

ADAPTIVE OPTICS DISCOVERY OF SUPERNOVA 2004ip IN THE NUCLEAR REGIONS OF THE LUMINOUS INFRARED GALAXY IRAS 18293–3413

S. MATTILA,¹ P. VÄISÄNEN,² D. FARRAH,³ A. EFSTATHIOU,⁴ W. P. S. MEIKLE,⁵ T. DAHLEN,⁶
C. FRANSSON,⁷ P. LIRA,⁸ P. LUNDQVIST,⁷ G. ÖSTLIN,⁷ S. RYDER,⁹ AND J. SOLLERMAN¹⁰

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ABSTRACT

We report a supernova discovery in K_s -band images from the NAOS CONICA adaptive optics (AO) system on the ESO Very Large Telescope. The images were obtained as part of a near-infrared search for highly obscured supernovae in the nuclear regions of luminous and ultraluminous infrared galaxies. SN 2004ip is located within a circumnuclear starburst at 1.4" (or 500 pc) projected distance from the K -band nucleus of the luminous infrared galaxy IRAS 18293–3413. The supernova luminosity and light curve are consistent with a core-collapse event suffering from a host galaxy extinction of up to about 40 mag in the V band, which is as expected for a circumnuclear starburst environment. This is the first supernova to be discovered making use of AO correction and demonstrates the potential of the current 8 m-class telescopes equipped with AO in discovering supernovae from the innermost nuclear regions of luminous and ultraluminous infrared galaxies.

Subject headings: galaxies: individual (IRAS 18293–3413) — galaxies: starburst — infrared: galaxies — instrumentation: adaptive optics — supernovae: general

1. INTRODUCTION

The observed rate at which stars more massive than $\sim 8 M_\odot$ explode as core-collapse supernovae (CCSNe) can be used as a direct measure of the current star formation rate (SFR), given a reasonable assumption for the initial mass function (IMF). In fact, CCSNe are beginning to be used as probes of the SFR at both low and high redshift (e.g., Cappellaro et al. 1999; Dahlen et al. 2004; Cappellaro et al. 2005) with the aim of providing a new independent measurement of the star formation history of the universe. A large fraction of the massive star formation at high z took place in luminous ($L_{\text{IR}} > 10^{11} L_\odot$) and ultraluminous ($L_{\text{IR}} > 10^{12} L_\odot$) infrared (IR) galaxies (LIRGs and ULIRGs, respectively), and their high SFRs can be expected to result in CCSN rates a couple of orders of magnitude higher than in ordinary field galaxies. However, most of the SNe occurring in LIRGs and ULIRGs are likely to be obscured by large amounts of dust in the nuclear starburst environment and therefore have remained undiscovered by optical SN searches, even in the local universe. The existence of hidden SN factories in the nuclei of LIRGs and ULIRGs has already been demonstrated by high-resolution radio observations. For example, VLBI observations of the nearby ULIRG Arp 220 have revealed luminous radio SNe within its innermost ~ 150 pc nuclear regions at a rate indicating a SFR high enough to power its entire IR luminosity (Lonsdale et al. 2006; Parra et al. 2006). However, not all CCSNe are likely to become luminous at radio wavelengths, and there-

fore radio searches for SNe can only provide a lower limit for the real SN rates.

In the near-IR K band, the extinction is strongly reduced while the sensitivity of ground-based observations is still good, making searches for SNe in starburst galaxies, LIRGs, and ULIRGs more promising (van Buren & Greenhouse 1994; Grossan et al. 1999; Mattila & Meikle 2001, hereafter MM01; Maiolino et al. 2002; Mannucci et al. 2003; Mattila et al. 2004). Furthermore, the recent introduction of adaptive optics (AO) for 8 m-class telescopes now enables near-IR searches for SNe at a spatial resolution comparable to some of the radio studies. In this Letter we report a SN discovery in the circumnuclear starburst of IRAS 18293–3413, which is a LIRG at a redshift of $z = 0.0182$ (Strauss et al. 1992) corresponding to a distance of 79 Mpc ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_M = 0.3$). The SN was detected as a result of our K_s -band search of highly obscured CCSNe in a sample of 15 nearby LIRGs and ULIRGs using the NAOS CONICA (NACO) AO system on the ESO Very Large Telescope (VLT).

