly due to an observational bias, as SNe with NIR excess are more often observed at such late times (see, for example, Gerardy et al. 2002). SN 1987A shows a peak luminosity similar to the other events and a decline rate intermediate between the ordinary and the slow declining events.

This brightening or stabilization of the luminosity at NIR wavelengths is usually attributed to thermal emission from dust forming in the ejecta or present in the pre-existing circumstellar medium (e.g., Gerardy et al. 2002), whereas the heating could be due to the interaction between the ejecta and the circumstellar medium (Fassia et al. 2000, 2001; Di Carlo et al. 2002). For this reason the effect is expected to be more common in the events occurring in the dense star forming regions as the type IIn SNe (Schlegel 1990). These SNe become much brighter than the others, but their constant luminosity makes their detection by the usual “blinking” technique almost impossible after the maximum light.

The 15 “ordinary events” show an inhomogeneous behavior during the first 4 months. Most of them reach a maximum 10–20 days after the optical peak, and decline linearly afterward. The NIR luminosity peak of core-collapse SNe is similar to that of the type Ia, estimated to be $M_K = -18.8$ 25 days after the optical maximum (Meikle 2000), even if the core-collapse SNe are usually much fainter in the optical. SN 1999em is the least luminous event, with $K$ magnitude about 1 mag fainter at the optical maximum than any other measured SN, and shows a very delayed peak, occurring at about 70 days after the optical maximum. The luminosity spread among the SNe of each class is comparable with the spread among the different classes, i.e., there is no evidence of systemic differences for the core-collapse SNe of different sub-types.

After the first 120 days, “ordinary” SNe show similar decline rates of about 0.025 mag/day, much faster than the optical decline rate of about 0.010 mag/day at comparable stages corresponding to the $^{56}$Co decay (0.0098 mag/day, e.g., Cappellaro & Turatto 2001).

The spread of the absolute magnitude near the K-band peak is about 3 mag, and about 1.5 mag at later times. To account this large spread we have defined the upper and lower envelopes of the distributions (see Fig. 2 and Table 6) and will use these curves to compute the maximum and minimum SN rate expected from the SFR. The upper envelope is defined by SNe 1979C and 1982R, the lower envelope by SN 1999em. A few SNe, such as 1983I and 1993J, are fainter than 1999em at epochs between 50 and 120 days, but are brighter near the optical maximum and therefore were not considered for the lower envelope.

For the average light-curve we used SN 1980K, an event showing a linear decline and a peak magnitude near the average value. We preferred to use an observed event instead of an average between the two envelopes since the latter is strongly dependent on peculiar sub- or super-luminous events and does not correspond to any observed SN.

7. SN rate and FIR luminosity

To compute the number of expected SNe in our sample, we need to discuss the relation between FIR luminosity and SN rate and the role of type Ia SNe. These will be the subject of the next two sections.

Several authors have computed the SN rates as a function of the host galaxy morphological type. These estimates are based on optical observations of local galaxies having dust contents and SFRs much lower than the objects in our sample.

Rates are generally normalized to the luminosity of the parent galaxy, either the $B$ luminosity or $L_{\text{FIR}}$. The former normalization is applied when using the SN unit (SNe), i.e., the number of SNe per century per $10^{10}$ $L_\odot$ of $B$ luminosity. This luminosity has an ambiguous physical meaning: in starburst galaxies it is roughly proportional to the SFR, in quiescent galaxies it is related to the total mass in stars, and in dusty starbursts it is very sensitive to the dust content and distribution. Here we will use the rate of $0.93 \pm 0.28$ SNe by Cappellaro et al. (1999, Table 4) for galaxies later than Sb and including the rates for types II and Ibc.

