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High angular resolution radio and infrared view of optically dark supernovae in luminous infrared galaxies

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Abstract. In luminous and ultraluminous infrared galaxies (U/LIRGs), the infall of gas into the central regions strongly enhances the star formation rate (SFR), especially within the nuclear regions which have also large amounts of interstellar dust. Within these regions SFRs of several tens to hundreds of solar masses per year ought to give rise to core-collapse supernova (SN) rates up to 1-2 SNe every year per galaxy. However, the current SN surveys, almost exclusively being ground-based seeing-limited and working at optical wavelengths, have been blinded by the interstellar dust and contrast issues therein. Thus the properties and rates of SNe in the nuclear environments of the most prolific SN factories in the Universe have remained largely unexplored. Here, we present results from high angular resolution observations of nearby LIRGs at infrared and radio wavelengths much less affected by the effects of extinction and lack of resolution hampering the optical searches.

Keywords. supernovae: general, dust extinction, galaxies: nuclei, galaxies: starburst, infrared: galaxies, instrumentation: adaptive optics, instrumentation: high angular resolution

1. Introduction

The current very wide-field supernova (SN) searches are increasing substantially the SN statistics locally covering a large fraction of the whole sky every few nights and in a less biassed manner than was possible before. However, most of the local searches are working at optical wavelengths and are limited by the ground-based seeing making the detection of SNe challenging especially within the dusty and often bright and complex nuclear (<500 pc) regions of the most strongly star-forming galaxies. Therefore, the rates and properties of the SNe occurring within the nuclear regions of galaxies have remained largely unexplored.

Deep infrared (IR) surveys will enable studies of the evolution of SN rates extending beyond the peak of the cosmic star formation history (SFH). As core-collapse SNe come from massive short-lived stars, their explosion rate directly reflects the on-going massive star formation rate (SFR) at the explosion sites, and thus CCSNe provide an independent way to probe the SFRs in their host galaxies and also the cosmic SFH (e.g., Dahlén *et al.* 1999, Madau & Dickinson 2014). Core-collapse SNe can thus provide a very useful consistency check on the cosmic SFH, independent from many assumptions and biases with the more conventional methods that are based on galaxy luminosities. Measuring the evolution of the core-collapse SN rate with redshift is of major importance for determining the universal history of metal production and thus for all galaxy formation and evolution models. Furthermore, the SN behaviour in such regions might be extreme as the interaction of the SN ejecta with the dense nuclear environment may convert a substantial fraction of the SN kinetic energy into radiation producing more luminous and slowly declining events.

2. Supernovae in luminous infrared galaxies

Despite the impressive statistics, the current SN rates may still suffer from significant systematic omissions. This was illustrated by Horiuchi *et al.* (2011) claiming a significant deficit of core-collapse SNe detected as a function of redshift compared to the expectations from the cosmic SFR. In fact, a large fraction of the massive star formation especially at intermediate and high redshifts (Magnelli *et al.* 2011) took place in luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs, respectively). The starburst-dominated LIRGs form several tens to hundreds of solar masses of stars per year. This corresponds to core-collapse SN rates up to several SNe yr^{-1} per galaxy, some hundred times higher than in "ordinary" spiral galaxies like the Milky Way. However, even in the local Universe this entire SN population has been almost completely neglected by the previous SN searches. A cross-correlation between the Asiago Supernova Catalog and the IRAS Revised Bright Galaxy Sample reveals about 45 confirmed core-collapse SNe discovered in these systems since year 2000 which is just the tip of the iceberg, the total intrinsic number being over 4000 SNe over this period (Kool *et al.* 2017, submitted). Furthermore, only a small number of such SNe have been followed-up and studied in detail (e.g., Kankare *et al.* 2014; Romero-Cañizales *et al.* 2014; Kangas *et al.* 2016).

The properties and the rates of SNe in the nuclear environments of the most prolific SN factories in the Universe have thus remained largely unexplored. A very promising approach to detect and study SNe within the dust obscured nuclear regions of starburst galaxies, LIRGs and ULIRGs is working at IR or radio wavelengths where the dust extinction is strongly reduced (e.g., Mattila *et al.* 2013). However, it has become very clear that high spatial resolution is also critically important for a successful detection and study of SNe within the bright and complex nuclear regions of U/LIRGs (e.g. Mattila *et al.* 2007, Perez-Torres *et al.* 2007). At IR wavelengths this can be achieved either by space telescopes or by ground-based Adaptive Optics (AO) imaging used to compensate for the blurring by a turbulent atmosphere. The combination of near-IR and AO instrumentation provides a spatial resolution ($\sim$0.1 arcsec) which is 10$\times$ better than typically available under ground-based natural seeing conditions and is comparable to that attainable with space telescopes. At radio wavelengths even higher angular resolution ($<$10 milliarcsec) is available thanks to the Very Long Baseline Interferometry (VLBI) imaging techniques. Radio observations are completely free from the effects of dust allowing studies of the SN population within the innermost nuclear regions of nearby U/LIRGs (e.g. Herrero-Illana *et al.* 2012).

