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SN 2006gy: DISCOVERY OF THE MOST LUMINOUS SUPERNOVA EVER RECORDED, POWERED BY THE DEATH OF AN EXTREMELY MASSIVE STAR LIKE η CARINAE

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ABSTRACT

We report the discovery and early observations of the peculiar Type IIn supernova (SN) 2006gy in NGC 1260. With a peak visual magnitude of about −22, it is the most luminous supernova ever recorded. Its very slow rise to maximum took ∼70 days, and it stayed brighter than −21 mag for about 100 days. It is not yet clear what powers the enormous luminosity and the total radiated energy of $\sim10^{51}$ erg, but we argue that any known mechanism—thermal emission, circumstellar interaction, or ^{56}Ni decay—requires a very massive progenitor star. The circumstellar interaction hypothesis would require truly exceptional conditions around the star, which, in the decades before its death, must have experienced a luminous blue variable (LBV) eruption like the 19th century eruption of η Carinae. However, this scenario fails to explain the weak and *unabsorbed* soft X-rays detected by *Chandra*. Radioactive decay of ^{56}Ni may be a less objectionable hypothesis, but it would imply a large Ni mass of $\sim22\ M_\odot$, requiring SN 2006gy to have been a pair-instability supernova where the star's core was obliterated. While this is still uncertain, SN 2006gy is the first supernova for which we have good reason to suspect a pair-instability explosion. Based on a number of lines of evidence, we eliminate the hypothesis that SN 2006gy was a "Type IIa" event, that is, a white dwarf exploding inside a hydrogen envelope. Instead, we propose that the progenitor was a very massive evolved object like η Carinae that, contrary to expectations, failed to shed its hydrogen envelope. SN 2006gy implies that some of the most massive stars can explode prematurely during the LBV phase, never becoming Wolf-Rayet stars. SN 2006gy also suggests that they can create brilliant supernovae instead of experiencing ignominious deaths through direct collapse to a black hole. If such a fate is common among the most massive stars, then observable supernovae from Population III stars in the early universe will be more numerous than previously believed.

Subject headings: circumstellar matter — stars: evolution — supernovae: individual (SN 2006gy)

1. INTRODUCTION

Supernovae (SNe) resulting from the deaths of massive stars span a wide range of peak absolute visual magnitude, typically between −15 and −20.5, and usually reach their peak within about 20 days. They also exhibit a range of spectral properties, depending on the extent to which products of nuclear burning are exposed at their surface, as well as on the expansion speed and the amount of circumstellar material. Their diversity depends on the star's initial mass and rate of mass loss during its lifetime. Current expectations are that stars born with initial masses above $\sim40\ M_\odot$, which never become red supergiants (RSGs; Humphreys & Davidson 1979; Fitzpatrick & Garmany 1990), will shed their hydrogen envelopes to expose their He core before they die (e.g., Abbot & Conti 1987; Conti 1976). As Wolf-Rayet (WR) stars, they are then expected to explode, producing Type Ib/c SNe (see Filippenko 1997). Based on observations of SN 2006gy that we discuss here, we speculate that this scenario does not always apply.

One way to prevent a star from reaching the WR phase before explosion would be if the star's mass-loss rate is insufficient to shed the hydrogen envelope before the end of core He-burning. This is thought to be the case for massive stars in the early universe, because their much lower (or zero) metallicity should make their line-driven stellar winds very inefficient (Baraffe et al. 2001; Kudritzki 2002; Heger et al. 2003). Depending on the mass at the time of death, very massive stars in this predicament might suffer a pair-production instability explosion (Barkat et al. 1967; Fraley 1968; Bond et al. 1984; Heger & Woosley 2002), where the star's core is obliterated instead of collapsing to a black hole.

However, there are reasons to suspect that the mass-loss properties of stars in the local universe may not be so different from these early stars. Namely, recent studies of line-driven winds from O-type stars and WR stars have shown that their winds are highly clumped, requiring that their mass-loss rates through line-driven winds on the main sequence could be an order of magnitude lower than previously believed (Fullerton et al. 2006; Bouret et al. 2005). In that case, for stars with initial masses above $\sim40\ M_\odot$ that never become RSGs, the burden of mass loss falls to the post–main-sequence luminous blue variable (LBV) phase, when very massive stars suffer multiple giant eruptions that shed several $M_\odot$ in just a few years (Smith & Owocki 2006). If these LBV eruptions are not sufficient to remove the star's entire outer hydrogen envelope fast enough, as may be the case for the most massive stars above 100 $M_\odot$, then the star would seem to explode early, as an LBV producing a Type IIn event. Interestingly, Gal-Yam et al. (2007) find that the rate of Type IIn events is in broad agreement with the hypothesis that they are the explosions of extreme LBVs. The fact that giant LBV eruptions are continuum-driven may hint that low-metallicity stars may be capable of shedding mass after all (Smith & Owocki 2006), which would affect the range of initial masses that are subject to the pair instability in Population III stars. Because stars that begin their lives above 100 $M_\odot$ are so few in number, their end fates are poorly constrained by observations (see Gal-Yam et al. 2007 for a relevant discussion) and are still an open question. For these reasons, any potential detection of a

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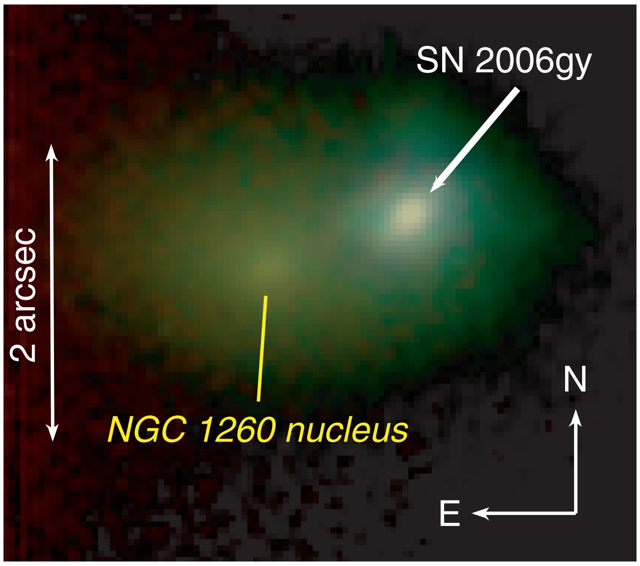

FIG. 1.—Laser guide star adaptive optics image of SN 2006gy and the nucleus of NGC 1260, showing a clear offset of the SN from the galaxy center. Blue is J band (1.25 μm), green is H band (1.65 μm), and red is K_s band (2.2 μm).

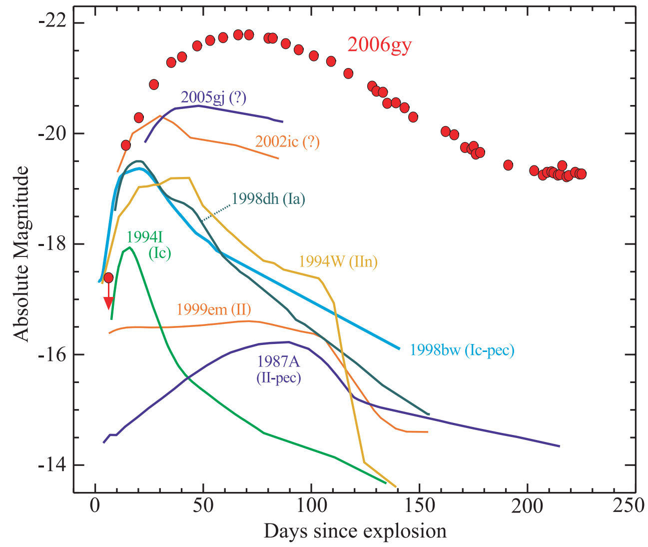

FIG. 2.—Comparison of the absolute R-band light curve of SN 2006gy with those of other SNe. We plot days since explosion, which we judge to be ~29 days prior to the discovery of SN 2006gy. SN 1998dh is a typical SN Ia, and the data are from our unpublished photometric database, with a typical absolute magnitude of $M_R = -19.5$ mag assumed. SN 1999em is a typical Type II (Leonard et al. 2002), SN 1994I is a well-observed SN Ic (Richmond et al. 1996), and SN 1998bw is a peculiar SN Ic (Galama et al. 1998). SN 1987A is a peculiar SN II, with a broad light curve but a low luminosity (from Hamuy et al. 1990). SN 1994W is a SN IIn that is powered by strong interaction with its circumstellar material (Sollerman et al. 1998). We also plot two unusual SNe that are relevant to the discussion of SN 2006gy: SN 2002ic (Hamuy et al. 2003) and SN 2005gj (Aldering et al. 2006).

pair-instability supernova in the modern universe would be of great interest to stellar astrophysics. Here we explore this notion, along with others, as a possible explanation for the bizarre properties of SN 2006gy.

SN 2006gy in the peculiar S0/Sa galaxy NGC 1260 was discovered and confirmed by the Texas Supernova Search (TSS; Quimby 2006a) with the ROTSE-IIIb telescope (Akerlof et al. 2003) at McDonald Observatory in unfiltered images (Quimby 2006b) taken on 2006 September 18.3 (UT dates are used throughout this paper). It was initially classified (Harutyunyan et al. 2006) as a SN II (actually SN IIn, based on the written description), but Prieto et al. (2006) nearly simultaneously suggested that the object was instead a bright active galactic nucleus (AGN). However, in the subsequent month, our group continued to follow SN 2006gy, and with additional astrometric, photometric, and spectroscopic data we announced that it did indeed appear to be a SN after all, and not an AGN (Foley et al. 2006). In this paper we present additional data and analysis of SN 2006gy, leading us to propose that it marked the death of a very massive star with much of its hydrogen envelope still intact, while surrounded by a massive circumstellar nebula. In many respects, the type of progenitor we infer for SN 2006gy resembles the LBV star η Carinae in our own Galaxy, as discussed below.

