RADIO DETECTION OF SUPERNOVA 2004ip IN THE CIRCUMNUCLEAR REGION OF THE LUMINOUS INFRARED GALAXY IRAS 18293–3413

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Received 2007 September 26; accepted 2007 October 17; published 2007 November 5

ABSTRACT

We report a radio detection of supernova SN 2004ip in the circumnuclear region of the luminous infrared galaxy IRAS 18293–3413, using Very Large Array (VLA) observations at 8.4 GHz on 2007 June 11. SN 2004ip had been previously discovered at near-infrared wavelengths using adaptive optics observations, but its nature (core collapse or thermonuclear) could not be definitely established. Our radio detection, about 3 years after the explosion of the supernova, indicates a prominent interaction of the ejecta of SN 2004ip with the circumstellar medium, confirming that the supernova was a core collapse event (probably a Type II) and strongly suggesting that its progenitor was a massive star with a significant mass loss prior to its explosion. SN 2004ip has a 8.4 GHz luminosity of \(3.5 \times 10^{37}\) erg s\(^{-1}\) Hz\(^{-1}\), about 3 times as bright as SN 2000ft in NGC 7469 at a similar age; given its projected distance to the nucleus (~500 pc), it is one of the closest of all known radio SNe to a galaxy nucleus and one of the brightest radio SNe ever.

Subject headings: galaxies: starburst — radio continuum: galaxies — radio continuum: stars — supernovae: individual (SN 2004ip)

1 INTRODUCTION

Stars more massive than \(\sim 8 M_\odot\) explode as core collapse supernovae (CCSNe), i.e., Types Ib/c and II. Given a reasonable assumption for the initial mass function, the observed CCSN rate can be used as a direct measure of the current star formation rate (SFR). Thus, CCSN searches (e.g., Cappellaro et al. 1999, 2005; Dahlen et al. 2004) can yield a new independent measurement of the star formation history of the universe. However, optical searches are only able to discover the SNe not severely affected by dust extinction, and therefore most of the SNe occurring in dusty starburst galaxies have remained undiscovered even in the local universe.

Furthermore, a large fraction of the star formation at high-\(z\) took place in luminous \((L_{16} > 10^{11} L_\odot)\,\text{LIRGs}\) and ultraluminous \((L_{16} > 10^{12} L_\odot)\,\text{ULIRGs}\) infrared galaxies (Pérez-González et al. 2005), where the dust extinction is even more severe. The existence of hidden SNe factories in the nuclear and circumnuclear regions of (U)LIRGs has already been demonstrated by high-resolution radio observations. For example, VLA observations of the circumnuclear starburst in NGC 7469 revealed an extremely bright radio supernova, SN 2000ft (Colina et al. 2001b). More recently, very long baseline interferometry (VLBI) observations of the nearby ULIRG, Arp 220, have revealed luminous radio SNe within its innermost 150 pc nuclear regions at a rate of \(4 \pm 2\) yr\(^{-1}\), which indicates an SFR high enough to power its entire IR luminosity (Lonsdale et al. 2006). These studies confirm that CCSN rates a couple of orders of magnitude higher than in ordinary field galaxies can be expected for starburst-dominated (U)LIRGs.

Ground-based near-infrared (IR) observations (with spatial resolution \(\sim 1\)\(''\)) can provide a complementary tool to high-resolution radio observations in the search for CCSNe in (U)LIRGs (Van Buren & Greenhouse 1994; Grossan et al. 1999; Mattila & Meikle 2001; Maiolino et al. 2002; Mannucci et al. 2003; Mattila et al. 2004, 2005a, 2005b). More recently, Mattila et al. (2007a, 2007b) reported the first ever adaptive optics (AO) assisted discovery of a SN making use of the NAOS CONICA (NACO) AO system on the ESO Very Large
The discovery of SN 2004ip could only be announced very recently (Mattila et al. 2007a), thus making any follow-up observations difficult. However, assuming that SN 2004ip was an SN 2000ft–like event, we could expect it to be bright enough as to be detectable with the VLA even 3 years after its explosion. Hence, we proposed rapid response science VLA time to search for centimeter-wavelength radio emission at its location. In this Letter, we report the first radio detection of SN 2004ip, indicating a strong interaction with its circumstellar medium (CSM).

