Search for Supernovae in Starburst Galaxies with HAWK-I

Matteo Miluzio[1]

[1] INAF–Osservatorio Astronomico di Padova, Italy

With the aim of testing the relation between supernova (SN) rate and star formation rate, we conducted a SN search in a sample of local starburst galaxies (SBs) where both star formation rates and extinction are extremely high. The search was performed in the near-infrared, where the bias due to extinction is reduced using HAWK-I on the VLT. We discovered six SNe, in excellent agreement with expectations, when considering that, even in our search, about 60 % of events remain hidden in the nuclear regions due to a combination of reduced search efficiency and very high extinction.

Why supernova rates?

The determination of the star formation history (SFH) of the Universe is one of the main goals of modern cosmology, as it is crucial to our understanding of how structures in the Universe form and evolve. The estimate of the star formation rate mainly relies on measurements of integrated galaxy luminosity, most often in the infrared or for specific emission lines, e.g., Hα. The luminosity measurements are converted to total luminosity assuming an initial mass function (IMF) for the stellar population and including a number of corrections to account for the presence of multiple stellar populations, non-thermal source contributions and extinction.

In principle a direct test of the star formation rate (SFR) estimate can be achieved by directly counting the number of dying massive stars, namely core collapse supernovae (CC SNe). Indeed, because of their short-lived progenitors, CC SNe trace the current SFR. On the other hand, for an adopted SFR, measurements of the CC SN rates give information on the mass range of their progenitors and on the slope of the IMF at the high-mass end. Type Ia SNe, however, are the results of thermonuclear explosions of white dwarfs in binary systems, and they trace the whole history of star formation, due to the wide range in the delay times of their progenitors. Recently, it was claimed that a significant fraction of SN Ia have a short delay time of about 10^7 years (Mannucci et al, 2006). As with CC SN, the rate of such prompt SNe Ia events is proportional to the current SFR.

Motivations: The SN rate problem

During the last decade significant effort has been devoted to the measurement of the cosmic SFR, using a combination of many different probes (e.g., Hopkins & Beacom, 2006). Also, as a result of a number of dedicated surveys, new estimates of the SN rate have become available. Although the focus was on type Ia SN, a few estimates of the CC SN rates have been published (e.g., Melinder et al., 2012). In particular, the evolution of SN rates with redshift was found to track the SFR evolution very well, considering the large uncertainties in the extinction corrections. Botticella et al. (2008) obtained a good match between the observed SN and star formation rates assuming a lower limit for CC SN progenitors of 10 $M_\odot$.

However, recent study of the core collapse SN progenitors, based on direct detection on pre-explosion archival images, set a lower limit of 8 $M_\odot$ (Smartt et al., 2009). It was claimed that if this value is adopted, the observed SN rates would be a factor of two lower than those expected from the observed SFR, sometimes called the SN rate problem (e.g., Horiuchi et al., 2011). While we should keep in mind the uncertainties in SFR calibrations, there are also possible important biases in the SN rate estimates. The two most severe are the possible existence of a large population of very faint CC SNe and/or underestimates of the correction for extinction. In particular, several authors (e.g., Mattila et al., 2012) argue that up to 70–90 % of CC SNe remain hidden in the highly dusty nuclear regions of starburst galaxies. If a correction for the hidden SN population is included in the rate calculation, the discrepancy between SN and star formation rates at high redshifts seems to disappear. It is unclear whether this effect is large enough to also explain the discrepancy observed in the local Universe.

An infrared search in starburst galaxies: Why?

Starburst galaxies have very high SFRs, in the range of 10–100 $M_\odot$/year, compared to the few solar masses per year of normal star-forming galaxies. Many starburst galaxies are in close pairs or have disturbed morphology, which is a sign that merging is enhancing their SFR. Since the ultraviolet radiation from young and massive stars heats the surrounding dust and is re-emitted in the far-infrared, the most luminous starbursts are Luminous Infrared Galaxies (LIRGS) with $10^{11} < L_{IR} < 10^{12}\ L_\odot$ and UltraLuminous Infrared Galaxies (ULIRGs) with $L_{IR} > 10^{12}\ L_\odot$.