Figure 1 shows examples of our high angular resolution near-IR and radio observations of the nearby LIRG Arp 299 (Kankare *et al.* 2014; Perez-Torres *et al.* 2009). The near-IR image comes from our AO observations and shows the entire merging system of galaxies with the locations of a number of circumnuclear SNe indicated. The radio image comes from VLBI observations and shows the innermost 150 pc regions of the eastern component of Arp 299 with a number of resolved compact radio sources, consistent with radio SNe and SN remnants. To have hope of detecting these events one clearly needs a high spatial

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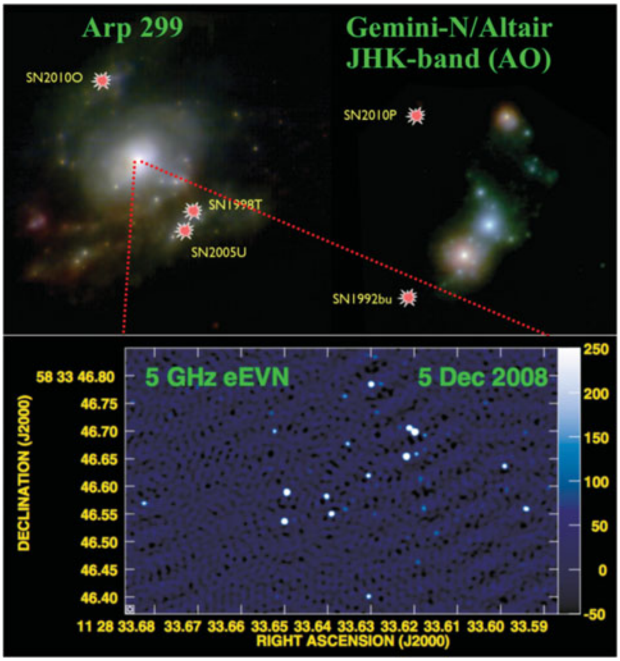

Figure 1. Top: Colour combined near-IR JHK-band image (FWHM = 0.1 arcsec) of the luminous infrared galaxy Arp 299 obtained with the Gemini-North telescope with the Altair/NIRI AO system with laser guide star (Kankare *et al.* 2014). The locations of a number of circumnuclear SNe detected at optical or near-IR wavelengths are indicated (for details see Mattila *et al.* 2012). Bottom: Interferometric radio image (FWHM = 8.5 mas) at 5 GHz of the central 150 pc nuclear regions of the eastern component of Arp 299 obtained with the electronic European VLBI Network (eEVN). The radio image shows a number of compact sources most of which are young radio SNe and SN remnants consistent with the high SFR within the nuclear regions of Arp 299 (Perez-Torres *et al.* 2009; Romero-Cañizales *et al.* 2011).

resolution and the use of either IR or radio observations to tackle the dust extinction. However, at larger distances even a 10 milliarsec angular resolution is not sufficient to resolve individual components that might be blended, and/or be embedded in diffuse emission (e.g., Romero-Cañizales *et al.* 2012).

3. AO assisted near-IR SN searches in luminous infrared galaxies

Our near-IR AO assisted programmes have already yielded the best available SN search dataset of nearby LIRGs. In our Gemini-North programme we used the laser guide star AO for repeatedly imaging a sample of 8 nearby LIRGs in near-IR K-band over a 2.5 year period. Follow-up observations in JHK bands allowed constraining the SN types and line-of-sight extinction. During the programme we discovered/confirmed a total of 6 nuclear SNe (Ryder *et al.* 2014) in good agreement with the expectations. For example, SN 2008cs detected in the circumnuclear regions of IRAS 17138-1017 was observed to suffer from a very high host galaxy extinction of A_V = 16 therefore making it only detectable at IR and radio wavelengths (Kankare *et al.* 2008). Furthermore, SNe 2010cu and SN 2011hi were discovered at only ∼180pc and ∼380pc (0.4 and 0.8 arcsec) galactocentric distances in the LIRG IC 883 and our follow-up observations allowed estimating their extinction of A_V = 0 and 5-7, respectively (Kankare *et al.* 2012). High resolution radio follow-up observations provided upper limits for the radio luminosities in agreement with their

