A NICMOS search for obscured Supernovae in starburst galaxies

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Abstract. The detection of obscured supernovae (SNe) in near-infrared monitoring campaigns of starburst galaxies has shown that a significant fraction of SNe is missed by optical surveys. However, the number of SNe detected in ground-based near-IR observations is still significantly lower than the number of SNe extrapolated from the FIR luminosity of the hosts. A possibility is that most SNe occur within the nuclear regions, where the limited angular resolution of ground-based observations prevents their detection. This issue prompted us to exploit the superior angular resolution of NICMOS-HST to search for obscured SNe within the first kpc from the nucleus of strong starbursting galaxies. A total of 17 galaxies were observed in SNAPSHOT mode. Based on their FIR luminosity, we expected to detect not less than $\sim 12$ SNe. However, no confirmed SN event was found. From our data we derive an observed nuclear SN rate $< 0.5$ SN/yr per galaxy. The shortage of SN detections can be explained by a combination of several effects. The most important are: i) the existence of a strong extinction, $A_V \gtrsim 11$; ii) most SNe occur within the first 0.5" (which corresponds in our sample to about 500pc) where even NICMOS is unable to detect SN events.

Key words. Supernovae: general – Galaxies: starburst – Infrared: galaxies

1. Introduction

Current measurements of supernova (SN) rate are entirely based on events detected during surveys carried out at the optical wavelengths. This constitutes a problem, since many SNe could be obscured by dust. As a consequence, the derived SN rates, especially for core–collapse and Ia “prompt” SNe (Mannucci et al. 2005, 2006) in the distant universe, may be only lower limits. As an example, we point out that several monitoring campaigns of starburst galaxies, carried out at the optical wavelengths, do not show evidences for an enhanced SN rate with respect to normal quiescent galaxies (e.g. Richmond et al. 1993, Navasardyan et al. 2001). Near-infrared (near-IR) observations can shed light on this problem, as the extinction at these wavelengths is about ten times lower than in the optical. The importance of near-IR was demonstrated by Maiolino et al. (2002), who showed, on the basis of a small sample of SNe detected in the near-IR, that the rate of supernovae measured in the optical could be significantly reduced by dust extinction up to an order of magnitude.

During the last decade other near-IR searches for extincted SNe were attempted. Van Buren et al. (1994) detected SN1992bu (a possible SN not confirmed spectroscopically). 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. Bregman et al. (2000) searched for line emission at longer wavelengths (6.63 $\mu$m using ISOCAM), but did not detected any feature connected with SN events. More recently, Mattila et al. (2004a, 2004b) discovered two SNe during their monitoring in Ks band with the William Herschel Telescope. Di Paola et al. (2002) reported the near-IR serendipitous discovery of SN2002cv, an high extincted ($A_V \sim 8$) type Ia SN.

In late 1999 Mannucci et al. (2003) started a K’-band monitoring campaign of a sample of 46 Luminous Infrared Galaxies (LIRGs, $L_{\text{FIR}} > 10^{11} L_{\odot}$), aimed at detecting obscured SNe in the most powerful starbursting galaxies.

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During the monitoring 4 SNe were detected, two of which were discovered by our group: SN1999gw (Cresci et al. 2002) and SN2001db, the first SN detected in the near-IR which has received a spectroscopic confirmation (Maiolino et al. 2002).

The number of detected events was about an order of magnitude higher than expected from the B band luminosity of the parent galaxies (Cappellaro et al. 1999), showing that the B band luminosity can not be used to trace the star formation in starburst galaxies. Although these results highlight the capability of near-IR observations to reveal obscured SNe, otherwise missed in classical optical surveys, Mannucci et al. (2003) also showed that the inferred SN rate was still 3-10 times lower than the expected number of SNe in our data, that is compared with the results obtained in Sect. 4; our conclusions follow in Sect. 5.

2. The use of NICMOS to search for nuclear obscured SNe

The HST near-IR camera NICMOS is an excellent tool to search for obscured nuclear SNe in starburst galaxies, since it joins a high sensitivity in the near-IR, where the dust extinction is greatly reduced, to a high angular resolution (0.2′′) and stable PSF, allowing for a much easier detection of SNe close to the nucleus in the difference image.