2. OBSERVATIONS

2.1. *Imaging and Photometry*

Figure 1 shows a laser guide star (LGS) adaptive optics (AO) near-infrared image of SN 2006gy and the nucleus of its host galaxy NGC 1260, revealing a clear offset of the SN from the galaxy center. Images at three wave bands (J, H, and K_s) were obtained on 2006 November 4 using the AO system in LGS mode (Lloyd et al. 2000; Max et al. 1997) on the Shane 3 m telescope at Lick Observatory. The total integration time in each band was 480 s, accumulated over eight exposures. The native scale of the 256 × 256 pixel Rockwell PICNIC array is 0.076″ pixel^{-1} (Perrin 2007). Mosaicked images have a scale of 0.04″ pixel^{-1}. The SN itself was bright enough to use as a "tip-tilt" star for the LGS system. The effective resolution (full width at half-maximum intensity; FWHM) is 0.2″ in the H band. The measured offset of the SN from the centroid of the galactic nucleus is 0.941″ west, 0.363″ north, with a 1 σ uncertainty of 0.01″ in each direction; this confirms and improves the earlier offset measurement (Foley et al. 2006) of 0.880″ west, 0.140″ north, ±0.08″. SN 2006gy is therefore located about 350 pc from the galaxy's center (at its assumed distance of ~73 Mpc), confirming that it is not an AGN.[4]

Figure 2 shows the R-band light curve of SN 2006gy obtained by our group using the Katzman Automatic Imaging Telescope (KAIT; Filippenko 2003) at Lick Observatory, compared to a sample of several other representative SN light curves. The unfiltered KAIT images for SN 2006gy were used to derive an R-band light curve. As demonstrated by Riess et al. (1999) and Li et al. (2002), the best match to broadband filters for the KAIT unfiltered data is the R band. Each image is aligned to a deep pre-SN image, and the contamination of the host-galaxy emission is carefully removed. The net flux for the SN is then compared to 19 bright stars using calibrations from the USNO-B1 catalog. We list the KAIT apparent R magnitudes of SN 2006gy in Table 1. To put the flux of SN 2006gy on an absolute magnitude scale, we adopt a distance to the host galaxy NGC 1260 of 73.1 Mpc, using $H_0 = 72$ km s^{-1} Mpc^{-1} and using a recession velocity for the central cluster galaxy of 5361 km s^{-1}. We also assume a Galactic reddening of $A_R = 0.43$ mag (Schlegel et al. 1998) and a host-galaxy reddening of $A_R = 1.25 \pm 0.25$ mag (see § 2.2 and Fig. 3). In Figure 2 we plot days since explosion instead of days since discovery. Our first measurement with KAIT was a nondetection made on 2006 August 26, which was 23 days before the discovery

[4] Ironically, NGC 1260 may contain a faint AGN after all, although SN 2006gy is a real SN explosion. Later in this paper we also present an X-ray image of SN 2006gy which shows two sources, one being the SN and the other the nucleus of NGC 1260.

TABLE 1
KAIT Photometry of SN 2006gy

MJD	m_R	Error
3973.96	(18.62)	0.03
3982.00	16.22	0.03
3987.98	15.72	0.03
3995.04	15.12	0.03
4003.03	14.72	0.03
4007.95	14.62	0.03
4014.97	14.42	0.03
4020.99	14.32	0.03
4026.92	14.27	0.03
4033.92	14.22	0.03
4038.85	14.22	0.03
4047.81	14.28	0.03
4049.92	14.28	0.03
4055.87	14.38	0.03
4061.88	14.49	0.03
4068.89	14.60	0.03
4076.83	14.90	0.03
4087.75	15.15	0.03
4089.77	15.24	0.03
4092.75	15.26	0.03
4094.76	15.46	0.03
4098.76	15.45	0.03
4102.74	15.54	0.03
4106.71	15.71	0.03
4121.71	15.97	0.03
4125.72	16.03	0.03
4130.60	16.26	0.03
4133.64	16.29	0.03
4134.63	16.24	0.03
4135.61	16.38	0.05
4137.69	16.35	0.04
4150.62	16.58	0.03
4162.65	16.68	0.05
4166.63	16.76	0.05
4168.64	16.71	0.05
4170.63	16.70	0.05
4171.63	16.72	0.05
4173.63	16.76	0.06
4174.64	16.75	0.07
4175.64	16.59	0.05
4177.64	16.79	0.05
4178.64	16.77	0.05
4181.64	16.71	0.05
4183.64	16.74	0.05
4184.64	16.74	0.08

of SN 2006gy (see note added in proof). Judging from the slowly rising curve, we estimate that the explosion date was roughly 6 days before the KAIT nondetection.

2.2. *Lick and Keck Spectroscopy*

Figure 3 shows two visual-wavelength spectra of SN 2006gy obtained on 2006 September 25.5 and 2006 October 30.4 using the Kast double spectrograph (Miller & Stone 1993) mounted on the Lick Observatory 3 m Shane telescope. The long slit of width 2″ was aligned along the parallactic angle (Filippenko 1982). The data were reduced using standard techniques as described by Foley et al. (2003, and references therein). The spectra were corrected for atmospheric extinction (Bessell 1999; Matheson et al. 2000) and then flux calibrated using standard stars observed at an air mass similar to that of the SN.

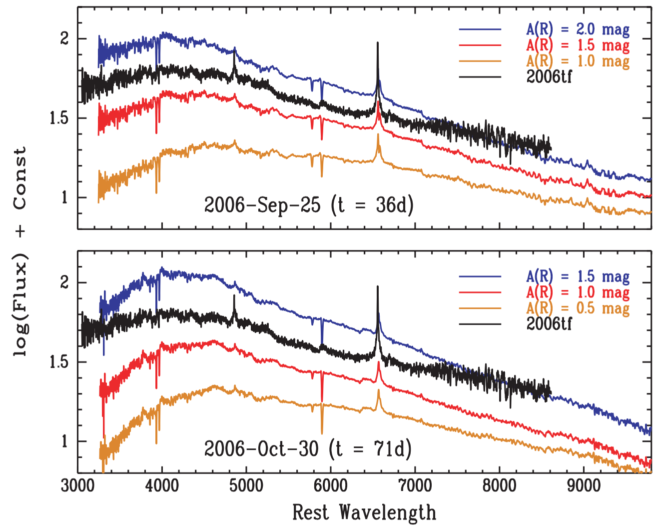

Fig. 3.—Lick Observatory spectra of SN 2006gy at two different epochs, corrected for a range of assumed host-galaxy reddening corresponding to the values of A_R listed at right (Cardelli et al. 1989). This extinction is in addition to Galactic extinction of $A_R = 0.43$ mag. These are compared to the day 32 spectrum of the Type IIn SN 2006tf (*black lines*) from our database, which is a SN with a spectrum similar to that of SN 2006gy, but seems to show little reddening. We adopt $A_R = 1.25 \pm 0.25$ mag for SN 2006gy; see text.

The closest match to SN 2006gy in our spectral database is SN 2006tf, taken on 2007 January 13, as shown in Figure 3.[5] The red continuum shape of SN 2006gy is unusual for SNe IIn, which are typically much bluer (Schlegel 1990), so we have plotted the SN 2006gy spectrum after removal of various amounts of reddening for comparison. Although a direct comparison to SN 2006tf is complicated by the temporal evolution, the early (day 36) spectrum of SN 2006gy seems most consistent with $A_R = 1.5$ mag, while the later (day 71) spectrum is more consistent with $A_R =$ 1.0 mag (the spectra of SN 2006gy were already corrected for Galactic extinction of $A_R = 0.43$ mag, as noted earlier). Comparison with other SNe IIn at similar phases (not shown) also suggests values of the host-galaxy value of $A_R = 1.0$–1.5 mag. We therefore adopt $A_R = 1.25 \pm 0.25$ mag for SN 2006gy. The extinction could be higher if SN 2006tf has its own significant reddening, although it appears to have very weak Na I D absorption. The strong Na I D absorption in the spectrum of SN 2006gy may suggest higher reddening than we have assumed here, so our estimates of luminosity for SN 2006gy are conservative.

Figure 4 shows the day 36 Lick spectrum from Figure 3, and also a spectrum with a smaller wavelength range and higher spectral resolution of $R \approx 4500$ taken near maximum light on day 96. The latter spectrum was obtained on 2006 November 24.51 using the DEIMOS spectrograph (Faber et al. 2003) on the Keck II telescope. Using a customized version of the DEEP data reduction pipeline, we obtained sky-subtracted, rectified two-dimensional images, and wavelengths were calibrated with respect to an internal calibration lamp (Foley et al. 2007). We checked carefully to make sure that the sky-subtraction procedure did not artificially introduce narrow absorption components; this is implausible based on the final results anyway, since H and He I lines show

[5] SN 2006tf was discovered in the course of the Texas Supernova Search on 2006 December 12 UT (Quimby et al. 2007). With a discovery magnitude of 16.7 and a redshift $z = 0.074$, the SN has an absolute magnitude of -20.7, which is extremely luminous but still less so than SN 2006gy. Our follow-up photometry also suggests that SN 2006tf exhibits a light-curve shape similar to that of SN 2006gy.

