SN 2006GY: AN EXTREMELY LUMINOUS SUPERNOVA IN THE GALAXY NGC 1260

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ABSTRACT

With an extinction-corrected V-band peak absolute magnitude of about −22, supernova (SN) 2006gy is probably the brightest SN ever observed. We report on multi-wavelength observations of this SN and its environment. Our spectroscopy shows an Hα emission line as well as absorption features which may be identified as Si II lines at low expansion velocity. The high peak luminosity, the slow rise to maximum, and the narrow Hα line are similar to those observed in hybrid type-Ia/IIn (also called Iia) SNe. The host galaxy, NGC 1260, is dominated by an old stellar population with solar metallicity. However, our high resolution adaptive optics images reveal a dust lane in this galaxy, and there appears to be an H II region in the vicinity of the SN. The extra-ordinarily large peak luminosity, \( \sim 3 \times 10^{44}\,\text{erg}\,\text{s}^{-1} \), demands a dense circum-stellar medium, regardless of the mass of the progenitor star. The inferred mass loss rate of the progenitor is \( \sim 0.1\,\text{M}_\odot\,\text{yr}^{-1} \) over a period of \( \sim 10\,\text{yr} \) prior to explosion. Such an high mass-loss rate may be the result of a binary star common envelope ejection. The total radiated energy in the first two months is about \( 1.1 \times 10^{51}\,\text{erg} \), which is only a factor of two less than that available from a super-Chandrasekhar Ia explosion. Therefore, given the presence of a star forming region in the vicinity of the SN and the high energy requirements, a plausible scenario is that SN 2006gy is related to the death of a massive star (e.g., pair production SN).

Subject headings: supernovae: general – supernovae: individual (SN 2006gy) – galaxies: individual (NGC 1260)

1. INTRODUCTION

SN 2006gy was discovered by the ROTSE-IIIb telescope at the McDonald Observatory on UT 2006 September 18.3 (Quimby 2006). The supernova (SN) was initially reported 2″ off the center of NGC 1260. Harutyunyan et al. (2006) obtained a spectrum on UT 2006 September 26 and reported a three-component Hα emission line: an unresolved narrow line; an intermediate component with Full Width at Half Maximum (FWHM) of 2500 km s\(^{-1}\); and a component with FWHM of 9500 km s\(^{-1}\). They suggested that the event was a type II SN.

Prieto et al. (2006) reported that a spectrum of the SN, obtained eight days after the discovery, was suggestive of a dust-extinguished type-IIn event. However, the Balmer lines were symmetric, which is unusual for SNe in their early phases. Moreover, after correcting for two magnitudes of extinction (based on observed Na I lines), the absolute magnitude is about −22. They further reported that the position of the SN is consistent with the center of the galaxy, suggesting it is more consistent with an eruption of the active galactic nucleus (AGN) of NGC 1260. Foley et al. (2006) noted that the SN is offset by about 1″ from the nucleus of NGC 1260. This fact along with a spectrum obtained six days after discovery, led them to suggest that SN 2006gy was a type IIn event.

Here we report on multi-wavelength observations of SN 2006gy. An independent contemporary analysis is presented by Smith et al. (2006).

2. OBSERVATIONS

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We initiated a photometric \((g,r,i,z)\) monitoring program with the Palomar 60-inch robotic telescope (Cenko et al. 2006). Not possessing pre-explosion images of NGC 1260, which are essential for accurate subtraction of the light from the host galaxy, we used archival R- and I-band images obtained with the Jacobus Kapteyn Telescope\(^{5}\) on 1996 January 13 and 1991 December 1, respectively. The \(r-\) and \(i-\) band measurements and errors, presented in Fig. 1 and Table 1, were produced by image subtraction using the Common Point-spread-function Method (CPM; Gal-Yam et al. 2004).

On UT 2006 September 26 and December 18 and 19 we obtained spectra using the Low Resolution Imaging Spectro-
graph mounted on the Keck-I 10-m telescope (LRIS; Oke et al. 1995). Spectra were also obtained on UT 2006 October 28.3, 29.4 and November 25.2, using the Double Beam Spectrograph (DBSP) mounted on the Hale 5-m telescope. The spectra are displayed in Fig. 2.

