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SN 1999ga: a low-luminosity linear type II supernova?

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ABSTRACT

Context. Type II-linear supernovae are thought to arise from progenitors that have lost most of their H envelope by the time of the explosion, and they are poorly understood because they are only occasionally discovered. It is possible that they are intrinsically rare, but selection effects due to their rapid luminosity evolution may also play an important role in limiting the number of detections. In this context, the discovery of a subluminous type II-linear event is even more interesting.
Aims. We investigate the physical properties and characterise the explosion site of the type II SN 1999ga, which exploded in the nearby spiral galaxy NGC 2442.
Methods. Spectroscopic and photometric observations of SN 1999ga allow us to constrain the energetics of the explosion and to estimate the mass of the ejected material, shedding light on the nature of the progenitor star in the final stages of its life. The study of the environment in the vicinity of the explosion site provides information on a possible relation between these unusual supernovae and the properties of the galaxies hosting them.
Results. Despite the lack of early-time observations, we provide reasonable evidence that SN 1999ga was probably a type II-linear supernova that ejected a few solar masses of material, with a very small amount of radioactive elements of the order of 0.01$M_{\odot}$.

Key words. stars: supernovae: general – stars: supernovae: individual: SN 1999ga – stars: supernovae: individual: SN 1979C – stars: supernovae: individual: SN 1980K – stars: supernovae: individual: SN 1990K

1. Introduction

Type II-linear supernovae (SNe IIL) form a rare and poorly studied class of core-collapse supernovae (SNe). Contrary to type II-plateau supernovae (SNe IIP) that show slow photometric evolution and well-correlated observed properties (see e.g. Hamuy 2003 and references therein), SNe IIL are characterised by fast-evolving light curves and a higher degree of heterogeneity. SNe IIL are believed to arise either from the explosion of moderate-mass progenitors (8-10$M_{\odot}$) that have lost a significant fraction of their H envelope via binary interaction or from more massive stars that lose mass before their explosion through strong stellar winds.

However, despite the mass loss, a significant amount of H still remains in the stellar envelope, and, consequently, the spectrum of a SN IIL still shows prominent H lines. The evidence that in SNe IIL the H envelope is not as massive as in SNe IIP comes mostly from analysis of the light curves. Because of the lack of a massive H envelope that recombines with cooling, the light curves do not show the characteristic long period (about three months) of almost constant luminosity typical of SNe IIP, but instead show a linear decline after maximum.

In Patat et al. (1993) and Patat et al. (1994) a compilation of light curves from the literature of a large number of SNe II was analysed. A high degree of heterogeneity in the light curve shapes was found, and many transitional objects between type IIP and IIL SNe were shown to exist. This is probably a consequence of the progressively declining mass of the residual H envelope along the sequence from type IIP to type IIL events. Up to the point of explosion, the progenitors of type IIP SNe have retained much of their H-rich envelopes. On the other hand, stars generating SNe IIL have already lost most of their H envelopes at the time of the explosion. In a few cases, the presence of this circumstellar material (CSM) is revealed at some point because of the interaction with the expanding ejecta. However, in general, this is not the dominant contribution to the luminosity of SNe IIL, at least at early phases. A consequence of this is that SNe IIL show a much more rapid photometric evolution than type IIn SNe (Schlegel 1990), in which

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Send offprint requests to: A. Pastorello the ejecta-CSM interaction is the main process regulating the output of energy of the SN even at early phases. Nevertheless, a few type II SNe show unequivocal evidence of interaction with CSM from specific spectral properties and the high peak luminosity without showing slowly evolving light curves. This is the case for a few SNe IIn with fast-declining light curves, like SN 1998S (e.g. Fassia et al. 2000, Liu et al. 2000), SN 1999el (Di Carlo et al. 2002), or SN 2006jc (and SNe Ibn) which interact with a He-rich CSM (Pastorello et al. 2007, Foley et al. 2007, Pastorello et al. 2008a). All these SNe have light curves with rapid evolution resembling those of SNe IIL.

The prototype of the classical SNe IIL is SN 1979C, which exploded in M100 and is by far the best studied object of this class, being extensively observed from X-ray to radio wavelengths (see e.g. Panagia et al. 1980, de Vaucouleurs et al. 1981, Branch et al. 1981, Weiler et al. 1991, Fesen & Matonick 1993, Immler et al. 1998, Fesen et al. 1999, van Dyk et al. 1999, Montes et al. 2000, Ray et al. 2001, Marcaide et al. 2002, Bartel & Bietenholz 2003, Immler et al. 2005). Other well studied SNe IIL discovered in the last 30 years are SN 1980K in NGC6946 (see e.g. Buta 1982, Barbon et al. 1982a for early-time data, and Uomoto & Kishner 1986, Fesen et al. 1999, and references therein, for late-time data), SN 1986E in NGC 4302 (Cappellaro et al. 1990, Cappellaro et al. 1995a) and SN 1990K in NGC 150 (Cappellaro et al. 1995b).

A few SNe IIL, sometimes dubbed as type IId SNe (Benetti 2000), show narrow P-Cygni Balmer lines of hydrogen superimposed on otherwise normal broad-lined spectra of type II SNe. This is interpreted as an evidence of super-winds occurred years to decades before the SN explosions. This group includes SNe 1994aj, 1996L, 1996al, 2000P (Benetti et al. 1998, Benetti et al. 1999, Benetti & Neuhauser 1996, Benetti 2000, Cappellaro et al. 2000, Jha et al. 2000). In all these cases, ejecta-CSM interaction takes place a few years after the explosion, when the fast SN ejecta reaches the slower wind. The ejecta-CSM interaction may be heralded by a number of different pieces of observational evidence, e.g. flattening of the late-time optical light curves, the peculiar profile of spectral lines (e.g. Schlegel 1990, Turatto et al. 1993a, Leibundgut et al. 1991, Fesen et al. 1999), strong X-ray (see Schlegel 1995, Immler et al. 1998, Aschenbach 2007 for reviews) and radio emission (e.g. van Dyk et al. 1996).

A special mention has to be given to the recently discovered type IIL SNe that have extremely high luminosities (M_V < -22.5). This small sub-group includes SN 2005ap (Quimby et al. 2007) and SN 2008es (Miller et al. 2009, Gezari et al. 2009). Their extraordinary luminosity and their spectra, which show no evidence of the narrow features typical of interacting objects (SNe IIn), are best explained by strong interaction of the ejecta with a dense, optically-thick CSM, rather than with very large ejected ^{56}Ni masses (Quimby et al. 2007).

In this paper we study the case of SN 1999ga, a type II SN (likely of type IIL) which was followed only at late phases. Some pre-explosion, ground-based images, and very late time Hubble Space Telescope (HST) frames have been studied in order to constrain the characteristics of the progenitor star and the site of explosion. Basic information on SN 1999ga and its spectacular host galaxy is reported in Sect. 2. Photometric and spectroscopic data are presented in Sect. 3 and Sect. 4, respectively. The explosion site, imaged in pre-SN archival observations and in deep HST frames obtained years after the SN explosion, are analysed in Sect. 5, while a discussion and a summary follow in Sect. 6.

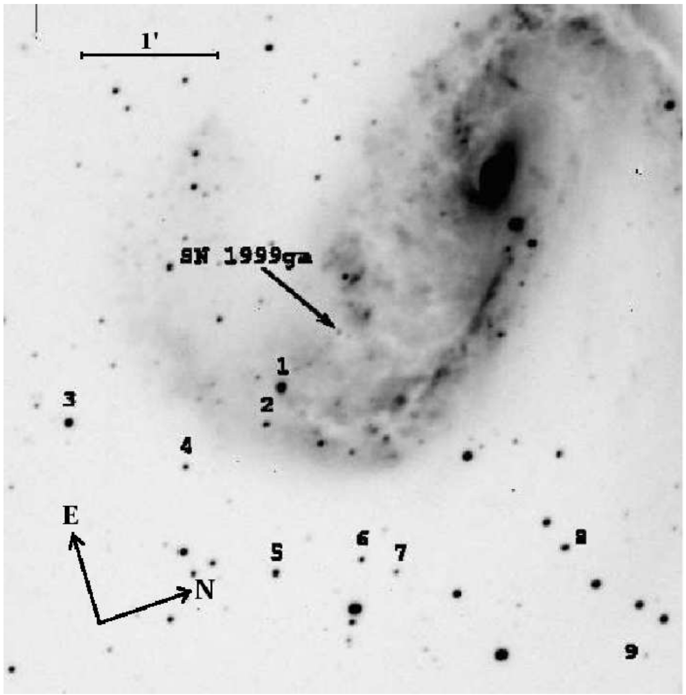

Fig. 1. SN 1999ga and NGC 2442. R-band image obtained on Apr 7, 2000 with the ESO 3.6m Telescope equipped with EFOSC2. A sequence of reference stars is marked by numbers.