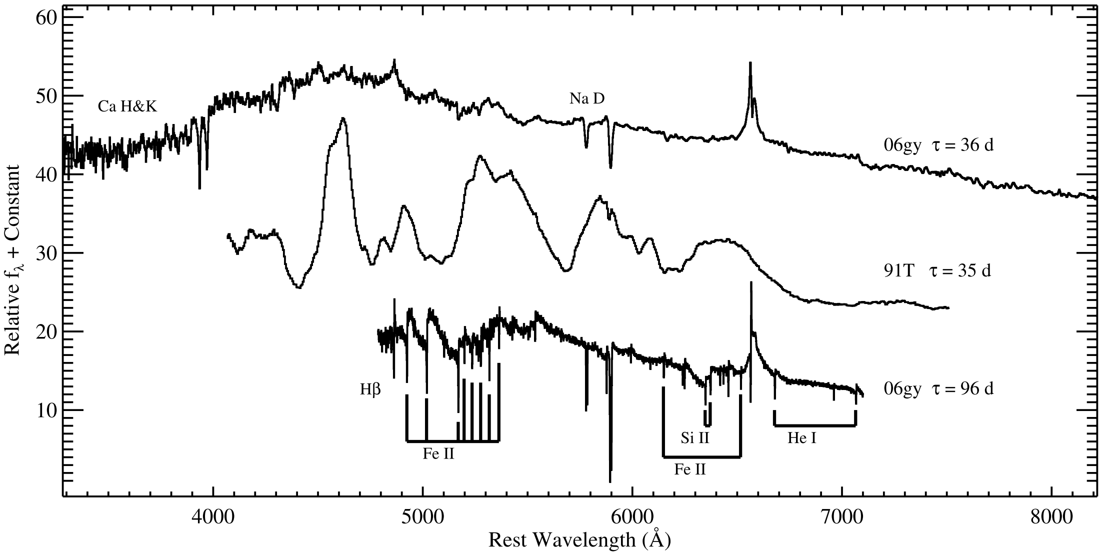

Fig. 4.—Dereddened visual-wavelength spectra of SN 2006gy at $t = 36$ and 96 days after explosion, obtained at Lick Observatory and with the Keck II telescope, respectively. Several narrow absorption lines in our high-resolution Keck spectrum have been marked, but there are some remaining unidentified lines. Also plotted is a spectrum of the Type Ia SN 1991T at $t = 35$ days (Filippenko et al. 1992) for comparison with our day 36 spectrum of SN 2006gy; there is essentially no similarity between the two spectra.

similar blueshifted absorption profiles. We corrected for telluric absorption (Matheson et al. 2000) by comparison with the standard star BD +28 4211.

Figure 5 shows the Hα profile of SN 2006gy near maximum light from a portion of the same Keck spectrum in Figure 4, with the flux normalized to the underlying continuum level, and the velocity scale chosen with the narrow Hα emission feature at $v = 0$ km s^{-1}. The Hα profile in Figure 5 reveals several different characteristic velocities relevant to interpretations of SN 2006gy. First, the very narrow emission component (FWHM $\approx$ 100 km s^{-1}) has an associated P Cygni absorption feature that indicates outflow speeds of 130 km s^{-1} (the trough) to 260 km s^{-1} (the blue edge) in the unshocked circumstellar gas. In addition to Hα, several lines identified in Figures 4 and 5 also have narrow absorption features.

A broad Hα emission component has an apparent FWHM $\approx$ 2400 km s^{-1} that is similar to Hβ at early times (Harutyunyan et al. 2006). The true unabsorbed FWHM of this broad Hα component is larger because of the broad blueshifted absorption. Extended faint wings out to $\pm$6000 km s^{-1} may be caused either by electron scattering or by the fastest SN ejecta.

The blue edge of the broad, blueshifted Hα absorption in Figure 5 indicates an outflow speed of 4000 km s^{-1}, where the emission jumps back up just to the level that would be expected for a symmetric profile. This jump is readily apparent when we take the redshifted side of the broad emission profile and reflect it to the blue side, to simulate what a symmetric profile would look like (Fig. 5). Because this absorption traces the speed of the dominant absorbing material along the line of sight at this epoch, we take this speed of 4000 km s^{-1} to represent dense material swept up by the SN blast wave in the circumstellar material (CSM) interaction hypothesis, which should closely trace the speed of the blast wave itself.

The broad-line profile differs from the smooth broad parts of Hα profiles normally seen in SNe IIn (e.g., Chugai et al. 2004). The blueshifted absorption trough flattens out and does not descend below the underlying continuum level. This may hint that the continuum luminosity and Hα emission/absorption have different

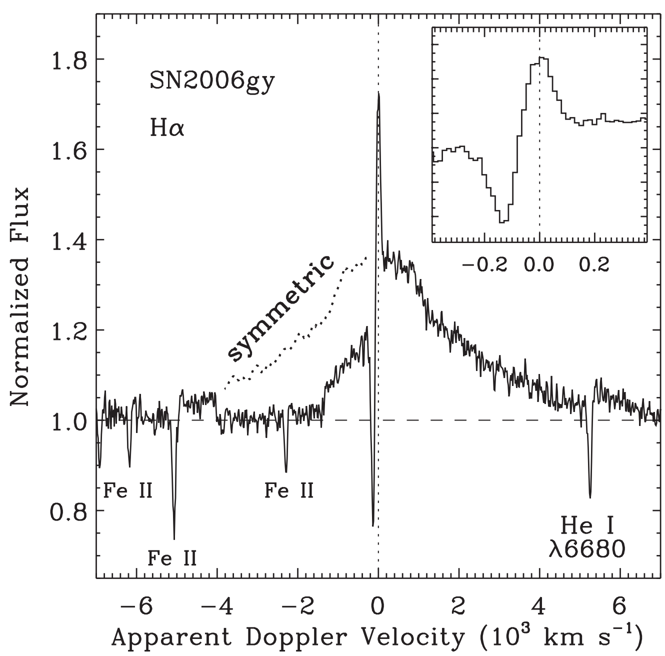

Fig. 5.—Keck DEIMOS spectrum of the Hα line seen in SN 2006gy, with the flux normalized to the underlying continuum. The upper right inset shows a closer view of the narrow P Cygni line profile that we believe to be associated with dense unshocked CSM. The blueshifted narrow absorption trough has a minimum at about -130 km s^{-1}, reaching -260 km s^{-1} at its blue edge. The other narrow absorption lines labeled as "Fe ii" are Fe ii $\lambda\lambda$6418, 6433, 6456, and 6517. The dashed line labeled "symmetric" is the red side of the broad Hα line reflected to blueshifted velocities, showing what the line shape would be if it were symmetric. Comparing this to the observed Hα profile, we see significant blueshifted Hα absorption from 0 km s^{-1} out to a sharp blue edge at about -4000 km s^{-1}, which we take to be the dominant speed of the SN blast wave. At that point, the blueshifted emission recovers to the level expected for a symmetric profile, and then gradually declines to the continuum level at about -6000 km s^{-1}, just as on the red side of the line (which overlaps with He i λ6680).

origins and provides important clues to the shell optical depth and CSM density. For example, the blueshifted absorption may arise in shocked CSM gas, whereas the continuum luminosity may originate in the SN ejecta. Asymmetric geometry in the CSM obviously may be relevant. These details have some bearing on the hypotheses for the power sources discussed in §§ 3.3 and 3.4. In any case, this broad, blueshifted Hα absorption probably shares an origin with the broad, blueshifted absorption features for other lines identified in Figure 4. In light of possible geometric complexities, we defer a detailed discussion of the line profiles to a later paper.

2.3. *X-Ray Observations, Data Reduction, and Analysis*

The *Chandra X-ray Observatory* began observing the location of SN 2006gy on 2006 November 14.86 using Director's Discretionary Time. The observation lasted 29.743 ks, and the data were taken with the Advanced CCD Imaging Spectrometer using an integration time of 3.2 s per frame. The telescope aim point was on the back side illuminated S3 chip, and the data were telemetered to the ground in "very faint" mode.

Data reduction was performed using the CIAO 3.4 software provided by the *Chandra* X-ray Center.[6] The data were reprocessed using the CALDB 3.3.0 set of calibration files (gain maps, quantum efficiency, quantum efficiency uniformity, and effective area), including a new bad-pixel list made with the `acis_run_hotpix` tool. The reprocessing was done without pixel randomization that is added during standard processing. This omission slightly improves the point-spread function (PSF). The data were filtered using the standard *ASCA* grades (0, 2, 3, 4, and 6) excluding both bad pixels and software-flagged cosmic-ray events. A search was done for strong background flaring, but none was found.

Absolute *Chandra* astrometry is typically good to 0.5″, and we sought to tie the *Chandra* frame to the KAIT image to obtain a reliable identification of the nucleus of NGC 1260 and the SN in the *Chandra* data. Several *Chandra* point sources were found using the CIAO `wavdetect` tool, and their positions were refined using ACIS Extract version 3.107 (Broos et al. 2002). Three of these sources had KAIT counterparts, although one had a somewhat poorly determined *Chandra* position due to its location ~3′ off-axis (the *Chandra* PSF degrades as a function of off-axis angle). Using all three sources, we obtained an astrometric correction to the *Chandra* data of 0.329″ in right ascension (α) and 0.089″ in declination (δ). Using the two best counterparts, we obtained shifts of $\Delta\delta = 0.104''$. We use this latter shift for the rest of our analysis.