For galaxies with a significant SFR it is more useful, for many applications and especially when the core-collapse SNe are considered, to normalize the observed number of SNe to the FIR luminosity, known to be proportional to the SFR. Several
Fig. 2. $K$-band light-curves of all the core-collapse supernovae available in the literature. The upper- and lower-envelope used for the computation of the control time are shown by the thick grey lines. The thick solid line shows SN 1980K. The part of the curves connected with dotted lines are varying too slowly to produce a detection and therefore were not considered to compute the envelopes. Some objects lie outside of the plot because only observations at epoch $>400$ days are available.

indirect methods based on radio, FIR or mid-infrared observations have been used to derive the SN rate in obscured starburst galaxies, as described in van Buren & Greenhouse (1994) and Mattila & Meikle (2001). These authors have derived the relation between the SN rate and $L_{\text{FIR}}$ using galaxies of low FIR luminosity, and therefore a large extrapolation is needed to apply these results to our sample. We have extended the observed range toward high luminosities by using the relation between radio luminosity and SN rate in Condon & Yin (1990) and data in Hackenberg et al. (2000) and Wilson et al. (1991). The SN rate appears to be proportional to $L_{\text{FIR}}$ with a small scatter for luminosities between $1.6$ and $30 \times 10^{10} L_\odot$ as shown in Fig. 3, without the detection of any dependence on the luminosity of the galaxy or on the SFR. Using the definition of $L_{\text{FIR}}$ in Eq. (1), we obtain the relation:

$$SNr = (2.4 \pm 0.1) \times (L_{\text{FIR}}/10^{10} L_\odot) \text{ SN/100 yr}$$

which, we stress, is based on indirect measures of the SN rate. A similar value of the proportionality factor (2.7) was also obtained by Mattila & Meikle (2001) even though they use a slightly different definition of $L_{\text{FIR}}$. In that case the data range was below $L_{\text{FIR}} = 10^{10.8} L_\odot$, a factor of two below the faintest galaxy in our sample. These authors discuss how this factor is in good agreement with the expectations from the models of galaxy stellar populations which predict the FIR luminosity from the UV flux and the SN rate from the product of the
Table 5. Core-collapse SNe used to define the NIR light curve. Name, type, epoch of optical maximum, distance modulus, number of $K$ band observations and references are reported.

<table>
<thead>
<tr>
<th>SN</th>
<th>Type</th>
<th>Epoch (JD)</th>
<th>$(m - M)$</th>
<th>$N_{\text{obs}}$</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979C</td>
<td>IIL</td>
<td>2443979</td>
<td>31.03</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>1980K</td>
<td>IIL</td>
<td>2444543</td>
<td>28.78</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>1982E</td>
<td>Ib</td>
<td>2445057</td>
<td>31.39</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>1982R</td>
<td>Ib</td>
<td>2445248</td>
<td>31.22</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>1983I</td>
<td>Ic</td>
<td>2445413</td>
<td>31.30</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>1983N</td>
<td>Ib</td>
<td>2445533</td>
<td>28.49</td>
<td>17</td>
<td>1.5</td>
</tr>
<tr>
<td>1983V</td>
<td>Ic</td>
<td>2445672</td>
<td>31.30</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>1984L</td>
<td>Ib</td>
<td>2445943</td>
<td>31.52</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>1985L</td>
<td>IIL</td>
<td>2446227</td>
<td>31.51</td>
<td>5</td>
<td>1</td>
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<tr>
<td>1985P</td>
<td>IIP</td>
<td>2446347</td>
<td>30.47</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>1987A</td>
<td>IIP</td>
<td>2446849</td>
<td>18.55</td>
<td>many</td>
<td>7</td>
</tr>
<tr>
<td>1993J</td>
<td>IIn</td>
<td>2449095</td>
<td>27.80</td>
<td>25</td>
<td>8–14</td>
</tr>
<tr>
<td>1994I</td>
<td>Ic</td>
<td>2449451</td>
<td>29.60</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>1995N</td>
<td>Iln</td>
<td>2449539</td>
<td>32.07</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>1997ab</td>
<td>Iln</td>
<td>2450186</td>
<td>33.49</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>1998S</td>
<td>Iln</td>
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<td>IIn</td>
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<td>35.11</td>
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<td>20</td>
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<tr>
<td>1999em</td>
<td>IIP</td>
<td>2451483</td>
<td>29.38</td>
<td>35</td>
<td>21</td>
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<tr>
<td>2002ap</td>
<td>Ic</td>
<td>2453314</td>
<td>29.52</td>
<td>6</td>
<td>22–25</td>
</tr>
</tbody>
</table>

