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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 multiwavelength observations of this SN and its environment. Our spectroscopy shows an Hα emission line as well as absorption features that may be identified as Si II lines at low expansion velocity. The slow brightening, the peak luminosity, and the Hα emission line resemble those observed in hybrid Type IIn/Ia SNe (also known as Type IIa) and may suggest that SN 2006gy is related to the Type IIa SNe class. 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 extraordinarily large peak luminosity, $\sim 3 \times 10^{44}$ ergs s^{-1}, demands a dense circumstellar medium, regardless of the mass of the progenitor star. The inferred mass-loss rate of the progenitor is $\sim 0.1\ M_{\odot}$ yr^{-1} over a period of ∼10 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 2 months is about 1.1×10^{51} ergs, which is only a factor of 2 less than that available from a super-Chandrasekhar Type 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.

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

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 a full width at half-maximum (FWHM) of 2500 km s^{-1}, and a component with a 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 8 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 2 mag 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 that it is more consistent with an eruption of the active galactic nucleus 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 6 days after discovery, led them to suggest that SN 2006gy was a Type IIn event.

Here we report on multiwavelength observations of SN 2006gy. An independent contemporary analysis is presented in Smith et al. (2006).

2. OBSERVATIONS

We initiated a photometric (g, r, i, z) monitoring program with the Palomar 60 inch (1.52 m) robotic telescope (Cenko et al. 2006). Not possessing preexplosion 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 Figure 1 and Table 1, were produced by image subtraction using the common point-spread function (PSF) method (Gal-Yam et al. 2004).

On UT 2006 September 26 and December 18 and 19, we obtained spectra using the Low Resolution Imaging Spectrograph (LRIS) mounted on the Keck I 10 m telescope (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 Figure 2.

On UT 2006 November 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 ∼15%. We obtained 660 and 300 s images in the K_s and J bands, respectively, using the high-resolution mode (25 mas pixel^{-1}) and a 240 s K_s-band image using the low-resolution camera (40 mas pixel^{-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 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

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[5] ING archive: http://casu.ast.cam.ac.uk/casuadc/archives/ingarch.
[6] PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA, Inc., for NASA.
[7] This latest observation was conducted under the Director's Discretionary Time (PI: D. Pooley).

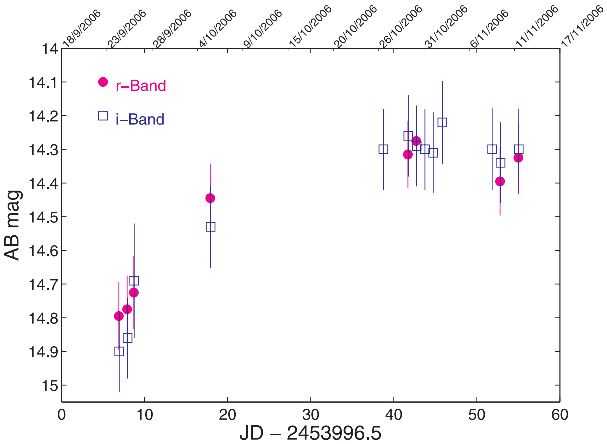

FIG. 1.—The *r*-band (*filled circles*) and *i*-band (*open squares*) light curves of SN 2006gy. Errors include the uncertainty in the absolute calibration. The bottom horizontal axis shows the time relative to the discovery of SN 2006gy (2006 September 18).

