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SN 2006gy: was it really extra-ordinary?

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ABSTRACT

We present the photometric and spectroscopic study of the very luminous Type IIn SN 2006gy for a time period spanning more than one year. The evolution of multiband light curves, the pseudo-bolometric (BVRI) light curve and an extended spectral sequence are used to derive constraints on the origin and evolution of the SN.

A broad, bright ($M_R \sim -21.7$) peak characterizes all monochromatic light curves. Afterwards, a rapid luminosity fading ($\gamma_R \sim 3.2$ mag $(100\,\mathrm{d})^{-1}$) is followed by a phase of slow luminosity decline ($\gamma_R \sim 0.4$ mag $(100\,\mathrm{d})^{-1}$) between day ∼170 and ∼237. At late phases (> 237 days), because of the large luminosity drop (> 3 mag), only upper visibility limits are obtained in the B, R and I bands. In the near-infrared, two K-band detections on days 411 and 510 open new issues about dust formation or IR echoes scenarios.

At all epochs the spectra are characterized by the absence of broad P-Cygni profiles and a multicomponent Hα profile, which are the typical signatures of type IIn SNe. Hα velocities of FWHM $\approx 3200\,\mathrm{km\,s^{-1}}$ and FHWM $\approx 9000\,\mathrm{km\,s^{-1}}$ are measured around maximum phase for the intermediate and high velocity components, respectively, and they evolve slowly with time.

After maximum, spectroscopic and photometric similarities are found between SN 2006gy and bright, interaction-dominated SNe (e.g. SN 1997cy, SN 1999E and SN 2002ic). This suggests that ejecta-CSM interaction plays a key role in SN 2006gy about 6 to 8 months after maximum, sustaining the late-time-light curve. Alternatively, the late luminosity may be related to the radioactive decay of $\sim 3M_\odot$ of ^{56}Ni.

Models of the light curve in the first 170 days suggest that the progenitor was a compact star ($R \sim 6-8 \cdot 10^{12}$cm, $M_{ej} \sim 5-14M_\odot$), and that the SN ejecta

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collided with massive ($6 - 10M_\odot$), opaque clumps of previously ejected material. These clumps do not completely obscure the SN photosphere, so that at its peak the luminosity is due both to the decay of ^{56}Ni and to interaction with CSM. A supermassive star is not required to explain the observational data, nor is an extra-ordinarily large explosion energy.

Subject headings: supernovae: individual (SN 2006gy), stars: circumstellar matter, mass loss — techniques: photometric, techniques: spectroscopic

1. Introduction

Textbook stellar evolution theory explains that Type II SNe are produced by the core collapse of H-rich stars with masses $\gtrsim 8M_\odot$ (Branch et al. 1990; Arnett et al. 1996). Confirmation of this scenario comes from the possible identification of the progenitors of a few SNe II, including SN 1987A (Arnett et al. 1989) and several more recent events (e.g. Smartt et al. 2004; Van Dyk et al. 2003).

On the other hand, a fully consistent picture of a SN progenitor evolution and explosion is still missing. Parameters like progenitor radius, ejecta mass, explosion energy, asymmetries and radioactive elements yield, all contribute to determining the SN display.

One of the most uncertain ingredients is the progenitor mass-loss history. Although some constraints on the progenitor mass loss can be derived from models of the SN light curves and spectra, direct measurements are only possible when the circumstellar material (CSM) becomes visible.

Denser CSMs and hence higher mass loss rates ($\sim 10^{-4}\,M_\odot\,yr^{-1}$, Salamanca et al. 2002) are required to explain the sudden halt in the late-time luminosity decline of several type II Linear SNe (e.g., SN 1979C, Branch et al. 1981; SN 1980K, Montes et al. 1998; SN 1986E, Cappellaro et al. 1995).

Mass loss plays a key role in type IIn SNe (Schlegel et al. 1990). The spectra of this class of SNe are characterized by emission lines with multiple components, which may range from very high ($\sim 20000\,km\,s^{-1}$) to low velocities (a few hundred $km\,s^{-1}$) with no associated (broad) P–Cygni absorptions. Such events may be very energetic (e.g., Aretxaga et al. 1999) and are characterized by a slow luminosity evolution beginning soon after discovery. It is generally believed that the shock produced when the high velocity ejecta impact on a relatively dense CSM causes the conversion of part of the ejecta kinetic energy into radiation. Depending on the CSM density distribution, the strong CSM-ejecta interaction may last for months (e.g., SN 1994W, Chugai et al. 2004) to years (e.g., SN 1988Z, Turatto et al. 1993; SN 1995N, Fransson et al. 2002 and Zampieri et al. 2005; SN 1995G, Pastorello et al. 2002).

The recent peculiar SN IIn 2006gy event attracted much interest. Discovered on 2006, September 18th in NGC 1260 (Quimby 2006), SN 2006gy was initially classified as a SN II (Harutyunyan et al. 2006) and shortly thereafter as a SN IIn (Foley et al. 2006). Although its spectroscopic features were not unprecedented, the photometric behavior was. A very bright luminosity peak ($M_R \sim -22$, Smith et al. 2007, hereafter S07) was in fact reached only ~ 70 days after explosion (estimated by backward extrapolation of the light curve, cr. §2). The amount of energy radiated in visible light during the first 200 days ($> 10^{51}\,\mathrm{erg\,s^{-1}}$, S07) was larger than in any previously observed SN, either core-collapse or thermonuclear.

On the other hand, in contrast with other bright SNe IIn (Zampieri et al. 2005, Chandra et al. 2005), only a weak and soft X–ray emission was detected by *Swift* and *Chandra* near the epoch of optical maximum (S07). The absorption-corrected, absolute X-ray luminosity in the band $0.65 - 2\,\mathrm{keV}$ was $1.65 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ (S07). It was argued (Ofek et al. 2007, S07) that if direct radiation from the ejecta-CSM interaction was the cause of the extraordinary SN luminosity, the X-ray flux should have been several orders of magnitude larger. A possible explanation is that the interaction region might have been hidden because of a very large optical depth. Alternatively, the source for the optical luminosity should be searched elsewhere.

Actually, the first model proposed by S07 was the explosion of a very massive star ($> 100\mathrm{M}_\odot$) via *pair–instability* phenomena. Such a violent explosion would cause the complete disintegration of the core and the ejection of a huge amount of ^{56}Ni, possibly up to $22\mathrm{M}_\odot$. In such a scenario the energy input from the radioactive decay chain $^{56}\mathrm{Ni} \rightarrow^{56} \mathrm{Co} \rightarrow^{56} \mathrm{Fe}$ accounts for the observed luminosity.

However, late luminosity measurements presented by Smith et al. (2008) (hereafter S08) and in this work set a much estimate to the possible ^{56}Ni mass. Other models call for the conversion of some of the ejecta kinetic energy into radiation, via a collision with a massive ($\sim 10\mathrm{M}_\odot$) and highly opaque ($\tau \sim$300) circumstellar shell (Smith & Mc Cray 2007 and S08). This scenario provides no direct information on the real nature of the explosion which, in principle, could even be a thermonuclear runaway (Ofek et al. 2007). However, this is difficult to reconcile with the presence of the massive circumstellar shell. Thus, the core collapse of a massive star is still the most appealing scenario. Alternatively, we may have witnessed the collision between high velocity shells originated in subsequent outbursts of a very massive star undergoing structural instabilities caused by pair production (*pulsational pair-instability*, Woosley et al. 2007). In any case, the presence of massive shells ($\sim 10\mathrm{M}_\odot$) at a large radius (i.e., a few 10^{15} cm) is required to explain the observed high luminosity.

Such a large shell mass, coupled with a high density, may result in long photon diffusion times (Smith & Mc Cray 2007), which could explain the broad peak of the light curve of SN 2006gy.

These scenarios can explain the light curve evolution during the first 5 months. However, the presence of a diffusion process implies fairly rapid fading of the luminosity after maximum (i.e., a time of the order of the photon diffusion time-scale). Observations instead indicate that the luminosity does not decline rapidly after maximum. On the contrary, the light curve decline slows down between day 170 and day 237 (see §3). This requires an additional energy source. Again, radioactive material has been proposed ($\sim 8\mathrm{M}_{\odot}$ of ^{56}Ni according to Smith & Mc Cray 2007), but new doubts have arisen after S08 reported a late-time drop of the optical luminosity and two infrared SN detections, which may support the formation of dust in the ejecta or the presence of IR echoes.

In this work we present new data, which include observations at all relevant phases, from discovery to more than 1 year later. Multiband light curves and an extended spectral sequence are shown and discussed. By comparison with other SNe and by means of modeling we try to verify to which extent this SN is really extra-ordinary and to provide new constraints for the progenitor and the explosion.

2. Observations

Optical (BVRI) and near–infrared (JHK') images of SN 2006gy were acquired at TNG, NOT (La Palma, Spain) and the Copernico 1.82m Telescope on Mt. Ekar (Asiago, Italy) over a period spanning more than 500 days from discovery. Optical spectroscopy was also performed, up to ∼389 days (see Table 1 for a complete log of the observations).