Figure 6 shows a 0.5–2 keV image of the *Chandra* data after this shift; arrows indicate the KAIT positions of the SN (*red arrow*) and galaxy nucleus (*blue arrow*). In addition to the raw image, Figure 6 shows a Gaussian-smoothed image and a maximum likelihood reconstruction of the data, as well as an image of the *Chandra* PSF on the same spatial scale. The maximum likelihood reconstruction was made by ACIS Extract using the `max_likelihood` procedure available in the IDL Astronomy User's Library;[7] we went through 200 iterations of the algorithm, using the PSF shown in the figure. The PSF was constructed by ACIS Extract through use of the CIAO tool `mkpsf` based on the off-axis location of the source and at an energy of 1.49 keV (the *Chandra* PSF is also a function of energy). As can be seen, there is excellent agreement between the locations of the reconstructed sources and the locations of the SN and host-galaxy nucleus. This argues strongly

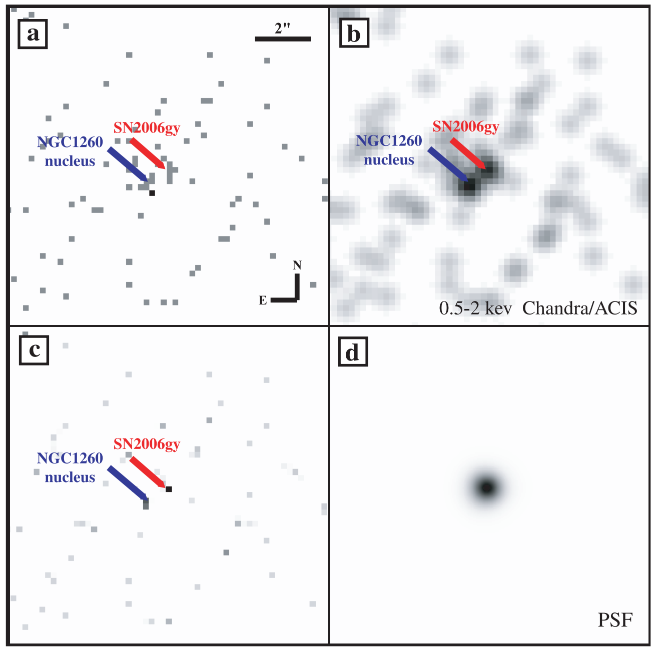

Fig. 6.—Soft-band (0.5–2 keV) *Chandra* images of NGC 1260. (*a*) Raw *Chandra* data (after our astrometric correction) with red and blue arrows indicating the KAIT positions of the SN and galaxy nucleus, respectively. (*b*) Gaussian-smoothed version of this image, in which the sources are more clearly apparent. (*c*) Maximum likelihood reconstruction of the 0.5–2 keV image (see text for details). (*d*) *Chandra* PSF at the location of the galaxy on the same spatial scale as the other panels.

that we have, in fact, detected SN 2006gy and spatially resolved it from the nucleus of NGC 1260.

We measured counts in the full 0.5–8 keV bandpass from the position of the SN using a small extraction region to minimize contamination from the galaxy nucleus. The extraction region has a radius of ~0.4″, corresponding to about 40% of the PSF. Response files were constructed with the CIAO tools, and ACIS Extract corrected them for the nonstandard extraction region. The background region is a source-free annulus centered on the position of the SN with inner and outer radii of 6″ and 14″, respectively. Based on the 241 counts detected in this region, we expect only 0.24 background counts in our extraction region. In the restricted energy range of 0.5–2 keV (used for the rest of this paper), we expect only 0.08 background counts in our extraction region.

Four counts were detected in our extraction region, which precludes a detailed spectral analysis. However, the counts were all detected below 2 keV, giving some indication of the spectral shape. We assume a thermal plasma spectrum (Raymond-Smith) with $kT = 1$ keV to estimate the luminosity. Such thermal spectra have successfully fit the X-ray spectra of SNe, and temperatures much higher than this would result in significant emission detectable by *Chandra* (which was not seen). Based on an assumed reddening toward SN 2006gy of $E(B-V) = 0.74$ mag, we assume an X-ray absorbing column of $n_{\rm H} = 4.1 \times 10^{21}$ cm^{-2} (Predehl & Schmitt 1995). Such an absorbed thermal plasma observed by *Chandra* would result in a ratio of 0.5–2 keV to 2–8 keV counts of ~10:1, in accordance with observations. We fit this model to the observed 0.5–8 keV spectrum in Sherpa (Freeman et al. 2001) using the statistic of Cash (1979). The only free parameter is the overall normalization of the model. From the best fit we find an unabsorbed X-ray luminosity (0.5–2 keV) of 1.65×10^{39} erg s^{-1}.

[6] See http://asc.harvard.edu.
[7] See http://idlastro.gsfc.nasa.gov/contents.html.

3. THE DEATH OF A VERY MASSIVE STAR WITH ITS HYDROGEN ENVELOPE INTACT

3.1. *The Energy Budget and a High-Mass Progenitor*

SN 2006gy has quickly distinguished itself as unique from other SNe in two important ways. First, after correcting for distance and extinction, it is the most luminous SN ever seen, and second, it has exhibited a remarkably slow rise to its peak luminosity and has stayed bright for a very extended time. SN 2006gy has peaked and is now on a slow decline, but even after 200 days it is still as luminous as the peak of a typical SN Ia.

SN 2006gy was classified as a SN IIn with narrow hydrogen lines in its spectrum at early times (Harutyunyan et al. 2006), although the spectrum has notable differences compared with prototypes of this class. It dramatically violates the expectation that SNe II are generally less luminous than SNe Ia (Fig. 2 includes a fairly typical Type II SN 1999em), and that SNe IIn usually take only ~20 days to reach their peak (Li et al. 2002). SN 2006gy, by contrast, took ~70 days to gradually climb to its peak. For about 100 days it was more luminous than $M_R = -21$ mag, brighter than any other SN known to date.

Simply put, for a supernova to be extremely luminous and to remain that way for such an extended time is truly spectacular. Integrating the light curve in Figure 2 and assuming zero bolometric correction, we calculate a total radiated energy of $E_{\rm rad} = (1.2 \pm 0.2) \times 10^{51}$ erg. This requires either very efficient conversion of blast wave kinetic energy into light, or some alternative energy source. One or a combination of the three following traditional mechanisms may power the visual light: (1) H recombination/thermal radiation of the supernova ejecta, (2) interaction of the supernova blast wave with the CSM, or (3) energy from radioactive decay of ^{56}Ni. Continued observations and probably extensive theoretical work will be needed to choose decisively between these options, but here we argue that regardless of which of these three mechanisms is responsible, the extreme energy budget of SN 2006gy requires that its very massive progenitor star retained its H envelope until it exploded.

The first option of thermal emission from the H recombination front in the supernova debris would require a huge ejected mass of order 100 $M_\odot$ or more, based simply on the total radiated energy. A heavy H envelope might help explain the unusually slow speed of only about 4000 km s^{-1} indicated by the Hα line (Fig. 5) and might provide a natural explanation for the long duration and rise time of the SN because of time needed for energy to diffuse out of the massive envelope. Whether or not the SN could actually radiate efficiently enough to produce the observed luminosity with this mechanism remains to be proven and should be investigated with detailed calculations. For example, at the temperature of the photosphere defined by the H recombination front (typically 5000–8000 K), the luminosity of SN 2006gy requires an emitting radius larger than what we might expect from its observed expansion speed of 4000–4500 km s^{-1} and from its age. Instead of 70 days, the observed peak luminosity would seem to require an age of 200–380 days since explosion (assuming linear motion), or rapid deceleration at early times. Such rapid deceleration at early times cannot be ruled out by our data.

The second option of powering the visible light entirely with CSM interaction is problematic, but is difficult to rule out conclusively. From the relatively weak soft X-ray flux of SN 2006gy detected by *Chandra*, we derive an upper limit to the progenitor star's mass-loss rate of $\sim 5 \times 10^{-4}$ $M_\odot$ yr^{-1} (see § 3.2). We find that this falls short of the circumstellar density that would be needed to power the visual light curve of SN 2006gy by 3 orders of magnitude (§ 3.3). In order to explain the high luminosity in whole or in part by CSM interaction, one would therefore need to assume that the X-ray emission is severely quenched and that the *Chandra* detection is erroneous; but this is difficult to accept, since we clearly detect soft (unabsorbed, not hard) X-ray emission from the position of the SN (Fig. 6). Even if it were true, however, a closer look at the demands placed on the circumstellar density make it difficult to explain with anything other than a massive star that coincidentally had an LBV outburst just before the supernova explosion.

Finally, the third option, radioactive decay of ^{56}Ni, is perhaps the least problematic, as we will discuss further in § 3.4. The main point of interest is that if this mechanism powers the visual light, then the high luminosity of SN 2006gy requires a very large Ni mass that cannot arise from a normal core-collapse SN. Instead, the large mass involved would require that SN 2006gy was a pair instability supernova in which the star's core was obliterated. If true, *SN 2006gy would be the first observed example of a pair-instability supernova*. This mechanism also has some potential difficulties, but they are more along the lines of uncharted theoretical territory, rather than fundamental physical or observational constraints. Therefore, SN 2006gy provides fertile ground for important theoretical work in this area.

3.2. *Limits to the Progenitor's Mass-Loss Rate from X-Ray Data*

If we interpret the X-ray emission detected by *Chandra* as the result of interaction of the outgoing shock with circumstellar material (CSM interaction), we can place an upper limit on the mass-loss rate of the progenitor star. This interaction has been explored in detail (e.g., Fransson et al. 1996). The softness of the X-ray emission points toward a reverse-shock origin, and we use the adiabatic case. A useful form of their eq. (3.10) is found in Pooley et al. (2002):

$$\frac{dL_{\rm rev}}{dE} = 2 \times 10^{35} \zeta (n-3)(n-4)^2 T_8^{-0.24} e^{-0.116/T_8} \times \left(\frac{\dot{M}_{-6}}{V_{w1}}\right)^2 V_{s4}^{-1} \left(\frac{t}{10 \text{ days}}\right)^{-1} \text{ erg s}^{-1} \text{ keV}^{-1}, \quad (1)$$

where $\zeta = 0.86$ for solar abundances, n is the index of the ejecta-density profile [$\rho_{\rm SN} \propto t^{-3}(r/t)^{-n}$], T_8 is the temperature in units of 10^8 K, $\dot{M}_{-6}$ is the progenitor's steady state mass-loss rate in units of 10^{-6} $M_\odot$ yr^{-1}, V_{w1} is its wind speed in units of 10 km s^{-1}, V_{s4} is the shock velocity in units of 10^4 km s^{-1}, and t is the time since explosion.