2. OBSERVATIONS AND RESULTS

2.1. NACO Observations and Data Reduction

IRAS 18293–3413 was observed for the first time with VLT/NACO (Rousset et al. 2003; Lenzen et al. 2003) in service mode on 2004 May 4.3 UT in the K_s band with the S27 camera ($0.027'' \text{ pixel}^{-1}$) using the autogitter imaging sequence (see Table 1 for details on the observing parameters and conditions). The AO correction was performed using the visual wavefront sensor with a natural guide star of $m_V \sim 15, 25''$ northeast from the science target. The observations were repeated on 2004 September 13.1 UT to allow SN detection by subtracting the images from the two epochs. The data obtained on September 13 were immediately reduced and searched for any obvious SNe (for details, see below and § 2.2). This analysis produced a clear detection of a new point source in the September 13 data. We therefore triggered the Target of Opportunity (ToO) part of the program to obtain a deep repeat observation in the K_s band on September 15.0 UT, 2 days after the discovery image. About 2 weeks later, on September 27.1 UT, we triggered VLT ToO again, this time to obtain both light curve

¹ Astrophysics Research Centre, School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, UK; s.mattila@qub.ac.uk.

² South African Astronomical Observatory, Observatory 7935, South Africa.

³ Department of Astronomy, Cornell University, Ithaca, NY 14853.

⁴ School of Computer Science and Engineering, Cyprus College, Engomi, 1516 Nicosia, Cyprus.

⁵ Astrophysics Group, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK.

⁶ Space Telescope Science Institute, Baltimore, MD 21218.

⁷ Department of Astronomy, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden.

⁸ Departamento de Astronomía, Universidad de Chile, Santiago, Chile.

⁹ Anglo-Australian Observatory, Epping, NSW 1710, Australia.

¹⁰ Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark.

TABLE 1
LOG OF VLT/NACO OBSERVATIONS OF IRAS 18293–3413

Date (UT 2004)	Band	Integration (s)	Seeing (arcsec)	Air Mass	SR ^a (%)
May 4.3	K_s	24 × 90	0.47–0.79	1.08–1.19	20–30 (22)
Sep 13.1	K_s	23 × 90	0.65–0.90	1.15–1.28	15–20 (21)
Sep 15.0	K_s	63 × 90	0.70–1.25	1.01–1.15	5–20 (41)
Sep 27.1	H	68 × 90	0.53–1.15	1.11–1.70	5–15 (38)
	K_s	15 × 90	0.69–0.81	1.81–2.13	5–10 (6)

^a The Strehl ratios of the frames used for the combined images are listed with the number of frames in parentheses.

and $H - K$ color information for the SN. The SN was reported on the “CBAT Possible Supernovae Page”¹¹ immediately after the discovery and was later assigned the designation SN 2004ip (Mattila et al. 2007).

The NACO data were reduced using the IRAF DIMSUM package and IDL. The jittered on-source frames were median-combined to form a sky frame. The sky-subtracted images were de-dithered, making use of the centroid coordinates of a bright field star visible in all the frames, and the de-dithered frames were median-combined, excluding frames with the lowest Strehl ratios (SRs; see Table 1).