Since the SN is located very close to the nucleus of the host galaxy, template subtraction was required for photometry. We used archival B, R and I band images of NGC1260 acquired at the Jakobus Kapteyn Telescope[1] (La Palma, Spain), and a V band image taken at the Schmidt Telescope at Kiso Observatory[2] (Japan). Additional information about the template images is given in Table 2.

All images were de-biased and flat–field-corrected. A local sequence of stars in the SN field was calibrated using observations of standard stars obtained during photometric

[1]web archive http://archive.ast.cam.ac.uk/ingarch/ingarchold.html

[2]web archive http://www.ioa.s.u-tokyo.ac.jp/kisohp/

nights. Template subtraction was performed using ISIS (Alard & Lupton 1998), and the SN magnitudes were measured on the subtracted image with a Point Spread Function-fitting technique, using custom-made DAOPHOT-based routines that were adapted specifically for supernova photometry.

For spectroscopy, all scientific exposures were acquired at low airmass and positioning the slit along the parallactic angle. Wavelength calibration was accomplished with arc-lamp exposures and checked against the night-sky lines. The flux was calibrated using instrumental sensitivity functions obtained from observations of spectrophotometric standard stars. These were used also to remove telluric absorptions from the spectra. In order to improve the signal-to-noise ratio, separate spectra taken during the same nights were combined. Finally, flux calibration was checked against photometry. If necessary, a constant multiplicative factor was applied to correct for flux losses caused by slit miscentering or non–photometric sky conditions.

The spectrum acquired on 2006 December 19th with the Ekar 1.82m telescope required further adjustments because of the poor seeing conditions and the residual contamination from the galaxy background. The latter was removed using the spectrum at 389 days, where the SN is not detected, as a background template.

Throughout this paper, for the sake of simplicity, phase refers to the same *reference epoch* as in S07, JD=2453967 (2006 August 19.5 UT). This was derived from a backward extrapolation of the rising branch of the light curve. S07 refer to this date as the explosion epoch, but this term may be misleading in view of some of the proposed scenarios[3].

3. Photometry

To compute the absolute magnitudes of SN 2006gy some assumptions regarding the host galaxy distance and SN extinction are needed.

Lacking other indicators, the distance to NGC 1260 was estimated from the Hubble law, $\mathrm{d} = \mathrm{v_{rec}}/\mathrm{H_0}$, where $\mathrm{v_{rec}} = 5822\mathrm{kms^{-1}}$ is the host galaxy recession velocity corrected for Virgo cluster infall (from *HyperLEDA*[4]) and $\mathrm{H_0} = 72 \pm 8\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Freedman et al. 2001). These values imply a distance modulus $\mu = 34.53$, equivalent to a distance of 80.86 Mpc.

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[3]In the shocked-shell diffusion model (Smith & Mc Cray 2007) the detection of the SN emission occurs a few weeks after the real explosion. In the scenario suggested by Woosley et al. (2007) there is not even a SN explosion, but only an outburst release of matter.

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

We adopted a Galactic extinction towards NGC 1260 of $E(B-V)_{gal} = 0.16$ ($A_{B,gal} = 0.69$, Schlegel et al. 1998). An estimate of the extinction in the host galaxy was obtained comparing the spectra of SN 2006gy to those of SN II 2007bw, another peculiar and bright SN IIn, photometrically similar to SN 2006gy. This yields $E(B-V)_{host} \simeq 0.4$, assuming for SN 2007bw little or no extinction. It is interesting to note that on the 42 days spectrum the EWs of NaID due to the galactic and interstellar absorption are 2.2Å and 5.5Å, respectively. Assuming for NGC 1260 a gas-to-dust ratio along the line of sight as in our Galaxy and adopting the extinction of Schlegel et al. (1998), the derived internal absorption is fully in agreement with that derived by comparison with SN 2007bw.

Therefore the total color excess is $E_{tot}(B-V) \simeq 0.56$. This is comparable to the estimate of S07, i.e. $E_{tot}(B-V) \simeq 0.48$, which was also obtained by comparison with SNe IIn, and slightly smaller than the value adopted by Ofek et al. (2007), $E_{tot}(B-V) \simeq 0.7$.

The BVRI absolute light curves of SN 2006gy are plotted in Figure 1. In all bands the light curve exhibits a slow increase to maximum, which is reached ~ 70 days after the reference epoch. The peak magnitudes are $B \sim -21$, $V \sim -21.4$, $R \sim -21.7$ and $I \sim -21.5$. Such an extended, plateau-like peak was noted for a type IIn SN only in the case of SN 2005kd (Tsvetkov et al. 2008).

Between day ~ 100 and day ~ 170, the light curve declined relatively rapidly ($\gamma_B \sim 3.0 \mathrm{mag}\,(100\,\mathrm{d})^{-1}$, $\gamma_V \sim 3.1$, $\gamma_R \sim 3.2$, $\gamma_I \sim 2.8$). Then, from day ~ 170 onwards the light curve evolution suddenly flattened: in the following ~ 70 days the decline was only $\gamma_R \sim 0.4 \mathrm{mag}\,(100\,\mathrm{d})^{-1}$. When the SN could be observed again after solar occultation, its luminosity was below the detection limit in the optical bands. A limit was obtained placing artificial stars of different magnitudes at the SN position. Despite the long exposure times, only relatively bright upper limits were derived because the SN is very close to the nucleus of the galaxy (cf. S07, Figure 1). The derived apparent magnitude limit on day 389 is $\gtrsim 20.3$ in R. Optical upper limits were obtained also at 423 days, when we derive $B \gtrsim 21.0$, $R \gtrsim 21.5$ and $I \gtrsim 19.75$. These measurements imply a new steepening in the luminosity decline after day 237.

Guided by the evolution of other SNe (e.g., SN 1998S, Pozzo et al. 2004 or SN 2006jc, Tominaga et al. 2007; Smith et al. 2008; Mattila et al. 2008; Di Carlo et al. 2008), we considered the possibility that at late epochs a significant fraction of the bolometric luminosity could be emitted at IR wavelengths. To test whether this was the case, late observations of SN 2006gy were obtained with NICS at the TNG, on 2007, October 5 (JHK' bands) and on 2008, January 12 (K' band only). We could not apply the template subtraction technique in the near-infrared because the available pre-discovery images of the host galaxy retrieved from the 2MASS archive are not deep enough to be compared to the TNG images. Therefore, we had to rely on the PSF fitting technique which, given the SN position, has a large uncertainty. Photometric calibration was performed adopting field star magnitudes as listed in the 2MASS Point Source Catalogue[5].

The SN was not detected in the J and H bands, for which we could only estimate upper limits, J $\gtrsim$ 17.0 and H $\gtrsim$ 16.5. Instead, a point source was detected in the K' band at the SN position (Figure 2). The SN was measured at K $\sim 16.0 \pm 0.5$ on day 411 and K $\sim 16.3 \pm 0.5$ on day 510. These values are ~ 1 mag fainter than those measured by S08 at similar epochs (K=15.1 $\pm$ 0.1 and K=15.4 $\pm$ 0.1 on day 405 and 468, respectively). Even allowing for the large error bars, the two sets of measurements do not agree, probably because of a different calibration.

3.1. Infrared emission and bolometric luminosity

Given the K'-band detection of the SN at 411 and 510 days, it cannot be excluded that at late phases a considerable amount of flux is emitted in the near-infrared.

S08 suggested two possible sources of the late K'-band luminosity. The K'-band emission could be associated with an IR light echo from circumstellar dust, for which the input energy is the light emitted by the SN near maximum. In this case the IR flux should not be considered when computing the late-time bolometric light curve. Alternatively, the IR flux may originate from circumstellar dust heated by an instantaneous energy supply (radioactive decay or on-going CSM-ejecta interaction), as was suggested by Pozzo et al. (2004) to explain the late phase photometric data of SN 1998S.

In order to get some constraints on the total emission from dust at $\sim$ 411-423 days we assumed a black body energy distribution multiplied to a factor $1/\lambda$, as an approximation of what reported in Spitzer (1998), and normalized it to the observed K-band flux. Given that we have no constraints on the dust temperature, we adopted three values including T=1200K, the dust temperature in the ejecta of SN 1998S derived by Pozzo et al. (2004). For each value we plotted the spectral energy distribution (SED) of the associated emission (Figure 3) and integrated over the entire wavelength range from $\lambda_{\mathrm{K}} = 2.16\,\mu$m to $\lambda = \infty$.

It is interesting to note that the K-band luminosity of SN 1998S measured at similar epochs (K=13.8 at $\sim$464 days) would differ from that of SN 2006gy by a factor 1-5 (adopting for SN 2006gy K=16.3 from this work or K=15.4 from S08) if scaled at the same distance. Therefore, given that the two fluxes are of the same order, it is plausible that any mechanism

[5]http://tdc-www.harvard.edu/software/catalogs/tmpsc.html

explaining the IR emission of SN 1998S can work also for SN 2006gy.