The value of n appropriate for SN 2006gy is uncertain, but typical values for core-collapse SNe are in the range 7–12. We assume a temperature of 1 keV, for which $T_8 = 0.116$. From Figure 5 we take the wind speed to be ~200 km s^{-1} ($V_{w1} = 20$), and the shock velocity to be 4500 km s^{-1} ($V_{s4} = 0.45$). The *Chandra* observation took place 87 days after the explosion.

This implies a mass-loss rate for the progenitor of 1.4×10^{-4} $M_\odot$ yr^{-1} assuming a steady mass-loss rate of the progenitor in the decades before explosion and adopting a SN ejecta density profile with $n = 12$. For a profile with $n = 7$, the mass-loss estimate rises to 5.4×10^{-4} $M_\odot$ yr^{-1}. This range of mass-loss rates is in good agreement with observed values in luminous H-rich WN stars (e.g., Hamann et al. 2006) or quiescent nonoutburst LBVs (Smith et al. 2004). As we discuss below, however, this range of mass-loss rates falls short of that needed to power the luminosity of SN 2006gy with CSM interaction by 3 orders of magnitude. This is a serious obstacle to any such model, which must now account for why we observe a relatively weak and soft (i.e., unabsorbed) X-ray flux from SN 2006gy. A likely explanation is that CSM interaction is important in creating the observed soft X-rays and in causing the emission-line spectrum of SN 2006gy (especially the broad Hα emission), but that something else drives its visual-wavelength continuum luminosity. Below, we consider the CSM interaction hypothesis (§ 3.3) as a power source for SN 2006gy aside from the difficulty posed by X-rays, as well as an alternative energy source for its radiated luminosity (§ 3.4).

3.3. *A Closer Look at Circumstellar Interaction*

Ofek et al. (2007) suggested CSM interaction as a means to power the visual light of SN 2006gy, but here we wish to make a clear distinction between two different scenarios. The first is where the blast wave from a SN Ia interacts with dense CSM from a companion star that provides the hydrogen in the spectrum (the so-called Type IIa scenario; e.g., Deng et al. 2004), as suggested in version 1 (in astro-ph/0612408) of the recent study by Ofek et al. (2007). This interpretation had also been suggested previously for the bright SNe 2002ic and 2005gj (Hamuy et al. 2003; Deng et al. 2004; Aldering et al. 2006). Note, however, that Benetti et al. (2006) have instead argued in favor of a core-collapse origin for SN 2002ic, so the true nature of these events is still controversial. The second type of scenario would be a blast wave from a core-collapse or pair-instability supernova from a massive star interacting with its own ejecta, analogous to the interpretation of the SN IIn 1994W by Chugai et al. (2004).

We argue here that the first scenario (SN IIa) is untenable for SN 2006gy for a number of reasons. Based in part on a preprint of our work presented here (version 1 of astro-ph/0612617), Ofek et al. (2007) revised their original Type IIa interpretation of SN 2006gy to include the possibility that it could have been a massive star as we originally proposed. The second SN 1994W-like scenario, on the other hand, is almost certainly relevant to SN 2006gy, but based on the weak X-ray emission we probably require a different source for the bulk of the radiated luminosity. If, for the sake of argument, we demand that CSM interaction powers the luminosity, we find that the extraordinary energy demands of SN 2006gy point to a circumstellar environment that is only likely to be produced by a very massive star that suffered a rare outburst immediately prior to the SN. In the case of SN 2006gy, the luminosity and total energy need to be scaled up by a factor of 40 or more from those for SN 1994W.

In order to power the luminosity of SN 2006gy with CSM interaction, the environment created by the progenitor star must be extraordinarily dense. Ofek et al. (2007) originally (version 1; of astro-ph/0612408) estimated that to achieve the luminosity of SN 2006gy with a shock plowing into CSM, the progenitor star (or its companion star in a close binary system) needed to have a wind with an average mass-loss rate of $\sim 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$ in the decades before explosion. However, this estimate scales with the adopted wind speed V_w and inversely with the shock speed V_s, which Ofek et al. originally took to be $V_w = 10\ \mathrm{km\ s^{-1}}$ and $V_s = 10^4\ \mathrm{km\ s^{-1}}$. Instead, however, we observe a much *faster* speed of $V_w \approx 200\ \mathrm{km\ s^{-1}}$ in the circumstellar environment indicated by the narrow P Cygni component in our spectra (Fig. 5; see § 3.5), raising this necessary mass-loss rate to $\sim 0.2\ M_{\odot}\ \mathrm{yr}^{-1}$ to achieve the same circumstellar density (Ofek et al. 2007 note this in version 2 of their paper, based on velocities in our Fig. 5). We also see a *slower* speed for the SN shock of only $V_s \approx 4000\ \mathrm{km\ s^{-1}}$ (Fig. 5) instead of $10^4\ \mathrm{km\ s^{-1}}$ (Ofek et al. 2007), raising the required progenitor mass-loss rate even further to about $0.5\ M_{\odot}\ \mathrm{yr}^{-1}$.[8] Thus, if CSM interaction is to power the visual light of SN 2006gy, the progenitor was probably an extremely massive star. Recall, however, that this required value of $0.5\ M_{\odot}\ \mathrm{yr}^{-1}$ is 1000 times above the highest likely value indicated by X-ray emission, making it problematic (see § 3.2). Let us put this last issue aside for the time being, assuming that the X-rays are somehow absorbed without hardening the spectrum, so that we can consider the implications of the CSM interaction hypothesis.

The expansion speed indicated by the Hα line (Fig. 5) is critical for addressing the extent to which interaction with CSM may power the observed radiation, because the FWHM $\approx 2400\ \mathrm{km\ s^{-1}}$ of the main intermediate-width emission component in Figure 5 has changed little from the initial value of FWHM $\approx 2500\ \mathrm{km\ s^{-1}}$ seen in the Hβ emission feature only a few days after discovery (Harutyunyan et al. 2006). (Recall that if the SN is powered by CSM interaction, then the observed expansion speed traces the blast wave speed and not the decrease in speed expected as the H recombination front progress deeper into the SN ejecta.) If the expanding blast wave has only slowed by about 10% in the first few months, conservation of momentum dictates that the mass of swept-up material is only about 10% of the ejected mass. Since at least a few $M_{\odot}$ of material needs to be swept up to power the luminosity of SN 2006gy,[9] the mass of the SN ejecta then needs to be *at least* 25 $M_{\odot}$. This clearly rules out a Type Ia event. Another way to approach the problem is that if the ejecta only slow by 10% after discovery, then only $\sim$20% of the initial kinetic energy can be converted into radiation during that time. The huge radiated energy of SN 2006gy would then require a SN with $\gtrsim 5 \times 10^{51}$ erg, again too great a demand for a SN Ia, even in a double-degenerate scenario or a super–Chandrasekhar-mass white dwarf.[10] In short, one cannot extract enough energy from the shock to power the light curve without slowing down the shock, unless the initial mass and kinetic energy of the SN ejecta are high.

Even if we somehow allow for very efficient conversion of all the 10^{51} erg of blast wave kinetic energy into radiation, we must ask: *what type of progenitor star is likely to have had such a stupendous mass-loss rate*? A rate of $0.5\ M_{\odot}\ \mathrm{yr}^{-1}$ would be unheard of for a low-mass (2–8 $M_{\odot}$) asymptotic giant branch (AGB) star, which is the most likely type of star to expect in the SN IIa scenario, for which observed mass-loss rates are 4–5 orders of magnitude lower (de Jager et al. 1988). Even the most extreme OH/IR stars have rates below $10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Netzer & Knapp 1987), while the highest rates during the final and brief proto–planetary nebula phase reach only $(1-2)\times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Bujarrabal et al. 2001). In fact, it is also more than 4 orders of magnitude larger than the Eddington accretion rate for a white dwarf, which would be relevant in a common-envelope scenario. Even massive stars in their normal (i.e., noneruptive) states do not come close to this rate.

The only type of star known to have a mass-loss rate higher than $0.1\ M_{\odot}\ \mathrm{yr}^{-1}$ would be an LBV during a giant eruption (Smith &

[8] One might suspect that even this value may underestimate what is required to power SN 2006gy. In a more detailed analysis of SN 1994W, Chugai et al. (2004) required a similar progenitor mass-loss rate of $0.2\ M_{\odot}\ \mathrm{yr}^{-1}$ for a short time preceding the SN, yet SN 1994W was more than 10 times less luminous than SN 2006gy.

[9] This comes from the required progenitor mass-loss rate, the duration of the SN at the time the spectrum in Fig. 5 was taken ($t \approx 96$ days), and the relative speed of the blast wave and circumstellar material: $M = \dot{M}\ t(V_S/V_w)$, which gives about 2.5 $M_{\odot}$.

[10] Invoking the hypothesis that the CSM interaction occurred before the first observation, and allowing the observed SN expansion speed to remain constant, does not help because it cannot account for how the light curve is powered continually for more than 100 days after that interaction (the ejecta cool quickly).