We selected a sample of 35 Luminous and Ultraluminous Infrared Galaxies (LIRGs and ULIRGs) closer than about 450 Mpc (z ≤ 0.1) and already observed once with NICMOS in the F160W filter with the NIC2 camera, so that a first epoch image was already available. We then obtained a second epoch in SNAPSHOT mode for 16 of the selected galaxies. For one galaxy, NGC 34, we have compared two images at different epochs already present in the archive (see Tab. 2). The list of these 17 galaxies is given in Tab. 1 along with their far-IR flux and redshift, while the relative observational setups are given in Tab. 2. Images were reduced by using the On The Fly Reprocessing system of the HST archive (Swam et al. 2001). The comparison of the images was in fact performed with ISIS, a tool developed by Alard & Lupton (1998) and refined by Alard (2000). The images are aligned using field stars, than the image with the best PSF is selected as reference to be compared with all others frames of the

| Galaxy      | R.A. (J2000) | DEC. | $L_{\text{FIR}}$ | z  |
|-------------|--------------|------|-------------------|----|
| NGC 34      | 00h11m06.3s  | −12d06m26s | 11.43            | 0.02 |
| NGC 1614    | 04h33m59.8s  | −08d34m44s | 11.41            | 0.016 |
| VV-ZW031    | 05h16m47.3s  | +79d40m12s | 11.94            | 0.053 |
| IRAS 05189-2524 | 05h21m01.4s | −25d21m45s | 11.89            | 0.042 |
| IRAS 08572+3915 | 09h00m25.4s | +39d03m54s | 11.99            | 0.058 |
| UGC 5101    | 09h35m51.4s  | +61d21m11s | 11.90            | 0.039 |
| NGC 3256    | 10h25m51.8s  | −43d54m09s | 11.44            | 0.009 |
| IRAS 10565+2448 | 10h59m18.1s | +24d32m34s | 11.87            | 0.042 |
| NGC 3690    | 11h28m31.9s  | +58d33m45s | 11.72            | 0.011 |
| NGC4418     | 12h26m54.6s  | −00d52m39s | 11.00            | 0.007 |
| Mrk 273     | 13h44m42.1s  | +55d53m13s | 12.10            | 0.038 |
| UGC 8782    | 13h52m17.7s  | +31d26m44s | 12.27            | 0.045 |
| IRAS 14348-1447 | 14h37m38.2s | −15d00m26s | 12.27            | 0.082 |
| Arp 220     | 15h34m57.3s  | +23d30m12s | 12.12            | 0.018 |
| NGC 6090    | 16h11m40.3s  | +52d27m26s | 11.35            | 0.029 |
| IRAS 20414-1651 | 20h13m29.4s | −16d40m16s | 11.99            | 0.087 |
| IRAS 23128-5919 | 23h15m46.8s | −59d03m14s | 11.80            | 0.044 |

Table 1. The galaxy sample. The RA and DEC position reported correspond to the optical center of the galaxies; $L_{\text{FIR}}$ is log($L_{\text{FIR}}/L_\odot$) (Mannucci et al. 2003) where $L_{\text{FIR}}$ is defined accordingly to Helou et al. 1988 as the luminosity between 42.5 to 122.5 μm; z is the redshift.
Table 2. Summary of the first epoch archive image and second epoch new NICMOS observation. Date is the date on which this image was taken, Exp. Time is the exposure time in second used for that image. Mag$_L$ the limiting magnitude obtained in the subtraction in the region of the galaxy interested by the subtraction residuals (in) and in the outer parts (out); Non-Det. Radius the radius of the central region where the detection of SNe is not possible.

galaxy. In order to correct the effects of the variable PSF, the reference image is convolved with an appropriate kernel determined by a least square fit. The images are then normalized in flux and subtracted. Typically we were able to subtract 98% of the galaxy flux. Although the NICMOS PSF is much more stable than in ground based images, the results of the subtraction of NICMOS images are still affected by residuals in the nuclear regions, but on a smaller scale. The residuals are brighter where the emission has a strong radial gradient and non circular structures (such as the diffraction spikes of the spider arms that are not well reproduced even by the complex ISIS kernel). The presence of residuals is due to the HST PSF variations over long time scale (e.g. Krist & Hook 1997) and to the different orientation of the diffraction spikes due to the different roll angle of HST at the various epochs of observation. As a consequence, the limiting magnitude for point sources detection is much brighter than expected from the photon noise and it is strongly dependent on the location and on the distance from the galactic center, as the subtraction residuals are concentrated in the nuclear regions of the galaxies.