From our multiwavelength photometry we can derive the pseudo-bolometric luminosity evolution of SN 2006gy integrating the flux in the optical bands (BVRI). The pseudo-bolometric light curve is shown in Figure 4, compared to those of the type II SNe 1987A, 1995G, 1997cy, 1999E and 2005gj. The pseudo-bolometric luminosities which include the dust contribution in the near IR are represented with plus symbols. It is remarkable that, at about 6 to 8 months, the luminosity and decay rate of SN 2006gy become comparable to those of other events, in particular to SNe 1997cy and SN 1999E. We will come back to this issue in §4 and §5.2.

4. Spectroscopy

The spectral evolution of SN 2006gy from day 37 to day 389 is presented in Figure 5. The spectra have been de-redshifted and corrected for extinction.

The early spectra (days 37 and 42) show the typical features of SNe IIn, namely a blue continuum and strong Hα and Hβ emission lines, without broad P-Cygni absorptions.

Using *GELATO* (Harutyunyan et al. 2008), the automatical spectra comparison tool applied to the Asiago Supernova Archive (ASA), the best match for the earliest available SN 2006gy spectrum (phase 37) is found with SN 1995G (~36 days since discovery, Pastorello et al. 2002), which is generally considered a typical SN IIn, although there are differences in the strength of the lines emission.

Three months after discovery, the spectrum of SN 2006gy became similar to those of other well-studied SNe II. In the high resolution spectrum taken on day 96 by S07 (their Figure 4) narrow absorption lines of Fe II (multiplets 42, 48, and 49 at 5000-5400 Å and multiplet 74 in the region 6100-6500 Å) are evident. A similar narrow line forest was identified in the spectra of SN 1999el (Di Carlo et al. 2002), SN 1995G (Pastorello et al. 2002) and SN 1994W (Sollerman et al. 1998; Chugai et al. 2004). In all cases these lines are associated with slowly expanding, unperturbed material surrounding the star.

Despite the lower resolution and S/N ratio, our spectrum at phase 122 days is broadly consistent with the features discussed by S08. At this phase the Hα flux has decreased by a factor of 2 with respect to the first spectrum, while Hβ emission almost disappeared.

At a phase of 174 days the near-IR Ca II triplet is strong in emission. For this epoch a good spectral match is obtained with SNe 1997cy, 1999E (Figure 6), 2002ic and 2005gj.

The Hα flux continues to decrease with time: on day 174 it is $\sim$3 times fainter than on day 37 and on day 204 even 5 times. Finally, the last spectrum (day 389) shows no evidence of the typical lines of SNe II; at this epoch, the narrow Hα emission should be attributed to the host galaxy. This is consistent with S08 and with the upper limit in the optical luminosity that was deduced from the photometry.

The emission peak of Hα remains at the rest frame wavelength at all phases, exhibiting a three–component profile (Figure 7). For the intermediate Hα component we measured a FWHM$\sim$ 2100 km s^{-1} at a phase of 42 days, and FWHM$\sim$ 3200 km s^{-1} at 174 days. S07 pointed out an asymmetry of the line at early times (also evident in our day 42 spectrum), likely caused by a blueshifted P-Cygni absorption, which vanishes with time. For this reason we can admit that the true unabsorbed profile Hα remained roughly constant during the SN evolution. A roughly constant FWHM$\sim$ 9100km s^{-1} is measured for the broad component of Hα.

The physical interpretation of the intermediate and broad components is still a matter of debate. S07 and S08 assumed that the intermediate component (v $\sim$ 4000 km s^{-1}) traces the kinematics of the SN shock wave, while the broader one is related to the SN ejecta (v $\sim$ 6000 km s^{-1}, a value significantly lower than what we obtain, v $\sim$ 9100km s^{-1}). The *intermediate* velocity component was used to compute the luminosity expected from CSM interaction. On the other hand, according to Chevalier & Fransson (1994, 2001) and to Zampieri et al. (2005), the luminosity originating from the reverse shock during ejecta-CSM interaction is proportional to the ejecta velocity, i.e. to the width of the *broadest* Hα component. There is still no consensus on this issue. Because of these ambiguities, one should be careful before assigning physical velocities to various regions from just line widths, especially for objects with peculiar individual features as are SNe IIn.

5. Discussion

As discussed in §3, the light curve of SN 2006gy shows three distinct phases: *i)* a very broad, exceptionally high luminosity peak (day 0 to $\sim$170), *ii)* an intermediate phase of slow decline (day $\sim$170 to $\sim$237) and *iii)* a late phase in which the optical luminosity drops below the detection limit and IR emission dominates (day >389). As we will show, the first phase requires a specific star+CSM configuration. The other two phases have been observed in other SNe.

In the following, we rewind the movie of the event and use the late observations to constrain the possible scenario. Starting from the late phases, we discuss the role of dust and ^{56}Ni in the ejecta, stressing that a very large amount of ^{56}Ni is not required. We then consider the evolution of the SN at intermediate phases and explain that, independently of the source that powered the luminosity at peak, interaction dominates between days ~ 170 and ~ 237. Finally, we discuss the light curve models for the first $\sim$5 months obtained with a semi-analytical code (Zampieri et al. 2003). Based on these results, we propose a new evolutionary scenario for SN 2006gy.

5.1. Nickel mass and dust emission

The late light curve of most SNe is powered by the radioactive decay of ^{56}Ni into ^{56}Co and ^{56}Fe via γ and e$^+$ deposition.

Thermonuclear SNe Ia eject a large ^{56}Ni mass ($0.1\mathrm{M}_\odot < \mathrm{M}_{^{56}\mathrm{Ni}} < 1.1\mathrm{M}_\odot$, Cappellaro et al. 1997; Mazzali et al. 2007), but become rapidly transparent to the γ-rays from the radioactive decay because of the small ejected mass and the high expansion velocity. As a consequence, at $t \sim 100$ days after explosion the luminosity declines at a rate $\sim$1.5mag (100 d)$^{-1}$, higher than the ^{56}Co decay input ($\sim$ 0.98mag (100 d)$^{-1}$). A similar behavior was found for most type Ib/c SNe (Clocchiatti & Wheeler 1997).

In the case of H-rich, core-collapse SNe the ejecta remain almost opaque to γ-rays for more than a year, and the late-time luminosity decline tracks the radioactive decay. In this case, if the date of the explosion is known, the late-time luminosity provides a direct estimate of the ejected ^{56}Ni mass. This spans a wide range of values ($0.005 < \mathrm{M}_{^{56}\mathrm{Ni}} < 0.3\mathrm{M}_\odot$; L. Zampieri et al., in preparation), but is typically smaller than in SNe Ia and Ib/c.

For SN 2006gy, in the optical bands only upper limits to the luminosity at very late phases (411 days) can be obtained. In the near infrared, the K-band detection reported in S08 and discussed in the previous section may be suggestive of the presence of low-temperature dust emitting in the far IR. This makes a precise estimate of the ejected ^{56}Ni mass difficult. The bolometric luminosity including the emission from dust (plus symbols in Figure 4) imply ejected ^{56}Ni masses up to $\sim 15\mathrm{M}_\odot$ for T=800K. However, given the uncertainty on the nature of dust and its temperature, a more significant estimate of M(^{56}Ni) can be obtained adopting the bolometric luminosity at earlier epochs, i.e. at $\sim$ 180 days. At this phase the relation $\mathrm{L} = 1.4 \cdot 10^{43}\mathrm{M}_{\mathrm{Ni}} \cdot \exp(-t/113.6)\,\mathrm{erg\,s^{-1}}$ provides $\mathrm{M}_{\mathrm{Ni}} \sim 3\mathrm{M}_\odot$ assuming complete γ-ray trapping (see also §5.3). This value is in disagreement with the value obtained by Smith & Mc Cray (2007) with the same relation ($\mathrm{M}_{^{56}\mathrm{Ni}} \sim 8\mathrm{M}_\odot$). A possible explanation may reside in a different estimate of the bolometric luminosity, which is about a factor 3 higher in Smith & Mc Cray (2007).

Of course, we expect the bolometric flux - and therefore the ^{56}Ni mass - to increase if the IR/longer wavelength emission contribution is taken into account. On the other hand, the luminosity decay at phase 170-137 days is much slower than what is expected from ^{56}Co decay. This suggests that an energy source additional to radioactive decay of ^{56}Ni has to be present. Compared to those measured for other SNe, an amount of $3M_{\odot}$ of ^{56}Ni may not appear unreasonably large (see for example SN 1999as, Deng et al. 2001).