Table 1. Magnitudes of reference stars in the SN field. The r.m.s. of the average magnitudes are reported in brackets.

Star	B	V	R	I
1	17.55 (0.02)	16.55 (0.01)	15.89 (0.02)	15.18 (0.02)
2	20.02 (0.02)	18.48 (0.01)	17.52 (0.01)	16.37 (0.02)
3	18.29 (0.03)	16.84 (0.01)	15.92 (0.05)	15.05 (0.03)
4	19.45 (0.02)	18.73 (0.01)	18.23 (0.01)	17.73 (0.02)
5	18.82 (0.01)	18.05 (0.01)	17.59 (0.01)	17.09 (0.01)
6	20.33 (0.02)	18.76 (0.01)	17.77 (0.01)	16.71 (0.02)
7	20.03 (0.01)	19.15 (0.02)	18.57 (0.01)	18.08 (0.02)
8	19.41 (0.04)	18.21 (0.03)	17.38 (0.04)	16.80 (0.03)
9		20.36 (0.04)		18.05 (0.02)

2. SN 1999ga in NGC 2442

SN 1999ga was discovered on November 19.76 UT in the spiral galaxy NGC 2442 by Woodings et al. 1999, on behalf of the Perth Astronomy Research Group (PARG, see e.g. Woodings et al. 1998), in the course of an automated supernova search performed with the Perth-Lowell 0.61-m reflector. The discovery magnitude quoted by Woodings et al. (1999), R∼18, is wrong, being almost 2 mag fainter than the true magnitude of SN 1999ga at that epoch (cf. Sect. 3). The exact position was measured on Nov. 22.54 with the 0.25-m Mike Candy Telescope at Perth Observatory and found to be R.A. = $7^h36^m16^s.70 \pm 0^s.03$, Dec. = $-69°33'21''.8 \pm 0''.4$ (equinox 2000.0), about 38″ west and 91″ south of the centre of NGC 2442 (Woodings et al. 1999).

Additional observations, obtained on November 25.18 UT by Rubinstein (1999) at the Cerro Tololo Interamerican Observatory, indicated that the magnitude of the transient was significantly brighter than that reported by Woodings et al. (1999) (B=18.3±0.3, V=17.1±0.1, R=16.2±0.1, V=15.6±0.1). On the basis of the SN location alone, Rubinstein (1999) suggested a possible type II classification for SN 1999ga. Because of its red colour, he also suggested significant interstellar red-

Table 2. Calibrated magnitudes of SN 1999ga. An additional detection limit in the U band (U > 21.9) was obtained on 1999, December 29.

Date	JD	B	V	R	I	Instrument
1999-11-19	2451502.29		16.90 (0.08)	16.11 (0.05)	15.40 (0.04)	PARG
1999-11-24	2451507.29		17.00 (0.07)	16.18 (0.06)	15.46 (0.06)	PARG
1999-11-26	2451509.02		16.98 (0.04)	16.18 (0.03)	15.45 (0.04)	PARG
1999-12-02	2451514.84			16.30 (0.03)	15.58 (0.05)	PARG
1999-12-10	2451522.79		17.36 (0.25)	16.46 (0.04)	15.70 (0.14)	PARG
1999-12-13	2451525.84		17.53 (0.05)	16.62 (0.04)	15.86 (0.04)	PARG
1999-12-20	2451532.87		17.86 (0.07)	17.05 (0.05)	16.28 (0.07)	PARG
1999-12-26	2451538.82	20.45 (0.07)				WFI⋆
1999-12-29	2451541.77	21.03 (0.08)	19.13 (0.03)	18.05 (0.04)	17.36 (0.06)	DF
2000-01-01	2451546.27		19.19 (0.42)	18.11 (0.21)	17.40 (0.32)	PARG ⋄
2000-01-29	2451573.13	21.29 (0.30)	19.57 (0.04)	18.35 (0.07)		AAT ∗
2000-02-17	2451591.67	21.46 (0.13)	19.74 (0.07)	18.42 (0.03)		WFI⋆
2000-03-13	2451617.02		20.0 (0.3)	18.8 (0.3)	18.4 (0.4)	DF†
2000-03-14	2451617.5		19.98 (0.07)			DF
2000-04-07	2451641.57	21.89(0.05)	20.26 (0.03)	19.01 (0.07)		EF2
2000-11-19	2451867.85		22.55 (0.24)	21.79 (0.21)	20.69 (0.24)	DF
2001-02-02	2451942.75	>23.1	23.66 (0.38)	23.02 (0.47)		EF2
2001-02-04	2451944.63		> 23.3	>22.5		WFI
2001-03-17	2451985.61	>23.6	>22.9	>22.4	>23.7	DF

∗ Anglo Australian Telescope Data Archive: *http://archive.ast.cam.ac.uk/arc-bin/wdb/aat_database/observation_log/make*;
⋆ ESO Data Archive: *http://archive.eso.org/eso/eso_archive_main.html*; ⋄ poor night; † spectrophotometric magnitude
PARG = Perth-Lowell 0.61-m Cassegrain Telescope + CCD (Perth, Australia); EF2 = ESO 3.6m Telescope + EFOSC2 (La Silla, Chile);
WFI = ESO/MPI 2.2m Telescope + Wide Field Imager (La Silla, Chile); DF = Danish 1.54m Telescope + DFOSC (La Silla, Chile).

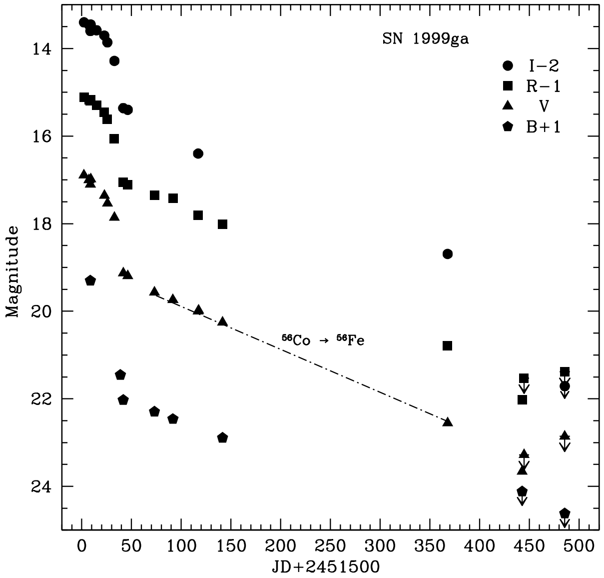

Fig. 2. B, V, R, I light curves of SN 1999ga. Unfortunately, only late time photometry is available for this SN, because the SN was not observed at early epochs as the host galaxy was too low on the horizon for most of the night. Another seasonal gap is visible between JD=2451650 and JD=2451850. The photometric points from Rubenstein 1999 are also included.

dening. However, we will see in Sect. 3 and Sect. 4 that SN 1999ga was discovered late, and it is well known that type II SNe are intrinsically red at the end of the photospheric phase (e.g. Pastorello et al. 2004).

The tentative SN classification of Rubinstein (1999) was confirmed spectroscopically by Salvo et al. (1999) on the basis of a spectrum taken on December 29 at ESO-La Silla. The classification spectrum (presented in this paper) shows that SN 1999ga is a type II SN observed a few months after explosion. In this paper we will adopt JD = 2451420 as an indicative epoch for the explosion of SN 1999ga, which was derived via comparisons with observed data of well-studied type II SNe (Sect. 3 and Sect. 4).

The spectral lines in the classification spectrum show P-Cygni profiles, while Hα has a peculiar flat-topped emission component indicative that the Hα emission mostly comes from a shell-like region (see Sect. 4 for discussion). Finally the spectrum shows evidence of little interstellar extinction (Salvo et al. 1999), suggesting moderate reddening.