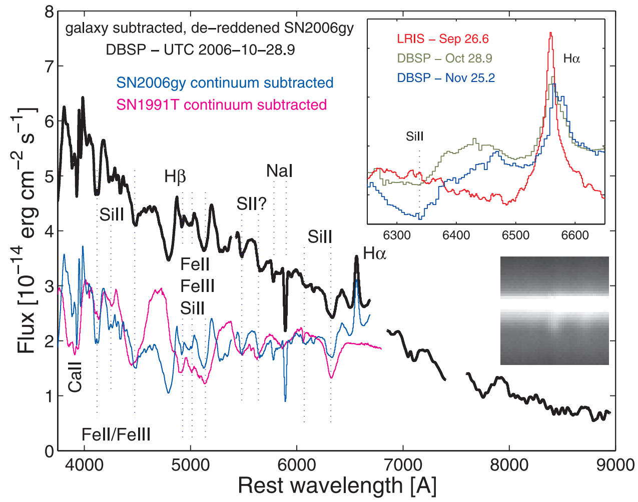

FIG. 2.—Spectrum of SN 2006gy after subtracting the scaled S0 template and correcting for Milky Way and NGC 1260 extinction (*black line*; see text). The blue line shows the same spectrum after subtraction of a third-degree polynomial fitted to the spectrum. The magenta line shows the spectrum of the luminous Type Ia SN 1991T at 9 days post–peak brightness, after the same processing. The spectrum of SN 1991T was redshifted by ∼8500 km s^{-1} in order that the possible Si II features in both spectra coincide. A zoom-in on the Hα emission line as observed by LRIS and DBSP is shown in the upper inset. The lower inset shows a section of the two-dimensional Keck spectrum of SN 2006gy obtained under good seeing conditions on 2006 December 18. The extension in the spatial (vertical) direction is an Hα emission near the SN location (as previously reported by Smith et al. 2006). For the LRIS spectra, with integration time ranging from 600 to 2400 s, we employed the 1.5″ slit, with the 400/8500 grating blazed at 7550 Å, and the 600/4000 grism on the red and blue sides, respectively. The December 19 spectrum was obtained using the high-resolution R1200/7500 grating centered on the Na I lines. The DBSP observations were obtained with a 1.5″ slit and R158/7500 and B600/4000 gratings on the red and blue arms, respectively. The spectrum marked October 28.9 is the sum of four spectra (1500 s) obtained during the October run. The integration time for the November DBSP spectrum was 900 s.

TABLE 1
LOG OF OBSERVATIONS AND MEASUREMENTS

Telescope/ Band	Date (UT 2006)	Magnitude or Flux[a]
P60[b]/*r*	Sep 24.9	14.80 ± 0.10
	Sep 25.9	14.78 ± 0.10
	Sep 26.7	14.73 ± 0.11
	Oct 05.9	14.45 ± 0.10
	Oct 29.7	14.32 ± 0.10
	Oct 30.7	14.28 ± 0.10
	Nov 09.8	14.40 ± 0.10
	Nov 12.0	14.33 ± 0.11
P60[b]/*i*	Sep 24.9	14.90 ± 0.12
	Sep 25.9	14.86 ± 0.12
	Sep 26.7	14.69 ± 0.17
	Oct 05.9	14.53 ± 0.12
	Oct 26.7	14.30 ± 0.12
	Oct 29.7	14.26 ± 0.12
	Oct 30.7	14.29 ± 0.12
	Oct 31.7	14.30 ± 0.12
	Nov 01.7	14.31 ± 0.12
	Nov 02.8	14.22 ± 0.12
	Nov 08.8	14.30 ± 0.12
	Nov 09.8	14.34 ± 0.12
	Nov 12.0	14.30 ± 0.12
P200[c]/*J*	Nov 01.3	12.96 ± 0.14
P200[c]/K_s	Nov 01.3	12.59 ± 0.17
VLA/X[d]	Nov 20.4	186 ± 80 μJy
VLA/K[d]	Nov 20.4	59 ± 110 μJy
VLA/Q[d]	Nov 23.2	56 ± 120 μJy

[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 σ upper limits, multiply the errors by 3.

[b] Palomar 60 inch (P60) magnitudes are given in the AB magnitude system. Absolute calibration was performed by fitting the *Hipparcos* $B_T V_T$ and 2MASS (Skrutskie et al. 2006) *JHK* magnitudes of three nearby Tycho-2 (Høg et al. 2000) reference stars to synthetic photometry of stellar spectral templates (Pickles 1998) in the same bands. The best-fit spectral template of each star was used to calculate its synthetic magnitudes in the *r* and *i* bands. The uncertainty in this calibration process, calculated from the scatter between the zero points derived from each Tycho-2 star, is about 0.1 mag.