5.2. Evidence of strong, late-time ejecta-CSM interaction

We mentioned in §3.1 and §4 that at 170-237 days SN 2006gy shares several properties with SNe 1997cy, 1999E, 2005gj and 2002ic. Although some authors regard some of these SNe as thermonuclear explosions (see Hamuy et al. 2003 for SN 2002ic and Prieto et al. 2007 for SN 2005gj, but see also Benetti et al. 2006 and S. Benetti et al. 2008, in preparation, for an alternative scenario) there is unanimous consensus on the fact that interaction dominates their emission at late phases. Despite the brighter magnitude at maximum, SN 2006gy has luminosity and luminosity decline rate comparable to the SNe mentioned above at 170-237 days (Figure 4), which is when they also show similar spectra.

Therefore, it is natural to assume that at this phase ejecta-CSM *interaction plays a dominant role also in SN 2006gy.* Although the low X-ray flux at this phase (cf. §1) might appear to be in contradiction with the ejecta/CSM interaction scenario, this may not be a problem, because for sufficiently high densities ($\rho \sim 10^{8}\,\mathrm{g\,cm^{-3}}$) the X-rays that are produced in the shock are immediately absorbed (Turatto et al. 2000).

In the context of interaction, the luminosity L arising from the shock is proportional to the progenitor mass loss rate $\dot{\mathrm{M}}$, to the ejecta velocity $\mathrm{V_{ej}}$ and to the unshocked CSM wind velocity $\mathrm{V_{CSM}}$, as follows: $\mathrm{L} \propto \mathrm{V_{ej}^{3}\dot{M}V_{CSM}^{-1}}$. Unfortunately, because of the ambiguity in the interpretation of emission line profiles (§4), we cannot precisely measure the velocities in the different circumstellar regions and thus derive a reliable estimate of the CSM density from the observational data. However, the emission lines in SNe 1997cy and 1999E are generally broader than in SN 2006gy (i.e., their ejecta are probably faster), but their luminosity is comparable. In view of the former relation, we expect that the shock wave of SN 2006gy encounters a higher CSM density at 170-237 days.

5.3. A highly energetic supernova impinging on massive gaseous clumps

The SN evolution during the first 170 days is explained reasonably well by the scenario proposed by Smith & Mc Cray (2007). In the shocked-shell diffusion model the supernova light is produced by diffusion of thermal energy after the passage of the SN shock wave through a shell of $10 M_{\odot}$ of material, ejected in the decade preceding the explosion. The shell is supposed to be initially optically thick and acts as a pseudo-photosphere, so that the long duration of the peak and the weakness of X-rays emission are explained in terms of a long diffusion time and a very large optical depth. The interaction features typical of type IIn SNe are supposed to arise in the observed spectra as soon as the blast wave breaks out of the opaque shell into the surrounding, lower-density wind.

However, in Smith & Mc Cray (2007) a number of items have not been considered. A first inconsistency concerns the model assumptions. According to the model of Falk & Arnett (1973, 1977) which is adopted in Smith & Mc Cray (2007), in order to reproduce the observed luminosity rise to maximum, the initial radius of the shocked shell has to be much smaller than the radius at peak luminosity. However, in the model of Smith & Mc Cray (2007) the initial and final radius differ only by a factor of 2. Thus the model of Falk & Arnett (1973) is not applicable: the simple assumption of the existence of a single shell at a large radius surrounding the exploding star can not explain the properties of the light curve of SN 2006gy, in particular the slow rise to maximum.

Secondly, in the model of Smith & Mc Cray (2007) the important role of ^{56}Ni is overlooked. No attempt has been made to estimate the amount of ^{56}Ni deposited by the SN and to determine its effect on the light curve during the diffusive phase[6].

The third problem concerns recombination, whose effects can not be neglected as soon as the decreasing photospheric temperature reaches the gas recombination temperature during the post-diffusive phase.

With these shortcomings in mind, we have developed an alternative, comprehensive scenario that attempts to take all these aspects into account. First of all, we divided the evolution of SN 2006gy into two distinct phases, before and after maximum luminosity. Each phase was modeled independently. The earlier phase (i.e., the rising branch of the light curve) was modeled as the explosion of a core-collapse SN originating from a compact progenitor. For the peak phase we adopted a scenario similar to that of Smith & Mc Cray (2007), in which the ejecta impact on very massive ($> 6 M_{\odot}$, see Table 5) clumps of previously ejected

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[6]The estimate of $8 M_{\odot}$ of ^{56}Ni reported in their paper derives from the extrapolation of the light curve luminosity after day 170 (cfr. §5.1)

material and deposit their kinetic energy. Because the density is very high, the energy of the shock produced by the ejecta-clump interaction is completely thermalized. A photosphere forms, so that the evolution of the shocked clumps can be modeled as if it was another SN with very large radius and little ejected ^{56}Ni.

A fundamental difference with respect to the model of Smith & Mc Cray (2007) is that, in our scenario, the true SN explosion is not completely hidden by the circumstellar material which is therefore not homogeneously distributed around the star. Rather, it is fragmented into big clumps which may be distributed symmetrically with respect to the centre of the star. This is motivated by the assumption that the progenitor of SN 2006gy may have undergone mass-loss episodes similar to those observed in η Carinae. The rise to maximum corresponds to the early emission of the SN ejecta during the initial phase in which the radius is rapidly expanding, similarly to the case of SN 1987A (Woosley 1988). In our model the peak luminosity is sustained by the *combined contribution* of the early SN explosion and the energy from the ejecta-clump interaction. Unfortunately, no early spectra are available to verify this claim. The first available spectrum (37 days) already shows signs of interaction, mainly in the Hα profile, probably caused by flux arising directly from the interaction, being not thermalized by the dense clumps. Therefore we can reasonably assume that at this phase the ejecta-clump collision had already started. Another assumption of our model is that the impact is instantaneous, i.e. that all material is reached by the ejecta at the same radial distance from the star.

Our semi-analytical code (see Zampieri et al. 2003 for more details) was used to estimate the parameters of the ejected envelope from a simultaneous comparison of the observed and computed light curve, photospheric gas velocity and continuum temperature. The radius of the star at the explosion, the mass and velocity of the ejecta and the explosion energy are fitting parameters, whereas the ejected ^{56}Ni mass is an input fixed parameter, which is based on the late-time light curve. The fitting parameters are estimated by means of a χ^2 minimization procedure for both evolutionary phases (i.e. the SN explosion and the ejecta-clumps impact).

The parameters of the models for each phase are listed in Table 5 and 6. Models of the earlier phase (*e1*, *e2*, *e3* and *e4*) refer to different values of the input parameters M_{Ni} and T_{rec}, while models of the later phase (*c1* and *c2*) refer to different χ^2 minima.

Critical parameters for the earlier phase are the initial radius and the mass of ^{56}Ni. As discussed before, the large increase in luminosity in the pre-maximum phase calls for small initial radii ($< 10^{13}$cm), which are not compatible with RSG stars but are consistent with BSG or Wolf Rayet stars. The amount of ^{56}Ni determines the peak luminosity. The adopted upper limit is $M_{Ni} \sim 2M_{\odot}$, considering that $\sim 3M_{\odot}$ were estimated at ~ 180 days neglecting the contribution of interaction, which instead *is* already active at that phase, as explained above (according to the model the γ-rays trapping is always more than 80% effective at a phase 170-237 days, given the large ejecta masses). A minimum ^{56}Ni yield of 0.75 $M_{\odot}$ was required to fit the early rise of the light curve, assuming no contribution from interaction (i.e., the CSM is supposed to be rarified in the vicinity of the exploding star).

Table 5 lists the best-fit-parameters for the initial radius of the star, for the ejecta mass and for the velocity and SN explosion energy, given the adopted ^{56}Ni masses and recombination temperatures. It should be noted that the radius estimated by the code is actually an upper limit: the initial part of the light curve is not very sensitive as long as it remains below the reported values. The SN parameters are not exceptionally high for a core-collapse SN. For example, the explosion energy is only $\sim 3 - 4.5$ times larger than that of SN 1987A. The explosion energy increases with increasing ^{56}Ni mass, as one may naively expect from the fact that larger amounts of ^{56}Ni may be synthetized in more energetics events. On the other hand, for a constant ^{56}Ni mass a smaller recombination temperature implies an increase in the ejecta velocity and mass, and therefore in the explosion energy.

