SN 2006gy: WAS IT REALLY EXTRAORDINARY?

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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 pseudobolometric (BVRI) light curve, and an extended spectral sequence is used to derive constraints on the origin and evolution of the supernova (SN). A broad, bright $(M_R \sim -21.7)$ peak characterizes all monochromatic light curves. Afterward, rapid luminosity fading $(\gamma_R \sim 3.2$ mag (100 days)$^{-1}$) is followed by a phase of slow luminosity decline $(\gamma_R \sim 0.4$ mag (100 days)$^{-1}$) between days $\sim 170$ and $\sim 237$. 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 infrared echo 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 $\sim 3200$ km s$^{-1}$ and FHWM $\sim 9000$ km s$^{-1}$ are measured around the maximum phase for the intermediate and high velocity components, respectively, and they slowly evolve 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–circumstellar material (CSM) interaction plays a key role in SN 2006gy about six to eight months after maximum, sustaining the late-time light curve. Alternatively, the late luminosity may be related to the radioactive decay of $\sim 3 M_\odot$ of $^{56}$Ni. Models of the light curve in the first 170 days suggest that the progenitor was a compact star $(R \sim (6–8) \times 10^{12}$ cm, $M_{ej} \sim 5–14 M_\odot$) and that the SN ejecta collided with massive $(6–10 M_\odot)$, opaque clumps of previously ejected material. These clumps do not completely obscure the SN photosphere, such that at its peak, the luminosity is due both to the decay of $^{56}$Ni and to interaction with CSM. Neither an extraordinarily large explosion energy nor a supermassive star is required to explain the observational data.

Key words: circumstellar matter – supernovae: individual (SN 2006gy) – techniques: photometric – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

Textbook stellar evolution theory explains that Type II supernovae (SNe) are produced by the core collapse of H-rich stars with masses $\gtrsim 8 M_\odot$ (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 such as 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 ($\sim 20,000$ 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 18 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 $\sim 70$ days after explosion (estimated by backward extrapolation of the light curve; see Section 2). The amount of energy radiated in visible light during the first 200 days ($\sim 10^{51}$ 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 keV was $1.65 \times 10^{39}$ 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 ($> 100 M_\odot$) 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 $22 M_\odot$. In such a scenario, the energy input from the radioactive decay chain $^{56}$Ni $\rightarrow$ $^{56}$Co $\rightarrow$ $^{56}$Fe accounts for the observed luminosity.

However, late luminosity measurements presented by Smith et al. (2008b; hereafter, S08) and in this work set a much lower 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 ($\sim 10 M_\odot$) and highly-opaque ($\tau \sim 300$) circumstellar shell (Smith & Mc Cray 2007; 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 originating 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 ($\sim 10 M_\odot$) at a large radius (i.e., a few $10^{15}$ cm) is required to explain the high luminosity observed. 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 timescale). Observations instead indicate that the luminosity does not decline rapidly after maximum. In contrast, the light-curve decline slows down between days 170 and 237 (see Section 3). This requires an additional energy source. Again, radioactive material has been proposed ($\sim 8 M_\odot$ 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 (IR) 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 extraordinary and to provide new constraints for the progenitor and the explosion.

### 2. OBSERVATIONS

Optical (BVRI) and near-infrared (NIR; JHK) images of SN 2006gy were acquired at Telescopio Nazionale Galileo (TNG), Nordic Optical Telescope (NOT; La Palma, Spain) and the Copernico 1.82 m Telescope on Mt. Ekar (Asiago, Italy) over a period spanning more than 500 days from discovery. Optical spectroscopy was also performed, up to $\sim 389$ 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 NGC 1260, acquired