The first attempts to measure SN rates in starburst galaxies in the optical band date back to 1999 (Richmond et al., 1998) with only a handful of events detected. The first results of a systematic search in starburst galaxies in the infrared (IR) domain were reported by Maiolino et al. (2002) and Mannucci et al. (2003). The main conclusion was that the observed SN rate in starburst galaxies is one order of magnitude higher than that expected from the blue luminosity of the galaxies, but still three to ten times lower than would be expected from the far-IR luminosity. They suggested that the most plausible explanation for this discrepancy was the extreme extinction in the galaxy nuclear regions ($A_V > 25$ mag) that hides SNe even in the IR. Recently, Mattila et al. (2007) conducted an IR search in starburst galaxies using ground-based telescopes with adaptive optics, a technique that allows the nuclear regions to be observed with high spatial resolution. This approach led to the discovery of a handful of SNe, but not yet an estimate of the CC SN rate. About a dozen SNe have been discovered by IR searches so far. Therefore the statistics are still based on very low numbers, and many of the original questions are still unanswered. Entering into this debate, we started a new search to measure the SN rate using the High Acuity Wide-field *K*-band Imager (HAWK-I), the infrared camera mounted at the ESO Very Large Telescope (VLT).

The search strategy

We conducted the HAWK-I search in *K*-band, monitoring a sample of local starburst galaxies retrieved from the IRAS Revised Bright Galaxy Sample. We selected galaxies with $z < 0.07$ and total infrared luminosity of $L_{TIR} > 10^{11}\ L_{\odot}$. We collected a sample of 30 starburst galaxies for Paranal observation, considering seasonal observability. Given that the SN IR light curves evolve relatively slowly, remaining within one or two magnitudes of maximum for two or three months, an IR SN search did not require frequent monitoring. We planned on average three visits per galaxy per semester, which implies a total of about 100 observing blocks per semester.

The programme was allocated three observing periods and the fraction of useful observing time was 100% of the allocated time in the first season and 70% in the second and third semesters. In total, we obtained 210 *K*-band exposures (with a single exposure time of 15 minutes). Spectroscopic confirmation of the SN candidates was obtained with ISAAC and X-shooter at the VLT (and in one case at the Gran Telescopio Canarias [GTC]). The average image quality was excellent: for about 90% of the exposures the seeing was less than 1.0 arcseconds, with an average value across the whole programme of 0.6 arcseconds. Data reduction was performed by integrating EsoRex (the ESO Recipe EXecution tool) with custom programs. Figure 1 shows the high quality of an image of the galaxy NGC 6926 (one galaxy of our sample) after reduction. SN detection was performed by subtracting images taken at different epochs with the technique of point spread function (PSF) matching. In many cases, the difference images showed significant spurious residuals that correspond to the galaxy nuclear regions, in particular when seeing was poor (full width at half maximum [FWHM] > 1 arcsecond; see Miluzio et al., 2013).

Figure 1. *K*-band HAWK-I image of the spiral galaxy NGC 6926 recorded with seeing of 0.4 arcseconds (from Miluzio et al., 2013).

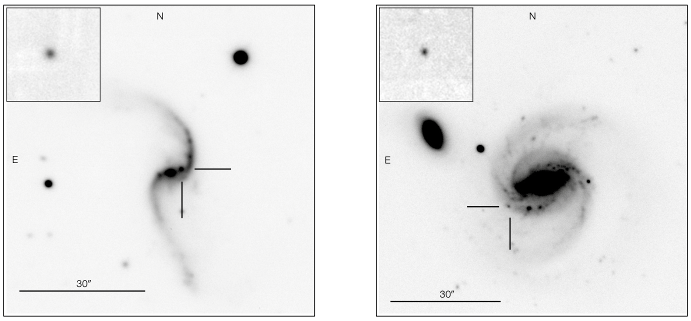

Figure 2. *K*-band finding charts for two SNe discovered in our search (left: SN 2012hp; right: SN 2011ee). The insets show the transients as they appeared in the difference images.