2.2. Supernova Detection and Photometry

The images from September 13, 15, and 27 were rotated and shifted to align them to the reference image (from May 4) using bright isolated stars around the galaxy. We used a slightly modified version of the Optimal Image Subtraction method (Alard & Lupton 1998; Alard 2000) as implemented in ISIS 2.2 to derive a convolution kernel to match the better seeing image to the image with the poorer seeing and to match the intensities and background differences between the frames. In MM01, we demonstrated the feasibility of this method in nuclear SN detection. The subtracted images show a clear point source (with its peak at the $\sim 20\sigma$ and $\sim 7\sigma$ levels in the September 13–15 and September 27 epochs, respectively) at $1.14''$ east and $0.78''$ north from the K_s -band nucleus of the galaxy (see Fig. 1). However, without a suitable reference image for image subtraction, we were unable to detect the SN in our H -band data. Using the world coordinate system from a 2MASS image of IRAS 18293–3413, we obtained R.A. = $18^{\text{h}}32^{\text{m}}41.26^{\text{s}}$ and decl. = $-34^{\circ}11'26.7''$ (equinox 2000.0) for the SN with an estimated precision of $\pm 0.4''$.

We adopted the photometric zero points provided by ESO for our nights of observations, and we estimate them to be accurate to ± 0.03 mag in comparison to 2MASS data. Since the SR changes as a function of the distance from the AO guide star, to measure the SN photometry with the associated uncertainties, we used two isolated bright stars lying, respectively, $12''$ and $38''$ from the guide star ($7.1''$ north, $18.3''$ east and $5.8''$ south, $11.5''$ west of the galaxy K -band nucleus) to provide a point-spread function (PSF) with a higher and lower SR, respectively compared to the actual SN. The two PSFs were scaled to correspond to magnitudes ranging between 18.5 and 19.1 in steps of 0.1. Sources with each magnitude and PSF were then simulated in the images at 20 different locations evenly distributed around the galaxy nucleus at the same offset as the real SN. The sources were added to the images one at a time before the images were aligned, matched, and subtracted. The magnitudes for both the real and simulated SNe were measured from each subtracted

image using aperture photometry with a $0.15''$ aperture radius and a sky annulus between $0.20''$ and $0.30''$. We then estimated a magnitude for the SN by comparing its photometry with the mean of the counts measured for the 20 simulated sources with each magnitude and PSF. This yielded SN magnitudes of $m(K_s) = 18.74$ and 18.64 for September 13 using the two different PSFs, respectively. Similarly, we obtained $m(K_s) = 18.66$ and 18.72 for September 15. We adopted the standard deviation (σ) of the 20 measurements as the uncertainty in our SN photometry, yielding $\sigma = 0.12$ and 0.09 for the two epochs, respectively. Measuring with a 50% larger aperture and sky annulus gave very similar magnitudes, only the uncertainties were increased. This is because the photometry is performed relative to the simulated sources. During the September 27 K_s -band observation, the air mass was high, resulting in a low SR and therefore a wider PSF for the images. For this epoch, stronger residuals were also present in the subtracted images, and we therefore excluded 10 of the 20 simulated sources that were affected by much stronger residuals than the SN. For the September 27 data, we used an aperture radius of $0.30''$ and a sky annulus between $0.40''$ and $0.50''$. This yielded $m(K_s) = 18.82$ and $m(K_s) = 18.99$ with $\sigma = 0.14$ using the two PSFs, respectively. We adopt the average of the magnitudes obtained with the two different PSFs as the best estimate for the SN magnitude. The uncertainties were obtained as a quadrature sum of the σ value and the error in the zero point.

2.3. Confirmation of the Supernova

Without a spectroscopic observation of the SN, its confirmation and possible typing have to be based on photometry and other available information. An asteroid origin for the source was immediately ruled out since the images, separated by 2 days, show the SN in exactly the same position (within $\pm 0.02''$). Furthermore, the SN is still at precisely the same location in the third epoch images, obtained 2 weeks from the discovery. Below we model the near- to far-IR spectral energy distribution (SED) of IRAS 18293–3413 and find a negligible contribution from an active galactic nucleus (AGN) to its luminosity. Also, the presence of an AGN is not favored by the X-ray results of Risaliti et al. (2000) or by the fact that IRAS 18293–3413 shows an “H II galaxy” spectrum in the optical (Veilleux et al. 1995). Therefore, an AGN flare can be ruled out as the origin for the source. A variable foreground star also provides a very improbable alternative explanation given the small field of view [$42'' \times 42''$, i.e., $1/(3 \times 10^8)$ of the whole sky] of our combined NACO frames. For example, the likelihood of catching a foreground nova would be extremely small given the Galactic nova rate of $\sim 35 \text{ yr}^{-1}$ (Shafter 1997). Furthermore, a classical nova in IRAS 18293–3413 would be several magnitudes fainter than the detected SN (Hachisu & Kato 2006). We therefore conclude that anything other than a SN origin for our source appears extremely unlikely.