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**Table 1**

| UT Date      | Telescope | Equipment | Bands | Grisms | Spec. Range (Å) | Resolution (Å) | Pixel scale [$''$/pix.] |
|--------------|-----------|-----------|-------|--------|----------------|-----------------|------------------------|
| 2006 Sep 25  | TNGa      | DOLORES   | ...   | LR-B, LR-R | 3200-9000     | 18, 17          | 0.25                   |
| 2006 Sep 30  | NOTb      | ALFOSC    | BVRI  | 4      | 3400-8800      | 21              | 0.19                   |
| 2006 Oct 29  | Ekari.82 m | AFOSC     | BVRI  | 4      | 3500-7500      | 24              | 0.46                   |
| 2006 Dec 19  | Ekari.82 m | AFOSC     | BVRI  | 4      | 3500-9800      | 21, 20          | 0.19                   |
| 2007 Feb 10  | NOT       | ALFOSC    | BVRI  | 4, 5   | 3400-7600      | 38, 24          | 0.46                   |
| 2007 Mar 10  | Ekari.82 m | AFOSC     | BVRI  | ...    | ...           | ...             | 0.46                   |
| 2007 Mar 12  | Ekari.82 m | AFOSC     | BVRI  | 2, 4   | 3400-7600      | 38, 24          | 0.46                   |
| 2007 Apr 13  | Ekari.82 m | AFOSC     | VRI   | ...    | ...           | ...             | 0.46                   |
| 2007 Sep 14  | Ekari.82 m | AFOSC     | R     | 4      | 3400-7600      | 24              | 0.46                   |
| 2007 Oct 05  | TNGa      | NICS      | JHK'  | ...    | ...           | ...             | 0.25                   |
| 2007 Oct 17  | TNGa      | DOLORES   | BRI   | ...    | ...           | ...             | 0.25                   |
| 2008 Jan 12  | TNGa      | NICS      | K'    | ...    | ...           | ...             | 0.25                   |

*Notes.*

a Telescopio Nazionale Galileo.

b Nordic Optical Telescope.
13 In the shocked-shell diffusion model (Smith & McCray 2007), the explosion, but only an outburst release of matter. In the scenario suggested by Woosley et al. (2007), there is not even a SN detection of the SN emission occurs a few weeks after the real explosion. In Tables 3 and 4.

...adapted for SN photometry. The resultant optical and NIR photometry of SN 2006gy (in apparent magnitudes) is reported in Tables 3 and 4.

For spectroscopy, all scientific exposures were acquired at low airmass and positioned 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 also used to remove telluric absorptions from the spectra. In order to improve the signal-to-noise ratio (S/N), 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 nonphotometric sky conditions.

The spectrum acquired on 2006 December 19 with the Ekar 1.82 m 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 referred to this date as the explosion epoch, but this term may be misleading in view of some of the proposed scenarios.

3. PHOTOLOGY

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, $d = v_{	ext{rec}} / H_0$, where

\[ v_{	ext{rec}} = 5822 \text{ km s}^{-1} \] is the host galaxy recession velocity corrected for Virgo cluster infall (from HyperLEDA\(^a\)) and $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2001). These values imply a distance modulus $\mu = 34.53$, equivalent to a distance of 80.86 Mpc.

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

Therefore, the total color excess is $E_{\text{tot}}(B - V) \simeq 0.56$. This is comparable to the estimate of S07, that is, $E_{\text{tot}}(B - V) \simeq 0.48$, which was also obtained by comparison

\(^a\) Web archive ~http://archive.ast.cam.ac.uk/ingarch/ingarchold.html
\(^b\) Web archive ~http://www.ioa.s.u-tokyo.ac.jp/kisohp/
\(^c\) In the shocked-shell diffusion model (Smith & McCray 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.

\(^{14}\) http://leda.univ-lyon1.fr/
with SNe IIn, and slightly smaller than the value adopted by Ofek et al. (2007), $E_{bol}(B-V) \lesssim 0.7$.

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 $\sim 70$ 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 $\sim 100$ and day $\sim 170$, the light curve declined relatively rapidly ($\gamma_B \sim 3.0$ mag (100 days)$^{-1}$, $\gamma_V \sim 3.1$, $\gamma_R \sim 3.2$, $\gamma_I \sim 2.8$). Then, from day $\sim 170$ onward, the light-curve evolution suddenly flattened: in the following $\sim 70$ days, the decline was only $\gamma_R \sim 0.4$ mag (100 days)$^{-1}$. 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 was very close to the nucleus of the galaxy (see S07, Figure 1). The apparent magnitude limit derived on day 389 is $\gtrsim 20.3$ in $R$. Optical upper limits were also obtained at 423 days, when we derived $B \gtrsim 21.0$, $R \gtrsim 21.5$, 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 1999hs, Pozzo et al. 2004 or SN 2006jc, Tominaga et al. 2007; Smith et al. 2008a; 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 the Near-Infrared Camera Spectrometer (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 NIR because the available prediscover images of the host galaxy retrieved from the Two Micron All Sky Survey (2MASS) archive are not deep enough to be compared with 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 by adopting field star magnitudes as listed in the 2MASS Point Source Catalogue.\textsuperscript{15}

The SN was not detected in the $J$ and $H$ bands, for which we could only estimate upper limits $J \gtrsim 17.0$ and $H \gtrsim 16.5$, respectively. 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 $\sim 1$ mag fainter than those measured by S08 at similar epochs ($K = 15.1 \pm 0.1$ and $K = 15.4 \pm 0.1$ on days 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. IR 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 NIR.