The spectacular galaxy hosting SN 1999ga, NGC 2442 (Fig. 1), is classified by HyperLeda[1] as an SBbc galaxy, with well-developed but asymmetric spiral arms. It belongs to the Volans group of galaxies, and Ryder et al. (2001) report a distance of about 15.5 Mpc (distance modulus μ = 30.95 mag). From the recessional velocity corrected by Local Group infall into Virgo, 1150 km s^{-1}, and assuming H_0 = 72 km s^{-1} Mpc^{-1}, we obtain a slightly higher distance, d $\approx$ 16 Mpc (μ = 31.02 mag), which will be adopted throughout this paper. The Galaxy extinction in the direction of NGC 2442 is rather high, being E(B-V)$_{Gal}$ = 0.20 mag (Schlegel et al. 1998). The low signal to noise and the late phase of the SN 1999ga spectra (see Sect. 4) do not allow precise measurement of the equivalent width (EW) of Galaxy and host galaxy interstellar Na I doublet (Na ID) absorptions. However, we tentatively estimated the two components of Na ID in the SN spectra and found that the NGC 2442 component has an EW $\approx$ 0.9Å, which is roughly 70 per cent that of the Galaxy. This would imply an E(B-V)$_{host}$ = 0.14 mag, which is consistent with what we find using the correlation between EW of the interstellar Na ID and E(B-V) of Turatto et al. (2003). Accounting for both the Galactic reddening component and that of the host galaxy, we

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[1] http://leda.univ-lyon1.fr/

obtain E(B-V)$_{tot}$ = 0.34 mag as our best estimate for the total reddening, and this value will be adopted hereafter.

Several attempts have been made in order to explain the disturbed morphology of NGC 2442, by searching for evidence of tidal interaction with a few nearby galaxies (Elmegreen et al. 1991, Sandage & Bedke 1994, Mihos & Bothun 1997, Houghton 1998). Ryder et al. 2001 found evidence that NGC 2442 is associated with an extremely massive cloud of H I, with a mass almost one third that of the galaxy itself. This gas cloud was probably produced in a recent tidal encounter with a moderately massive companion, though both ram pressure-stripping, and HI rings/arcs stripped from the outer envelope of a low surface brightness galaxy (Bekki et al. 2005) are also possible scenarios. Moreover, Bajaja et al. (1995), Mihos & Bothun (1997) and Bajaja et al. (1999) found an elliptical, circumnuclear, star-forming molecular ring. Finally, the intensity ratios of emission lines of the galaxy nucleus indicate that NGC 2442 is likely a LINER (Bajaja et al. 1999).

3. Light Curve

Follow-up photometric observations were carried out using a number of telescopes in Australia and Chile. Available imaging of SN 1999ga was reduced following a standard procedure (see e.g. Pastorello et al. 2005): the images were first overscan, bias and flat-field corrected. SN magnitudes were then measured using a PSF-fitting technique after the subtraction of template images. The recovered magnitudes were then scaled using the night zero-points computed comparing the instrumental magnitudes of several well-known standards fields with those reported in the Landolt catalogue (Landolt 1992). Finally the SN magnitudes were fine tuned with reference to the magnitudes of 7 stars in the field of NGC 2442 (see Fig. 1) obtained by averaging the estimates obtained in photometric nights. The magnitudes of the sequence stars, as denoted in Fig. 1, are reported in Tab. 1, while the B, V, R and I magnitudes of SN 1999ga are given in Tab. 2.

In Fig. 2 the photometric evolution of SN 1999ga in the optical bands is shown. The late discovery of SN 1999ga prevents us from studying the early evolution of its light curve, with particular reference to the immediate post-maximum behaviour. As a consequence, uncertainty as to the shape of its light curve (linear or plateau) remains, although there is some evidence in favour of a type IIL classification for SN 1999ga (see Sect. 4).

SN 1999ga was discovered during the post-maximum decline phase. The light curve shows a rapid luminosity drop (by 1.5-2 mag in all bands), followed by a less steep decline corresponding to the exponential (radioactive) tail. As evidenced in Fig. 2, at late time the V-band light curve of SN 1999ga closely matches the ^{56}Co →^{56}Fe decay slope (0.98 mag/100^{d}, assuming complete gamma-ray trapping), even though at very late phases (from ∼400 days after explosion) the light curves in all bands show steeper declines. This is has been seen in other type II SNe, and it is generally interpreted as dust forming in the SN ejecta and/or incomplete γ-ray trapping (e.g. Elmhamdi et al. 2003).

The slopes in the period between 120 and 450 days, as derived from a least squares fit to the light curves, are γ_B=0.87 mag/100^{d}, γ_V=1.02 mag/100^{d}, γ_R=1.15 mag/100^{d} and γ_I= 1.00 mag/100^{d}, on average rather consistent with those expected by the radioactive decay of ^{56}Co in the case of complete γ-ray trapping. This might be an indication of relatively massive ejecta.

In Fig. 3 (top panel) the V-band absolute light curve of SN 1999ga is compared with those of a number of type II SNe, four SNe IIL (1979C, 1980K, 1990K and the peculiar 1994aj, which belongs to the IId sub-type, Benetti 2000), the over-luminous type IIL SN 2008es, the transitional type IIP/IIL SN 1992H and three SNe IIP (2004et, 2005cs and the peculiar 1987A). The phases for SN 1999ga have been computed assuming JD = 2451420 as an indicative epoch for the core-collapse, as derived from a comparison of the light curve and spectra with those of other SNe II. The apparent flattening in the very early light curve of SN 1999ga would suggest a plateau-like behaviour (or, at least, a transitional object). However, Patat et al. (1993, 1994) noted that a shoulder in the light curves of SNe IIL (especially in the R band) is frequently observed after maximum. Hence the available photometry of SN 1999ga does not allow us to definitely discriminate between a *linear* or a *plateau* type light curve. We will see in Sect. 4 that more clear clues in favour of a type IIL classification for SN 1999ga come from the spectroscopy.

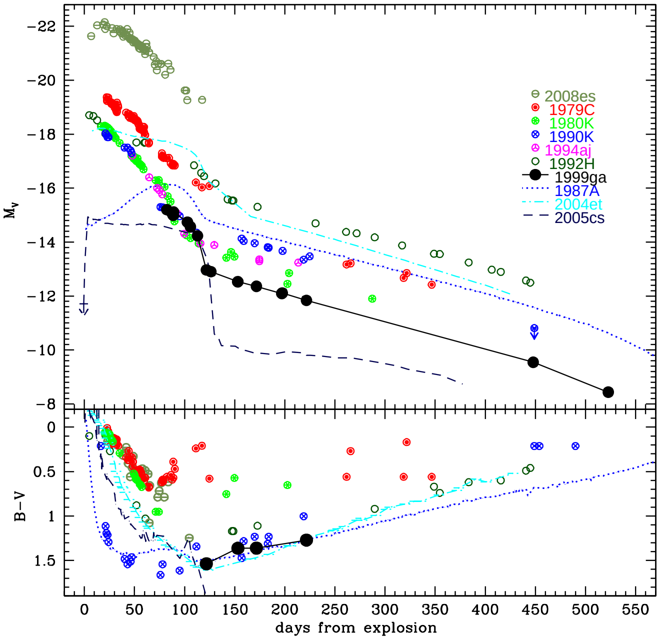

Fig. 3. Top: V-band absolute light curves of SN 1999ga and a number of type II SNe: the high-luminosity SN 2008es (Gezari et al. 2009, Miller et al. 2009), the type IIL SNe 1979C (Balinskaya et al. 1980, de Vaucouleurs et al. 1981, Barbon et al. 1982b), 1980K (Barbon et al. 1982a, Buta 1982, Tsvetkov 1983), 1990K (Cappellaro et al. 1995b), 1994aj (Benetti et al. 1998); the transitional type IIP/IIL SN 1992H (Clocchiatti et al. 1996); the peculiar SN 1987A (Whitelock et al. 1989 and references therein) and the type IIP SNe 2004et (Sahu et al. 2006, Misra et al. 2007) and 2005cs (Tsvetkov et al. 2006, Pastorello et al. 2006, Pastorello et al. 2009). The explosion epochs of SNe IIL have been estimated to occur roughly 2-3 weeks before their maximum light (Patat et al. 1993). Bottom: comparison of the B-V colour curves of SNe 1999ga, 2008es, 1979C, 1980K, 1990K, 1992H, 1987A, 2004et.