The later phase is not powered by ^{56}Ni alone. The main source of energy is in fact the transformation of the kinetic energy of the ejecta into thermal energy and radiation inside the dense clumps, which form a photosphere. The duration and shape of the luminosity peak depends on the radius and mass of the clumps and on their expansion velocity. The parameters listed in Table 6 are the clump radius, mass and velocity, the amount of ^{56}Ni in the clumps, the recombination temperature, the energy released by the ejecta-clumps interaction and the diffusion time. The recombination temperature adopted is $T = 6500 \pm 1000$K, as measured from the 37-day spectrum. For both models reported (*c1* and *c2*) the energy deposited by the ejecta in the CSM is about a factor ∼2-30 smaller than the SN explosion energy. This value may result naturally, considering that the clumps cover a solid angle not larger than 2π as seen from the centre of the star. In the two models the radius of the clump is significantly different. For an ejecta velocity of 8000 $\mathrm{km\,s^{-1}}$, and assuming that the ejecta-clump impact occurs at ∼30-40 days, the distance of the clumps is $\sim 10^{15}\,\mathrm{cm\,s^{-1}}$. Adopting a characteristic sound speed of $\sim 10^{8}\mathrm{cm^{-1}}$, the shock wave produced by the impact takes ~ 100 days to cross the clump in model *c1* and ~ 10 days in model *c2*. On these grounds, model *c2* seems to be favored, as the optical display of the shocked clumps is fully developed by $\sim$ 40 days after explosion. The values obtained for the clump distance and mass are roughly consistent with those derived by Smith & Mc Cray (2007).

Our simple model gives a satisfactory fit for both the explosion and collision phase (Figure 8). We did not attempt to fit the light curve in the transition phase. The parameters that characterize the explosion of SN 2006gy are actually not particularly remarkable. An extra-ordinary amount of ^{56}Ni in the ejecta is not necessary to fit the light curve. The estimated amount of ^{56}Ni is 2 to 6 times larger than that derived for other well studied, bright core-collapse events (Turatto et al. 2000; Mazzali et al. 2006). It should be noted that an high amount of ^{56}Ni is even not to relate to the huge brightness of the recently discovered SN 2008es, the second most luminous SN known, according to Gezari et al. (2008) and to Miller et al. (2008). SN 2006gy was certainly a highly energetic event compared to other normal CC-SNe, perhaps comparable to the class of *hypernovae* (e.g., SN 2003dh, Matheson et al. 2003; SN 2003jd, Valenti et al. 2008; SN 1998bw, Iwamoto et al. 1998). The combined mass of the ejecta and of the clumps is $\sim 20 M_{\odot}$, indicating an originally very massive progenitor, likely much more massive than $\sim 30 M_{\odot}$ if account is taken of the likely large mass loss in the pre-SN stage. Still, these values are significantly smaller than those claimed in some of the previously proposed scenarios ($> 100 M_{\odot}$).

There is increasing evidence for the association of bright SNe IIn and LBVs (Salamanca et al. 2002; Smith & Owocki 2006; Kotak & Vink 2006; Gal-Yam et al. 2007; Trundle et al. 2008). The properties of these events seem to require that their progenitor stars experienced mass loss rates of the order of $\sim 0.1 M_{\odot} yr^{-1}$, which are only compatible with those estimated for stars like η Carinae. Also in this case strong, LBV-like mass-loss phenomena are required to produce massive clumps around the star. Given the radius at explosion derived by the model, a star in a LBV or early Wolf-Rayet phase might be good candidates for the progenitor of SN 2006gy.

6. Summary and conclusions

New observational data of SN 2006gy allow us to derive constraints on the physical processes underlying SN 2006gy. We confirm the luminosity drop in the R band at days 362 and 394 first reported by S08, and find a similar drop also for the B and I bands at similar epochs. The absence of SN features in the spectrum at t $\sim$ 389 days supports this. In all bands the light curves exhibit a broad luminosity peak at day $\sim$ 70, followed by a steep decline and then by a flattening at $\sim$170-237 days. At very late phases the SN was detected in the K band. This may deal either with dust formation in the ejecta or with IR echoes events. However, the uncertainties on the late-phases scenario do not hamper the estimate of ^{56}Ni mass ejected. Based on the bolometric luminosity at day $\sim$180 un upper limit of $\sim 3 M_{\odot}$ is derived. At this epoch interaction, rather than radioactive decay, has been proved to be the dominant source.

During the first 3 months the behavior of SN 2006gy can be reproduced as the explosion of a compact progenitor star (with explosion energy $\sim 4 - 9 \cdot 10^{51}$erg, R $\sim 6 - 8 \cdot 10^{12}$cm).

The SN ejecta collide with some previously ejected material ($\sim 6-10\mathrm{M}_{\odot}$) distributed in highly opaque clumps. The increasing size of the SN ejecta, the relatively large amount of ^{56}Ni ejected, the collision with the extended, opaque clumps with a long diffusion time are the "ingredients" responsible for the slow increase of the light curve to maximum and for the brightness and extension of the peak. The values derived for the mass of the clumps and their radial distance are consistent with those derived for the shocked shell by Smith & Mc Cray (2007).

The spectra of SN 2006gy at ∼170-237 days are similar to those of a number of bright, interaction-dominated SNe (Figure 6), with which SN 2006gy shares remarkable photometric similarities (Figure 4). This confirms that at this epoch interaction plays a dominant role also in the case of SN 2006gy. In the massive-clump scenario, it is likely that interaction signatures start to dominate the spectra when the clumps become transparent because they recombine. The ejecta encounter regions of progressively lower density with time. At the epoch of our last optical observation (∼423 days), interaction has probably already ceased. This is consistent with the non-detection of Hα in the Keck spectrum of S08.

In conclusion, although SN 2006gy was very luminous and energetic ($\sim$ 3 to 4.5 times more energetic than SN 1987A), it does not appear to be an extraordinary event. In fact, neither the explosion of a supermassive progenitor, nor extremely high Ni-rich ejecta are required to explain the observations.

Unfortunately, the nature of the progenitor star of SN 2006gy still remains obscure. Nevertheless, to account for such a violent and energetic explosion as well as for the existence of an extremely dense CSM around the exploding star it is natural to consider a very massive progenitor, likely more massive than $30\mathrm{M}_{\odot}$, which experienced strong mass loss episodes just before the explosion.

LBV-like mass loss rates resulting in highly dense circumstellar shells seem to be common near the bright end of interacting supernovae (e.g., SN 2006jc, Pastorello et al. 2006; SN 1997eg, Hoffman et al. 2007; SN 2005gj, Trundle et al. 2008 and S. Benetti et al. 2008, in preparation). A LBV-like outburst was also claimed by Smith et al. (2008) to explain the observational data of SN 2006tf. Considering the radius of the progenitor required to explain the long luminosity rise to maximum, the progenitor of SN 2006gy was probably a LBV or an early Wolf-Rayet star.

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Table 1. Journal of photometric and spectroscopic observations of SN 2006gy.

UT Date	Telescope	Equipment	Bands	Grisms	Spec. range [Å]	Resolution [Å]	Pixelscale [”/pix.]
06/09/25	TNG[b]	DOLORES	-	LR-B, LR-R	3200-9000	18, 17	0.25
06/09/30	NOT[a]	ALFOSC	BVRI	4	3400-8800	21	0.19
06/10/29	Ekar1.82m	AFOSC	BVRI	-	-	-	0.46
06/12/19	Ekar1.82m	AFOSC	BVRI	4	3500-7500	24	0.46
07/02/10	NOT	ALFOSC	BVRI	4, 5	3500-9800	21,‘20	0.19
07/03/10	Ekar1.82m	AFOSC	BVRI	-	-	-	0.46
07/03/12	Ekar1.82m	AFOSC	-	2, 4	3400-7600	38, 24	0.46
07/04/13	Ekar1.82m	AFOSC	VRI	-	-	-	0.46
07/09/14	Ekar1.82m	AFOSC	R	4	3400-7600	24	0.46
07/10/05	TNG[b]	NICS	JHK’	-	-	-	0.25
07/10/17	TNG[b]	DOLORES	BRI	-	-	-	0.25
08/01/12	TNG[b]	NICS	K’	-	-	-	0.25

[a]Nordic Optical Telescope

[b]Telescopio Nazionale Galileo

Table 2. Main data on the archive images used for the photometric template subtraction.

UT Date	Telescope	Equpment	Bands	Exp.time	Seeing [”]	Pixelscale [”/pix.]
91/12/01	JKT[c]	AGBX	B	600	1	0.33
91/12/01	JKT	AGBX	R	300	1.15	0.33
96/01/13	JKT	AGBX	I	360	1.5	0.33
03/02/12	Schmidt Tel.		V	300	3.7	1.46

[c]Jakobus Kapteyn Telescope

Table 3. Optical photometry of SN 2006gy.

UT Date	JD -2,400,000	Phase [days][a]	B	Berr	V	Verr	R	Rerr	I	Ierr
06/09/18	53996.5	29.5	-	-	-	-	15[b]	-	-	-
06/09/30	54008.5	41.5	16.00	.08	15.19	.22	14.51	.10	14.48	.07
06/10/29	54037.5	70.5	15.84	.06	14.85	.13	14.28	.04	14.10	.06
06/12/19	54088.5	121.5	16.23	.06	15.08	.15	14.99	.04	14.37	.06
07/02/10	54142.4	174.5	17.87	.08	16.75	.22	16.69	.10	15.86	.07
07/03/10	54169.5	204.5	18.07	.06	17.74	.15	16.67	.04	16.19	.06
07/04/13	54203.5	236.5	-	-	17.66	.15	16.93	.04	16.32	.06
07/09/14	54356.5	389.5	-	-	-	-	>20.30	-	-	-
07/10/17	54390.6	423.5	>21	-	-	-	>21.55	-	>19.75	-

[a]With respect to JD=2453967.0

[b]From ATEL 644 (2006)

Table 4. Near–infrared photometry of SN 2006gy.