Owocki 2006). Those events typically last about a decade or less (Van Dyk 2005), which would be of the right order [$t = (150\ \mathrm{days})(V_S/V_w)$] to account for the required circumstellar environment of SN 2006gy. The outbursts are impulsive, so the large masses in their nebulae (Smith & Owocki 2006) averaged over the durations of the visible eruptions yield these mass-loss rates. If it were the case that the pre-SN mass-loss event before SN 2006gy was of such short duration, then we would predict the luminosity of SN 2006gy to soon plummet rapidly to the late-time luminosity of a normal SN II. If such a drop is not observed, it will strengthen the case for the pair-instability hypothesis discussed next in § 3.4. Such a sudden drop was clearly seen in SN 1994W at roughly day 110 (Chugai et al. 2004).

This interpretation, however, forces us back once again to the hypothesis that the progenitor was an extremely massive star, since only the most powerful LBV outbursts from the most massive stars with initial masses above $\sim 100\ M_\odot$ are known to have such high mass-loss rates. Coincidentally, the mass-loss rate of η Carinae during its phenomenal 1843 eruption was about 0.5 $M_\odot\ \mathrm{yr}^{-1}$ if averaged over 20 years (Smith et al. 2003). Another such extreme case is SN 1961V in NGC 1058 (Goodrich et al. 1989; Filippenko et al. 1995; Van Dyk et al. 2002), which is thought to have had an initial mass well above 100 $M_\odot$. To expect such an extraordinary feat from a low-mass or intermediate-mass star is unreasonable even in the most imaginative circumstances.

Further difficulties for the SN IIa scenario—and even for moderately massive progenitors—arise if we consider geometry. If one attempts to account for the unusually dense circumstellar environment by invoking a high mass-loss rate tidal stripping "event" in a close binary or common envelope/merger,[11] for example, then this would almost certainly distribute material in a flattened disk as mass is shed from the system through the outer Lagrangian point (e.g., Taam & Ricker 2006). In that case, however, even with 100% efficiency in the local conversion of kinetic energy into radiation, the global fraction of energy available is only that of the solid angle that can be intercepted by the disk, which will probably be less than 10%.

Altogether, then, there are several clear reasons why the Type IIa scenario originally advocated by Ofek et al. (2007, version 1 of astro-ph/0612408) fails to power SN 2006gy through CSM interaction. It is perhaps not surprising, then, that the visual spectrum of SN 2006gy does not resemble a SN Ia or the other SN IIa candidates. Hamuy et al. (2003) argued that SN 2002ic was a variant of the SNe Ia phenomenon on the basis of the similarity of its spectral evolution to that of a diluted version of SN 1991T (Filippenko et al. 1992). While the continuum of the earliest spectrum of SN 2005gj was relatively featureless, it too developed the prominent broad iron lines typical of a SN Ia by two months after explosion (Aldering et al. 2006). Our earliest spectrum of SN 2006gy is plotted in Figure 4 along with SN 1991T at a similar epoch relative to explosion. The only strong spectral feature in the SN 2006gy spectrum is Hα. The weaker features that are present do not match those of SN 1991T. In particular, the deep minima in the SN 1991T spectrum near 5700 and 6200 Å are lacking in SN 2006gy. At no later epoch did SN Ia features become visible in SN 2006gy, as can be seen in the day 71 and 96 spectra plotted in Figures 3 and 4. We therefore have no compelling reason to believe that an exploding white dwarf was present in this event.

We find that conversion of the blast-wave kinetic energy into radiated luminosity might potentially power SN 2006gy, as has been proposed for SN 1994W (Chugai et al. 2004), but only if the swept-up environment is consistent with extreme environments observed around the most massive evolved stars known, such as η Carinae. This agrees with the conclusions in § 3.5, where the properties of the circumstellar nebula independently rule out progenitor stars with initial masses below 40 $M_\odot$; initial masses above 60–80 $M_\odot$ are favored.

This last conclusion about the progenitor and its environment should not be taken lightly. It requires that an extremely rare event analogous to the 19th century eruption of η Carinae occurred a decade or so before the SN explosion. *Why would these two events be synchronized*? We are left with a choice: either this is such an unlikely event that the underlying power source for SN 2006gy must be some other mechanism and CSM interaction only contributes a fraction of the radiated energy (see § 3.4), or instead, it is an indication that giant LBV eruptions may be a sign of things to come, i.e., an "early warning sign" of an impending SN. The second possibility would be astounding if true, and SN 2006gy may not be alone in this regard. SN 1994W (Chugai et al. 2004; Sollerman et al. 1998), SN 2001em (Chugai & Chevalier 2006), and SN 2006jc (Foley et al. 2007) all show signs of dense environments that were probably produced by a giant mass-loss event just before the SN. Smith & Owocki (2006) have noted several other cases as well. SN 2006jc, in particular, was even observed as a "supernova imposter" two years before the final explosion (Nakano et al. 2006; Foley et al. 2007; Pastorello et al. 2007). Furthermore, such an outburst preceding the SN event may have some theoretical expectation (e.g., the pulsation pair instability described by Heger & Woosley 2002). This may be a profound clue to the fates of the most massive stars.

In any case, it is a marked difficulty for the CSM interaction hypothesis in general that, in addition to the softness and faintness of the detected X-rays noted above, the light curve, spectrum, and multiwavelength properties of SN 2006gy differ from those of other SNe IIn powered by CSM interaction, such as SNe 1988Z (Filippenko 1991; Stathakis & Sadler 1991; Turatto et al. 1993), 1995N (Fox et al. 2000; Fransson et al. 2002), and 1998S (Leonard et al. 2000; Pooley et al. 2002). SN 1988Z was bright in X-ray and radio emission (Schlegel & Petre 2006; Van Dyk et al. 1993; Williams et al. 2002), unlike SN 2006gy. The complex and unique spectral evolution of SN 2006gy will be discussed in a later paper, when more complete data are available.

3.4. *Initial Thoughts on Radioactive Decay and the Pair-Instability Hypothesis for SN 2006gy*

In previous sections, we have noted some obstacles, primarily observational in nature, with simple fireball or CSM interaction models as the engine for SN 2006gy. Although a suitable choice of extreme conditions may allow them to work, at least in part, our observation of soft unabsorbed X-rays from SN 2006gy and the corresponding upper limits to the progenitor star's mass-loss rate make it worthwhile to consider other options. Powering SN 2006gy with radioactive decay does not suffer from these problems, because this mechanism is known to work in other SNe. The question here centers around whether it is plausible to simply scale up the ^{56}Ni decay that powers fainter SNe, how that large mass of Ni may be created, and what happens to the radiation mechanisms in that extreme case. If SN 2006gy is powered by radioactive decay, the large Ni mass would require a pair-instability SN, as discussed below.

Scannapieco et al. (2005) presented model light curves for pair-instability SNe, where the progenitor stars were assumed to be red supergiants. The resulting light curves showed an initial small peak, but then a long, slow rise to maximum powered by ^{56}Ni and ^{56}Co decay. Some of their models come close to the peak luminosity of SN 2006gy, but they rise more slowly to maximum than SN

[11] Ignore for the moment that this hypothetical event needs to be synchronized with the supernova.

2006gy did. However, their calculations were for zero metallicity, nonrotating stars with no pre-SN mass loss. Different assumptions about the metallicity, mass-loss, and the presence of rotational mixing may change things considerably (e.g., Maeder 1987; Yoon & Langer 2005; Woosley & Heger 2006). Also, if the progenitor of SN 2006gy had a small radius as we expect for an LBV (RSGs are not observed at high luminosity in normal-metallicity stars), then the initial peak may be lost due to adiabatic cooling, and the delayed rise after $\sim$50 days would be dominated by ^{56}Co decay. Interestingly, this is similar to the case of SN 1987A, where the progenitor was a blue supergiant with a small radius, and where its late (70–100 days) peak was powered by radioactive ^{56}Co decay. SN 2006gy took a similarly long time to reach its peak luminosity, and its light curve thus far has a shape resembling that of SN 1987A (Fig. 2), except that it was 250 times more luminous.

In addition, the pair-instability models of Scannapieco et al. (2005) predict slow expansion speeds of $\sim$5000 km s^{-1} and the presence of H in the spectrum, again compatible with SN 2006gy. These clues are tantalizing, and it would be interesting to see models for pair-instability SNe at metallicity closer to solar values and with compact progenitors. This is still somewhat virgin territory and will require continued observational constraints and detailed calculations to find a suitable model that will work for the case of SN 2006gy. Below, we sketch a plausibility argument for the hypothesis that SN 2006gy was a pair-instability SN based simply on the required power source for its radiated luminosity.

The *R*-band magnitude at the peak of SN 2006gy was at least as bright as -21.8, but could have been significantly brighter because of our conservative assumptions for the reddening, as noted in §§ 2.1 and 2.2. Assuming no bolometric correction (again, conservative), this corresponds to a peak luminosity of $\gtrsim(1.7 \pm 0.3) \times 10^{44}$ erg s^{-1}. If this peak luminosity traces the instantaneous decay rate (Arnett 1982), we can estimate the necessary mass of initial nickel in the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay. With a late peak at $t \approx 70$ days, this will put us well into cobalt decay instead of nickel, as noted above. The radiated luminosity from cobalt decay (Sutherland & Wheeler 1984) is

$$\begin{aligned} L &= 1.42 \times 10^{43} \text{ erg s}^{-1} e^{-t/111 \text{ days}} M_{\rm Ni}/M_\odot \\ &= 8 \times 10^{42} \text{ erg s}^{-1} M_{\rm Ni}/M_\odot, \end{aligned} \quad (2)$$

where $M_{\rm Ni}$ is the initial ^{56}Ni mass. The extreme luminosity of SN 2006gy, then, would require an extraordinarily high Ni mass of roughly 22 $M_\odot$ to be synthesized in the explosion. This can be scaled down somewhat if CSM interaction contributes part of the energy, but unless that interaction dominates the light output, this large Ni mass cannot be explained with a core-collapse SN. (Compare this to a normal SN II arising from a star of 15–20 $M_\odot$, with a typical Ni mass of about 0.07 $M_\odot$.)