Supernova discoveries and characterisation

During our monitoring campaign six transients were detected in at least two consecutive epochs separated by around one month. We obtained spectroscopic confirmation for four of them: three as CC SN (SN2010bt; SN2012hp, see CBET2446; and SN2011ee, see CBET 2773) and one as a type Ia SN (SN 2010gp). Two candidates were too faint for spectroscopy and the transient classification was based on analysis of multicolour photometry. We argued that they are also likely CC SN. SN e2010bt and 2010gp were discovered by optical searches before our detection, but we rediscovered them independently (Miluzio et al., 2013). Figure 2 shows the *K*-band HAWK-I discovery images of SN 2010hp and SN 2011ee found in MCG-02-01-52 and NGC 7674, respectively. The inset box is a zoom of the difference image where we detected the SN.

Search detection limit

In order to derive the SN rate from the number of detected events, it is crucial to obtain an accurate estimate of the detection efficiency of the search. Through artificial star experiments, we estimated the magnitude detection limit for each of the search images and for different locations in the images. The detection efficiency is influenced by the sky conditions at the time of observations (namely seeing and transparency) and by the location of the transient inside the host galaxy. Indeed, the magnitude limit is brighter in the nuclear regions for a typical galaxy of our sample, corresponding to the inner 1.5–2.0 kpc. While the detection limit in the galaxy outskirts is largely independent of the seeing of the images (typically K ~ 19 mag), this is not true in the nuclear region, where the magnitude limit is significantly brighter when the seeing is poor (in the worst case even 5–6 mag brighter than in the galaxy outskirts; see Miluzio et al., 2013).

SN search simulation

To evaluate the significance of the detected events, we developed a simulation tool that computes the number and properties of the expected events based on specific assumptions and features of our SN search. The basic ingredients of the simulation are:
- the properties of the starburst galaxies of our sample;
- the expected SN properties;
- the details of the search campaign;
- the number of SNe expected from the stellar population after a star formation episode;
- the depth and distribution of dust extinction inside the parent galaxies;
- the star formation location in the parent galaxies.

The tool uses a Monte Carlo approach that simulates the stochastic nature of SN explosions. Based on the analysis of several Monte Carlo experiments with the same input parameters, we can test whether the observed events are within the expected distribution. On the other hand, to test the influence of specific assumptions, we varied some of the input parameters in the Monte Carlo experiments.

Observed *vs.* expected SN discoveries

Outcomes of the simulations are the expected number of SN discoveries, their types, magnitudes, extinctions and positions inside the host galaxies. In Figure 3 we show the histogram of the number of expected SNe compared to the number of observed events (dashed vertical line). Each bin represents the predicted probability of observing the specific number of actual SNe discovered and the shaded areas shows its 1σ Poissonian uncertainty range.

We found that, with the consolidated simulation scenario and input parameters, we could predict the discovery of 5.3 ± 2.3 SNe on average, of which 5.1 are CC SNe and 0.2 are type Ia SNe (Miluzio et al., 2013). This is in excellent agreement with the observed number of six events, one of which is a type Ia SN. If we had computed the expected number of SNe in our survey based on the cosmic average of the SN rate per unit *B*-band luminosity or mass, we would predict the discovery of only 0.5 events. The observed number is one order of magnitude higher, which is consistent with the fact that the thermal IR emission of starburst galaxies is about ten times higher than for average galaxies with the same *B*-band luminosity (Miluzio et al., 2013).

As a consistency check, we verified that the distribution of the expected and observed apparent magnitudes at discovery and the simulated *vs.* observed extinction distributions are in good agreement. This agreement confirms the consistency of our estimates of the magnitude detection limit and the assumption that the extinction is very high in the nucleus and rapidly decreases with the galaxy radius, following the same trend as the SFR.

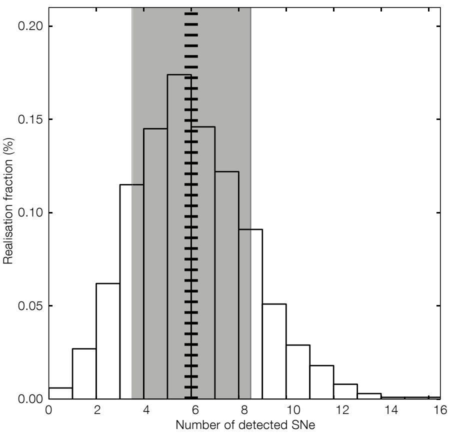

Figure 3. Histogram showing the number of expected SNe from our Monte Carlo simulations. The dashed vertical line indicates the number of observed events and the grey area its 1σ Poissonian uncertainty (from Miluzio et al., 2013).