On UT 2006 Nov 1.3 we observed the event with the Adaptive Optics system (Troy et al. 2000) equipped with the Palomar High Angular Resolution Observer (Hayward et al. 2001) camera mounted on the Hale 5-m telescope. We used the wavefront reconstruction algorithm – denominator-free centroiding and Bayesian reconstruction (Shelton 1997), which delivered $K_s$-band images with $0.1''$ FWHM and a Strehl ratio of $\sim 15\%$. We obtained 660s and 300s images in the $K_s$ and $J$-bands, respectively, using the high-resolution mode ($25\text{maspix}^{-1}$) and a $240\times K_s$-band image using the low-resolution camera ($40\text{maspix}^{-1}$). Each frame was flat-fielded, background subtracted, and repaired for bad pixels using custom PyRAF software.$^6$

The field of SN 2006gy/NGC 1260 was observed by the Swift X-Ray Telescope (XRT) on 2006 October 30 and the Chandra X-ray Observatory on 2004 December 23 and 2006 November 14.$^7$. For the Swift observations, assuming a Galactic neutral Hydrogen column density $N_H = 1.3 \times 10^{21} \text{cm}^{-2}$ (Dickey & Lockman 1990), and a power-law spectrum with index 1.8, we set a 3-$\sigma$ upper limit for the flux in the 0.2–10keV band of $<1.8 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$. The Chandra observations reveal a variable source at the position of the nucleus of NGC 1260. The spatial coincidence lead us to attribute this source to an active galactic nucleus. In order to constrain the X-ray luminosity of the SN, we fitted the X-ray image with a model containing three components: A narrow Gaussian centered on the galaxy position; a wide Gauss-

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**TABLE I**

| Date  | Tel & Band | Magnitude$^a$ | Date  | Tel & Band | Magnitude or Flux$^a$ |
|-------|------------|---------------|-------|------------|----------------------|
| 09-24.9 | P60$r$ | 14.80±0.10 | 10-30.7 | P60$i$ | 14.29±0.12 |
| 09-25.9 | 14.78±0.10 | 10-31.7 | 14.30±0.12 |
| 09-26.7 | 14.73±0.11 | 11-01.7 | 14.31±0.12 |
| 10-05.9 | 14.45±0.10 | 11-02.8 | 14.22±0.12 |
| 10-29.7 | 14.32±0.10 | 11-08.8 | 14.30±0.12 |
| 10-30.7 | 14.28±0.10 | 11-09.8 | 14.34±0.12 |
| 11-09.8 | 14.40±0.10 | 11-12.0 | 14.30±0.12 |
| 11-12.0 | 14.33±0.11 | 11-01.3 | 12.96±0.14 |
| 09-24.9 | P60$i$ | 14.90±0.12 | 11-01.3 | P200$K_s$ | 12.59±0.17 |
| 09-25.9 | 14.86±0.12 | 11-23.2 | VLA Q$^d$ | 56±120μJy |
| 10-05.9 | 14.53±0.12 | 11-20.4 | VLA X$^d$ | 186±80μJy |
| 10-26.7 | 14.30±0.12 | 11-20.4 | VLA K$^d$ | 59±110μJy |
| 10-29.7 | 14.26±0.12 | 11-23.2 | VLA Q$^d$ | 56±120μJy |

$^a$ Observed magnitude or flux density of the SN. Magnitude errors include the uncertainty in absolute calibration, which dominates the errors. To convert specific-flux errors to 3-$\sigma$ upper limits multiply the errors by 3.

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$^6$ PyRAF is a product of Space Telescope Science Institute, which is operated by AURA for NASA.

$^7$ This latest observation was conducted under Director’s discretionary time (PI: Pooley).
sian centered on the galaxy position (i.e., diffuse emission); and a narrow Gaussian centered on the SN position. We find that the SN flux is consistent with zero, and that its flux is \(< 1.6 \times 10^{40} \text{erg s}^{-1}\) at the 3-\(\sigma\) confidence level, assuming a photon index of 1.8, a distance of 73 Mpc to NGC 1260 and a neutral Hydrogen column density of \(N_H = 6.3 \times 10^{21} \text{cm}^{-2}\) (in the Galaxy and NGC 1260). This field was also observed using the Swift Ultraviolet/Optical Telescope. We are awaiting late epoch observations in order to properly remove the host contamination.

We performed radio observations of NGC 1260 with the Very Large Array (VLA) on 2006 Nov 20 and 23 UT. The observations were obtained in continuum mode with a bandwidth of \(2 \times 50 \text{ MHz}\). We observed 3C 48 (J0137+331) for flux calibration, while phase referencing was performed against J0319+415. The data were reduced using the Astronomical Image Processing System. We did not detect a source at the position of the SN (see Table I).

3. SPECTRAL ANALYSIS

In the optical spectra we identify two Na I absorption lines, one of Galactic origin and the other at the redshift of NGC 1260 (\(z = 0.019\)). Based on the ratio between the equivalent widths of these two absorption lines (e.g., Munari & Zwitter 1997), we estimate the total extinction toward SN 2006gy to be \(~ 4.4\) times the Galactic extinction (\(E_{B-V} = 0.16\); Schlegel et al. 1998), which gives \(E_{B-V} = 0.7\). The high-resolution spectrum, obtained on 2006 December 19, resolves the Na I doublet. Based on this spectrum, we find that both the Galactic and NGC 1260 doublets have similar line ratios and are not saturated. We note that using the Na I extinction correlation derived by Turatto et al. (2003), we find a total \(E_{B-V}\) extinction in the range 1 to 3.5 mag. Moreover, the extinction is derived by assuming that all the Na I absorption is of light emitted by the SN, rather than of light emitted by the host galaxy. Therefore, the extinction toward SN 2006gy is uncertain and this issue will require further study.