For each galaxy we have evaluated two different limiting magnitudes, Mag$_L$(in), in the region of the galaxy affected by the residuals of the subtraction (between 0.5′′ and 1.35′′ from the nucleus, on average) and Mag$_L$(out) in the outer parts. The SN detection limit was estimated through simulations, by adding artificial stars to the original images before image subtraction. The artificial stars were added at random locations, respectively inside and outside the circular aperture around the nucleus were significant residuals of the subtraction are visible, and with different luminosities. The inferred limiting magnitudes for SN detection, defined as the completeness level of 90%, are listed in Tab. 2. However, the limiting magnitude is strongly dependent from the particular location inside the circular area around the nucleus, due to the presence of stronger residuals corresponding to the diffraction spikes or to secondary nuclei of the galaxies. As an example, in Fig. 1 we report the results of our SN recovering completeness simulations inside the circular area around the nucleus in ARP 220. Although some SNe are lost in correspondence with the strongest residuals at the most conservative Mag$_L$(in) = 19.0, much dimmer sources are still detectable at different locations, such as the possible SN observed in this galaxy which was detected with H = 20.5 (see Appendix).

In the following the number of expected SNe will be evaluated using both Mag$_L$(out) and the more conservative limiting magnitude Mag$_L$(in), relative to the nuclear regions of the galaxies where most of the starburst activity are expected to be hosted.

Furthermore the ISIS kernel, that is used to convolve one of the images in order to correct the effects of the variable PSF, was derived in regions around the brightest objects in the field. Since only a few field stars were present in the field of view, we were forced to include the galactic nucleus in order to properly evaluate the PSF and to obtain a good subtraction over the whole field. Unfortunately, this method prevented us to discover the most inner SNe. We have estimated the size of the non-detectability region by simulations: bright point sources ($m_H = 16.5$) were added
Fig. 1. Example of SN recovering simulations for the circular regions 1.35″ around the nucleus in ARP 220. Although some SN are lost in correspondence with the strongest residuals at the most conservative $M_{L}(\text{in}) = 19.0$ (dashed line), corresponding to the 90% recovering completeness in this region, much dimmer sources are still detectable at different locations, such as the possible SN discussed in Appendix which was detected with $H = 20.5$ (dotted line).

3. Expected number of SNe

According to the relation provided by Mannucci et al. (2003), the expected number of SNe in each galaxy every 100 yr is given by:

$$SN_{e_{FIR}} = (2.4 \pm 0.1) \frac{L_{FIR}}{10^{10} L_{\odot}} \frac{SN}{100 \text{ yr}}$$  (1)

as a function of the far-IR luminosity $L_{FIR}$ of the host galaxy.

For each galaxy we have computed the control time (the amount of time in which a SN is expected to be brighter than the detection limit in each of our images) by using the limiting magnitudes in Tab. 2 and the mean H-band light curve for core-collapse SNe derived by Mattila & Meikle (2001). The control time in each image is defined as the amount of time the H-band light curve of a SN, at the distance of the galaxy, is brighter than our detection limit. Using the FIR flux of each galaxy and the derived control time, eq. (1) yields (after assuming no extinction):

$$SN_{e_{exp}}(\text{out}) = 26.8 \pm 4.9$$

by using the limiting magnitude outside the subtraction residuals, and

$$SN_{e_{exp}}(\text{in}) = 12.6 \pm 4.7$$

after assuming the more conservative limiting magnitude in the nuclear regions. The uncertainty on the expected number of SNe is dominated by the large intrinsic dispersion of the SN light curves in the near-IR, while uncertainties due to the the limiting magnitude estimates and the use of equation (1) are negligible. Therefore the error bars correspond to an upper and a lower limit on the number of events, as expected when using as reference the light curves corresponding, respectively, to the brighter and fainter envelope of the H-band SN light curves. The control time and the number of expected events for the two images of each galaxy are listed in Tab. 3.

| Galaxy          | C-Time (days) | Exp. SNe $M_{L}(\text{out})$ | Exp. SNe $M_{L}(\text{in})$ |
|-----------------|---------------|-----------------------------|-----------------------------|
| NGC34           | 155.6         | 0.49                        | 0.22                        |
| NGC 1614        | 132.6         | 0.70                        | 0.22                        |
| VII-ZW031       | 79.4          | 1.56                        | 0.45                        |
| IRAS 05189-2524 | 10.8          | 1.56                        | 0.05                        |
| IRAS 08572+3915 | 156.4         | 1.25                        | 1.00                        |
| UGC 5101        | 98.6          | 1.60                        | 0.51                        |
| NGC 3256        | 331.8         | 0.95                        | 0.60                        |
| IRAS 10565+2448 | 121.8         | 1.38                        | 0.59                        |
| NGC 3690        | 311.8         | 1.61                        | 1.08                        |
| NGC 4418        | 428.6         | 0.38                        | 0.28                        |
| Mrk 273         | 120.2         | 2.40                        | 0.99                        |
| UGC 8782        | 153.2         | 4.04                        | 1.88                        |
| IRAS 14348-1447 | 43.2          | 2.13                        | 0.53                        |
| Arp 220         | 254.8         | 3.68                        | 2.21                        |
| NGC 6090        | 158.6         | 0.52                        | 0.23                        |
| IRAS 20414-1651 | 171.0         | 1.20                        | 1.10                        |
| IRAS 23128-5919 | 103.2         | 1.35                        | 0.43                        |