2.4. Supernova Type and Extinction

To estimate the SFR for IRAS 18293–3413, we compiled its 1–100 μm archival (2MASS and IRAS) photometry and fitted the resulting SEDs (see Fig. 2) both with the starburst models of Efstathiou et al. (2000) and with the cirrus model of Efstathiou & Rowan-Robinson (2003). The combination of the starburst models and the cirrus model provides a very good fit to the near- to far-IR SED and is consistent with a negligible contribution from an AGN. The model assumes an exponentially decaying starburst, with a time constant of 40 Myr, an

¹¹ See http://cfa-www.harvard.edu/iau/CBAT_PSN.html.

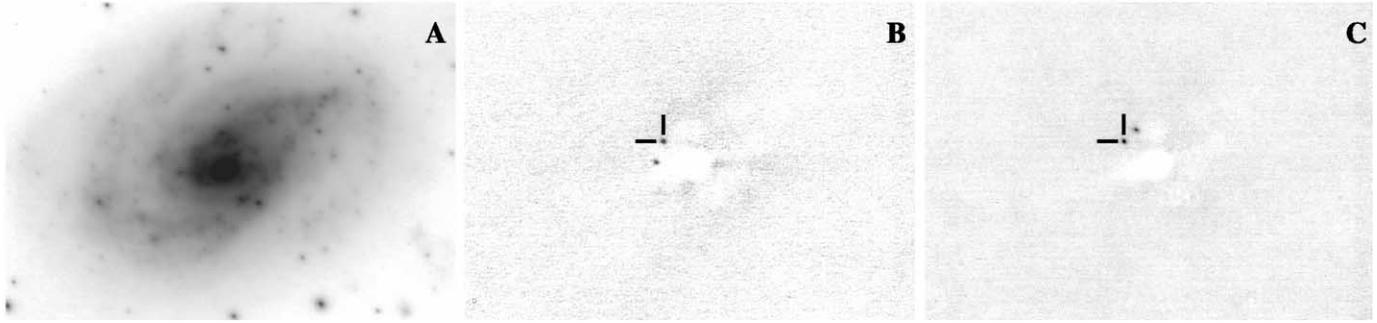


FIG. 1.—(a) $16.5'' \times 11.5''$ subsection of the NACO K_s -band image of IRAS 18293–3413 obtained on 2004 September 15.0 UT; north is up, and east is to the left. The results of image matching and subtraction of the NACO K_s -band reference image (May 4.3) from the images obtained on (b) September 13.1 and (c) September 15.0 are shown. SN 2004ip (indicated by tick marks) is clearly detected in the subtracted images at $1.14''$ east and $0.78''$ north of (or 500 pc projected distance) from the K -band nucleus. Simulated sources of $m(K_s) = 18.7$ are shown southeast and northwest of the SN in the two subtracted images, respectively. A strong negative residual is visible at the location of the galaxy nucleus in the subtracted images. All the images are shown with an inverted brightness scale.

age of 70 Myr, and an underlying 12.5 Gyr old stellar population. The cirrus A_V is assumed to be 1.7, and the initial A_V of the molecular clouds that constitute the starburst is 100. The SFR at the peak is $285 M_\odot \text{ yr}^{-1}$, and it is $135 M_\odot \text{ yr}^{-1}$ when averaged over the duration of the starburst. We estimate a rest-frame 8–1000 μm luminosity of $5.8 \times 10^{11} L_\odot$ and a bolometric luminosity of $6.5 \times 10^{11} L_\odot$ for IRAS 18293–3413.