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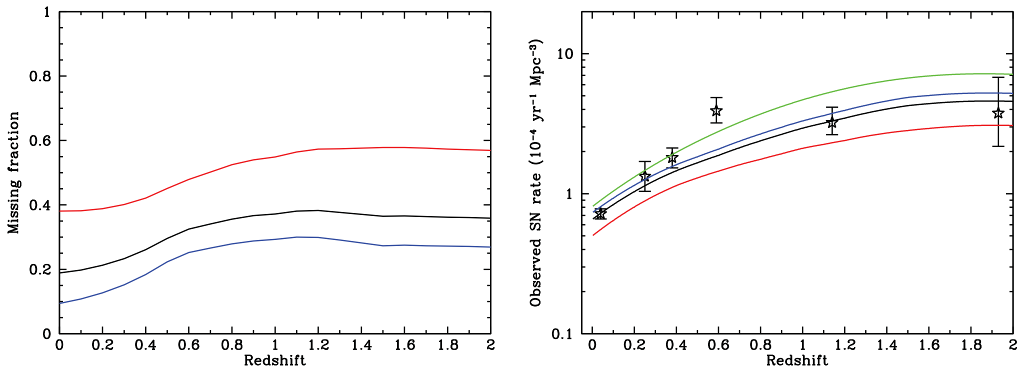

Figure 2. Left: The fraction of SNe missed by rest-frame optical searches as a function of redshift (from Mattila *et al.* 2012). Black line shows the best (nominal) estimate together with low and high missing fraction models as blue and red lines, respectively. Right: Average observed core-collapse SN rates (stars) from Strolger *et al.* (2015) as a function of redshift compared with the expectations from the cosmic SFH (lines) and assuming a Salpeter IMF and stars with initial masses between 8 and 20 solar masses resulting in luminous core-collapse SNe (green line = no missing SNe; black, blue and red lines correspond to the nominal, low and high missing fractions, respectively). This demonstrates that the measured core-collapse SN rates between z = 0 and 2 are consistent with those expected from the cosmic SFH if taking into account the missing SNe in U/LIRGs.

likely classification as type II-P SNe based on the near-IR light curves (Romero-Cañizales *et al.* 2012). Neither of the two objects were detectable in ground-based seeing-limited images highlighting the importance of high spatial resolution for the detection and study of SNe within the LIRG innermost nuclear regions. Also, SN 2010P discovered within the C' component of Arp 299 suffered from a high extinction of $A_V = 7$. An optical spectrum from Gemini-N provided a best match with the type IIb SN 2011dh (Kankare *et al.* 2014) whereas our radio follow-up showed it to be the most distant and most slowly evolving type IIb radio SN detected to date (Romero-Cañizales *et al.* 2014).

More recently, we have expanded our efforts to make use of laser guide star AO with NIRC2 on the Keck telescope, as well as the Gemini Multi-Conjugate Adaptive Optics System (GeMS) on the Gemini-South telescope. The combination of improved angular resolution and increased field of view yielded by GeMS has already allowed the detection of four likely SNe (AT 2013if, 2015ca, 2015cb and 2015cf) within the nuclear regions of the LIRGs IRAS 18293-3413, NGC 3110 and IRAS 17138-1017. Near-IR and radio follow-up observations were obtained for all the four objects confirming their nature as core-collapse SNe (Kool *et al.* 2017, in prep.). In addition, our work has already resulted in some of the sharpest and deepest images of LIRGs ever obtained from the ground allowing also detailed studies of their star formation properties and super star cluster populations (Randriamanakoto *et al.* 2013a,b).

4. Implications of missing core-collapse SNe to cosmic SFH

Our combined use of high angular resolution near-IR and radio observations has allowed an empirical determination of the fraction of core-collapse SNe missed within the nuclear regions of U/LIRGs in the local Universe. With a number of assumptions we extrapolated these estimates up to cosmological redshifts (Mattila *et al.* 2012). For a volume-limited rest-frame optical SN survey we find the missing SN fraction to increase from its average local value of ∼19% to ∼38% at z∼1.2 and then stay roughly constant up to z = 2 (see Fig. 2). The uncertainties in the correction factors for the missing SNe are still substantial

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due to the limited statistics and our imperfect understanding of the nature of the nuclear SNe and the evolution of U/LIRGs as a function of redshift. A more accurate evaluation of the number of SNe lost in local U/LIRGs will eventually allow a more reliable estimate of the evolution of core-collapse SN rate as a function of redshift. With knowledge of the mass range of the stars producing luminous core-collapse SNe (e.g. Eldridge *et al.* 2013, Smartt 2015) this will allow a detailed comparison with the cosmic star formation rates (e.g. Botticella *et al.* 2012; Mattila *et al.* 2012; Dahlén *et al.* 2012; Cappellaro *et al.* 2015; Strolger *et al.* 2015).