All galaxies: 7.8 yr 26.8 yr 12.4 yr

4. Results and Implications

Despite the high number of SNe expected in the NICMOS imaging of our sample, only a possible candidate was
discovered in Arp 220 and it is discussed in Appendix. This corresponds to an observed rate over the full sample smaller than

\[ \text{SN}_{\text{obs}} < \frac{N_{\text{obs}}^{\text{max}}(90\%)}{\text{CT}(\text{in})} = \frac{3.89 \text{ SN}}{7.8 \text{ yr}} = 0.5 \text{ SN/yr} \]  

(2)

where \( N_{\text{obs}}^{\text{max}}(90\%) \) is the maximum number of SNe compatible with one detection at 90% confidence level, assuming Poisson statistics, and \( \text{CT}(\text{in}) \) is the total Control time for the more conservative Mag.\(L\)\( (\text{in}) \) limiting magnitude. The observed lack of SNe can be explained in several ways:

1. The FIR flux is dominated by obscured Active Galactic Nuclei. In this case most of the FIR luminosity would not be related to the star formation, but it would be AGN heated. Indeed some of the sources in our sample do host an AGN, as inferred from X-rays and optical spectra (e.g. UGC 5101, Mrk 231, NGC 3690). However, even in these cases most of the FIR luminosity appears to be dominated by the starburst component (Corbett et al. 2002, Thean et al. 2001, Genzel et al. 1997, Lutz et al. 1998, Clements et al. 2002).

2. Another possibility is based on the fact that underluminous SNe (e.g. Pastorello et al. 2004) may form a significant fraction of all core-collapse events. If this is the case, these SNe would stay above our detection limit for a shorter time, thus decreasing the total control time in Tab. 5. However, even assuming that all SNe in our galaxies are underluminous, we still expect \(~ 22\) or \(~ 8\) SNe using Mag\(L\)\( (\text{out}) \) and Mag\(L\)\( (\text{in}) \) limiting magnitudes respectively.

3. If most starburst activity is concentrated within the inner 200-300 parsec of the galaxy a large fraction of SN events would not have been detected in our images (last column of Tab. 2). It was indeed shown (e.g. Petrosian & Turatto 1990; Bressan et al. 2002) that active and star forming galaxies show a higher concentration of SNe toward the center than it is observed in normal galaxies. As discussed in detail in Mannucci et al. (2003), current data do not put tight constraints on the size of the starburst region in those galaxies. Smith et al. (1998), Rovilos et al. (2005) and Lonsdale et al. (2005) have monitored the central arcsec of the nucleus of Arp 220 with VLBI at 18 cm, with a resolution of a few milli-arcsec, and in principle they could detect the SNe inside our “non-detection” zone. They detected a total of 9 new sources in 9 years of observations, thus providing a radio SN rate of \(~ 1\) SN/yr. However, this value is still uncertain, as core-collapse SNe show a broad range of radio luminosities (e.g. Weiler et al. 2005). Similar results were obtained in NGC 3690 (Neff et al. 2013) and Mrk 273 (Bondi et al. 2005), finding a nuclear rate between 0.5-1 SN/yr. After comparing these results with the “observed” rate of \(< 0.5\) SN/yr discussed in this paper, or even with an observed rate of \(< 0.25\) SN/yr as derived using Mag\(L\)\( (\text{out}) \) instead of Mag\(L\)\( (\text{in}) \) limiting magnitude, one can infer that at least some SNe have been lost in the IR because they occurred too close to the nucleus. However, the nuclear SN rate observed at radio wavelengths in these galaxies is only the 25% of the total rate expected from their FIR luminosity (see Table 3).

