Highly extinguished supernovae in the nuclear regions of starburst galaxies

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Abstract

A handful of nearby supernovae (SNe) with visual extinguions of a few magnitudes have recently been discovered. However, an undiscovered population of much more highly extinguished ($A_V > 10$) core-collapse supernovae (CCSNe) is likely to exist in the nuclear (central kpc) regions of starburst galaxies. The high dust extinction means that optical searches for such SNe are unlikely to be successful. Here, we present preliminary results from our ongoing near-infrared Ks-bands search programme for nuclear SNe in nearby starburst galaxies. We also discuss searches for SNe in Luminous and Ultraluminous Infrared Galaxies.

Key words: supernovae, starburst galaxies, extinction

1 Introduction: Obscured supernovae

Core-collapse (types II and Ib/c, hereafter CCSNe) supernovae are observed to occur in sites of recent star formation. Such regions contain large quantities of dust, especially the nuclear (central kiloparsec) regions of starburst galaxies. Consequently, SN search programmes working at optical wavelengths most likely miss a significant number of events in starburst galaxies. The distributions of the host galaxy extinguions for samples of nearby thermonuclear (type Ia) SNe, and CCSNe are shown in Fig.1. Although, most of the discovered SN events have extinguions below $A_V = 1$, the extinction distributions of both types of SNe show tails extending to several magnitudes. In particular,
Fig. 1. The host galaxy extinctions of nearby type Ia SNe (left) [4,9,10], and CCSNe (middle) [1,2,5,11,12]. The extinctions towards the SNRs of M 82 (right) [12].

four nearby SNe with host galaxy extinctions of several magnitudes ($A_V > 5$) [1,2,3,4,5] have been discovered during the last couple of years. The type II SNe 2001ci [6] and 2002hh [7] were detected at optical wavelengths thanks to their small distances of only 14 and 6 Mpc respectively. The more distant type II SN 2001db [2] (37 Mpc) and type Ia SN 2002cv [8] (22 Mpc) were discovered in the near-infrared (IR). All these SNe have active host galaxies (either H II or LINER/Seyfert 2) according to NED\textsuperscript{1}. Three of them have projected galactocentric distances smaller than $\sim 2$ kpc, and one, SN 2002cv, is located behind an optical dust lane. Recent optical spectra of SN 2002hh are shown in Fig.2. The effects of the high extinction ($A_V \sim 6$) [5] are clearly visible as a dramatic drop of the signal towards the shorter wavelengths (note also the lack of H$\beta$ emission). However, an as yet unrevealed population of much more highly extinguished CCSNe is likely to exist in the nuclear (central kiloparsec) regions of starburst galaxies. In the nuclear regions ($\sim 600$pc diameter) of the starburst galaxy M 82, large hydrogen column densities indicate extinctions [12] of $A_V = 30$ ($\sigma \sim 16$) (Fig.1 right) towards the group of young supernova remnants (SNRs) observed at radio wavelengths. Furthermore, recent VLBA monitoring [13,14] has revealed a group of luminous radio SNe/SNRs within the nuclear regions ($\sim 100$ and $\sim 200$ pc diameter around the Eastern and Western nuclei respectively) of the nearest Ultraluminous Infrared Galaxy (ULIRG) Arp 220. The estimates for the explosion rates of such luminous radio SNe range between $\sim 0.5$ and 2.0 yr\textsuperscript{-1} [13,14]. However, it is likely that not all the CCSNe in Arp 220 have suitable CSM/ISM conditions to produce high radio luminosities i.e. many SNe which happen to explode in less extreme environments probably remain undetected in the radio. Therefore, near-IR monitoring campaigns of starburst galaxies having a range of IR luminosities should be carried out to complement the rate estimates from the radio observations. Near-IR SN searches were first attempted over a decade

\textsuperscript{1} The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Fig. 2. Optical spectra of the obscured ($A_V \sim 6$) type II SN 2002hh observed with WHT/ISIS (14 June 2003) and NOT/ALFOSC (7 July 2003). The former spectrum has been shifted upward by $1.1 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ for clarity. The zero-levels of the spectra are shown with dotted lines. The most prominent SN lines are identified.

ago [15,16] but it is only now, with the introduction of large format (1024 x 1024) small pixel scale (<0.3") near-IR detectors on 2-4 meter telescopes, that such searches have become realistically feasible.