References. 1: Mattila & Meikle (2001); 2: Dwek et al. (1983); 3: Graham (1985); 4: Muller (1985); 5: Elias et al. (1985); 6: Clocchiatti et al. (1997); 7: Bouchet et al. (1989); 8: Calamai et al. (1993); 9: Odewahn et al. (1993); 10: Lawrence et al. (1993); 11: Romanishin (1993); 12: Smith (1993); 13: Kidger et al. (1993); 14: Matthews et al. (2002); 15: Grossan et al. (1999); 16: Gerardy et al. (2002); 17: Fassia et al. (2000); 18: Patat et al. (2001); 19: Di Carlo et al. (2002); 20: this paper; 21: Hamuy et al. (2001); 22: Motohara et al. (2002); 23: Yoshii et al. (2002); 24: Mattila et al. (2002) 25: Mannucci et al., in prep.

Table 6. Reference $K$-band light curve and lower- and upper-envelopes for core-collapse SNe. Epoch refers to the optical maximum.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Lower</th>
<th>SN $1980K$</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>−1</td>
<td>−16.07</td>
<td>−18.66</td>
<td>−19.25</td>
</tr>
<tr>
<td>9</td>
<td>−16.30</td>
<td>−18.44</td>
<td>−19.87</td>
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<tr>
<td>22</td>
<td>−16.60</td>
<td>−18.23</td>
<td>−19.85</td>
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<tr>
<td>30</td>
<td>−16.70</td>
<td>−18.11</td>
<td>−19.70</td>
</tr>
<tr>
<td>55</td>
<td>−16.98</td>
<td>−17.57</td>
<td>−19.08</td>
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<tr>
<td>75</td>
<td>−16.95</td>
<td>−17.11</td>
<td>−18.58</td>
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<tr>
<td>109</td>
<td>−16.32</td>
<td>−16.34</td>
<td>−17.73</td>
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<tr>
<td>123</td>
<td>−15.37</td>
<td>−16.02</td>
<td>−17.38</td>
</tr>
<tr>
<td>144</td>
<td>−15.14</td>
<td>−15.54</td>
<td>−16.85</td>
</tr>
<tr>
<td>300</td>
<td>−11.25</td>
<td>−11.64</td>
<td>−12.95</td>
</tr>
</tbody>
</table>

SFR times the integral of the Initial Mass Function (IMF) over the appropriate mass range. Finally, Cappellaro et al. (1999) obtained the ratio between the rate of unobscured SNe from optical monitoring and the FIR luminosity of a large number of galaxies from the RC3 catalog. They obtained a coefficient of 2.5, in good agreement with our calibration.

Fig. 3. SN rates vs. $L_{\text{FIR}}$ for a sample of galaxies with active star formation. From left to right: UGC 1347 (Hackenberg et al. 2000); NGC 253 (Mattila & Meikle 2001 and references therein); NGC 7673 (Condon & Yin 1990) M 82 (Mattila & Meikle 2001 and references therein); NGC 4038 (Neff & Ulvestad 2000); NGC 1068 and NGC 7469 (Wilson et al. 1991). When not available, errors of 50% of the measured values were assumed. The solid line shows a fit to these points passing through the origin, the shaded region the associated 1σ error. The double arrow shows the upper- and lower limits for NGC 7771 (Smith et al. 1999) due to a poorly known correction for incompleteness.

Smith et al. (1999) measured the SN rate in the central 10" of NGC 7771, a starburst galaxy with $\log(L_{\text{FIR}}/L_\odot)=11.25$. This value cannot be used for the above relation because it only referred to the central part of the galaxy. To correct this SN rate to a value appropriate to the total galaxy, we assume that the FIR luminosity is well traced by the 15 $\mu$m emission (see, for example, Elbaz et al. 2002) and use the growth profile by Dale et al. (2000). This is probably an overcorrection, as the size of the region emitting 80% of the 15 $\mu$m luminosity is 54" while Zink et al. (2000) obtain an upper limit to the 100 $\mu$m emitting region of about 20". In Fig. 3 we show the upper- and lower-limits to the SN rate in NGC 7771: the value predicted by Eq. (4) is within the permitted range.