4. The most likely possibility is that many events are so embedded in dust to be highly extincted even in the near-IR. In order to compute the (average) \(A_V\), we have dimmed the template light curve with different amount of extinction up to match one (or less) SN detection, at a formal confidence level of 90%. We have obtained \(A_V > 25\) and \(A_V > 11\), after using Mag\(L\)\( (\text{out}) \) and Mag\(L\)\( (\text{in}) \), respectively, and assuming the standard Galactic extinction law (Rieke & Lebofsky 1985). If we include the candidate SN in Arp 220, the needed extinction decreases to \(A_V > 22\) and \(A_V > 9\). We noticed that such high extinctions are not unlikely to occur in these powerful starbursting systems (e.g. Genzel et al. 1997, Sturm et al. 1998).

5. Conclusions

We have presented the analysis of near-IR NICMOS-HST images of 17 galaxies, which were observed at two different epochs, with the goal of detecting nuclear obscured SNe. This study was prompted by the shortage of SNe detected in near-IR monitoring campaigns of starburst galaxies and by the possibility that most of the missing SNe occur in the nuclear region, where the limited angular resolution of ground-based observations prevents their detection.

Taking advantage from the high angular resolution of NICMOS and its stable PSF, we were able to explore the central regions of starbursting galaxies to search for obscured SNe, up to about 0.5″ from the nucleus and down to a limiting magnitude ranging from \(~ 18.0\) in the very nuclear regions of the galaxies (closer than \(~ 1″\) to the nucleus) to \(~ 21\) further away from the strongest subtraction residuals. This is a clear improvement with respect to ground based searches which are limited to \(~ 3″\) from the nucleus. Within a radius of \(~ 0.45″\) from the center, even NICMOS is unable to reliably detect SNe. Our analysis found a possible SN in Arp 220, but due to its faintness and proximity to the nucleus we were not able to provide the spectroscopic confirmation of this event. From our data we have derived a nuclear SN rate \(\leq 0.5\) SN/yr per galaxy. The comparison with rates measured via radio-surveys suggests that some SNe occurring in the inner \(~ 500\) pc are lost. However, this is not enough to explain the discrepancy between expected and observed number of SNe. We have discussed various possible explanations, the most likely of which is that in these starburst galaxies dust extinction is so high (\(A_V \geq 11 - 25\)) to be effective in obscuring SNe even in the near-IR.

Appendix A: A possible Supernova in Arp 220

A possible SN was discovered in ARP 220, the most active galaxy in our sample, observed on January 10th, 2004.
(see Fig. 1). It was found at 1.1'' from the brightest nucleus of the galaxy (SN location: R.A. 15:34:57.13; DEC. +23:30:12.0; J2000), and it might be the most nuclear SN ever discovered. It was detected as a positive residual after careful alignment, normalization, reduction to the same PSF and subtraction of two images of the galaxy taken at different epochs. The SN was detected with a significance of 3.5 σ with respect to the background noise, and it results in a magnitude of H ~ 20.5. It is unlikely that the "bright spot" shown in Fig. 2 is the result of an incorrect subtraction of the PSF. In fact, the luminosity of the SN candidate is about twice larger than the contribution of the PSF of the bright galactic nucleus computed at the position of the SN candidate. In addition, the candidate SN is located away from the bright PSF spikes (that can not be perfectly subtracted due to their highly asymmetric shape), where the limiting magnitude is much higher than the most conservative Mag_ l reported in Tab. 2. In fact, our simulation show that a SN with H = 20.5 would be recoverable close to the candidate SN location with comparable S/N.

The absolute magnitude of the detected object is about M_H = -13.8, i.e. about 4 magnitudes fainter than an average type II SN at maximum light. This may indicate that this SN has been discovered at about 300 days from its maximum light, according to the template H-band light curve by Mattila & Meikle 2001. Alternatively this SN could have been discovered near its maximum light, but it is a very extincted object, about 4 magnitudes in the H band, corresponding to A_V = 23.

We have obtained spectroscopic follow-up of this object in the J band using ISAAC at the VLT, with the low resolution grism (R=500) and a 1'' slit, in order to detect the broad lines typical of the nebular phase of a SN such as Paβ and [CaII]λ7300,8500 (see e.g. Maiolino et al. 2002). The spectrum was obtained on April 11th, 2004, 3 months after detection. Although the spectrum exposure time of 1h42' was chosen in order to have clear detection of the SN features, assuming a source up to H ~ 21.5, the signal to noise of the spectrum was not sufficient to detect SN features over the bright galaxy spectrum. The non-detection may still be due to the long delay time between the HST discovery image and spectroscopic observations. In fact, a SN is expected to became ~ 2 magnitudes fainter in the three months occurred between the two observations in the near-IR, corresponding to H ~ 22.5. As a result the SN detection in ARP 220 remains tentative.

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