With the assumption on the explosion epoch mentioned above, a comparison between the integrated late-time BVRI luminosity of SN 1999ga with that of SN 1987A at similar epochs provides an approximate estimate of the ^{56}Ni mass synthesized by SN 1999ga, being about 0.013 ± 0.003 M$_{\odot}$, which is to our knowledge the smallest ever registered for a type IIL SN,

Table 3. Spectroscopic observations of SN 1999ga. The spectrum at 39.5 days is the one used to classify SN 1999ga (Salvo et al. 1999).

Date	JD(+2400000)	Phase[†]	Instrumental configuration	Exposure	Resolution (Å)	Range (Å)
1999-12-29	51541.76	39.5	Danish 1.54m + DFOSC + gr.4	1200s	11	3650-9050
2000-03-12/13	51617.02[‡]	114.8	Danish 1.54m + DFOSC + gr.4 + gr.5	1800s + 1800s	11+12	3570-10200
2000-04-07	51641.58	139.3	ESO 3.6m + EFOSC2 + gr.11	2 × 1800s	18	3380-7500
2001-02-02	51942.71	440.5	ESO 3.6m + EFOSC2 + gr.11	3 × 1800s	18	3490-7460

[†] Days from discovery (JD=2451502.26); [‡] Spectrum obtained averaging two spectra obtained in subsequent days.

and only marginally higher than those registered for the low-luminosity SNe IIP (e.g. Pastorello et al. 2004).

A comparison among B-V colour curves of SN 1999ga and some other SNe II is also shown in Fig. 3 (bottom panel). Surprisingly, the overall behaviour of the colour curve of the type IIL SN 1990K within the first ~250 days closely resembles that of SN 1987A, more than that of other SNe IIL shown in Figure. However, we should remember that the luminous light curve peaks and the bluer colours of SN 1979C and SN 1980K are probably signatures of interaction with a CSM (see Sect. 6). Unfortunately, only a few points are available for SN 1999ga and this does not allow us to study in detail its colour evolution. At ~120 days, the B-V colour of 1999ga is around 1.5 mag, then it becomes marginally bluer (by about 1.3 mag) 4 months later. However, the overall similarity with the colour evolutions of SNe 1987A, 2004et, 1992H and 1990K (between +110 and +230 days) is an additional argument in favour of a late discovery of SN 1999ga.

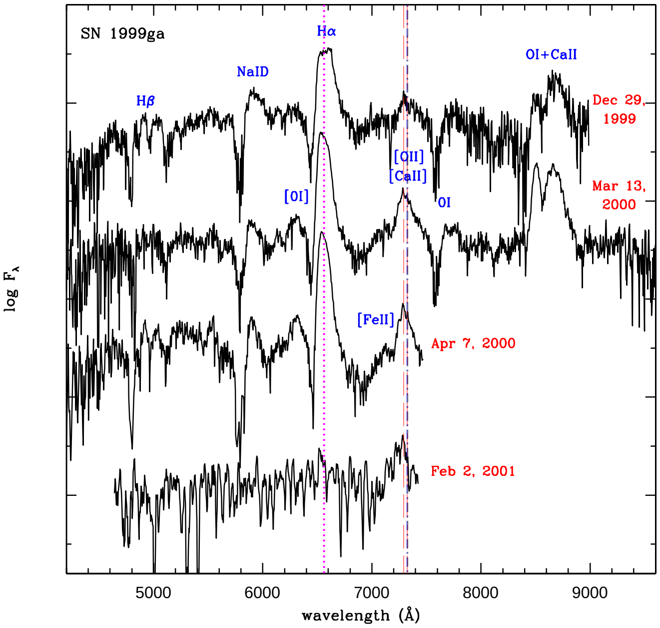

Fig. 4. Sequence of nebular spectra of SN 1999ga. The main features are labelled. The vertical lines mark the rest positions of Hα (magenta, dotted line), [Ca II] $\lambda\lambda$7291,7324 (red, dashed lines) and [O II] $\lambda\lambda$7320,7330 (blue, dot-dashed lines). There is minor evidence of residual Hα in the February 2, 2001 spectrum. All spectra, reported at the host galaxy rest wavelength, have been reddening corrected.

4. Late Spectral Evolution

Four spectra of SN 1999ga have been obtained with the ESO telescopes at La Silla (Chile), and basic information about these spectra is reported in Tab. 3. The available spectral sequence is shown in Fig. 4.

The earliest spectrum is typical for a type II SN transiting from the photospheric to the nebular phase. Prominent Hα and Hβ are visible, with relatively weak P-Cygni absorptions, along with strong P-Cygni lines of Na ID and O I λ7774. The minima of the absorption components of Hα and Na ID are blue-shifted by about 5800 km s^{-1} and 5300 km s^{-1}, respectively. The feature at about 8600Å is attributed to a blend of O I λ8446 plus the Ca II near-infrared triplet. A few Fe II lines are possibly detected near the region of Hβ. It is worth to note that Hα shows an unusual flat-topped emission profile. A photospheric spectrum showing a P-Cygni Hα line with flat-topped profile is indicative that the Hα emission mostly is produced in a detached region. Detached atmospheres are not common in SNe (Jeffery & Branch 1990) and this is the first time we see such a structure in a type II supernova. This could be caused by a temporary peak in the density profile of the hydrogen layer. A flat-topped profile may be also produced in a cool dense shell (CDS) that forms at the interface between the SN ejecta and the wind produced by the progenitor (Chugai et al. 2007).

The evolution of SN 1999ga is slow and the two subsequent spectra show basically the same features as the first spectrum, plus much stronger nebular lines of [O I] $\lambda\lambda$6300-6364 and the classical feature around 7300Å due to a blend of [Ca II] $\lambda\lambda$7291,7324, [O II] $\lambda\lambda$7320,7230 and [Fe II]. The Hα feature is narrower and, in contrast to the December 29 spectrum, has evolved developing a rounded profile. In the ejecta-wind interaction scenario of Chugai et al. (2007), this evolution of Hα is expected to be accompanied by an absorption component that progessively shifts toward redder wavelengths. This is not observed in SN 1999ga, making the CDS scenario quite unlikely.

Interestingly, the two intermediate spectra of SN 1999ga show Hα with a slightly blue-shifted peak (see Fig. 4). Blue-shifted emission peaks are observed in many young type II SNe (see e.g. Turatto et al. 1993b) and this in agreement with theoretical predictions (Jeffery & Branch 1990, see also Dessart & Hillier 2008), but unexpected at late phases, unless caused by the formation of dust in the SN ejecta (like in SN 1999em, Elmhamdi et al. 2003). However the dust formation in the SN ejecta is usually accompanied by an increased slope of the optical light curves and, eventually, an IR excess. Interestingly, in the case of SN 1999ga a deviation from the ^{56}Co decay slope is clearly visible only at later phases (after 450-500 days from the explosion, see Fig. 3).

A further spectrum was obtained about 13 months after the first one. Surprisingly there is no significant evidence for Hα or other H Balmer lines, while the emission feature at 7300Å is still quite prominent. This is indeed the only spectral line unequivocally visible in this spectrum.

Table 4. Pre- and late, post-explosion (ground-based and HST) images. The magnitudes of *source A* in the ground-based observations are also reported in column 5.