8. The role of type Ia SNe

The progenitors of the type Ia SNe are expected to be old systems containing a white dwarf accreting mass from a companion star. If all Ia SNe are produced by the same old progenitors, their properties (as absolute magnitude at maximum, decline rate and expansion velocity of the ejecta) should not correlate with the current SFR of their host location. On the other hand several authors have discovered systematic differences between type Ia SNe in galaxies of different Hubble types in terms of optical spectral properties (Branch & van den Berg 1993,
Fig. 4. Upper panel: type Ia SN rate by Cappellaro et al. (1999) normalized to that in the elliptical galaxies. The rates were measured in SNu, i.e., were compared to the $B$ luminosity of the galaxies. The bars show the errors in the observed rates. Lower panel: the relative SN rate are normalized to the total stellar mass of the galaxies as in Bell & de Jong (2001). A factor of 7 of increase is observed from the ellipticals to the irregular galaxies. The grey region show the effect of the uncertainties on $M/L$ due to the color spread in each galaxy Hubble type. The dotted line is the same of the upper panel and is shown as reference.

and references therein), photometric differences (Della Valle & Panagia 1992), photometric evolution (Hamuy et al. 2000) and rates of occurrence (Della Valle & Livio 1994).

If the progenitors are old, the number of type Ia SNe should also roughly correlate with the total stellar mass. This fact is barely detectable from the SN rate expressed in SNu as the $B$ luminosity is not a good tracer of stellar mass. On the contrary, the luminosity in the $K$ band is a much better tracer, as discussed for example by Brinchmann & Ellis (2000). The dominating uncertainties are due to the age of the stellar population, and Bell & de Jong (2001) propose a method to correct for this effect from the observed colors. We have therefore corrected the rates in Cappellaro et al. (1999) by using the average $B-K$ colors for galaxies of the various Hubble type by Fioc & Rocca-Volmerange (1999) and the corrections to the $M/L$ ratio by Bell & de Jong (2001). show an increase of about a factor of 2 of the SN rate in the Sbc-Sd galaxies over that in the ellipticals, rising to about a factor of 7 for Sm-I galaxies. These values could be affected by systematic errors, but the results are consistent with the hypothesis of a substantial enhancement of the type Ia SN rate due to young stars. The details of this computation and the relation between the stellar mass and the type Ia rate will be subject of a forthcoming paper.

Based on this kind of evidences, Della Valle & Livio (1994) found that late type spirals are more prolific producers of type Ia SNe and proposed the association of part of the type Ia SNe with younger stellar populations.

For these reasons, we will make the calculations under two opposite limiting hypothesis that (1) none, and (2) all the type Ia SNe derive from young progenitors. In the second hypothesis the expected SN rate is raised by about 30% as this is the fraction of type Ia SNe vs. the core-collapse SN measured by Cappellaro et al. (1999) for galaxies later than Sbc. In this case the number of detected SN is also increased, as the type Ia SN 1999gd must be included in the sample, and the two effects (larger expected rates and more observed events) tend to cancel each other.

9. The infrared SN rate

The rates we can finally compute depend on the control time and therefore on the limiting magnitude. In the central 1 or 2 arcsecs of the galaxy nucleus the capability of detecting SNe is dimmed because of the presence of residuals after the subtraction, as discussed in Sect. 4. Although the area affected by the residuals is a small fraction of the total galaxy, this part could contain a significant fraction of events because it could host a compact nuclear starburst region at the bottom of the potential well. In Appendix A we discuss the information on the size of the starburst region coming from the mid-IR and far-IR data, and we conclude that many galaxies might be dominated by a compact starburst but that the spatial resolution of the data is too poor to obtain definitive conclusions.

As a consequence we compute the rates in the two limiting cases that the FIR flux in the nuclear region is (a) negligible (labeled as off-nuclear case) and (b) dominant (nuclear). Given that in many cases most of the starburst activity seem to originate in the nuclear part of the galaxy, we have also considered a third intermediate case (0.2off+0.8nuc) in which 80% of the starburst is contained in nucleus and the remaining 20% is distributed in the rest of the galaxy. Such a scenario is conservative but compatible with all the observations mentioned in Appendix A.