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 1999S.

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 by a factor $1/\lambda$, as an approximation of what was 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 $T = 1200$ K, 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 $\lambda K = 2.16 \mu m$ to $\lambda = \infty$.

It is interesting to note that the K-band luminosity of SN 1999S measured at similar epochs ($K = 13.8$ at $\sim 464$ days) would differ from that of SN 2006gy by a factor of 1–5 (by adopting $K = 16.3$ from this work or $K = 15.4$ for SN 2006gy) if scaled at the same distance. Therefore, given that the two fluxes are of the same order, it is plausible that any mechanism explaining the IR emission of SN 1999S can also work for SN 2006gy.

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

\textsuperscript{15} http://tdc-www.harvard.edu/software/catalogs/tmpsc.html
Figure 3. Comparison between the optical (day 423) and NIR (day 411) flux measured for SN 2006gy. We also show the expected emission from dust at different temperatures, normalized to the $K$-band magnitude.

(A color version of this figure is available in the online journal.)

Figure 4. Pseudobolometric light curve of SN 2006gy compared with 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 NIR contribution due to a possible cold dusty region in SN 2006gy ejecta, based on the $K$-band detection and on three possible dust temperatures ($T_1 = 800$ K, $T_2 = 1000$ K, and $T_3 = 1200$ K; see Section 3.1). For SN 1997cy and SN 1999E the epochs of the associated gamma-ray burst (GRB) explosions (GRB 970514 and GRB 980919) are adopted as phase reference epochs.

(A color version of this figure is available in the online journal.)
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 a phase of 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 $\sim 9100$ km 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, $v \sim 9100$ km s$^{-1}$). The intermediate velocity component was used to compute the luminosity expected from CSM interaction. By contrast, according to Chevalier & Fransson (1994, 2001) and Zampieri et al. (2005), the luminosity originating from the reverse shock during ejecta–CSM interaction is proportional to the ejecta velocity, that is, 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, such as SNe IIn.

5. DISCUSSION

As discussed in Section 3, the light curve of SN 2006gy shows three distinct phases: (1) a very broad, exceptionally high luminosity peak (days 0 to $\sim 170$), (2) an intermediate phase of slow decline (days $\sim 170$ to $\sim 237$), and (3) a late phase in which the optical luminosity drops below the detection limit and IR emission dominates (days $>389$). 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 discuss the evolution of the event in a chronological inverse order, 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, independent of the source that powered the luminosity at peak, interaction dominates between days $\sim 170$ and $\sim 237$. Finally, we discuss the light-curve models for the first $\sim 5$ months obtained with a semianalytical 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 $\gamma$ and $e^+$ deposition.

Thermonuclear SNe Ia eject a large $^{56}$Ni mass ($0.1 M_\odot < M_{56Ni} < 1.1 M_\odot$; Cappellaro et al. 1997; Mazzali et al. 2007), but be-
Figure 6. GELATO comparison between the spectrum of SN 2006gy at a phase of \(\sim 174\) 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\(\lambda_\alpha = 12,800\) km s\(^{-1}\) in SN 1997cy according to Turatto et al. 2000), the objects show an overall remarkable similarity.

(A color version of this figure is available in the online journal.)

Figure 7. Detail of the H\(\alpha\) profile in the spectrum obtained at NOT on 2007 February 10. The line is decomposed into three Gaussian profiles, having FWHM = 685 (unresolved), 3200, and 9000 km s\(^{-1}\).

(A color version of this figure is available in the online journal.)