Date	JD	Telescope	Filter	Exposure time (s)	*Source A* magnitude	Proposal ID / Source
1989-12-31	2447891.53	SSO1m	Hα	3×1000		Ryder & Dopita 1993
1989-12-31	2447891.57	SSO1m	R_c	2×500	>18.76	Ryder & Dopita 1993
1990-03-04	2447955.45	SSO1m	V	2×250	>20.70	Obs. S. Ryder
1991-01-11	2448267.62	SSO1m	I	2×250	>20.20	Obs. S. Ryder
1995-02-22	2449771.06	AAT	unfilt.	300+60	21.85±0.40[‡]	Obs. Whiteoak & Koribalski
1995-03-01	2449777.57	CTIO1.5m	B	2×600	22.76±0.32	Obs. G. Purcell
1995-03-01	2449777.58	CTIO1.5m	I	300	21.37±0.37	Obs. G. Purcell
2006-01-28	2453764.70	ESO2.2m	Hα	4×720		076.C-0888 (PI: Y. Bialetski)
2006-01-29	2453764.77	ESO2.2m	V	2×600	22.07 ± 0.09	076.C-0888 (PI: Y. Bialetski)
2006-01-30	2453765.73	ESO2.2m	B	2×300	22.89 ± 0.08	076.C-0888 (PI: Y. Bialetski)
2006-11-29	2454068.78	ESO2.2m	B	4×600	22.87 ± 0.22	MPI Time (PI: W. Hillebrandt)
2006-10-21	54030.31	HST	F435W	1580		10803 (PI: S. Smartt)
2006-10-21	54030.37	HST	F658N	1350		10803 (PI: S. Smartt)
2006-10-21	54030.39	HST	F814W	1200		10803 (PI: S. Smartt)

[‡] magnitude from unfiltered image, rescaled to the R band photometry.
SSO1m = 1m-Telescope + CCD (Siding Spring Observatory, Australia);
AAT = 4m Anglo Australian Telescope + CCD (Siding Spring Observatory, Australia);
CTIO1.5m = 1.5m-Telescope + CCD (Cerro Tololo Inter-American Observatory, Chile)
ESO2.2m = ESO/MPI 2.2m Telescope + Wide Field Imager (La Silla, Chile);
HST = Hubble Space Telescope + ACS/WFC Camera.

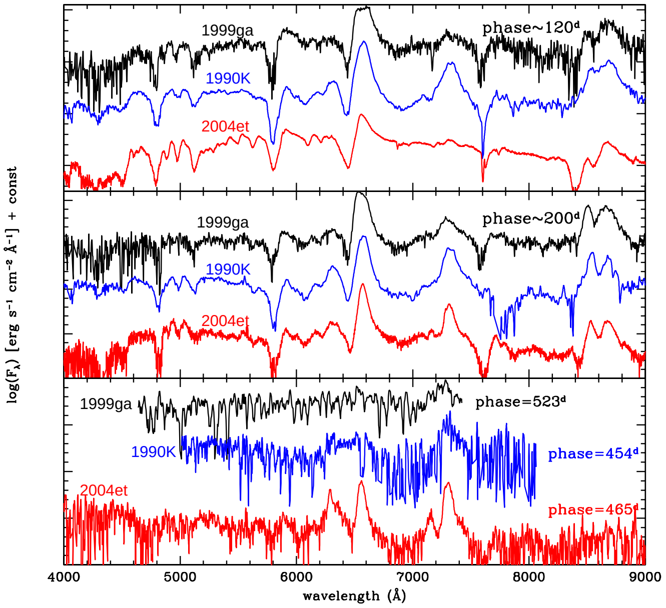

Fig. 5. Comparison between spectra of SN 1999ga, the type IIL SN 1990K (Cappellaro et al. 1995b) and the type IIP SN 2004et (Sahu et al. 2006) at different phases. The phases are computed with reference to an approximate estimate of the explosion dates. For SN 1990K we adopted JD = 2448020 as explosion time, which is about 17 days before the discovery epoch (JD=2448037.3). Our assumption is in good agreement with that of Cappellaro et al. (1995b), who estimated the explosion of SN 1990K to occur about two weeks before its discovery. Finally, for SN 2004et we adopt the same explosion epoch as Sahu et al. (2006) (JD = 2453270.5, see also Li et al. 2005).

In Fig. 5 three spectra of SN 1999ga are compared with those of the type IIL SN 1990K (Cappellaro et al. 1995b) and the type IIP SN 2004et (Sahu et al. 2006)[2]. The three SNe appear to have a rather similar spectra at ~120 and ~200 days. The ~120 days spectra of all SNe show a prominent Hα line, although only in SN 1999ga Hα has a flat-topped profile. Subsequent spectra of the three SNe (phase of about 200 days) show a rather normal, rounded Hα profile which is expected in non-interacting SNe II. As a remarkable difference with the H-rich type IIP SN 2004et, very late spectra of SNe 1999ga and 1990K obtained around 15 and 17.5 months (respectively) after their explosions surprisingly do not show any prominent Hα line (Fig. 5, bottom panel), but – this is more clearly visible in SN 1990K – only a broad, weak bump around 6300-6400Å, which is mostly due to the [O I] λ6300-6364 doublet. The only (relatively) prominent feature is that at ~7300A, possibly a blend of several forbidden lines ([CaII], [O II], [Fe II]). The lack of prominent Hα at very late times supports the scenario of a progenitor star with a small residual H envelope and, hence, a type IIL classification for SN 1999ga.

Apart from the peculiar Hα line profile in the earliest spectrum, there is little evidence that the SN is interacting with a CSM. The lack of the flattening in the optical light curves typical of SNe which are strongly interacting with a CSM is in good agreement with this scenario. As a further support, no emission was detected at the position of SN 1999ga in 6 cm (5170 MHz) images analysed by Harnett et al. (2004), neither in images obtained during the 1990s, before the SN explosion, or in a post-explosion image obtained on 2000 December 31 (i.e. more than one year after the explosion). Therefore, if the earliest optical spectrum may eventually suggest the presence of material lost by the progenitor in pre-SN mass loss events, the subsequent SN evolution allows us to exclude major ejecta-CSM interaction episodes.

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[2] The spectra of the comparison objects have been downloaded from the Online Supernova Spectrum Archive SUSPECT *(http://bruford.nhn.ou.edu~suspect/index1.html)*.