The large Ni mass implicates a progenitor star that began its life with a mass well above 100 $M_\odot$. The consequences of this are potentially far-reaching, and could turn out to be the most interesting result of this study, namely, the only way to get such an extraordinarily high Ni mass to power the radiated energy would be from a pair-instability supernova, where the star's core is obliterated instead of collapsing to a black hole (Barkat et al. 1967; Fraley 1968; Bond et al. 1984; Heger & Woosley 2002). This type of supernova is only expected to occur in extremely massive stars. For the mechanism to work in the modern universe, even the most massive stars would need to retain most of their initial massive envelopes, providing a self-consistent interpretation of SN 2006gy in light of other evidence for its high mass discussed here. This is not wild speculation—it may even be the most promising explanation—but it deserves close scrutiny because of its far-reaching importance.

As SN 2006gy continues to evolve, it will become easier to determine if ^{56}Co decay or CSM interaction is the power source. If CSM interaction drives the visible light, we might expect the light curve to plummet precipitously, down to the luminosity of a normal SN II, when the shock reaches the outer extent of the LBV shell. Such a drop occurred in SN 1994W, although the light-curve shape of SN 2006gy so far is quite different from that of SN 1994W (Fig. 2). On the other hand, if SN 2006gy continues to decay smoothly from its peak, like SN 1987A but at an elevated luminosity, then it was almost certainly a pair-instability SN event because of the large nickel mass required. So far, SN 2006gy shows no sign of plummeting; in fact, the latest photometry seems to imply that it is settling onto a plateau.

Of course, SN 2006gy could be a combination of both CSM interaction and pair instability. Any very massive star capable of suffering a pair-instability SN is likely to have a strong stellar wind in its late preexplosion stages anyway, consistent with the values of $(1-5) \times 10^{-4}$ that we infer from the X-ray interaction. The pair-instability SN models of Heger & Woosley (2002) predict mass-loss pulses that precede the final explosion. In fact, the observed optical spectrum of SN 2006gy *requires* that CSM interaction is occurring at some level, but the critical question is whether this interaction is capable of powering the enormous continuum luminosity of SN 2006gy. Current indications are that it cannot.

3.5. *A Massive Circumstellar LBV Nebula*

Independent of the energy-budget arguments, the properties of the unshocked circumstellar gas around the progenitor of SN 2006gy are also consistent with the interpretation that it was a very massive star and provide critical clues that strongly refute the hypothesis that it was powered by the Type Ia explosion of a low-mass star interacting with dense CSM. The high-resolution spectrum in Figure 5 contains a narrow component to the Hα line, which also exhibits a clear P Cygni absorption profile. It indicates that the SN is expanding into a hydrogen-rich dense stellar wind or outflowing circumstellar nebula of the progenitor star, which has an expansion speed of 130–260 km s^{-1} indicated by the absorption component. This same narrow absorption component is seen in other lines in the spectrum of SN 2006gy, such as He I (He I λ6680 and Fe II lines are shown in Fig. 4), Si II, Fe II, Ca II, O I, etc. The narrow He I lines are unusual, and may suggest He-enriched material in the CSM.

This expansion speed is a critical clue to the nature of the progenitor star that cannot be neglected. It is much faster than typical wind speeds of AGB stars (10–20 km s^{-1}), effectively ruling out the interpretation of SN 2006gy as a SN IIa. While it is unclear if the expansion speed itself is in direct conflict with an interpretation involving a common envelope mass-loss phase (e.g., Taam & Ricker 2006, and references therein), as suggested by Livio & Riess (2003) to explain the properties of SN 2002ic, and in the first version of Ofek et al. (2007, in astro-ph/0612408) to explain SN 2006gy, that interpretation is ruled out for SN 2006gy, based on the energy budget (see § 3.3). This speed is also too fast for a RSG wind (20–40 km s^{-1}), making it difficult to believe that the progenitor star had an initial mass in the range 10–40 $M_\odot$. Moreover, the speed is an order of magnitude too slow for the wind of an O-type supergiant, H-rich WN, or Wolf-Rayet (WR) star progenitor. On the other hand, this speed is entirely consistent with an LBV wind or nebula (e.g., Smith et al. 2004; Smith 2006). Similar absorption speeds were seen in the narrow P Cygni absorption of SN 1998S, which Fassia et al. (2001) also interpreted as a prior

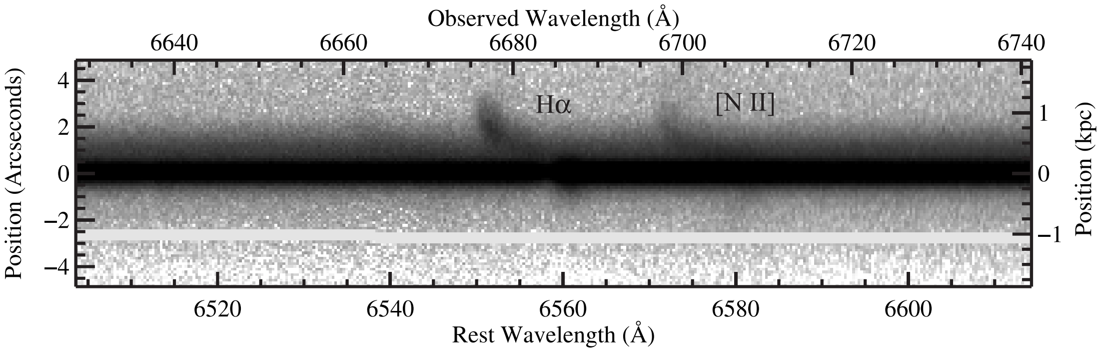

FIG. 7.—Long-slit Keck DEIMOS spectrum of SN 2006gy and NGC 1260 in the region around Hα. It includes the central point source SN 2006gy at the zero-offset position, plus extended emission from the host galaxy NGC 1260 on either side of it. The extended Hα and [N II] emission, which follows the rotation curve of the galaxy and has an [N II]/Hα intensity ratio typical of H II regions, indicates that NGC 1260 does have active star formation. The light row below SN 2006gy is a bad row in the CCD and has been masked.

blue-supergiant phase. Chugai et al. (2002), however, interpreted it somewhat differently as a fast blue-supergiant wind sweeping into a red-supergiant wind. Significant acceleration of the slow red-supergiant wind would require a swept-up mass comparable to the fast-wind mass shortly before the SN, which makes this scenario implausible in the case of SN 2006gy, because of the large mass implied. The typical LBV ejecta speed agrees well with our constraints from § 3.3.

Narrow blueshifted absorption components similar to Hα are seen in a number of other lines throughout the spectrum of SN 2006gy along with some relatively broad blueshifted absorption (Figs. 4 and 5). Those absorption features are not always present (Fig. 4), while narrow Hα emission remains. Thus, we cannot be certain that the narrow emission and absorption components of Hα constitute a true P Cygni scattering profile, so we consider both cases here. For each case, the luminosity of the narrow Hα emission component is a relevant quantity. At a distance of 73 Mpc, the luminosity of the narrow emission component of the Hα line on day 96 (Fig. 5) is $L_{H\alpha} \approx (1.3 \pm 0.3) \times 10^6\ L_\odot$ (the absolute flux was calibrated by scaling the red continuum to match observed KAIT photometry at the appropriate date and correcting for $A_R \approx 1$ mag). Note that the true luminosity may be somewhat larger than this because the apparent luminosity may be reduced by the blueshifted narrow absorption.

If the narrow Hα component arises in an unshocked CSM wind, we can make a rough estimate of the density immediately outside the radius of the shock, given by $R_s = V_s t$, where we again take $V_s = 4000$ km s^{-1} and $t = 96$ days is the time the Keck spectrum was taken. Such estimates are plagued with uncertainties in the ionization fraction and H mass fraction, so the estimate below is a lower limit assuming fully ionized pure H gas. Following equation (1) of Chugai & Danziger (2003), for example, our measured value of $L_{H\alpha}$ implies a density of roughly 2×10^8 cm^{-3} just outside $R_s \approx 3.3 \times 10^{15}$ cm (adopting $\alpha^{\rm eff}_{H\alpha} = 8.64 \times 10^{-14}$ cm^3 s^{-1} for the Case B Hα recombination coefficient as noted below). If V_w is taken to be 200 km s^{-1}, this implies a mass-loss rate for the progenitor star of roughly 0.01–0.02 $M_\odot$ yr^{-1}. While this is an exceptionally high mass-loss rate, higher than what we infer from the X-ray emission (§ 3.2), it still falls short of what is required to power the visual luminosity of SN 2006gy by more than a factor of 25–50. It is interesting, however, that this value is comparable to progenitor mass-loss rates estimated for other SNe IIn with similar narrow Hα P Cygni features from the unshocked CSM, such as SNe 1997ab and 1997eg (Salamanca et al. 1998, 2002).