UT Date	JD -2,400,000	Phase [days][a]	J	Jerr	H	Herr	K	Kerr
07/10/05	54378.5	411	> 17	-	> 16.5	-	16.00	.50
08/01/12	54477.5	510	-	-	-	-	16.3	.50

[a]With respect to JD=2453967.0

Table 5. Model output parameters of the semi-analytical code for the first evolutionary phase.

model	$R_{star}[\cdot 10^{12}\mathrm{cm}]$	$M_{ej}[M_\odot]$	V_{ej}[km/s]	$M_{Ni}[M_\odot]$	T_{rec}[K]	$E_{expl}[10^{51}\mathrm{erg}]$
(*e1*)	8.4	5.3	7700	0.75	7000	3.8
(*e2*)	5.9	8.3	8900	1.0	6500	7.9
(*e3*)	8.4	6.9	7700	1.0	7000	4.9
(*e4*)	8.4	14.4	7300	2.0	7000	9.2

Table 6. Model output parameters of the semi-analytical code for the second evolutionary phase.

model	$R_{cl}[\cdot 10^{12}\mathrm{cm}]$	$M_{cl}[M_\odot]$	V_{cl}[km/s]	$M_{Ni}[M_\odot]$	T_{rec}[K]	$E_{imp}[10^{51}\mathrm{erg}]$	diff. time [days]
(*c1*)	1339.9	6.5	1900	0.1	6500	0.3	100
(*c2*)	290.6	10.0	3600	0.1	6500	1.6	10

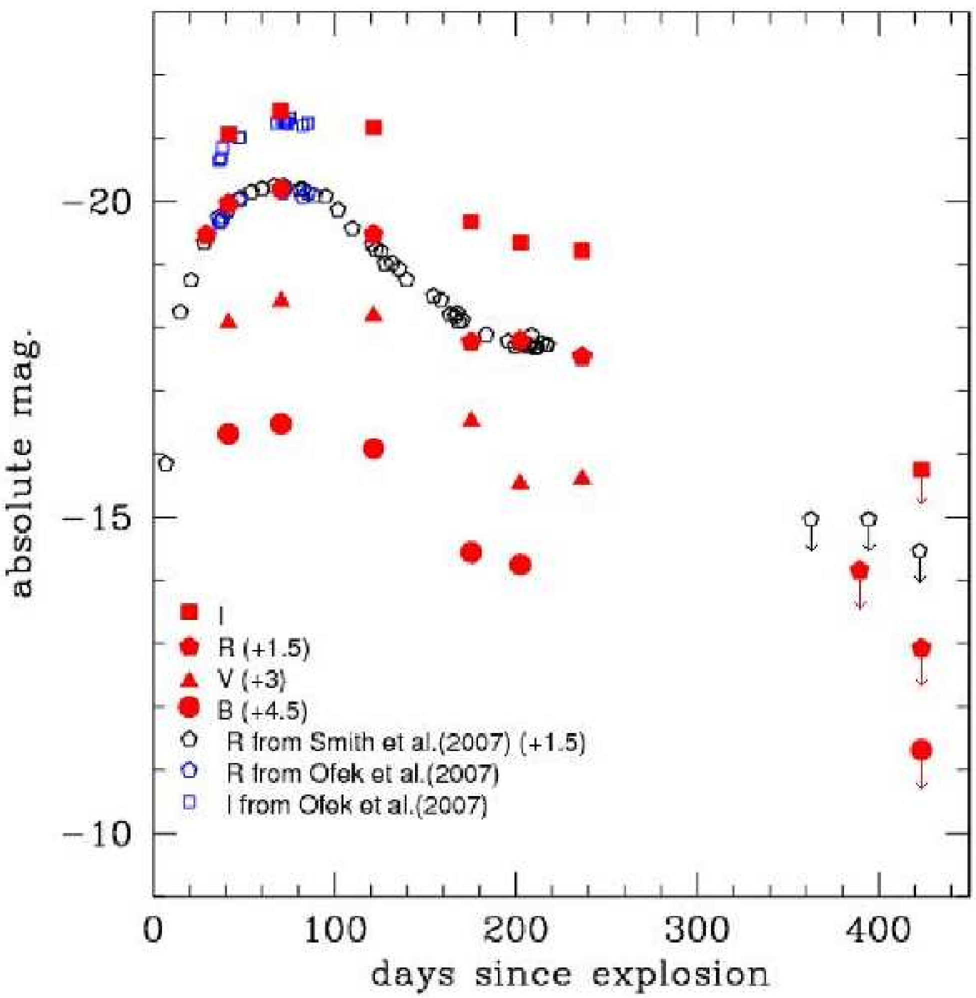

Fig. 1.— BVRI absolute light curves of SN 2006gy, obtained with the distance and extinction reported in the text. Late phase (>300 days) detection limits are marked with an arrow. R data from Smith et al. (2007) and Smith et al. (2008), as well as R and I data from Ofek et al. (2007) are also reported.

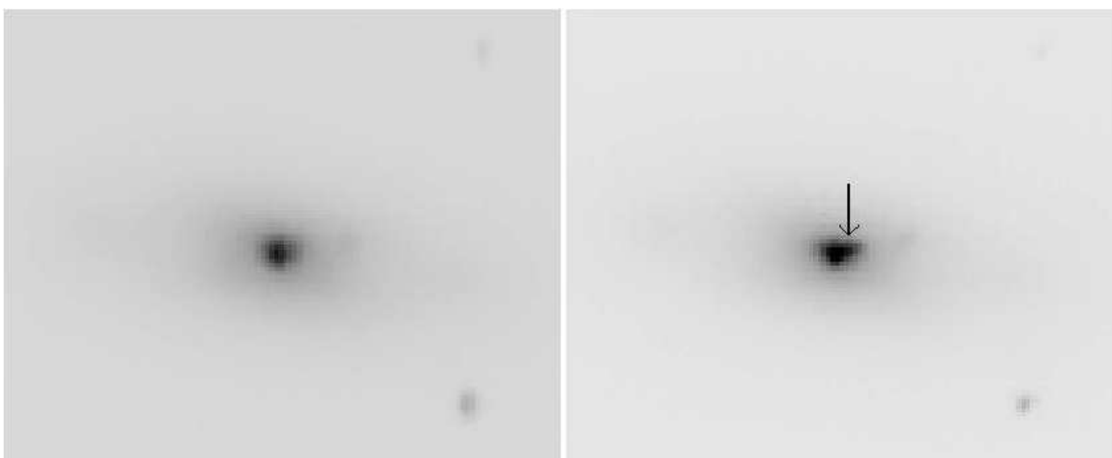

Fig. 2.— Images aquired with NICS at TNG with filter J (left panel) and K' (right panel) on October 5th, 2007 (JD 2454378.5). SN 2006gy is still clearly visible near the host galaxy nucleus in the K' band image, whereas there is no detectable source at that position in the J band frame.

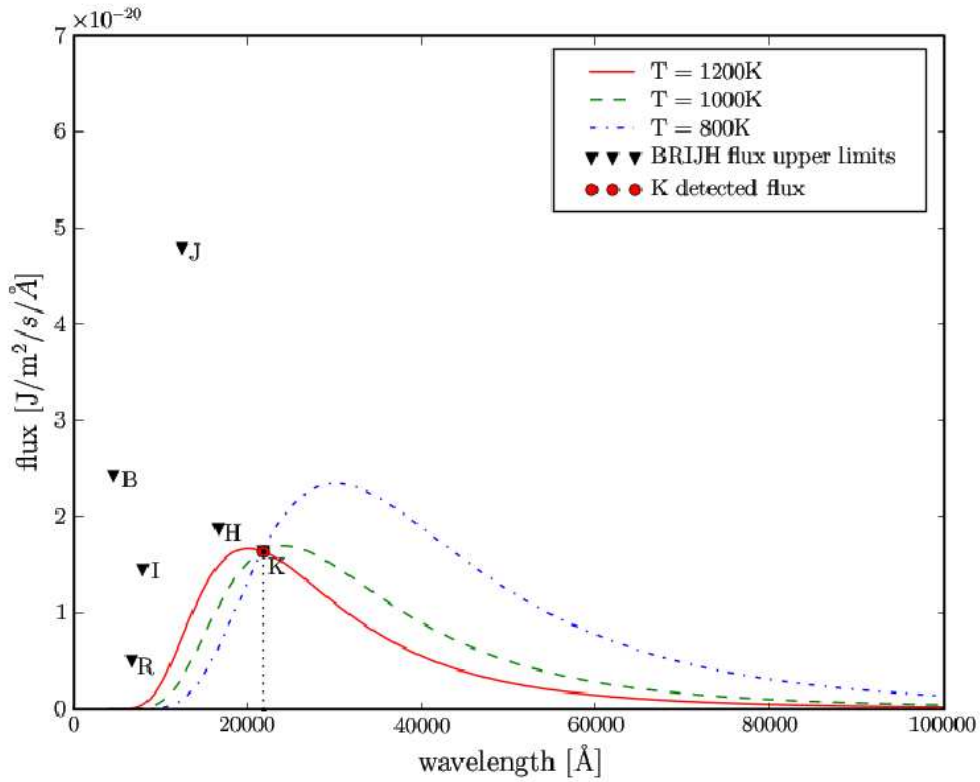

Fig. 3.— Comparison between the optical (day 423) and near–infrared (day 411) flux measured for SN 2006gy. We also show the expected emission from dust at different temperatures, normalized to the K band magnitude.