2 Supernovae in nearby starburst galaxies

Since August 2001 we have been carrying out a near-IR search programme for CCSNe in the nuclear regions of nearby starburst galaxies [17]. We use the INGRID near-IR camera at the William Herschel Telescope (WHT) on La Palma. We repeatedly image a sample of the 40 most-luminous nearby (d < 45 Mpc) starburst galaxies in the Ks-band where the extinction is greatly reduced and the sensitivity of ground-based observations is still good. These galaxies have been selected such that their far-IR luminosities are comparable to or greater than those of the two prototypical nearby starburst galaxies, M 82 and NGC 253. Galaxies whose far-IR luminosity is expected to be powered by a population of old stars or an AGN have been excluded from the sample. One night of observations is carried-out every $\sim$3 months. 20-30 galaxy images per clear night are obtained. More details of the search can be found in the 'Nuclear SN search' web pages at [http://astro.imperial.ac.uk/nSN.html](http://astro.imperial.ac.uk/nSN.html)
2.1 Preliminary results from the WHT search

The total number of Ks images obtained with the WHT so far is \( \sim 110 \). Archival K-band data having an acceptable seeing and similar depth to our INGRID images provides a further 10 images. Thus, our total database currently contains repeat images for 33 starburst galaxies, on average 3.4 epochs per target. However, the SN detection efficiency (especially within the galaxy nuclear regions) falls rapidly as seeing quality declines. Therefore, for the analysis presented here we include only data having seeing better than FWHM = 1.1”. Within this constraint, about 60% of our INGRID images have acceptable seeing, reducing the number of targets with repeat images to 21. On average, this is \( \sim 2.6 \) epochs of data per target.

2.1.1 A possible SN in NGC 7714

Comparison of archival (UKIRT IRCAM3) data with our INGRID images yielded the discovery of a possible SN with \( m_K = 17.3 \) only 1 kpc projected distance from the nucleus of the starburst galaxy, NGC 7714 [18]. From the non-detection of this SN in the H-band we estimated a lower limit for the extinction towards the SN of \( A_v \sim 6 \). Radio confirmation of this event was also sought. At radio wavelengths CCSNe are often still luminous several years from the explosion, with the most luminous reaching their peak luminosities up to 4 years after explosion [19]. Therefore, radio follow-up observations of nuclear SNe may still be feasible long after the SN has faded below near-IR detectability. We obtained VLA observations of NGC 7714 in the L and C-bands on 11 April 2002, but the possible SN was not detected. The 3\( \sigma \) upper limits in the L and C-bands are 0.213 mJy and 0.147 mJy respectively (C. Stockdale, private communication). These upper limits indicate that the SN was probably fainter than the type IIln SN 1998S at radio wavelengths.

2.1.2 Expected number of SN discoveries

We have made preliminary estimates of the expected number of SN discoveries from the data collected so far. To do this we used Monte Carlo simulations similar to those described in [12]. We assumed that outside the innermost 100 pc region of our starburst targets all the SNe brighter than the possible SN in NGC 7714 (\( m_K = 17.3 \)) would have been detected in the images with seeing better than 1.1”. We used our K-band template light curves for linearly declining ”ordinary” CCSNe and ”slowly-declining” CCSNe [12], the amount and distribution of extinction found for the SNRs of M 82 (Fig.1 right) [12], and the CCSN rates calculated from the far-IR luminosities of the targets according to \( r_{\text{SN}} = 2.7 \times 10^{-12} \times L_{\text{FIR}}/L_\odot \text{ yr}^{-1} \) [12]. In Fig.3(left) the expected
Fig. 3. The simulated number of SNe discovered with the WHT as a function of the slow-decliner fraction (left) and the extinction towards the SNe (right). In the left-hand plot, the two different histograms correspond to a fixed extinction of \( A_V = 10 \), and an M 82-like extinction distribution towards the SNe. In the right-hand plot, the histograms correspond to fixed slow-decliner fractions of 5 and 30%.