The rates are computed both for core-collapse SNe only and also by including the type Ia events. The results are summarized in Table 8.

In each case, we have computed the control time (i.e., the amount of time a SN remains visible in our images) for each galaxy in Table 1 by using the average type Ia light curve and, for the core-collapse events, the light curve of SN 1980K and the upper- and lower envelopes in Fig. 2. From the control time we computed the expected number of detected SNe using the galaxy’s $B$ and FIR luminosities and using the appropriate limiting magnitude (see discussion in Sect. 4). The control times computed in this way corresponding to the off-nuclear limits are listed in Table 7. Table 8 gives the expected number of detections for the whole sample and the corresponding number of detections.

The uncertainties on the number of expected events are due to (1) the spread of the SN $K$-band luminosity (see Fig. 2), (2) the uncertainties in the ratio between $B$ luminosity and SN rate, and (3) the spread of the limiting magnitude in our images. The first effect is the dominant one: for example, when using the average light curve (SN 1980K) and the off-nuclear limits, 0.70 core-collapse SNe are expected from
the B luminosity, while 0.90 and 0.46 events are expected when using the light curves corresponding, respectively, to the upper and lower envelope of Fig. 2.

From Table 8 it is apparent that in all cases the number of SNe predicted from the B luminosity, between 0.31 and 0.84, is much lower than our 4 detections. When the SN rate is estimated from the FIR luminosity we obtain drastically different results: the expected number of SNe is higher by a factor of 3–10 than the SNe actually detected (see next section).

The number of the detected SNe can also be used to derive a near-IR SN rate (SN$_{\text{NIR}}$), i.e., based on near-IR observations. We consider only the case with 80% of FIR luminosity coming from the nucleus. The rates were computed by dividing the total number of SNe by the sum of the luminosity of the galaxies times the control time. By using both the B luminosity and $L_{\text{FIR}}$ we obtain, respectively:

\[
\text{SN}_n^{\text{NIR}} = 7.6 \pm 3.8 \pm 2.8 \text{ SNe (}\text{B})
\]

\[
\text{SN}_n^{\text{NIR}} = 0.53 \pm 0.27 \pm 0.21 \text{ SNeIR.}
\]

The two errors terms in each equation are due to the statistics of the number of detections and the uncertainties in the computation of the control time, respectively. It should be noted that the first one (statistics) is the dominant term due to the small number of detections, and that the second one (control time) is not a standard “1σ” 68% value but rather a total 100% uncertainty.

### 10. Comparison between expected and detected SN rates

The first conclusion is that NIR searches for SN in starburst galaxies are, as expected, more efficient than similar searches at optical wavelengths since at least some of the SNe occurs in dusty environments. Two SNe were in fact only detected in the NIR, and Maiolino et al. (2002) demonstrated that at least SN 2001db was too absorbed ($A_V$ ~ 5.6 mag) to be detected during routine optical SN surveys even at its maximum. This is also the case for the type Ia SN 2002cv discovered in the NIR by Di Paola et al. (2002) and for which Meikle & Mattila (2002) derived an extinction in excess of $A_V = 6$ mag.

The second conclusion is that we are detecting more SNe than expected from the B luminosity, both considering or neglecting the contribution from type Ia SNe. The hypothesis that the detected number of core-collapse SNe (3) is still compatible with the expectations (0.34) can be rejected at more than the 99.5% confidence level. A very similar result is obtained if we include the type Ia SNe (0.49 predicted vs. 4 observed).

This high value for the observed SN rate reflects the higher extinction affecting the B light (which is the normalizing factor for SNe) of the galaxies in our sample, and the higher SN detection efficiency of the NIR observations with respect to the optical.

This result is not only due to obscuration, as 2 of the 4 detected SNe were also observed in the optical. For this reason
the low success rate of previous NIR surveys for SNe is probably due to modest star forming activity of the monitored galaxy sample: for this work we used galaxies with higher rates of star formation which translates into a higher expected SN rate.