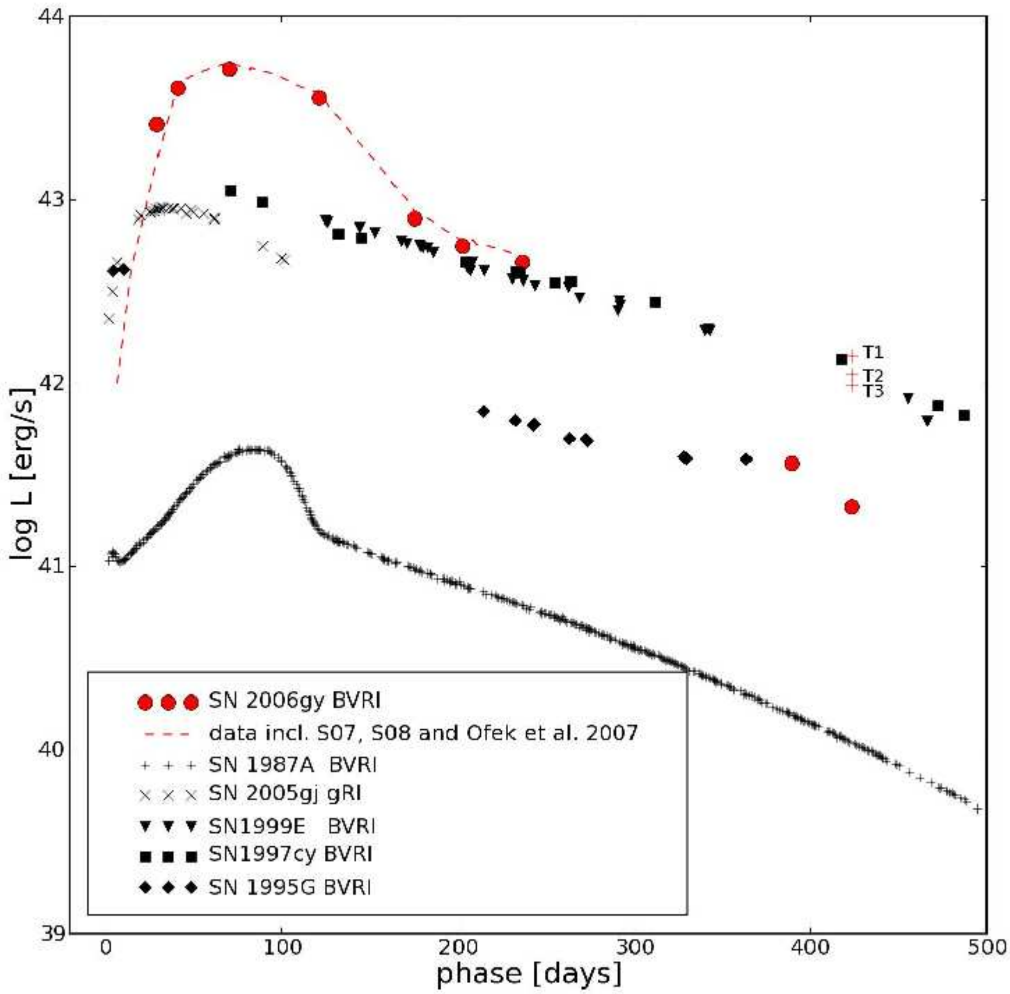

Fig. 4.— Pseudo-bolometric light curve of SN 2006gy compared to those of type IIP SN 1987A (White & Malin 1987), type IIn SN 2005gj (Prieto et al. 2007), SN 1999E (Rigon et al. 2003), SN 1997cy (Turatto et al. 2000; Germany et al. 2000) and SN 1995G (Pastorello et al. 2002), all integrated in the same wavelength range. Red crosses at late times include the near-IR contribution due to a possible cold dusty region in SN 2006gy ejecta, based on the K-band detection and on three possible dust temperatures (T1=800K, T2=1000K and T3=1200K, see §3.1). For SN 1997cy and SN 1999E the epochs of the associated GRB explosions (GRB 970514 and GRB 980919) are adopted as phase reference epochs.

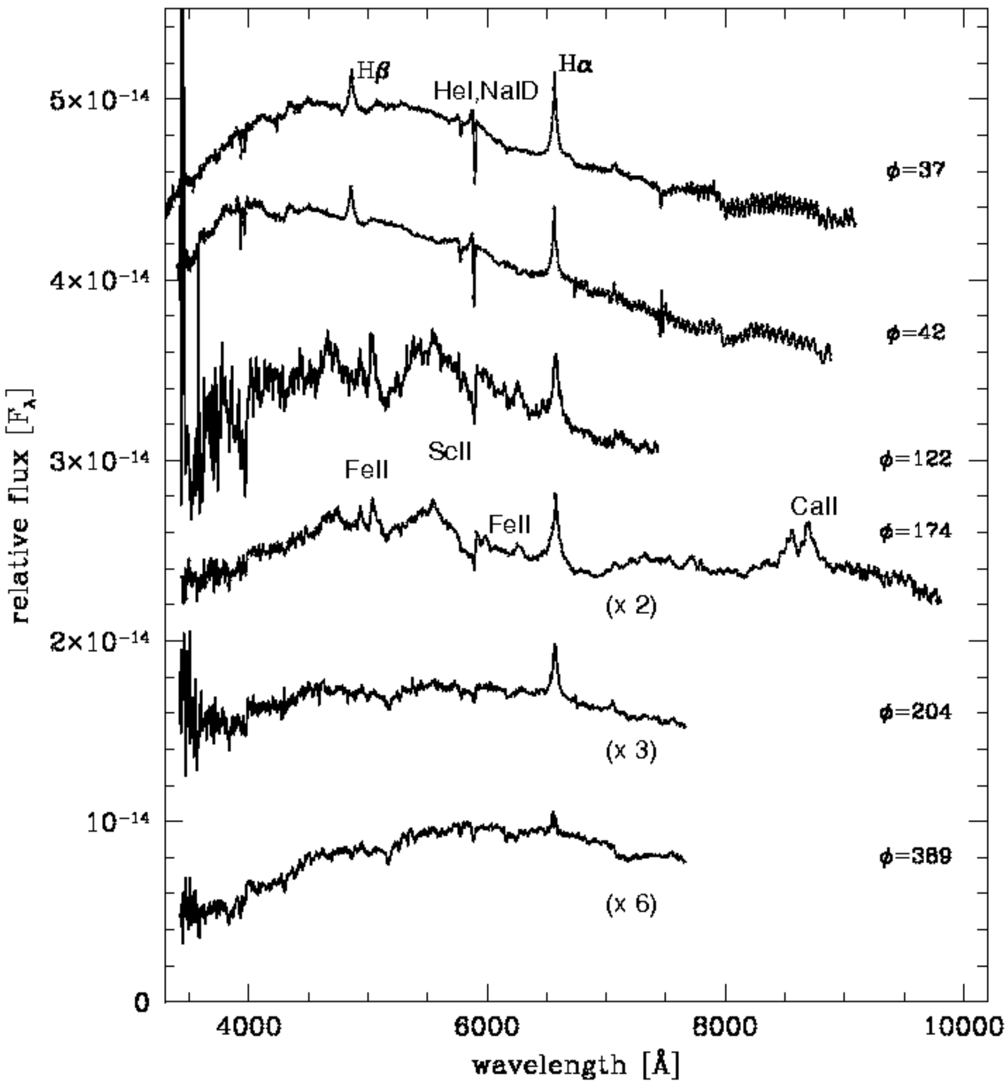

Fig. 5.— Spectroscopic evolution of SN 2006gy from 37 days to 389 days since explosion in the host galaxy rest-frame, corrected for extinction assuming E(B−V)=0.56. The spectra at phase 174, 204 and 389 were multiplied by a factor 2, 3 and 6 respectively.