2. VLA OBSERVATIONS

We observed the host galaxy of SN 2004ip, IRAS 18293−3413, on 2007 June 11 at the frequency of 8.4 GHz with the VLA in A configuration, aimed at resolving and detecting SN 2004ip at radio wavelengths. We used rapid response exploratory VLA Time, since the angular distance of the supernova to the nucleus (about 1.4") made it necessary to ask for the VLA in its most extended, A-configuration. We observed at 8.4 GHz, which resulted in an angular resolution of 0.21' and 0.62" in right ascension (R.A.) and declination (decl.), respectively, enough to discern the radio emission from the supernova from that of the nucleus. Also, at 8.4 GHz any extended radio emission from the galaxy and its nucleus should be less prominent than at lower frequencies (the only previously existing VLA radio observations of IRAS 18293−3413 were carried out at 1.4 GHz with an angular resolution of about 5", indicating a large flux density, ≈130 mJy for the entire galaxy), while at higher frequencies the supernova was expected to be too faint to be detectable.

The observations lasted for 2 hours and consisted of ~11.5 minute scans on SN 2004ip (for a total on-target time of ~81 minutes), interleaved with ~2.5 minute scans on the phase and amplitude calibrator J1820−254, and each time ending with a ~5 minute observation of the quasar 3C 286 (1331+305) to set the absolute flux density scale. We edited, calibrated, and imaged our 8.4 GHz VLA data by following standard data reduction techniques implemented within the NRAO Astronomical Image Processing System (AIPS).

3. RESULTS

Our results are summarized in Figure 1 and Table 1. Figure 1 shows the 8.4 GHz radio emission from the central parts of IRAS 18293−3413 (contours) overlaid on a subtracted NACO $K_s$-band image (shown with an inverted brightness scale), which is the result of subtracting a $K_s$-band image obtained on 2004 May 4 from the image obtained on 2004 September 15 (for details see Mattila et al. 2007b). A strong negative residual coincident with the $K_s$-band nucleus is visible in white color, and SN 2004ip is clearly visible as a positive point source (in black color). A local

![Image](image_url)
maximum of radio emission within the circumnuclear region of the galaxy is right coincident with SN 2004ip.

The radio contours also indicate evidence for a number of bright, compact objects whose discussion is beyond the scope of this Letter. We only note here that we have found eight such compact regions with signal-to-noise ratios larger than 20 (S_r ≥ 460 μJy), but which have no clear counterpart in the near-IR image. Future multiwavelength VLA observations of this galaxy will allow us to shed some light on the nature of these compact sources. In Table 1, we show the 8.4 GHz VLA flux densities of the nucleus of IRAS 18293−3413 and a source we identify as SN 2004ip, which exploded between 2004 May 4 and September 13 within the nuclear starburst of the galaxy.

The absolute position of SN 2004ip was only reported with an estimated precision of ±0.4″ by Mattila et al. (2007b). To compare with the position of the source detected in our VLA image (see Fig. 1), the precision of the supernova astrometry first needed to be improved. For this purpose we used archival K-band data of IRAS 18293−3413 obtained with the SOFI near-IR camera on the New Technology Telescope (NTT) on 2001 September 8. The final K-band image, reduced using standard IRAF routines, has an on-source exposure time of 30 minutes and a seeing FWHM of ~1.2″. Due to the low galactic latitude, a large number of stars is visible within the ∼7″ × 7″ field of view of the combined NTT image. Therefore, we were able to identify over 400 bright and isolated stars with astrometry available from 2MASS. These yielded a world coordinate system (WCS) solution for the NTT image with rms of 4 and 3 mas in R.A. and decl., respectively. We then used the centroid coordinates of 14 isolated stars, detected within the field of view of both the 42″ × 42″ NACO and NTT images, to align the images in IRAF using a general geometric transformation with no nonlinear part. This yielded an rms of 34 and 22 mas in R.A. and decl., respectively. Finally, the position of the supernova was measured in a NACO K-band image which is the result of subtracting an image obtained on 2004 May 4 from an image obtained on 12004 September 5 (for details on the images and the subtraction method, see Mattila et al. 2007b). We adopted the average from three different methods (centroid, gauss, ofilter) used in IRAF as the SN position. The position uncertainty as indicated by the standard deviation of these measurements was very small, ~1 mas for both x and y, thanks to the well-sampled NACO PSF and the flat and close to zero background in the subtracted image. Using the WCS of the NTT image aligned to the NACO image, we obtained R.A. = 18h32m41.207″ and decl. = −34°11′26.80″ (equinox J2000.0) for the SN with an estimated precision of ±34 and ±22 mas in R.A. and decl., respectively.