The third conclusion is that the majority of SNe expected from the FIR luminosity are still missing, i.e., we have detected only about 10–30% of the expected SNe. This small number of detections can be explained in several ways:

1. Most of the SNe are so embedded into the dust that their luminosity is vastly reduced even at near-IR wavelengths. The average extinction $A_V$ needed to reduce the expected number of 15 SNe to the observed number of 4 is $A_V = 31$ mag, or $A_V > 26$ (corresponding to 8 SNe) with a formal confidence level of 90%. These values for the extinction are similar to those obtained by Genzel et al. (1998) from mid-infrared spectroscopy of several luminous galaxies, and by Mattila & Meikle (2001) for M82 by assuming a gas-to-dust ratio similar to the Milky Way. In this case, a NIR search for SN can detect only a fraction of the total SN rate, and a radio survey should also be planned.

2. If 100% of the FIR flux comes from the central arcsec, only 11 events are expected because of the residuals present in the nuclear region even after applying a PSF matching algorithm. When considering also the uncertainties in the predictions, dominated by the dispersion in luminosity of the SNe, the number of expected SNe is compatible with the observed one without the need of a large additional extinction. The presence of a large number of SNe in the central arcsec of the starburst galaxies can be tested by near-IR monitoring from space: NICMOS on HST can provide images with higher resolution ($\approx 0.2''$) and the more stable PSF to considerably reduce the central residuals and reveal the nuclear SNe. Early results on such a project based on 4 galaxies will be presented in a forthcoming paper (Cresci et al. 2003, in preparation).

3. Another possibility is the presence of AGNs dominating the FIR flux of most of the galaxies: in this case the FIR flux would not be related to the SN rate. There is evidence that the AGN does not dominate the energetics of the galaxies with $L_{\text{FIR}} < 2 \times 10^{12} L_{\odot}$ (e.g., Sanders & Mirabel 1996). Nevertheless it is sometimes difficult to exclude the presence of an AGN completely enshrouded by dust and therefore elusive in the optical/IR or even in the X-rays (Marconi et al. 2000; Maiolino et al. 1998).

4. Equation (4) may overestimate the SN rate for a given FIR luminosity. Many of the points in Fig. 3 and in particular that for the most luminous galaxy NGC 7496 are, directly or indirectly, derived from radio observations and make use of the empirical relations by Condon & Yin (1990). In turn, this is based on radio observations of the Milky Way and on the estimate of its SN rate (Tammann 1982). If the SN radio luminosity has a strong dependence on environment or if the estimates of the Galactic SN rate are subject to strong incompleteness, the coefficient in Eq. (4) could be inadequate. We believe that this is not a likely possibility as there is a robust concordance among several different methods and this relation has been stable through the years (see, for example, Rieke et al. 1980).

5. Part of the difference could also be due to a different IMF in the starburst regions with respect to more quiescent galaxies. Such an effect, studied in M 82 by Rieke et al. (1993), could change the relation between luminosity and SN rate. If present, it is not likely to be a dominant effect as both the FIR luminosity and the core-collapse SNe derive from massive stars.

6. An environment dependence could also be present in the SN luminosity: as an example, SN in dense environments are expected to show a flatter light curve because of the presence of a light echo (e.g., Roscherr & Schaefer 2000). This has some consequences on the expected number of SNe: events showing the “ordinary” decline rate can be detected even if observed only after the maximum light, while the detection of “slow” events need the comparison of images taken before and after the explosion. In the former case the total useful time contains also one control time before the first image, in the latter case only the time between the images should be considered, and the control time is reduced by about 25%. Therefore this effect could be present but is not strong enough to explain the reduced number of detections.

11. Summary and conclusions

We have monitored 46 infrared luminous galaxies at near-infrared wavelengths to look for obscured SNe, and detected 4 SNe, 3 core-collapse and 1 type Ia events. The analysis of this data set has allowed us to derive for the first time the infrared SN rate in starburst galaxies.

To apply the control-time technique, we have collected more than 200 observations of 21 core-collapse SNe to derive their average, maximum and minimum $K$-band luminosities. We have also extended the relation by Mattila & Meikle (2001) between SN rate and FIR luminosity toward objects with higher SFR in order to cover the luminosity range of the galaxies in our sample. This relation remains linear, i.e., the SN rate is proportional to the FIR luminosity, pointing toward a substantial uniformity in this property between quiescent and active galaxies.