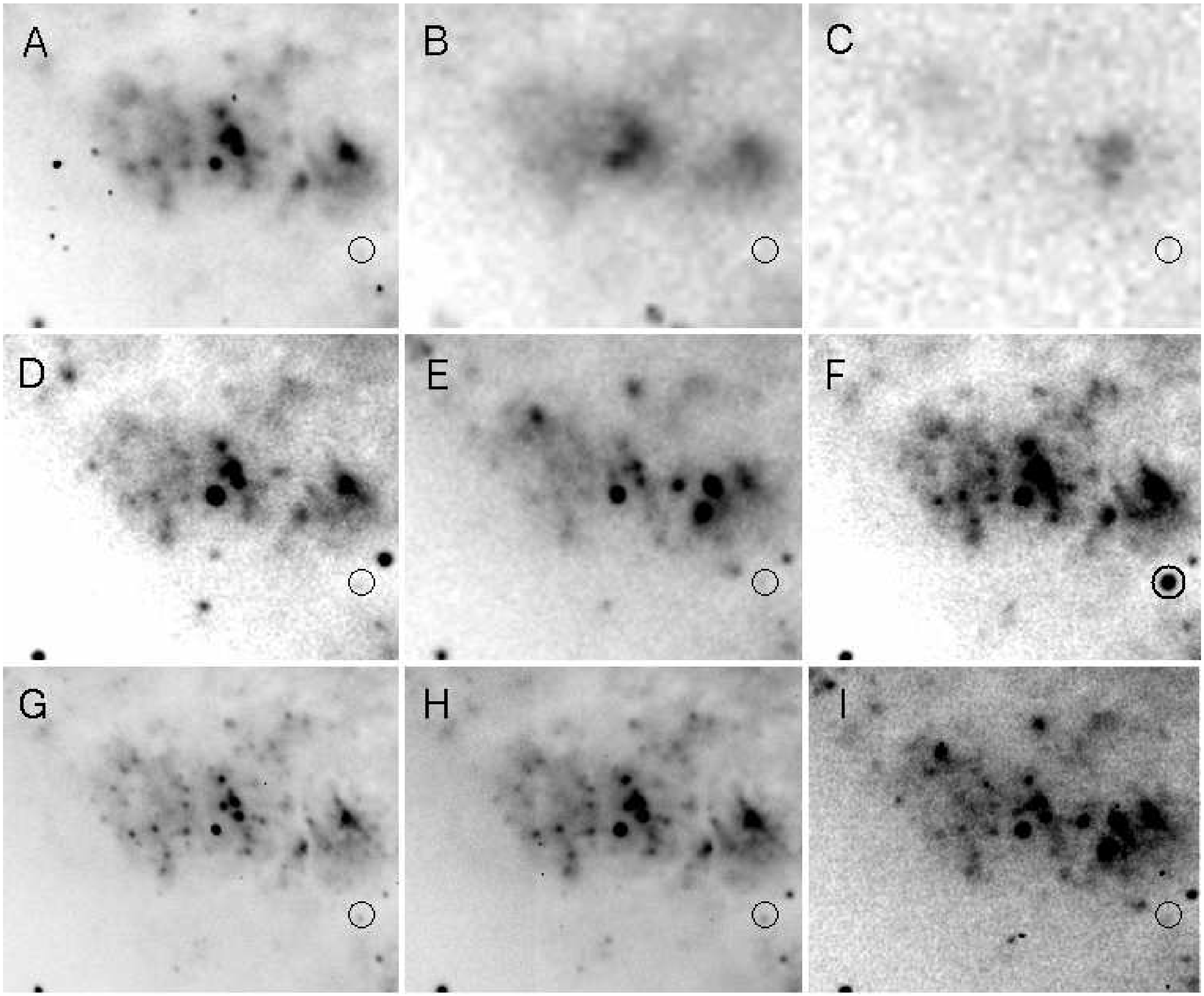

Fig. 6. The explosion site of SN 1999ga: low-resolution frames obtained with different ground-based telescopes. (A): pre-explosion B band image obtained on March 1, 1995 with the 1.5m CTIO telescope. (B) pre-explosion V band image obtained March 4, 1990 with the 1m Telescope at Siding Spring Observatory (SSO). (C) pre-explosion Hα image obtained on January 31, 1989 at the SSO 1m Telescope. (D) pre-explosion I band image obtained on March 1, 1995 with the 1.5m CTIO telescope. (E) pre-explosion unfiltered image obtained on February 22, 1995 at the Anglo Australian Telescope. (F) B band image of SN 1999ga obtained on December 29, 1999 with the ESO/MPI 2.2m Telescope in La Silla. (G) post-explosion B band image obtained on January 30, 2006 with the ESO/MPI 2.2m Telescope. (H) post-explosion V band image obtained on January 29, 2006 with the ESO/MPI 2.2m Telescope. (I) post-explosion Hα image obtained on January 28, 2006 with the ESO/MPI 2.2m Telescope. The SN location is marked by a circle. Only an extended source (denoted as *source A* in the text) is visible both in the pre- and post-explosion images in the SN vicinity. In all figures, north is up, east is to the left.

5. The birthplace of SN 1999ga

A method to understand the nature of the star which exploded as SN 1999ga is to study the site of explosion, trying to derive information on the progenitor via the direct detection of the star (or constraining robust detection limits) in available pre-explosion images (e.g. Smartt et al. 2004, van Dyk et al. 2003, Maund & Smartt 2005, Smartt et al. 2009). The site of explosion of SN 1999ga was occasionally monitored in the past using small-size telescopes (see Tab. 4). A large sample of low-resolution archive images obtained using different filters and showing the explosion site over a period of about 17 years is presented in Fig. 6, while in Fig. 7 the region of the SN is shown in a sequence of B band images obtained before, during and after the SN outburst, including a high-resolution HST image of the post-explosion site (panel D).

In particular, pre-explosion images were obtained during the 1990s at the 1m Telescope and the 3.9m Anglo Australian Telescope at Siding Spring Observatory (Australia), and the 1.5m Telescope of the Cerro Tololo Inter-American Observatory (CTIO) in Chile (Fig. 6, inserts A to E, and Fig. 7, insert A). Some of the images here analysed were published in Ryder & Dopita 1993. The best-quality pre-explosion images are those in the B and I bands obtained on March 1995 at the

CTIO 1.5m-Telescope. Unfortunately, most pre-SN frames are not deep enough to provide robust detection limits for the putative progenitor star.

One problem is the SN location, which is on the northern edge of an elongated luminous region (that will be labelled hereafter as *source A*, see Fig. 6 and Fig. 7), visible in most pre- and post-explosion images. This region is particularly luminous in the B band, indicating that it is probably associated with luminous blue stars. Interestingly, *source A* is faint in the Hα images. This, together with the lack of evidence in the SN spectra of narrow lines from the galactic background, suggests a stellar nature (possibly stellar clusters) for this vast source near the SN location, rather than a star-forming region. Since the SN exploded at the edge of *source A*, it is very difficult to extrapolate the flux contribution of a single star from that of the entire environment. We measured the integrated magnitudes of the unresolved *source A* in the ground-based images before and several years after the SN explosion, and we found (within the errors) no significant differences. This implies that the contribution of the progenitor of SN 1999ga to the flux of the whole extended region was negligible. The magnitudes of *source A* as derived in the low resolution images are reported in Tab. 4 (column 6).

We also collected some deep post explosion images (Fig. 6, inserts G, H, I; Fig.7, insert C) obtained with the ESO/MPI 2.2m Telescope in January (under the proposal ID: 076.C-0888, PI: Y. Bialetski) and November 2006 (reserved MPI time, program ID 078.A-9046(A), PI: W. Hillebrandt). We used the best seeing B-band images (those of January 2006) as templates in our attempt to recover the progenitor star in the March 1995 B-band image. After combining the best seeing images obtained at the same epoch, and after geometrical and photometric registration of the pre- and post-explosion images, we subtracted the latter image from the former. With this procedure, the whole host galaxy and, hence, also the emitting region in the SN vicinity were removed. Nevertheless, any attempt to recover the progenitor star in the B-band failed, since there was no evidence of the progenitor of SN 1999ga in the subtracted image at the SN position at a B-band magnitude brighter than 23.15. Similar attempts were made with other images, and none showed evidence of the presence of any star at the position of the SN. Adopting the distance and reddening estimates discussed in Sect. 2, we obtain $M_B \gtrsim -9.3$ which is not, obviously, a very significant detection limit.

In order to study in more detail the structure of the extended *source A*, the site was targeted by the Hubble Space Telescope (HST) on October 21st, 2006, 7 years after the SN explosion (proposal ID: 10803, PI: S. J. Smartt). *Source A*, which appears to be elongated (roughly) in the North-South direction in the ground based images, in reality consists of two major sources (plus a few much fainter sources visible in their vicinity), as one can clearly gather from the high-resolution HST images (see blow-up panels of the F814W HST/ACS image, Fig. 8). Both these sources are extended with FWHM which is about twice that of the stellar PSF, so that we suggest that they are both compact stellar clusters.

We performed PSF-fitting photometry using the *DOLPHOT*[3] package. *DOLPHOT* classifies the southern source as a single, point-like object (type 1) and the northern source as extended (type 5). However, rather significant residuals are visible at the sites of both objects after PSF subtraction, and we conclude that no one of them is well fit by this photometry package.

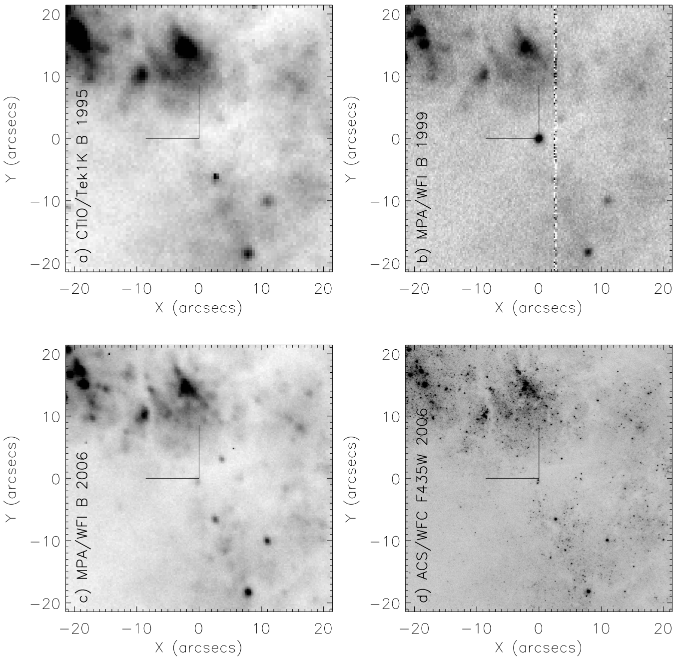

Fig. 7. The explosion site of SN 1999ga in the B band. Top-left: low resolution, pre-explosion CTIO 1.5-m telescope image obtained on March 1, 1995. Top-right: low-resolution SN image obtained on December 29, 1999 with the 1.54-m Danish Telescope (La Silla, Chile) equipped with DFOSC. Bottom-left: late time low resolution frame obtained on January 30, 2006 with the 2.2m ESO/MPI Telescope (plus Wide Field Camera) in La Silla. Bottom-right: late time (October 21, 2006) ACS HST image (filter F435W) of the explosion region. Information on these images is reported in Table 4. All images are centered at the SN position and oriented such that north is up and east is to the left.