[c] Palomar 200 inch (P200) IR Vega-based PSF-fitting magnitudes, relative to the 2MASS star 03172629+4124103 within the field.

[d] The center frequencies of the VLA bands are as follows: 8.4 GHz (X), 22.5 GHz (K), and 43.3 GHz (Q).

hydrogen column density $N_H = 1.3 \times 10^{21}$ cm^{-2} (Dickey & Lockman 1990) and a power-law spectrum with index 1.8, we set a 3 σ upper limit for the flux in the 0.2–10 keV band of $<1.8 \times 10^{-13}$ ergs s^{-1} 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 Gaussian 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 $<1.6 \times 10^{40}$ ergs s^{-1} at the 3 σ confidence level, assuming a photon index of 1.8, a distance of 73 Mpc to NGC 1260, and a neutral hydrogen column density of $N_H = 6.3 \times 10^{21}$ cm^{-2} (in the Galaxy and NGC 1260). This field was also observed using the *Swift* UV/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)[8] on 2006 November 20 and 23 UT. The observations were obtained in continuum mode with a bandwidth of 2 × 50 MHz. We observed 3C 48 (J0137+331)

[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.

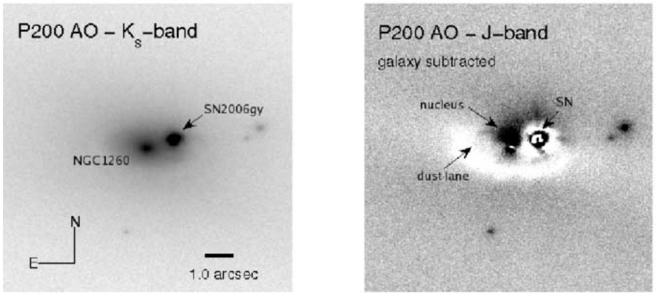

FIG. 3.—*Left*: K_s-band image. The SN (marked) is clearly resolved from the galaxy nucleus. *Right*: *J*-band image after subtracting the best-fit Sérsic profile from the galaxy and a Gaussian profile from the SN using GalFit (Peng et al. 2002). The Sérsic model parameters are as follows: an index of 3.7, an effective radius of 34″, an axial ratio of 0.51, and a position angle of 80°. A dust lane (*white band*) is seen southward of the galaxy nucleus. Based on three 2MASS sources, we derived the galaxy nucleus position, $\alpha = 03^h17^m27.241^s$, $\delta = +41°24'18.55''$, and the SN position (end numbers), 27.158^s (α) and 18.88″ (δ). The astrometric solution has an rms of 0.04″ and 0.01″ in α and δ, respectively.

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 1).

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 $E_{B-V} \approx 0.7$. 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 of 1–3.5 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 Figure 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 was 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 et al. 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 Hα and Hβ emission lines with P Cygni profiles, characteristic of Type IIn SNe. We note that the equivalent width of the Hα line is decreasing with time. Interestingly, we detected several absorption features that may be Si II, S II, Fe II, Fe III, and Ca II lines. Such lines are usually observed in Type Ia SNe. However, with the exception of the S II line, which identification is questionable, these lines are also seen in core-collapse SNe. We stress that the relative lines strengths and apparent low expansion velocities (i.e., ∼1000–2000 km s^{-1}) are peculiar, making line identifications *tentative only*. To emphasize this, we show in Figure 2 the spectrum of SN 1991T (Filippenko et al. 1992) at 9 days from maximum light, redshifted by 8500 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 redshifted relative to those of SN 1991T, indicating that SN 2006gy had a lower expansion velocity than Type Ia SNe.