number of SN detections is plotted as a function of the intrinsic fraction of slowly-declining events. The results are plotted for a fixed extinction of \( A_V = 10 \) towards the nuclear SNe, and for an extinction distribution similar to the SNRs of M 82. For one likely SN detection from the data collected so far, and an extinction of \( A_V = 10 \) we obtain an upper limit (>90% confidence) of 30% for the slow-decliner fraction. However, assuming an M 82-like extinction distribution yields a most probable slow-decliner fraction of ∼10%. In Fig.3(right) the simulation results are plotted as a function of the extinction towards the nuclear SNe. Again, assuming one detected event and a slow-decliner fraction of 30% indicates a lower limit (>90% confidence) for the extinction of \( A_V = 10 \). Assuming a slow-decliner fraction between 5% (observed outside the nuclear starburst regions) and 30% yields a most probable extinction, \( A_V \), between ∼20 and ∼30 magnitudes (for one detected SN).

3 Supernovae in Luminous and Ultraluminous Infrared Galaxies

Maiolino et al. [2] and Mannucci et al. [20] used an arsenal of ground-based telescopes (ESO NTT at La Silla, TNG on La Palma, and AZ61 on Mount Bigelow) to obtain a total of ∼230 K-band observations of 46 Luminous Infrared Galaxies (LIRG) \( (10^{11} \ L_\odot < L_{\text{IR}} < 10^{12} \ L_\odot) \) between Oct. 1999 and Oct 2001. Their targets have distances ranging between ∼40 and ∼300 Mpc, with 28 of them being more distant than 100 Mpc. From these data they discovered two SNe, the type II SN 2001db (d ∼ 40 Mpc), and SN 1999gw (d ∼ 170 Mpc) with no spectroscopic typing. These SNe have projected galactocentric (K-band) distances of ∼1.5 kpc (8.5") and ∼3 kpc (3.5") respectively. In ad-
Fig. 4. The fraction of simulated SNe discovered with the NTT (Mannucci et al. [20]) as a function of the SN age. The different histograms correspond to three combinations of the host galaxy distance and the fraction of SNe exploding within the nuclear regions. A fixed extinction of $A_V = 30$ is assumed towards all the events.

In addition, during their search two more SNe were detected in their target galaxies but at optical wavelengths. These are the type Ia SN 1999gd ($d \sim 80$ Mpc) and the type IIIn SN 2000bg ($d \sim 100$ Mpc) with the projected galactocentric distances of $\sim 7$ and $\sim 8$ kpc respectively. The extinctions towards the two optically detected SNe are most likely negligible. Furthermore, the discovery magnitude of SN 1999gw of $m_{Ks} = 17.45$ ($M_{Ks} = -18.7$) is very close to the peak magnitudes of both ‘ordinary’ CCSNe [12] and ‘Branch-normal’ type Ia SNe [21] indicating a likely small extinction towards this event (regardless of its type). However, SN 2001db has a host galaxy extinction of about $A_V = 5$ [2]. In summary, only one of the four detected SNe has a derived visual extinction of several magnitudes and is located (projected distance) fairly close to (but not within) its host galaxy nuclear regions. We also note that this SN occurred in the nearest ($d \sim 40$ Mpc) of the 46 target galaxies.