come rapidly transparent to the \(\gamma\)-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 of \(\sim 1.5\) mag (100 days\(^{-1}\)), higher than the \(^{56}\)Co decay input (\(\sim 0.98\) mag (100 days\(^{-1}\))). 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 \(\gamma\)-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 < \(M_{56\text{Ni}}\) < 0.3 \(M_\odot\); L. Zampieri et al. 2009, 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 NIR, 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 (FIR). 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) implies ejected $^{56}\text{Ni}$ masses up to \(\sim 15 M_{\odot}\) for \(T = 800\) K. However, given the uncertainty on the nature of dust and its temperature, a more significant estimate of \(M(^{56}\text{Ni})\) can be obtained by adopting the bolometric luminosity at earlier epochs, that is, at \(\sim 150\) days. At this phase, the relation \(L = 1.4 \times 10^{38} M_{\odot}\cdot \exp(-t/113.6)\) erg s\(^{-1}\) provides \(M_{\text{Ni}} \sim 3 M_{\odot}\), assuming complete \(\gamma\)-ray trapping (also see Section 5.3). This value is in disagreement with the value obtained by Smith & Mc Cray (2007) with the same relation (\(M_{\text{Ni}} \sim 8 M_{\odot}\)). A possible explanation may reside in a different estimate of the bolometric luminosity, which is about a factor of 3 higher in Smith & Mc Cray (2007).

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

### 5.2. Evidence of Strong, Late-Time Ejecta–CSM Interaction

In Sections 3.1 and 4, we mentioned 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 Humay et al. 2003 for SN 2002ic and Prieto et al. 2007 for SN 2005gj, but also see Benett et al. 2006 and S. Benett et al. 2009, 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 also plays a dominant role in SN 2006gy. Although the low X-ray flux at this phase (see Section 1) might appear to be in contradiction with the ejecta–CSM interaction scenario, this may not be a problem, because for sufficiently high densities (\(\rho \sim 10^8 \text{g cm}^{-3}\)), 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 \(M\), to the ejecta velocity \(V_{\text{ej}}\), and to the unshocked CSM wind velocity \(V_{\text{CSM}}\). Unfortunately, because of the ambiguity in the interpretation of emission line profiles (Section 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 SN Impinging on Massive Gaseous Clumps

The SN evolution during the first 170 days is reasonably well explained by the scenario proposed by Smith & Mc Cray (2007). In the shocked-shell diffusion model, the SN 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 pseudophotosphere, 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 spectra observed 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 radii differ only by a factor

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**Table 3**

| UT Date | JD-2400000 | Phase (days)\(^a\) | \(B\) | \(B_{\text{err}}\) | \(V\) | \(V_{\text{err}}\) | \(R\) | \(R_{\text{err}}\) | \(I\) | \(I_{\text{err}}\) |
|---------|-------------|-----------------|-----|----------------|-----|----------------|-----|----------------|-----|----------------|
| 2006 Sep 18 | 53996.5 | 29.5 | ... | ... | ... | ... | ... | ... | ... | ... |
| 2006 Sep 30 | 54008.5 | 41.5 | 16.00 | 0.08 | 15.19 | 0.22 | 14.51 | 0.10 | 14.48 | 0.07 |
| 2006 Oct 29 | 54037.5 | 70.5 | 15.84 | 0.06 | 14.85 | 0.13 | 14.28 | 0.04 | 14.10 | 0.06 |
| 2006 Dec 19 | 54088.5 | 121.5 | 16.23 | 0.06 | 15.08 | 0.15 | 14.99 | 0.04 | 14.37 | 0.06 |
| 2007 Feb 10 | 54142.4 | 174.5 | 17.87 | 0.08 | 16.75 | 0.22 | 16.69 | 0.10 | 15.86 | 0.07 |
| 2007 Mar 10 | 54169.5 | 204.5 | 18.07 | 0.06 | 17.74 | 0.15 | 16.67 | 0.04 | 16.19 | 0.06 |
| 2007 Apr 13 | 54203.5 | 236.5 | ... | ... | ... | ... | ... | ... | ... | ... |
| 2007 Sep 14 | 54356.5 | 389.5 | ... | ... | ... | ... | ... | ... | ... | ... |
| 2007 Oct 17 | 54390.6 | 423.5 | > 21 | ... | ... | ... | ... | ... | ... | ... |

**Notes.**

\(^a\) With respect to JD = 2453967.0.

**Table 4**

| UT Date | JD-2400000 | Phase (days)\(^a\) | \(J\) | \(J_{\text{err}}\) | \(H\) | \(H_{\text{err}}\) | \(K\) | \(K_{\text{err}}\) |
|---------|-------------|-----------------|-----|----------------|-----|----------------|-----|----------------|
| 2007 Oct 05 | 54378.5 | 411 | > 17 | ... | > 16.5 | ... | 16.00 | 0.50 |
| 2008 Jan 12 | 54477.5 | 510 | ... | ... | ... | ... | 16.3 | 0.50 |

**Note.** \(^a\) With respect to JD = 2453967.0.
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 cannot explain the properties of the light curve of SN 2006gy, in particular the slow rise to maximum.