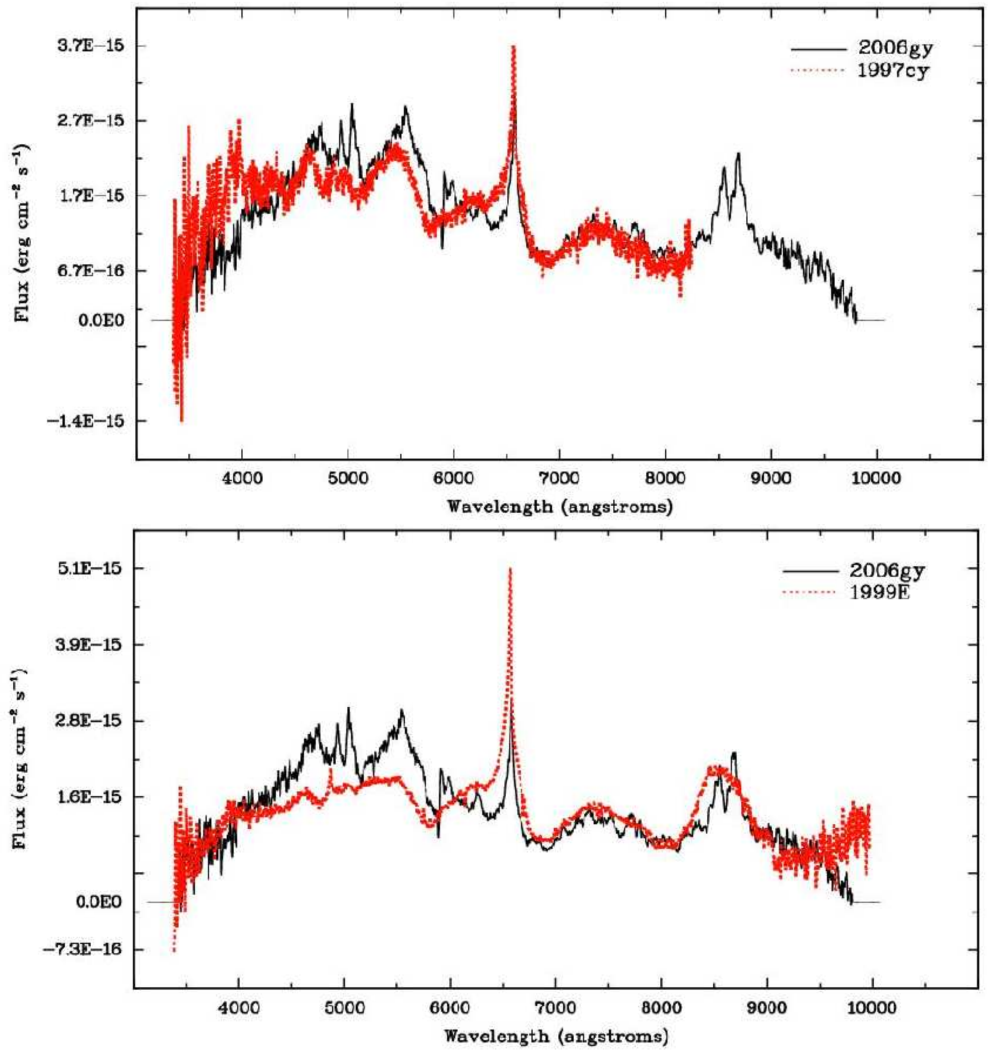

Fig. 6.— GELATO comparison between the spectrum of SN 2006gy at phase ∼174 days, SN 1997cy (top, Turatto et al. 2000) and SN 1999E (bottom, Rigon et al. 2003) at similar phases. Although the comparison SNe have broader lines, (e.g., FWHM$_{\mathrm{H}\alpha}$=12800 km s^{-1} in SN 1997cy according to Turatto et al. 2000), the objects show an overall remarkable similarity.

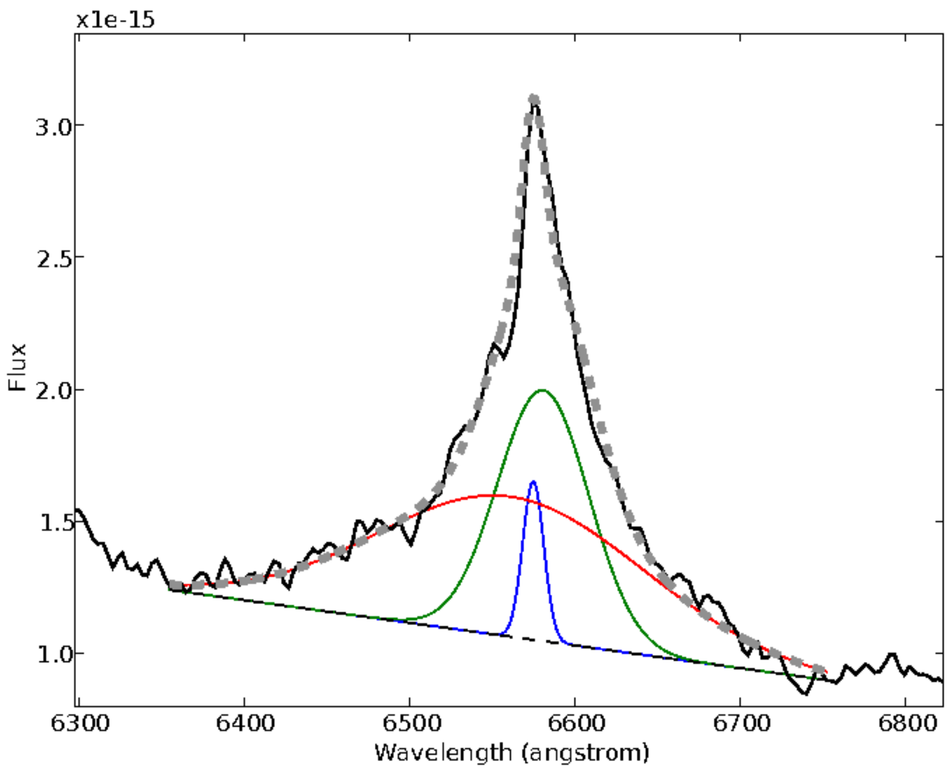

Fig. 7.— Detail of the Hα profle in the spectrum obtained at NOT on February 10th, 2007. The line is decomposed into three gaussian profiles, having FWHM = 685 (unresolved), 3200 and 9000 $\mathrm{km\,s^{-1}}$.

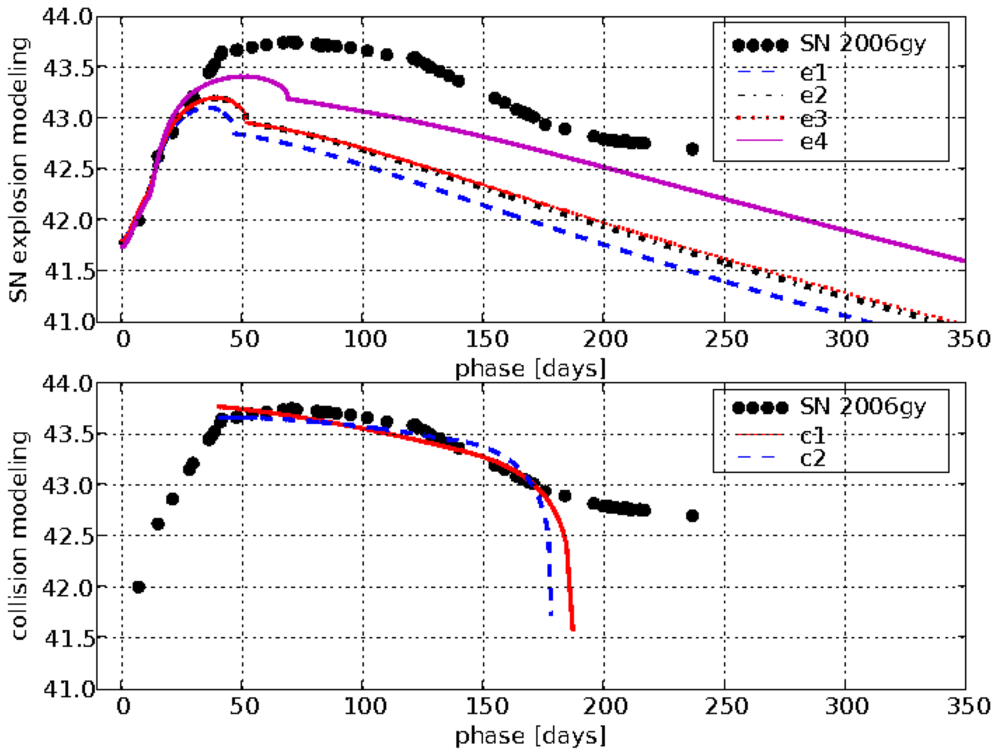

Fig. 8.— Best fits of the light curve of SN 2006gy obtained with the semi-analytical model (Zampieri et al. 2003), showed separately for the rising branch and maximum/post maximum phase. The code in the legenda refers to the models summarized in Table 5 and 6.