In order to judge the efficiency of the reported Maiolino/Mannucci SN search for host galaxies of different distances, we carried out Monte Carlo simulations similar to those described in Section 2.1.2. We simulated two scenarios: (1) 100% of the SNe occur within the nuclear regions, and (2) 80% of the SNe occur within the nuclear regions, and 20% outside the nuclear regions. We adopted the reported [20] NTT/SOFI limiting magnitudes for SNe ‘on-nucleus’ and ‘off-nucleus’ (outside the central $\sim 2''$, corresponding to $\sim 1$ kpc at 100 Mpc distance) of $m_K = 16.9$ and 19.3 respectively. We assumed an intrinsic fraction of slowly-declining CCSNe of 5%, and a fixed extinction of $A_V = 30$ towards all the events. In Fig.4 the fraction of simulated SNe discovered is plotted as a function of the SN epoch. In galaxies at 40 Mpc distance, $\sim 15\%$ of the SNe ‘on-nucleus’ are detectable near maximum light whereas at 70 Mpc distance the SN detection efficiency falls to less than 1%, i.e., the survey was not sensitive to highly obscured SNe within the nuclear regions of
target galaxies at $\sim 70$ Mpc distance or further (only 2/46 of the targets were closer than this). However, if we allow 20% of the SNe to occur outside the central regions, about 6% of the SNe near maximum light can be recovered at distances as high as 100 Mpc (this includes 18/46 of the targets). Therefore, the average extinction of $A_V \sim 30$ derived by Mannucci et al. [20] can only be valid for SNe occurring outside the galaxy nuclear regions rather than for all SNe regardless of their location within the host galaxy. However, as none of the SNe which were detected outside the nuclear regions had such a high extinction, a more plausible reason for the lack of SN detections would be the concentration of almost all the SNe within the nuclear (central kpc) regions in the LIRG targets since this survey was not sensitive to highly obscured SNe in those regions. Also, the concentration of the luminous radio SNRs (or SNe) within the innermost nuclear regions in M 82, Arp 220, and other galaxies support a scenario where $\sim 100\%$ of the SNe occur within the nuclear regions in starburst galaxies over a range of IR luminosities.

The large star formation rates (SFRs) within Ultraluminous Infrared Galaxies (ULIRGs) ($L_{\text{IR}} > 10^{12} L_{\odot}$) imply CCSN rates which are an order of magnitude higher than in nearby starburst galaxies. Consequently it may be argued that ULIRGs provide the best laboratories for the detection and study of CCSNe in the extreme starburst environment. The serendipitous VLBI discovery of a dozen luminous radio SNe/SNRs [13] in the nuclear regions of the archetypal ULIRG Arp 220 has already demonstrated that nuclear CCSNe at very late phases can be detected at radio wavelengths. However, with the unprecedented spatial resolution of the Naos Conica (NACO) adaptive optics camera on the ESO Very Large Telescope (VLT) ($\times 15$ better than previous ground-based studies [2,20], and $\times 3$ better than HST/NICMOS) it is now possible to discover these SNe shortly after explosion when they are still bright at near-IR wavelengths. Therefore, we have started a Ks band survey for highly extinguished CCSNe within the nuclear regions of the nearest ULIRGs, using the VLT/NACO. We anticipate that the first SN discoveries will be made during the ESO Period 73, between April 2004 and September 2004.

4 Discussion

The WHT SN search data collected by us so far indicates that SNe within the nuclear (central kpc) regions of nearby ($d < 45$ Mpc) starburst galaxies (mostly $10^{10} L_{\odot} < L_{\text{IR}} < 10^{11} L_{\odot}$) probably suffer from extinctions higher than $A_V = 10$, with the most likely average extinction between $A_V \sim 20$ and 30. The monitoring of a sample of more distant (mostly $d > 70$ Mpc) and more luminous ($10^{11} L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$) targets recently reported by Mannucci et al. [20] indicates that either (1) $\sim 100\%$ of the SNe in LIRGs occur within the nuclear (central kpc) regions, or (2) if 20% of the SNe occur outside the nuclear
regions then the extinction towards these off-nuclear SNe is probably very high, \( A_V \sim 30 \). Only very few obscured SNe (with \( A_V \sim 5 \)) have been detected so far. However, a number of infrared SN search campaigns have begun in the past few years. These include high resolution surveys by Maiolino et al. using HST/NICMOS and by ourselves using VLT/NACO. Therefore, the number of obscured SN discoveries is expected to increase substantially in the near future. This will eventually allow complete SN rates to be estimated for galaxies in the local Universe. In addition, the discovered SNe will be invaluable as probes of the extinction in the optically obscured parts of galaxies.

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