Adopting the average SFR and assuming CCSN progenitors between 8 and $50 M_\odot$ and a Salpeter IMF with cutoffs at 0.1 and $125 M_\odot$ (see also MM01), we obtain a CCSN rate of $\sim 1 \text{ yr}^{-1}$ for IRAS 18293–3413. We note that this CCSN rate also agrees with the model predictions of Genzel et al. (1998) for an exponentially decaying starburst with similar time constant, age, and bolometric luminosity. Recent observational evidence shows that the Type Ia SN (SN Ia) rate is likely to depend on both the stellar mass and the mean SFR of their host galaxies (see Sullivan et al. 2006 and references therein). The rate of SNe Ia associated with the old stellar population is not expected to be enhanced in IRAS 18293–3413 compared with normal field galaxies, but the rate associated with the recent star formation could be higher. This rate has been found to depend on the host galaxy SFR averaged over the last 500 Myr (SFR_{ave}) according

to $\sim 4 \times 10^{-4} \text{ SNe yr}^{-1} / \text{SFR}_{\text{ave}}$ (Sullivan et al. 2006). Using $135 M_\odot \text{ yr}^{-1}$ as an upper limit for SFR_{ave} , we obtain an upper limit for its SN Ia rate of $\sim 0.05 \text{ yr}^{-1}$, which is ~ 20 times smaller than the estimated CCSN rate. We therefore conclude that SN 2004ip was very likely a core-collapse event.

After correcting for a Galactic extinction of $A_V = 0.47$ (Schlegel et al. 1998), the absolute magnitude of the SN at the time of the discovery becomes $M_{K_s} = -15.85$ (before correcting for the host galaxy extinction). In Figure 3, we compare the photometry of the SN with template K -band light curves for ordinary and slowly declining CCSNe from MM01. These templates comprise two and three linear components, respectively, and are based on the light curves of 11 (Types II and Ib/c) and two (the Type III SN 1979C and the Type II SN 1998S) CCSNe. The slow decliners are significantly more luminous than the ordinary events, even at early times, therefore requiring a larger host galaxy extinction to match the observations. Assuming that the SN was discovered at the K -band maximum light, we need to dim the ordinary and slowly declining templates by $A_K = 2.75$ and 4.15 mag, respectively, to match the observations. To estimate the lowest plausible extinction toward the SN, we sought the latest possible SN epoch of discovery to match the templates. The time interval between the reference and discovery images was ~ 130 days, and the template light curves of MM01 have rise times of ~ 25 days to the K -band maximum light. The latest SN epoch of discovery, assuming that the SN exploded soon after the observation of the reference image, is therefore about 100 days past the K -band maximum light. We found that the ordinary and slowly

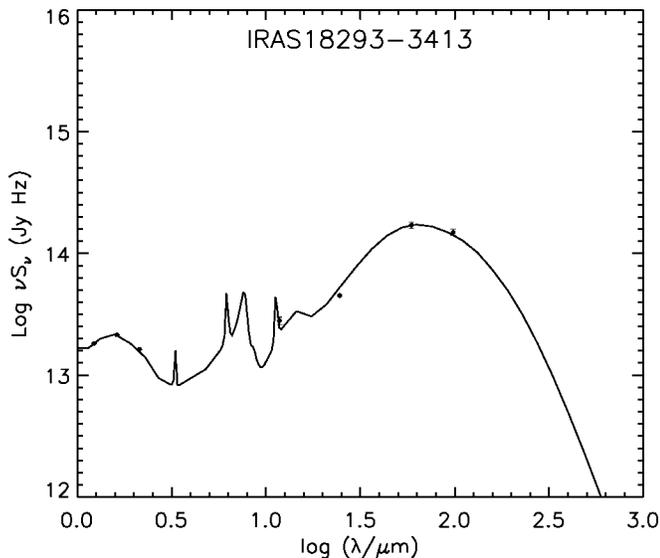


FIG. 2.—IR SED of IRAS 18293–3413 fitted with the starburst models of Efstathiou et al. (2000) and the cirrus model of Efstathiou and Rowan-Robinson (2003). No AGN contribution was needed to explain the SED.