We also analysed the distribution of the locations of the expected events for an ideal case, where the magnitude detection limit in the nuclear regions is as deep as in the outskirts, and extinction is negligible. The experiment shows that the fraction of events that remain hidden to our search in the galaxy nuclear regions, due to the combined effect of reduced search efficiency and extinction, is very high, about 60%. The number of CC SNe found in starburst galaxies is consistent with what is predicted from the high SFR (and the canonical mass range for the progenitors) when we recognise that a major fraction of the events remain hidden in the inaccessible starburst regions. This has important consequences for the use of CC SN as a probe of the cosmic SFR, because the fraction of SBs is expected to increase with redshift (Miluzio et al., 2013). This conclusion appears to agree with that of previous, similar searches (e.g., Mannucci et al., 2003; Mattila et al., 2012).

Finally, to understand how a different choice of the test parameters can influence the expected rate, we varied each of them and computed the rate, repeating the Monte Carlo simulation. One of the main sources of uncertainty is related to the estimate of the magnitude detection limit, which can vary the predicted number of SNe by about 15%. The other source of uncertainty is the assumption of the CC SN progenitor mass range: in particular considering that a different upper limit (10 $M_\odot$ instead of 8 $M_\odot$) results in an expected number of SNe about 30% lower than the reference case (5.3 SNe). Moreover, while the uncertainty on the extinction does not significantly affect the simulation (because where the extinction is high our search is limited by the bright magnitude detection limit), the most uncertain input of the galaxy characterisation is the spatial distribution of the star formation; uncertainty in the adopted distribution propagates with an error of about 50% on the expected SN number (Miluzio et al., 2013).

The future of IR SN searches

While continuing to search for SNe in starburst galaxies in the optical and infrared can certainly help to improve the still poor statistics, one may argue at this point for a change in strategy. In this respect, it is worth mentioning the attempt to reveal the hidden CC SNe through infrared SN searches that exploit adaptive optics at large telescopes, e.g., Gemini or the VLT. The early results are encouraging, with the discovery of two SNe with very high extinction (SN 2004ip with A_V between 5 and 40 mag, and SN 2008cs with A_V of 16 mag) and another two SNe discovered very close to the galaxy nucleus, although in these cases with low extinction. On account of the need to monitor one galaxy at a time and to access heavily subscribed large telescopes, this approach cannot promise a large statistical sample, although even a few events would be valuable, mostly for exploring the innermost nuclear regions. On the other hand, a new opportunity that should be exploited is to piggyback on wide-field extragalactic surveys by the next generation of infrared facilities, in particular the Euclid mission. This would allow, for the first time, IR SN searches to be performed on a large sample of galaxies, exploring a range of star formation activity and, by monitoring galaxies at different redshifts, probing the cosmic evolution of SN rates.

References

Botticella, M. T. et al. 2008, A&A, 479, 49
Horiuchi, S. et al. 2011, ApJ, 738, 154
Hopkins, A. M. & Beacom, J. F. 2006, ApJ, 651, 142
Maiolino, R. et al. 2002, A&A, 389, 84
Mannucci, F. et al. 2003, A&A, 401, 519
Mannucci, F., Della Valle, M. & Panagia, N. 2006, MNRAS, 370, 773
Mattila, S. et al. 2007b, ApJ, 659, L9
Mattila, S. et al. 2012, ApJ, 756, 111
Melinder, J. et al. 2012, A&A, 545, A96
Miluzio, M. & Cappellaro, E. 2010, Central Bureau Electronic Telegrams, 2446, 1
Miluzio, M. et al. 2011, Central Bureau Electronic Telegrams, 2773, 1
Miluzio, M. et al. 2013, A&A, 554, A127
Richmond, M. W., Filippenko, A. V. & Galisky, J. 1998, PASP, 110, 553
Smartt, S. J. 2009, ARA&A, 47, 63