4. ENVIRONMENT

NGC 1260 is an early-type galaxy within the Perseus Cluster of galaxies. Its heliocentric recession velocity is 5760 km s^{-1}, and its velocity dispersion is 201 ± 12 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 (AO) images (Fig. 3) show that SN 2006gy is located 0.99″ (projected distance 380 pc), at a position angle of 290°, from the nucleus of NGC 1260. A dust 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 of 0.24–0.27 mag (Davies 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 an 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 Hα emission line resemble those observed in hybrid Type IIn/Ia SNe (also known as Type IIa; Deng et al. 2004) and may suggest that SN 2006gy is related to Type IIa SNe. 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 extraordinary peak luminosity of $L_p \sim 3 \times 10^{44}$ ergs s^{-1} (after correction for extinction), and the radiated energy of $E_{rad} \sim 1.1 \times 10^{51}$ ergs over the first 2 months (assuming an 11,000 K blackbody that roughly matches the Rayleigh-Jeans slope in DBSP spectra). We note that even if the extinction in NGC 1260 was overestimated and if the SN light suffers only from Galactic extinction, the total radiated energy within the first 2 months is about 3×10^{50} ergs.

The high peak luminosity suggests that the blast wave from the explosion efficiently converts the mechanical energy to radiation. This means that the shock has to be radiative, which requires the circumstellar medium (CSM) density to exceed 10^6 cm^{-3}. Moreover, the conversion of the mechanical energy of an explosion to radiation requires that the ejecta sweep up matter with comparable mass. The slow rise time, $t_p \sim 50$ days to peak luminosity, implies that the dense region has a size of at least $R \sim v_s t_p \sim 2 \times 10^{15}$ cm, where $v_s \sim 5 \times 10^8$ cm s^{-1} is the speed of the blast wave. The peak luminosity, L_p, requires density of the order $n \sim L_p/(2\pi R^2 v_s^3) \sim 10^{10}$ cm^{-3}. Assuming

[9] Assuming the Hubble parameter $H_0 = 72$ km s^{-1} Mpc^{-1}, a matter content of $\Omega_m = 0.27$, and a dark-energy content of $\Omega_\Lambda = 0.73$.

an upper limit on v_s of 10^9 cm s^{-1} at early times, the minimum mass contained within this radius is $\gtrsim 0.2\ M_\odot$. The 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, $\dot{M} \sim 1\ M_\odot/(t_p v_s/v_w) \sim 10^{-1}\ M_\odot$ yr^{-1}, over a timescale of at least about 10 years, 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).

SN 2006gy shares some properties with Type IIa and Type IIn SNe. Type IIn SNe are most plausibly the result of a core-collapse SN embedded in a dense CSM, while Type IIa events have been explained as thermonuclear explosions taking place in a dense medium (e.g., Livio & Riess 2003; Han & Podsiadlowski 2006). In the context of Type Ia SNe, a possible explanation for 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 it is consistent with the inferred high mass-loss rate and its velocity (i.e., ~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 Type Ia events is limited to about (1–2) $\times 10^{51}$ ergs (Khokhlov et al. 1993), and it can get up to 2.5×10^{51} ergs for super-Chandrasekhar models (e.g., Yoon & Langer 2004). Therefore, unless we considerably overestimated the extinction, the total radiated energy of SN 2006gy in the first 2 months alone is challenging for Type Ia–like SN models.

Smith et al. (2006), noting that the envelope of a massive star (>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 ability of the photons to leak out is limited by the long diffusion timescale for photons (several months or more; 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 the previous suggestions 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 (~10^{52} ergs), 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 (e.g., Ober et al. 1983; Heger et al. 2003), 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 for the high mass-loss rate (e.g., common envelope ejection). SN 2006gy and other Type IIa (and maybe many Type IIn) events may result from one of these energetic explosions that are able to produce ~10^{52} ergs.

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. 2007). 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 determine the outcome of the explosion (e.g., Type IIa or Type IIn). Finally, the rarity of such energetic SNe reflects the rarity of the progenitors.

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