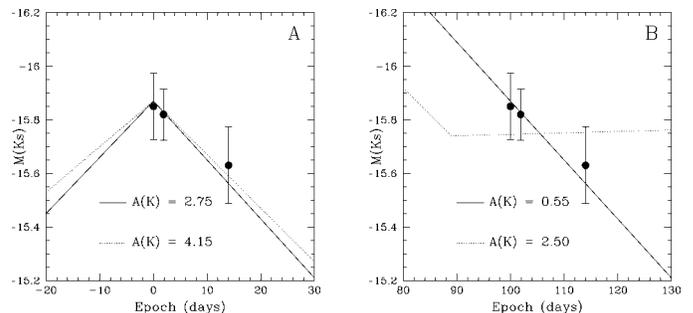


FIG. 3.—Absolute magnitudes of SN 2004ip compared with template K -band light curves (MM01) for ordinary (solid line) and slowly declining (dotted line) CCSNe. The SN epoch of discovery was assumed to be at (K -band) maximum light (a), 100 days past the maximum light (b). The host galaxy extinctions used for dimming the light curves are shown in the figures.

declining templates can match the observations at this epoch if $A_K = 0.55$ and 2.50 mag, respectively. Adopting the extinction law of Rieke & Lebofsky (1985), the range of likely host galaxy extinctions toward SN 2004ip is therefore between about 5 and 40 mag in A_V .

3. DISCUSSION

The number of CCSNe discovered in the infrared (van Buren et al. 1994; Maiolino et al. 2002; Mattila et al. 2005a, 2005b) is still rather small. However, these few events can have an important impact on the SN statistics when estimating the *complete* local CCSN rate, including also the SNe in the optically obscured parts of the galaxies. Detecting CCSNe directly in starburst galaxies over a range of IR luminosities ($L_{\text{IR}} = 10^{10}$ – $10^{12} L_{\odot}$) is also vital 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.

SN 2004ip is the first reported supernova discovered using adaptive optics. This discovery demonstrates the great potential of the current 8 m-class telescopes equipped with AO correction in discovering SNe from the innermost nuclear regions of LIRGs and ULIRGs. In addition, the next generation wide-field AO systems can be used for expanding near-IR SN searches to the high- z universe. Near-IR-discovered SNe in nuclear starbursts are not only important for SN rate estimates but they can also be used to estimate the amount and distribution of extinction within their host galaxies, and follow-up observations can provide us with a better understanding of the behavior of SNe within the dusty, high-density starburst environment. The extinction of up to 40 mag in

A_V estimated for SN 2004ip is consistent with those derived toward the radio supernova remnants in the nuclear (central 500 pc) regions of M82 (MM01). We note that *Infrared Space Observatory* (ISO) studies (Genzel et al. 1998) indicate much higher extinctions of A_V (mixed) ~ 50 – 1000 toward the highly excited mid-IR line-emitting innermost nuclear regions in LIRGs and ULIRGs. However, SN 2004ip is located in a circumnuclear starburst at a distance of 500 pc from the K -band nucleus where the conditions could be expected to be similar to the M82 nuclear environment.

Many of the SNe exploding in the nuclear starburst environment can be expected to produce very luminous radio SNe as a result of the interaction of the SN ejecta with a dense surrounding medium (Chevalier & Fransson 2001). In fact, the radio-discovered SN 2000ft (Colina et al. 2001; Alberdi et al. 2006), in a circumnuclear starburst ring (600 pc from the nucleus) of its LIRG host NGC 7469, showed a luminosity comparable to the brightest known radio SNe. In the future, radio follow-up observations of SN 2004ip and other SNe discovered in LIRGs and ULIRGs will therefore provide important information on their progenitor stars and on the conditions in the surrounding circumstellar medium.

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