We have computed the rate of type Ia SN as a function of the stellar mass of the galaxy, finding a clear evidence of its increase toward galaxies with higher activity of star formation. This is an other indication that a fraction of type Ia SNe is probably associated with relatively young stellar populations.

We estimated the expected SN rate from the optical ($B$) and FIR luminosities of the sample of galaxies and compared those predictions to the number of detections. The SN rate predicted from the $B$-band luminosity is several times below the observed rate. This is likely to be explained by a number of reasons, the most important of which is the effect of dust obscuration on the optical luminosity of the galaxies. On the contrary, a factor of 3–10 more SNe than observed are predicted by the FIR luminosity. Among various possibilities, this can be explained by the presence of dust extinction of at least $A_V = 30$. This result prompts to the revision of the local SN rate obtained in the
past, as optical monitoring campaigns have probably missed a significant fraction of SNe.

Acknowledgements. We are grateful to S. Mattila and P. Meikle for useful discussions and to Marcia and George Rieke for the use of the AZ61 near-infrared camera.

Appendix A: The spatial dimension of the starburst activity

The spatial resolution at 100 μm is too low to image the spatial distribution of the starburst activity; the highest resolution achieved of this type of galaxies is about 23″ by Zink et al. (2000), much larger that the scale of about 2′ of importance here. Even at this coarse resolution, these authors were able to clearly resolve 6 of their 22 galaxies, and obtain “some evidence for extension” in 7 more objects: as a result about two third of this incomplete sample have 100 μm dimension above 20″.

Indirect evidence, but on a smaller scale, can be found by considering the images at mid-infrared wavelengths. The tight correlation existing between the emission at 100 μm and at 15 μm for galaxies over 4 orders of magnitudes of luminosity (Elbaz et al. 2002) implies that the mid-infrared should trace the 100 μm emission (unless an AGN is present). High resolution mid-infrared images of luminous infrared galaxies were obtained by Dale et al. (2000) using ISO. Most of the galaxies show emission coming from several kpc of size, corresponding to several (2–20) arcsec in our galaxies. A possible correlation is also seen between \( L_{\text{FIR}} \) and the size of the region emitting 80% of the 15 μm emission (see Fig. A.1) for the galaxies with \( L_{\text{FIR}} > 10^{10} L_\odot \). According to this relation, no starburst region in the galaxies in our sample should have dimensions below 4″.

Bushouse et al. (1998) studied the relative distributions of several indicators of star formation, such as Hα, mid-infrared, far-infrared and radio continuum, and found a good correlation between these indicators in the central regions of a few nearby galaxies. At 10 μm, the emitting source is usually not resolved at their resolution of about 5″, indicating that most of the starburst is concentrated in the nucleus. The upper limits to the size of the far-infrared region are generally compatible with those from the mid-infrared. In one case, NGC 660 (log(\( L_{\text{FIR}}/L_\odot \)) = 10.38), the infrared emission is resolved both in the mid- and in the far-infrared: at 10 μm Bushhouse et al. (1998) found a size of about 320 pc, while Smith & Harvey (1996) obtained about 2 kpc at 100 μm. At least in this case the far-infrared emission seems more extended than at shorter wavelengths.

Soifer et al. (2001) imaged a small number of high-luminosity galaxies with Keck at 12.5 μm with a field-of-view of 17″×17″. They generally find that most of the emission comes from the central 2–3″, much more compact regions than found in the sample by Dale et al. (2000). This result is somewhat unexpected because of the small field-of-view, but suggests once more that the nuclear star formation contributes most of the mid- and far-IR.

In conclusion, current data don’t put tight constraints of the dimension of the starburst activity and therefore it is not possible to estimate the amount of FIR flux originating the in the central 2 arcsec. For this reason we have computed the SN rate in the two limiting cases that none and all the FIR flux comes from the nuclear region. Given that most galaxies seem to be dominated by nuclear starburst we have also computed the SN rate by assuming the 80% of the FIR flux originates from the nucleus and 20% from the rest of the galaxy.

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