Aperture photometry of these objects is complicated by the non-stellar nature of their PSFs. This makes it difficult to define aperture corrections and the objects are too close one another to use a large aperture.

The *BAOLAB* task *ISHAPE* (Larsen 1999, Larsen 2004) was used to determine the intrinsic size and shape of these assumed clusters. *ISHAPE* convolves an analytical function that is assumed to represent the actual source (e.g. a delta function for a star) with the stellar PSF. *ISHAPE* then compares this convolved function to the data to determine the best fit and therefore the intrinsic FWHM of the source function. An elliptical Moffat function with a power index of 1.5 was used to fit our proposed clusters. The resulting parameters for the southern and northern sources (computed for all HST images) are reported in Tab. 5.

It is worth noting that the intrinsic size, major/minor axis ratio and position angle of each object are consistent between the two broadband filters, while in Hα (F658N) they appear to have completely different shapes and orientations. In the case of the southern source, its extent in the Hα image is significantly larger than those derived in the broadband images. These measurements suggest that there is nebular Hα emission which is significantly elongated relative to the the cluster.

The *BAOLAB* task *MKCMPPSF* was used to calculate synthetic PSF matching of these two sources in each filter. These were added to fake images and used to calculate appropriate aperture corrections for the objects. This resulted in the corrected aperture photometry reported in Tab. 5 (bottom).

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[3] *DOLPHOT* is a stellar photometry package that was adapted from HSTphot (Dolphin 2000) for general use.

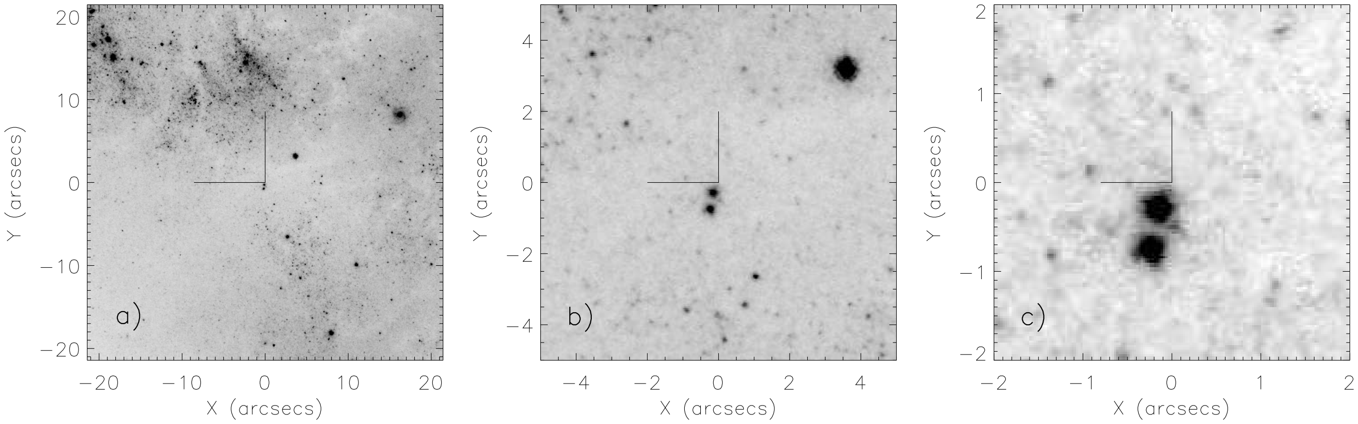

Fig. 8. HST F814W band (roughly I) image obtained 7 years after the SN explosion (left panel) and blow ups of the SN region: ×4 (central panel) and ×10 (right panel). The SN position is marked by the cross-hairs, and no source is visible at that position. The high resolution of the HST/ACS images allows us to resolve *source A* into two main components (probably two stellar clusters) plus other (though much fainter) sources. The images are centered at the SN position. North is up, east to the left.

Table 5. Basic parameters for the two putative clusters forming *Source A*, as derived by BAOLAB/ISHAPE in each of the three HST filters.

Source	F435W	F658N	F814W
FWHM of semi-major axis (pixels)			
Northern	1.94	1.96	2.22
Southern	1.16	1.70	1.37
Ratio of major/minor axis			
Northern	0.98	0.61	0.95
Southern	0.72	0.44	0.83
Position Angle (degrees)			
Northern	-43.9	-2.6	-48.1
Southern	-14.1	-69.0	-14.6
Photometry (Vegamag)			
Northern	23.49	22.35	21.95
Southern	23.62	22.46	22.09

With the distance and extinction toward SN 1999ga adopted in this paper (see Sect. 2), we obtain absolute magnitudes of F435W ∼ -8.9 and F814W ∼ -9.5 for both objects[4], which are certainly brighter than we would expect single stars to be.

Finally, the half-light/effective radii of the clusters from the F814W image was computed and found to be $R(\mathrm{eff})_{Northern} = 9.5 \pm 0.4$ pc and $R(\mathrm{eff})_{Southern} = 5.5 \pm 0.3$ pc. The northern cluster has a projected separation from the SN position of about 28 ± 5 pc (7.3 ± 1.3 pixels). Although previous studies allowed constraints to be placed on SN progenitors by estimating the ages and the main sequence turn-off masses of host stellar clusters (Maíz-Apellániz et al. 2004, Crockett et al. 2008a, Crockett et al. 2008b, Östlin et al. 2008), in the case of SN 1999ga the progenitor was probably too far from the northern cluster to claim that it was coeval. Therefore, despite the large amount of pre- and post-explosion images available for NGC 2442, no robust information can be derived for the progenitor star of SN 1999ga, since the only thing we can exclude is that the precursor was a very luminous star (e.g. a luminous blue variable).

6. Discussion and Conclusions

Despite lacking early-time photometric monitoring of SN 1999ga, which would have allowed us to conclusively discriminate between the different subtypes of SNe II, we believe that spectroscopy has provided enough evidence to support a designation of type IIL for this object. The non-detection of Hα in the latest spectrum, in particular, indicates that the residual H envelope of the exploding star was not very massive (although probably more massive than that of a type IIb SN).

A sub-division of SNe IIL into two groups (bright, like SN 1979C, and regular events, depending on their intrinsic luminosities) was proposed by a number of authors (Young & Branch 1989, Gaskell 1992, Patat et al. 1994). Richardson et al. (2002) estimated the average absolute magnitudes for bright and normal SNe IIL to be around $M_B \approx -19.3$ and $M_B \approx -17.6$, respectively. It is evident from a simple check of the absolute magnitudes of SN 1999ga at any time that this object is much fainter than regular SNe IIL. This may possibly indicate the existence of a low-luminosity tail in the luminosity distribution of type IIL SNe, similar to that already observed in SNe IIP (Hamuy 2003, Pastorello et al. 2004). Even if the peak luminosity can be questioned because of the late discovery of SN 1999ga, the radioactive tail is much fainter than that observed in other SNe IIL (see Fig. 3) and is comparable in luminosity with those of low-luminosity SNe IIP (Pastorello et al. 2004). This faint radioactive tail is consistent with the ejection of a small mass of ^{56}Ni ($\sim 10^{-2}$ $M_\odot$), an amount which is only marginally higher than that reported for low-luminosity SNe IIP (Pastorello et al. 2004, Pastorello et al. 2009). However, in stark contrast to faint SNe IIP, the broad spectral features observed in the SN 1999ga spectra are indicative of high-velocity ejecta (5000-6000 km s^{-1}, see Sec. 4). These two observed quantities suggest a normal explosion energy and moderate mass of the ejected material (including radioactive ^{56}Ni) for SN 1999ga. There is indeed robust evidence from spectroscopy that the mass of the H envelope was rather small and/or that there was a non-negligible amount of CSM, resulting from mass loss episodes during the late stages of the stellar life. Several attempts have been made to estimate the explosion parameters of past SNe IIL. The observed evolution of the nebular Hα line in the cases of the bright SNe 1980K and 1990K (Cappellaro et al. 1995b

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[4] Note that the adopted extinction is not necessarily appropriate for these proposed clusters. However, without photometry in more filters and/or spectra of these objects, it is not possible to provide a direct measurement of the extinction towards the two sources.