Therefore, the radio source we identified as SN 2004ip appears coincident with the near-IR position of the supernova within 10 and 20 mas in R.A. and decl., respectively. This is within the uncertainties of the SN near-IR position (as derived above) and radio position (±20 and ±10 mas in R.A. and decl., respectively), which confirms that the radio emission corresponds to SN 2004ip.

4. DISCUSSION AND SUMMARY

Thermonuclear (Type Ia) supernovae are not expected to be strong radio emitters and have not yet been detected at radio wavelengths (e.g., Panagia et al. 2006). Current modeling of their radio emission indicates that the circumstellar wind around the progenitor star is much less dense than in the case of CCSNe and would be overrun in about 1 day due to its proximity and the much higher velocity of the supernova blast wave. At the distance of IRAS 18293−3413, this would result in an SN Ia radio emission reaching 8.4 GHz peak values of 13–50 μJy at ~3–10 days after the explosion and quickly decreasing below 0.3–3 μJy after 100 days, depending on the particular model (P. Lundqvist 2007, private communication). Therefore, a thermonuclear origin for SN 2004ip—detected at ~470 μJy after more than 1000 days after its explosion—can be ruled out.

CCSNe are expected—as opposed to thermonuclear SNe—to become strong radio emitters when the SN ejecta interact with the CSM that was ejected by the progenitor star before its explosion as a supernova (Chevalier 1982; Weiler et al. 1986). Indeed, the interaction gives rise to a high-energy density shell, which is Rayleigh-Taylor unstable and can drive turbulent motions that may amplify the existing magnetic field and efficiently accelerate relativistic electrons, thus enhancing the emission of synchrotron radiation at radio wavelengths (Chevalier 1982). The duration of this radio SN phase is limited, however, by the extent of the expanding wind of the progenitor star, which can reach a radius where the ram pressure of the wind, ρ_v^2, equals the external pressure of the interstellar medium (ISM), PISM (Chevalier & Fransson 2001). For a spherically symmetric, steady wind (ρ_s ∝ r^−3), this radius is r_s ≈ 0.18 M_p^{1/2} v_w^{1/2} p_s^{−1/2} pc, where M_p is the mass-loss rate in units of 10^{-4} M_⊙ yr^{-1}, v_w is the wind velocity in units of 10 km s^{-1}, and p_s is the ISM pressure in units of 10^{-7} cm^{-3} K, which is the estimated pressure for the central region of the starburst in M82 (Chevalier & Clegg 1985). At this distance, a CCSN would then enter the supernova remnant (SNR) phase, and the radio emission would no longer be due to the interaction with the CSM but rather with the ISM. However, even if the ejecta of SN 2004ip would have been freely expanding at a constant velocity of v_e = 10^4 km s^{-1}, the distance reached by the circumstellar shock in 3 years would be r_s = 0.03 pc, which is much smaller than r_s, assuming an ISM pressure similar to M82. We conclude that SN 2004ip is still in its SN phase, and its radio emission is being powered—even 3 years after the SN explosion—by prominent interaction with the CSM. This fact confirms that the supernova was a core collapse event and implies that its progenitor was a massive star with a significant mass loss (M ∼ 10^{-4} M_⊙ yr^{-1}) prior to its core collapse.

SN 2004ip exploded sometime between 2004 May 4 and September 13, so its radio emission is now likely in a decaying phase. The 8.4 GHz flux density of SN 2004ip detected in the 2007 June observations (∼470 μJy) corresponds to an isotropic luminosity of 3.5 × 10^{17} ergs s^{-1} Hz^{-1}, or 3 times as luminous as SN 2000ft in NGC 7469 at a similar age. Given the fact that it exploded about 3 years earlier, SN 2004ip might have been one of the most luminous radio SNe ever at its peak (and probably significantly brighter than the nucleus of its host galaxy) and would therefore belong to the class of extremely bright and long-lasting radio SNe, like SN 1978K (Schlegel et al. 1999), SN 1986J (Weiler et al. 1990; Pérez-Torres et al. 2002), SN 1988Z (Van Dyk et al. 1993b), or SN 2000ft (Colina et al. 2001b), which at their peak emission were a thousand to a few thousand times more luminous than Cas A, the brightest radio SN in the Milky Way (Weiler et al. 1986). In addition to its extreme radio brightness, SN 2004ip shares with SN 2000ft in the LIRG NGC 7469 (Alberdi et al. 2006), and with the young radio supernovae in the central regions of Arp 299 (Neff et al. 2004), other characteristics in common. Indeed, SN 2004ip exploded in the circumnuclear region of a LIRG, is located at a similar projected distance (r ~ 500 pc) from the galaxy nucleus, is still in its radio SN phase, and is detectable several
years after its explosion. These facts indicate that such radio SNe might be a relatively common phenomenon in circum-nuclear starburst environments.