Second, in the model of Smith & McCray (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.

The third problem concerns recombination, whose effects cannot be neglected as soon as the decreasing photospheric temperature reaches the gas recombination temperature during the postdiffusive 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 independently modeled. 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 & McCray (2007), in which the ejecta impact on very massive (> 6 $M_\odot$; see Table 5) clumps of previously-ejected 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 & McCray (2007) is that, in our scenario, the true SN explosion is not completely hidden by the CSM, which is, therefore, not homogeneously distributed around the star. Rather, it is fragmented into big clumps, which may be symmetrically distributed with respect to the center 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 rapidly expands, similar 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, that is, all material is reached by the ejecta at the same radial distance from the star.

Our semianalytical 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 $\chi^2$ 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 Tables 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 $\chi^2$ 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 premaximum 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 $M_{Ni} \sim 2 M_\odot$, considering that ~ 3 $M_\odot$ were estimated at ~ 180 days by neglecting the contribution of interaction, which instead is already active at that phase, as explained above (according to the model, the $\gamma$-rays trapping is always more than 80% effective at a phase of 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 ~ 3–4.5 times larger than that of SN 1987A. The explosion energy increases with increasing $^{56}$Ni mass, as one may naively

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16 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 (see Section 5.1).
expect from the fact that larger amounts of $^{56}$Ni may be synthetized in more energetics events. However, 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 of $\sim 2$–30 smaller than the SN explosion energy. This value may result naturally, considering that the clumps cover a solid angle not larger than $2 \pi$ as seen from the center of the star. In the two models, the radius of the clump is significantly different. For an ejecta velocity of 8000 km s$^{-1}$, and assuming that the ejecta–clump impact occurs at $\sim 30$–40 days, the distance of the clumps is $\sim 10^{15}$ cm s$^{-1}$. Adopting a characteristic sound speed of $\sim 10^8$ cm s$^{-1}$, the shock wave produced by the impact takes $\sim 100$ days to cross the clump in model $c1$ and $\sim 10$ 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 extraordinary amount of $^{56}$Ni in the ejecta is not necessary to fit the light curve. The estimated amount of $^{56}$Ni is 2–6 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 a 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. (2009) and Miller et al. (2009). 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 the likely large mass loss in the pre-SN stage is taken into account. 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 LBV’s (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 experience mass-loss rates of the order of $\sim 0.1 M_\odot$ yr$^{-1}$, which are only compatible with those estimated for stars, such as $\eta$ 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 an 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 also find a similar drop 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 ~ 70, followed by a steep decline and then by a flattening at ~ 170–237 days. At very late phases, the SN was detected in the K band. This may deal with either dust formation in the ejecta or IR echo events. However, the uncertainties on the late-phases scenario do not hamper the estimate of $^{56}\text{Ni}$ mass ejected. Based on the bolometric luminosity at day ~ 180, an upper limit of ~ $3M_\odot$ 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 an explosion energy of ~ $4\times 10^{51}\text{ erg}$, $R$ ~ $6\times 10^{12}\text{ cm}$). The SN ejecta collide with some previously-ejected material ($\sim 6–10M_\odot$) distributed in highly opaque clumps. The increasing size of the SN ejecta, the relatively large amount of $^{56}\text{Ni}$ 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 & McCray (2007).

The spectra of SN 2006gy at ~ 170–237 days are similar to those of a number of bright, interaction-dominated SNe (Figure 4), with which SN 2006gy shares remarkably photometric similarities (Figure 4). This confirms that at this epoch, interaction also plays a dominant role 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 nondetection of Hα in the Keck spectrum of S08.

In conclusion, although SN 2006gy was very luminous and energetic (~ 3–4.5 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 is 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 and 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 $30M_\odot$, which experienced strong mass-loss episodes just before the explosion.

$\text{LBV}$-like mass-loss rates resulting in highly dense circumstellar shells seem to be common near the bright end of interacting SNe (e.g., SN 2006jc, Pastorello et al. 2007; SN 1997eg, Hoffman et al. 2007; SN 2005gj, Trundle et al. 2008 and S. Benetti et al. 2009, in preparation). A $\text{LBV}$-like outburst was also claimed by Smith et al. (2008c) to explain the observational data of SN 2006t. Considering the radius of the progenitor required to explain the long luminosity rise to maximum, the progenitor of SN 2006gy was probably an $\text{LBV}$ or an early Wolf-Rayet star.

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