If the narrow Hα emission component arises instead from unshocked ionized gas in a detached CS shell nebula, however, then the mass implied would add yet another requirement that the progenitor star was very massive. It may arise in a circumstellar shell like the Homunculus Nebula of η Carinae (Smith 2006), for example. Using $L_{H\alpha}$, and assuming that the line originates from a circumstellar shell nebula of constant density, the ionized gas mass can be expressed as

$$M_{H\alpha} \approx \frac{m_H L_{H\alpha}}{h\nu\, \alpha^{\rm eff}_{H\alpha} n_e}, \qquad (3)$$

where $h\nu$ is the energy of an Hα photon, $\alpha^{\rm eff}_{H\alpha} = 8.64 \times 10^{-14}$ cm^3 s^{-1} is the Case B Hα recombination coefficient, and n_e is the average electron density. This yields $M_{H\alpha} \approx 11.4\ M_\odot\ (L_{H\alpha}/n_e)$. We do not know the electron density in the nebula around SN 2006gy, but values of 10^5–10^6 cm^{-3} are the highest densities typically seen in young LBV nebulae like the one around η Carinae (Smith 2006). With the observed Hα luminosity and densities of this order, the nebular mass is probably above 5 $M_\odot$, and it could plausibly be as high as 20–30 $M_\odot$. Lower densities typically seen in circumstellar nebulae around lower mass stars would require implausibly high emitting masses to account for the observed radiation, exceeding their own stellar masses. Environments this massive obviously cannot be produced by low-mass stars and are not seen around moderately massive stars of 20–40 $M_\odot$, but they are quite typical of the nebular shells around LBVs with $L > 10^6\ L_\odot$ (Smith & Owocki 2006), which descend from stars with initial masses of 80–150 $M_\odot$. Such large masses are consistent with the $\gtrsim$12.5 $M_\odot$ nebula around η Car (Smith et al. 2003).

Thus, the flux of the narrow Hα component that we observe is only likely to arise in the circumstellar nebula of an extremely massive star. Taken together, this high mass and the shell's expansion speed give self-consistent evidence that the progenitor star was indeed very massive. This line of reasoning is independent of the uncertainty associated with the mechanism that powers the radiated energy of the SN. It is also consistent with the presence of strong hydrogen lines in the spectrum, since LBVs have not yet shed their H envelopes. Although dominated by hydrogen, LBV shells also have elevated helium abundances, consistent with the presence of narrow He I lines in the spectrum of SN 2006gy. If SN 2006gy really is surrounded by a dense LBV nebula like that of η Carinae, then we might expect to see strong, narrow emission lines of [N II] λλ6548 and 6583 in its late-time spectral evolution, since LBV nebulae like that of η Car tend to be enriched with CNO-cycle ashes (Smith & Morse 2004).

3.6. *Do We Expect Massive Stars in the Host Galaxy?*

SN 2006gy has been compared (Ofek et al. 2007) to two peculiar supernovae, SN 2002ic and SN 2005gj (Fig. 2), which have been proposed as SNe Ia interacting with dense CSM (the so-called Type IIa SNe), as noted earlier. One factor that motivated Ofek et al. (2007) to originally favor the SN IIa hypothesis was that the host galaxy, NGC 1260, was apparently not a star-forming galaxy. It should not have massive stars, because S0 galaxies are dominated by old stellar populations.

We note, however, that the SN host is actually a peculiar S0/Sa galaxy with infrared (IR) emission from dust. NGC 1260 was detected by the *Infrared Astronomical Satellite* (*IRAS*), and Meusinger et al. (2000) give an infrared luminosity of $\log(L_{IR}/L_{\odot}) = 9.85$. According to Kennicutt (1998), this would translate to a star formation rate of $\sim 1.2\ M_{\odot}\ \mathrm{yr}^{-1}$, which is certainly high enough to permit this galaxy to host some massive young stars. Furthermore, we detect extended Hα and [N II] λ6583 emission from the galaxy in our spectra; Figure 7 presents the original long-slit Keck spectrum before the Hα profile of SN 2006gy was extracted, revealing extended emission from gas that follows the rotation curve of the host galaxy. These emission lines, having intensity ratios typical of H II regions, are indicative of current star formation and are absent in non–star-forming galaxies.

A related point concerns the statistics involved. SN 2006gy is the most luminous SN seen to date, but it is also spectrally peculiar, almost in a class by itself. Its unusual nature would not be at all surprising, in principle, if its origin were the explosion of a $>100\ M_{\odot}$ star, since these stars are so phenomenally rare to begin with. On the other hand, if it results from normal evolution for low-mass stars or even moderately massive stars of 10–40 $M_{\odot}$, then we would expect such events to be more common.

4. SUMMARY: EXPLOSION AS A MASSIVE LBV AND THE RELEVANCE OF A PAIR-INSTABILITY SUPERNOVA

All available observations are broadly consistent with the hypothesis that the progenitor of SN 2006gy was a very massive star that retained a massive hydrogen envelope until it exploded. Retaining this envelope does not mean that the progenitor was a RSG; the most luminous stars evolve to the LBV phase before losing their envelopes, and during that phase they are hot supergiants with relatively small radii. This can strongly affect the early light-curve shape. A mass below 60 $M_{\odot}$ may be possible if the event was powered by CSM interaction, but then one must invoke exceptional conditions inconsistent with observed properties of stars below that mass. If CSM interaction dominates, we find it more likely that the progenitor star had an initial mass of 100–150 $M_{\odot}$, although we still lack a satisfactory explanation for the weak unabsorbed X-rays in that case.

By contrast, the huge radiated luminosity, the long duration, the presence of hydrogen in the spectrum, the low expansion speed of the SN ejecta, and the various critical clues from the circumstellar environment are all consistent with the hypothesis that this event was powered by a pair-instability supernova that also has some moderate CSM interaction, implying that the progenitor star's initial mass may have been near the upper mass limit for stars of $\sim 150\ M_{\odot}$ (Figer 2005). Regardless of the power source, several clues hint that the progenitor star may have resembled the LBV star η Carinae.

If this hypothesis of explosion as a massive LBV is correct, it would have important consequences for our understanding of stellar evolution. It is currently thought that variability in the LBV phase is responsible for the mass shedding that marks the transition from the end of core H burning to core He burning, after which a star appears as a He-rich WR star (Abbot & Conti 1987; Langer et al. 1994; Smith & Owocki 2006; Smith et al. 2004). During this brief evolutionary phase, a massive star might undergo sequential bursts of mass loss when it can repeatedly shed more than 10 $M_{\odot}$ of material in a decade (Smith & Owocki 2006). These events are seen in other galaxies as faint SNe IIn, or "supernova impostors" (Van Dyk 2005, and references therein). They may dominate the mass loss of the most massive stars, shedding more total mass than line-driven winds during the star's lifetime (Smith & Owocki 2006). Consequently, LBV stars are frequently surrounded by circumstellar nebulae with masses of order 10 $M_{\odot}$, like the one that may reside around SN 2006gy. It would appear that one of these events may have occurred within a decade or so immediately preceding SN 2006gy.

The core He-burning WR phase that should follow after the massive hydrogen envelope is stripped away is expected to last a few hundred thousand years before the star reaches even more advanced stages of nuclear burning and finally explodes (Abbot & Conti 1987). If LBVs explode before reaching the WR phase, however, it means that they could be in more advanced stages of nuclear burning than currently predicted by stellar evolution theory. SN 2006gy adds to mounting evidence (e.g., Smith & Owocki 2006; Kotak & Vink 2006; Gal-Yam et al. 2007; Smith 2007) that stars may explode "early" during the LBV phase, and it hints that reaching the pair instability could be a reason for this.

It seems intuitively possible, although difficult to prove, that it would be the most massive LBVs above $\sim 100\ M_{\odot}$ that are more likely to explode prematurely, as they have a greater burden of removing their massive envelopes before transitioning to WR stars. Gal-Yam et al. (2007) have drawn a similar conjecture, considering LBVs as the most likely progenitors of SNe IIn. If the most massive stars can indeed explode before the WR phase, then our current ignorance of the instability underlying the LBV phase presents a critical challenge. The possibility that SN 2006gy could have been a pair-instability supernova weighs heavily on the importance of understanding these LBVs as well. SN 2006gy may be giving us a clue that the wild instability of the most luminous LBVs like η Carinae could be early warning signs of a massive star's imminent demise, and there may be theoretical reasons to think this is the case. One implication is that we had better keep a watchful eye on η Carinae.

The chief reason why pair-instability SNe are expected to occur for high-mass stars in the early universe is because their low metal content is expected to reduce their mass-loss rates, causing them to retain their massive H envelopes (Heger et al. 2003; Heger & Woosley 2002; although see Smith & Owocki 2006). Also, the initial mass function of the first stars is thought to have been skewed to higher masses due to the lack of metal cooling and, consequently, a lack of fragmentation in the star formation process (e.g., Bromm & Larson 2004). SN 2006gy may have been a very massive star that exploded as an LBV *before* it could shed its H envelope, and it may have done so by the pair-instability mechanism.

The fact that SN 2006gy was able to explode successfully instead of winking away into a black hole has far-reaching implications. In particular, one primary goal of the *James Webb Space Telescope* will be to search for these first explosions in the universe, and the brilliant display of SN 2006gy may bode well for the possibility of their infrared detection at high redshift.

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Note added in proof.—NGC 1260, the host galaxy of SN 2006gy, is routinely monitored with KAIT as part of the Lick Observatory Supernova Search (LOSS; Filippenko 2003), but LOSS did not discover SN 2006gy because it is only about 1″ from the bright galactic nucleus. A circular region of radius 2.4″ around such nuclei is excluded from the search, since the point-spread function of KAIT is variable, and bright unresolved sources often leave a residual in the difference (new minus template) images. However, after the discovery of SN 2006gy by Quimby (2006a), we were able to conduct photometry of the object in our prediscovery KAIT images; see the first four entries in Table 1.