In Fig. 2 we show the DBSP spectrum of SN 2006gy (black line) after the subtraction of a scaled S0 galaxy template (Kinney et al. 1996). The template was reddened to account for Galactic extinction in the direction of the SN, and scaled so that the synthetic \(r-i\) color of the host-subtracted SN spectrum matches the photometrically observed value at the same epoch. Next, we flux-calibrated the spectrum by requiring its \(r\)-band synthetic photometry to equal the observed magnitude of the SN at the same epoch. Finally, we corrected the spectrum for extinction, assuming \(E_{B-V} \approx 0.7\) mag and \(R_V = 3.08\) (Cardelli, Clayton, & Mathis 1989). From the final spectrum we find, at maximum light, an extinction corrected synthetic \(V\)-band magnitude (Vega system) of about 12.4 mag.

Our spectra show an H\(\alpha\) and H\(\beta\) emission lines with a P-cygni profile, characteristic of type-IIn SNe. We note that the equivalent width of the H\(\alpha\) line is decreasing with time. Interestingly, we detected several absorption features which may be Si II, S II, Fe II, Fe III and Ca II lines. Such lines are usually observed in type-Ia SNe. However, we stress that the relative line strengths and apparent low expansion velocities (i.e., \(~ 1000-2000\text{km s}^{-1}\)) are peculiar, making line identifications tentative only. To emphasize this, we show in Fig. 2 the spectrum of SN 1991T (Filippenko et al. 1992) at nine days from maximum light redshifted by \(8500\text{km s}^{-1}\), and the spectrum of SN 2006gy at 42 days since discovery, after the subtraction of third-degree polynomials fitted to each spectrum. The lines of SN 2006gy are narrower and red-shifted relative to these of SN 1991T, indicating that SN 2006gy had a lower expansion velocity compared to type-Ia SN.

4. ENVIRONMENT

NGC 1260 is an early-type galaxy within the Perseus cluster of galaxies. Its Heliocentric recession velocity is \(5760\text{km s}^{-1}\) and its velocity dispersion is \(201 \pm 12\text{km s}^{-1}\) (Wegner et al. 2003). Based on the recession velocity of the cluster the distance modulus to NGC 1260 is 34.5 mag\(^9\).

Our adaptive optics images (Fig. 3) show that SN 2006gy is located 0.99 (projected distance 380 pc), at a position angle of 290 deg, from the nucleus of NGC 1260. A dusty lane, passing about 300 pc (projected) from the SN location, is clearly seen in our galaxy-subtracted \(J\)-band image. Moreover, we confirm the detection by Smith et al. (2006) of an H II region in the SN vicinity (Fig. 2).

The Mg\(_2\) index of this galaxy was measured to be in the range 0.24-0.27 mag (Davis et al. 1987; Wegner et al. 2003). This value, along with the synthetic spectral models of Vazdekis (1999), suggests that the metallicity of NGC 1260 is not low, [Fe/H] \(\gtrsim -0.2\).

5. DISCUSSION

With estimated peak absolute magnitude of \(V \approx -22\), SN 2006gy is probably the brightest SN ever observed. The slow brightening, the peak luminosity and the H\(\alpha\) emission line and the possible SN-Ia-like features suggest that SN 2006gy may be related to the hybrid IIn/Ia SNe class (also known as type-IIa: Deng et al. 2004). The other possible members in the type-IIa group are SN 2002ic (Hamuy et al. 2003) SN 2005gj (Aldering et al. 2006); SN 1997cy (Germany et al. 2000) and SN 1999E (Rigon et al. 2003).

Any model of SN 2006gy has to explain the spectral lines, the extra-ordinary peak luminosity of \(L_p \sim 3 \times 10^{44}\text{erg s}^{-1}\) (after correction for extinction), and a radiated energy over the first two months of \(E_{radi} \sim 1.1 \times 10^{53}\text{erg}\) (assuming 11,000-K black body which roughly matches the Rayleigh-Jeans slope in DBSP spectra). We note that even if the extinction in NGC 1260 was overestimated and the SN light suffers only from Galactic extinction, the total radiated energy within the first two months is about \(3 \times 10^{56}\text{erg}\).