In Figure 2, we compare the measured evolution of the core-collapse SN rate as a function of redshift with the expectations from the latest consensus cosmic SFH from Madau & Dickinson (2014) assuming a Salpeter initial mass function (IMF) with initial mass cut offs for core-collapse SN progenitors of 8 and 20 solar masses. The resulting core-collapse SN rates are shown for (1) no SNe missed within the nuclear regions of U/LIRGs and (2) for the missing fractions evaluated in Mattila *et al.* (2012). This demonstrates that the measured core-collapse SN rates between $z = 0$ and 2 are consistent with those expected from the cosmic SFRs after accounting for the missing SNe in U/LIRGs. We note that the uncertainties due to the missing SN fraction correction are currently at a similar level as the statistical uncertainties in the measured core-collapse SN rates. However, the SN statistics will be improved significantly in the near-future thanks to the Large Synoptic Survey Telescope (LSST) as well as deep IR surveys (e.g. by the James Webb Space Telescope) also in the highest redshift bins and thus the evaluation of more precise missing SN fractions will become crucial.

References

Botticella, M. T., Smartt, S. J., Kennicutt, R. C., *et al.* 2012, *A&A*, 537, A132
Cappellaro, E., Botticella, M. T., Pignata, G., *et al.* 2015, *A&A*, 584, A62
Dahlén, T. & Fransson, C. 1999, *A&A*, 350, 349
Dahlén, T., Strolger, L.-G., Riess, A. G., *et al.* 2012, *ApJ*, 757, 70
Eldridge, J. J., Fraser, M., Smartt, S. J., Maund, J. R., & Crockett, R. M. 2013, *MNRAS*, 436, 774
Herrero-Illana, R., Pérez-Torres, M. Á., & Alberdi, A. 2012, *A&A*, 540, L5
Horiuchi, S., Beacom, J. F., Kochanek, C. S., *et al.* 2011, *ApJ*, 738, 154
Kangas, T., Mattila, S., Kankare, E., *et al.* 2016, *MNRAS*, 456, 323
Kankare, E., Mattila, S., Ryder, S., *et al.* 2008, *ApJ*, 689, L97
Kankare, E., Mattila, S., Ryder, S., *et al.* 2012, *ApJ*, 744, L19
Kankare, E., Mattila, S., Ryder, S., *et al.* 2014, *MNRAS*, 440, 1052
Madau, P. & Dickinson, M. 2014, *ARA&A*, 52, 415
Magnelli, B., Elbaz, D., Chary, R. R., *et al.* 2011, *A&A*, 528, A35
Mattila, S., Väisänen, P., Farrah, D., *et al.* 2007, *ApJ*, 659, L9
Mattila, S., Dahlen, T., Efstathiou, A., *et al.* 2012, *ApJ*, 756, 111
Mattila, S., Fraser, M., Smartt, S. J., *et al.* 2013, *MNRAS*, 431, 2050
Pérez-Torres, M. A., Romero-Cañizales, C., Alberdi, A., & Polatidis, A. 2009, *A&A*, 507, L17
Pérez-Torres, M. A., Mattila, S., Alberdi, A., *et al.* 2007, *ApJ*, 671, L21
Randriamanakoto, Z., Escala, A., Väisänen, P., *et al.* 2013a, *ApJ*, 775, L38
Randriamanakoto, Z., Väisänen, P., Ryder, S., *et al.* 2013b, *MNRAS*, 431, 554
Romero-Cañizales, C., Mattila, S., Alberdi, A., *et al.* 2011, *MNRAS*, 415, 2688
Romero-Cañizales, C., Pérez-Torres, M. A., Alberdi, A., *et al.* 2012, *A&A*, 543, A72
Romero-Cañizales, C., Herrero-Illana, R., Pérez-Torres, M. A., *et al.* 2014, *MNRAS*, 440, 1067
Ryder, S. D., Mattila, S., Kankare, E., & Väisänen, P. 2014, *Proc. SPIE*, 9148, 91480D
Smartt, S. J. 2015, *PASA*, 32, e016
Strolger, L.-G., Dahlen, T., Rodney, S. A., *et al.* 2015, *ApJ*, 813, 93