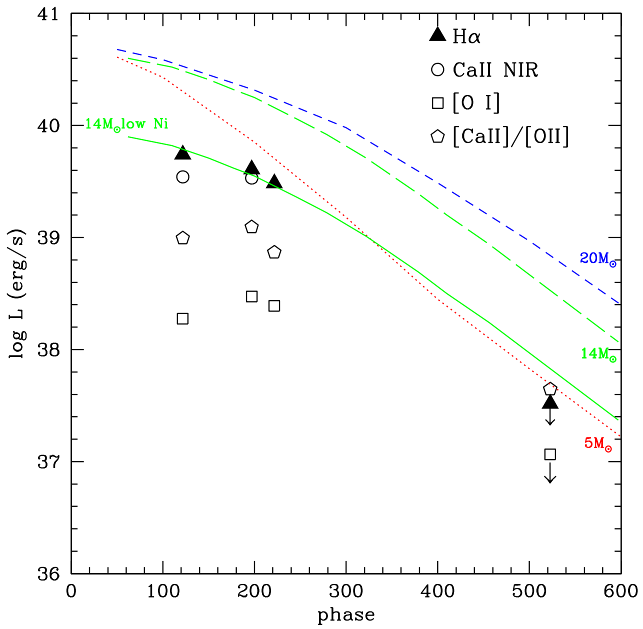

Fig. 9. Luminosity evolution of the main nebular features in the spectra of SN 1999ga. Models of Chugai 1991 showing the evolution of Hα in SNe II under the assumption of pure radioactive decay of ^{56}Co are also shown. The dotted red line marks the Hα luminosity evolution for an ejected mass of 5M$_{\odot}$, the long-dashed green line for 14M$_{\odot}$ and the dashed blue line for 20M$_{\odot}$. All models were computed with an explosion energy of 10^{51} erg and an ejected ^{56}Ni mass of 0.075M$_{\odot}$. The solid green lines is the 14M$_{\odot}$ model, but rescaled to 0.015M$_{\odot}$ of ^{56}Ni.

and references therein) was well reproduced by the models of Chugai 1991 with 5M$_{\odot}$ of ejecta, canonical explosion energy (E$_0$ = 10^{51} erg) and intermediate ^{56}Ni mass (M(^{56}Ni) = 0.075M$_{\odot}$). Slightly higher values of the above parameters are probably necessary to account for the higher luminosity of Hα in SN 1979C, even though the luminous light curve peak probably did not result from anomalous explosion parameters, but through reprocessing of UV light in a shell generated by pre-SN wind (Bartunov & Blinnikov 1992).

In Fig. 9 we compare the luminosity evolution of the Hα line in SN 1999ga with models of Hα luminosity expected in type II SNe, assuming that the source of the luminosity is purely radioactive decay (Chugai 1990, 1991). The models were obtained adopting ejected masses of 20M$_{\odot}$ (blue dashed line), 14M$_{\odot}$ (green long-dashed line), 5M$_{\odot}$ (dotted red line), and computed with E$_0$ = 10^{51} erg and M(^{56}Ni) = 0.075M$_{\odot}$. In Fig. 9 the luminosity evolution of other typical nebular lines ([O I]$\lambda\lambda$6300-6364, the [Ca II] plus [O II] blend around 7300 Å and the Ca II NIR triplet) is also shown. We note that the Hα luminosities are systematically lower than those predicted by Chugai's models with 0.075M$_{\odot}$ of ^{56}Ni, although the early decline rate is quite consistent with that of the 14M$_{\odot}$ model. We therefore rescaled the 14M$_{\odot}$ model of Chugai (1990) to M(^{56}Ni) = 0.015M$_{\odot}$. This value is consistent with the ^{56}Ni mass deduced from the late time light curve of SN 1999ga (see Sect. 3). The rescaled 14M$_{\odot}$ model is shown in Fig. 9 (solid green line), and fits reasonably well to the observed Hα luminosities of SN 1999ga only at earlier epochs, while it fails to match the late-time Hα detection limit. A lower ejected mass would help to better reproduce the faster Hα luminosity decline observed at late time, although it would fail to fit the earliest observed point of SN 1999ga. A reasonable range for the total ejected mass of SN 1999ga is therefore 6-8M$_{\odot}$, with only 1-2$_{\odot}$ of H.

SNe IIL belong to a sequence of supernova types produced by progenitors with increasing mass loss occurring during the late phases of their evolution, i.e. SN IIP → SN IIL → SN IIb → SN Ib → SN Ic (e.g. Nomoto 1997, Chevalier 2006). However, the nature of their progenitor stars is still unclear. Two channels have been proposed for type IIL SNe: single, massive progenitors (M$_{ZAMS}$ $\geq$ 20M$_{\odot}$), and lower mass stars (7-10M$_{\odot}$, Swartz et al. 1991) in binary systems, where the mass loss is triggered by the companion star.

Unfortunately, the lack of high-resolution, deep, pre-explosion HST images prevents us from providing robust constraints on the nature of the progenitor of SN 1999ga. With the remarkable exception of the detection of the K supergiant progenitor of SN 1993J (Aldering et al. 1994, Maund et al. 2004, Maund & Smartt 2009), most attempts to identify the progenitors of stripped (or partially stripped) envelope core-collapse SNe have failed (Smartt et al. 2002, van Dyk et al. 2003, Maund & Smartt 2005, Maund et al. 2005, Gal-Yam et al. 2005, Crockett et al. 2007, Crockett et al. 2008a) or are disputed (Gal-Yam et al. 2007, Crockett et al. 2008b). However, the lack of any detection in ground based pre-explosion images, the analysis of the surrounding environment, and the observed SN properties (unusual spectral and Hα luminosity evolutions, sub-luminous light curves, small ^{56}Ni mass) all suggest that the precursor of SN 1999ga at the time of core-collapse was likely a moderate-mass star (8-10M$_{\odot}$), with a moderate-to-low mass residual H envelope. The fact that the H lines and not the He lines dominate the SN spectra in the early nebular phase is indicative that the star retained a significant mass (1-2M$_{\odot}$) of H at the time of the explosion. This is more than the few $\times$ 10^{-1}M$_{\odot}$ expected for type IIb SNe (e.g. SN 2008ax, see Pastorello et al. 2008b and references therein), but surely less than the several solar masses estimated for a normal type IIP SN (e.g. Nadyozhin 2003). Although the ejecta mass implies a moderate mass star (8-10M$_{\odot}$) at explosion, the initial mass is somewhat uncertain. As the hydrogen mass is low, the progenitor likely lost mass through either stellar winds or mass-transfer to a binary. In either case, the amount of mass-loss could be significant (e.g. 5-10M$_{\odot}$). The pre-explosion images are not deep enough to distinguish between these two scenarios and the SN is not close enough to the compact clusters to assume that it is coeval with their stellar population.

SN 1999ga is probably the first (relatively) under-luminous, ^{56}Ni poor core-collapse supernova that can be classified as type IIL. The velocity of the ejecta, as constrained by the width of the spectral lines, is not as low as observed in faint type II-P SNe (Pastorello et al. 2004). This provides further evidence, in contrast with SNe IIP, for a moderate mass ejected by SN 1999ga. The detection of this kind of objects is a rare event, probably because of their faint nature coupled with a fast photometric evolution. The discovery of SN 1999ga should be seen as motivation for searches for more extreme, fast-evolving, sub-luminous, envelope-stripped core-collapse SNe. These are expected to occur (e.g. Woosley 1993) but, apart from a few remarkable exceptions (see Valenti et al. 2009), usually elude detection. Similar SNe have been also proposed to be responsible for a class of long γ-ray bursts that do not show evidence of associated SNe (Della Valle et al. 2006, Fynbo et al. 2006, Gal-Yam et al. 2006, Gehrels et al. 2006, Ofek et al. 2007, Dado et al. 2008).

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