The high peak luminosity suggests that the blast wave from the explosion efficiently converts the mechanical energy to radiation. This mean the shock has to be radiative which requires the circum-stellar medium (CSM) density to exceed \(10^{-3} \text{cm}^{-3}\). Moreover, the conversion of mechanical energy of an explosion to radiation requires that the ejecta sweep up matter with comparable mass. The slow rise time, \(t_p \sim 50\text{d}\) to peak luminosity implies that the dense region has a size of at least \(R \sim v_{t} t_{p} \sim 2 \times 10^{15}\text{cm}\), where \(v_{t} \sim 5 \times 10^{8}\text{cm s}^{-1}\) is the speed of the blast wave. The peak luminosity, \(L_p\), requires density of the order, \(n \sim L_p/(2\pi R^2 v_{t}^3) \sim 10^{10}\text{cm}^{-3}\). Assuming an upper limit on \(v_{t}\) of \(10^9\text{cm s}^{-1}\) at early times, the minimum mass contained within this radius is \(\gtrsim 0.2\text{M}_\odot\). The

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\(^8\) The Very Large Array is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

\(^9\) Assuming Hubble parameter \(H_0 = 72\text{km s}^{-1}\text{Mpc}^{-1}\), matter content \(\Omega_m = 0.27\), and dark-energy content of \(\Omega_\Lambda = 0.73\).
gradual decrease in the radiated energy, and possibly lower expansion velocities would easily bring it closer to a solar mass. The mass loss rate by the progenitor has to be stupendous, $M \sim 1 M_\odot/(vp/v_w) \sim 10^{-1} M_\odot yr^{-1}$, over a time scale of at least about 10yr, where $v_w = 200\, km\, s^{-1}$ is the speed of the progenitor wind (Smith et al. 2006; $v_w \sim 130–260\, km\, s^{-1}$). Finally, the high CSM density accounts for the lack of substantial X-ray and radio emission (being absorbed by photoelectric and free-free absorption, respectively).

SN2006gy shares some properties with type-IIa and type IIn SNe. Type-IIa SNe are most plausibly the result of a core collapse SN embedded in dense CSM, while IIn events have been explained as thermo-nuclear explosions taking place in a dense medium (e.g., Livio & Riess 2003; Han & Podsiadlowski 2006). The thermo-nuclear model is attractive from a spectroscopic perspective. In the context of type-IIa SNe, a possible explanation to the high-mass loss rate is that it is the result of a common-envelope phase in a binary system (e.g., Taam & Ricker 2006 and references therein). This scenario was suggested by Livio & Riess (2003) to explain the properties of SN 2002ic, and is consistent with the inferred high mass loss rate and its velocity (i.e., $\sim 200\, km\, s^{-1}$). However, this scenario requires the ejection of matter from the progenitor to shortly precede the SN explosion (Chugai & Yungelson 2004). Moreover, the total kinetic energy of Ia events is limited to about $1–2 \times 10^{51}\, erg$ (Kohklov et al. 1993), and it can get up to $2.5 \times 10^{51}\, erg$ for super-Chandrasekhar models (cf. Yoon & Langer 2004). Therefore, unless we considerably over-estimated the extinction, the total radiated energy of SN 2006gy in the first two months alone is challenging for type-IIa-like SN models.

Smith et al. (2006), noting that the envelope of a massive star ($\sim 100\, M_\odot$) contains a reservoir of thermal energy that can power the SN, suggested that such a star was the progenitor of SN 2006gy. However, most of the thermal energy will be lost due to expansion and the abundance of the photons to leak out is limited by the long diffusion timescale for photons ($\sim 10^8\, km$; e.g., Kulkarni 2005). Therefore, it will be difficult for this specific model (alone) to explain the high peak luminosity of SN 2006gy.

Along the general lines of previous suggestion by Benetti et al. (2006; for SN 2002ic) and Smith et al. (2006; for SN 2006gy), we speculate that the large energy budget for SN 2006gy may hint at a highly energetic explosion ($\sim 10^{52}\, erg$), from a massive stellar progenitor. Two possibilities are an CSM-embedded collapsar (e.g., Woosley & MacFadyen 1999), or a pair production SN (e.g., Ober et al. 1983; Smith et al. 2006). Pair production SNe, however, require low-metallicity progenitors, but it may be possible to overcome this requirement by the merger of two massive stars. We further speculate that such a merger may be responsible to the high mass-loss rate (e.g., common envelope ejection). SN 2006gy and other IIa (and maybe many IIn) events may result from one of these energetic explosions that are able to produce $\sim 10^{52}\, erg$.

The general issues of the large energy release into a dense CSM have been discussed for some type IIn events (e.g., Chugai et al. 2004, Gal-Yam et al. 2006). For reasons we do not understand the explosion is preceded by a phase of stupendous mass loss. The mass and geometry of the hydrogen envelope may determines the outcome of the explosion (e.g., IIa or IIn). Finally, the rarity of such energetic SNe reflect the rarity of the progenitors.

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