Extremely bright and long-lasting radio SNe are identified in the optical as Type II supernovae, and because of their huge radio luminosities, their progenitors are believed to be massive stars in the $20-30 \, M_{\odot}$ range (Weiler et al. 1990; Van Dyk et al. 1993) that explode in very dense environments (e.g., Chugai 1997). The typical spectral index for normal Type II supernovae is $-0.6$ to $-0.8$ (Weiler et al. 2002). Type II radio SNe also exhibit slow rises and declines and normally take more than 1 year to reach their 8.4 GHz peak radio emission. On the other hand, Type Ib/c supernovae can also produce bright radio SNe, e.g., SN 1983N (Sramek et al. 1984; Weiler et al. 1986), SN 1990B (Van Dyk et al. 1993a), and the brightest of all, SN 1998bw (Kulkarni et al. 1998). However, the radio emission of these supernovae is characterized by a rather fast rise and decay (few days to a few weeks), and by radio spectral indices of about $-1.1$ to $-1.2$ (Weiler et al. 2002). While the measured single radio flux of SN 2004ip does not allow a definite classification, the fact that its radio luminosity is so high even 3 years after the explosion favors strongly a Type II origin since their radio flux densities tend to decrease much more slowly than the radio emission from Type Ib/c SNe.

The level of the 8.4 GHz radio emission of SN 2004ip detected in our 2007 June observation ($\sim 470 \, \mu$Jy) suggests that we might be able to monitor the radio flux density evolution of SN 2004ip with the VLA for some years from now, thus probing the circumstellar interaction around the supernova, eventually allowing us to detect its transition from the SN phase to the SNR phase, as has been suggested for a number of compact sources in the nuclear starburst of Arp 220 (Parra et al. 2007). In addition, a radio light-curve follow-up could provide more detailed information on the progenitor of SN 2004ip. For example, Ryder et al. (2004) inferred the action of a binary companion from periodic modulations in the radio light curve of SN 2000Q, which was subsequently confirmed from imaging at Gemini (Ryder et al. 2006). This would make SN 2004ip the second case, only after SN 2000R in NGC 7469, where such radio monitoring has been carried out for a SN in the circumnuclear starburst of a LIRG and will help to better understand the behavior of SNe within dense starburst environments (e.g., Alberdi et al. 2006). Furthermore, Mattila et al. (2007b) estimated an average SFR of $135 \, M_{\odot} \, yr^{-1}$ for IRAS 18293$-$3413 corresponding to a CCSN rate of $\sim 1.0$ SN per year. Therefore, radio monitoring at high resolution and sensitivity with the VLA might easily result also in the discovery of new radio SNe.

The number of CCSNe discovered in circumnuclear regions of (U)LIRGs, both at infrared and radio wavelengths, is still small. However, these events may have an important impact when estimating the complete local CCSN rates including also the SNe in the optically obscured parts of the galaxies. The direct detection and study of CCSNe in starburst galaxies over a large range of IR luminosities ($L_{\text{IR}} = 10^{10-12} \, L_{\odot}$) is also crucial for interpreting the results of the high-$z$ CCSN searches, since a large fraction of the massive star formation at high-$z$ took place in IR-luminous galaxies. Therefore, our discovery shows that the combination of high-resolution observations at near-infrared and radio wavelengths is a powerful tool to search for CCSN events from LIRGs in the local universe, and thus establish their core collapse supernova rates and star formation rates, as well as to constrain the nature of the discovered events through their interaction with the surrounding medium.

We are grateful to an anonymous referee for helpful comments on the manuscript. We are also grateful to the National Radio Astronomy Observatory (NRAO) for granting us Rapid Response, Very Large Array (VLA) time for this project. NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. MAPT research is supported by the Ramón y Cajal programme of the Spanish Ministry of Education and Science. M. A. P.-T., A. A., and J. M. T. acknowledge support from the Spanish grants AYA2006-14986-C02-C01 and AYA2005-08523-C03, respectively. S. M. acknowledges financial support from the Participating Organisations of EURYI and the EC Sixth Framework Programme and from the Academy of Finland (project: 8120503).

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