

DISCOVERY OF THE EXTREMELY ENERGETIC SUPERNOVA 2008fz

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Received 2009 August 13; accepted 2010 June 24; published 2010 July 12

ABSTRACT

We report on the discovery and initial observations of the energetic type II_n supernova 2008fz. This object was discovered at redshift $z = 0.133$ and reached an apparent magnitude of $V \sim 17$. After correcting for Galactic extinction and redshift, we determine the peak absolute magnitude of the event to be $M_V = -22.3$, placing it among the most luminous supernovae discovered. The optical energy emitted by SN 2008fz (based on the light curve over an 88 day period) is possibly the most ever observed for a supernova ($> 1.4 \times 10^{51}$ erg). The event was more luminous than the type II_n SN 2006gy, but exhibited the same smooth, slowly evolving light curve. As is characteristic of type II_n supernova, the early spectra of SN 2008fz initially exhibited narrow Balmer lines which were replaced by a broader component at later times. The spectra also show a blue continuum with no signs of Ca or Na absorption, suggesting that there is little extinction due to dust in the host or circumstellar material. No host galaxy is identified in prior co-added images reaching $R \sim 22$. From the supernova's redshift, we place an upper limit on the brightness of the host of $M_R \sim -17$ (similar to the brightness of the Small Magellanic Cloud). The presence of the supernova within such a faint galaxy follows the majority of recently discovered highly luminous supernovae. A possible reason for this is the combination of a high star formation rate in low-mass galaxies with a low-metallicity environment.

Key words: galaxies: stellar content – supernovae: general – supernovae: individual (SN 2008fz)

Online-only material: color figures

1. INTRODUCTION

The recent discovery of highly energetic type II supernovae, such as SN 2006gy (Quimby et al. 2006; Smith et al. 2007) and SN 2005ap (Quimby et al. 2007), has stirred interest in the energy sources and fate of the most massive and luminous stars. Although the bulk of the energy expelled from such core-collapse (CC) supernovae is believed to be in the form of neutrinos (for a recent review see Haxton 2008), these measurements are extremely difficult for most SNe. On the other hand, the amount of optical energy released can be readily assessed from the redshift and photometric measurements covering the outburst. In the case of SN 2006gy, the energy released was found to require a progenitor star with mass $> 40 M_\odot$ (Smith et al. 2007). This event was suggested to be the result of either the explosion of a luminous blue variable (LBV), like η Carinae (Smith et al. 2007), or the pair-instability destruction of a very massive, low-metallicity star (Woosley et al. 2007; Ofek et al. 2007).

Recent direct evidence for the destruction of a massive LBV comes from a type II_n supernova, SN 2005gl, with an average outburst luminosity. This event was first noted to be due to a η Carinae-like star by Gal-Yam et al. (2007). Comparison of pre- and post-explosion *Hubble Space Telescope* data showed the disappearance of a likely progenitor with a luminosity consistent with a very massive star (Gal-Yam & Leonard 2009). On the other hand, pair-instability supernovae are expected to either directly form black holes or completely disintegrate as they undergo thermonuclear runaway (Heger & Woosley 2002). Such

pair-instability events are also a possible link between SNe occurring with Population III progenitors and long-timescale gamma-ray bursts (GRBs; Stanek et al. 2003). Some evidence for the existence of pair-instability SNe comes from the slow-evolving type Ic SN 2007bi, discovered by the SNfactory (Nugent et al. 2007). This event was found to have a core mass of $\sim 100 M_\odot$, placing it well within the massive star regime (Gal-Yam et al. 2009).

A number of other luminous and energetic supernovae have also been discovered recently with peak brightnesses $M_V < -21$ at the peak. Commonly observed CC supernovae range in peak magnitude from $M_B \sim -17$ to ~ -20 depending on spectral type (Richardson et al. 2002). These recent luminous events include SN 1999as (Knop et al. 1999), 2005ap (Quimby et al. 2007), 2006gy (Smith et al. 2007), 2007bi (Gal-Yam et al. 2009), 2008es (Gezari et al. 2009), 2008fz (Drake et al. 2008a), 2008iu (Drake et al. 2009b), and 2009de (Drake et al. 2009c). In order to roughly distinguish these supernovae from regular CC supernovae, we call them extremely luminous supernovae (ELSNs). However, we caution that a better method of separating such events from regular events is by considering magnitude distributions for a given supernova spectral type, rather than a cutoff magnitude.

All of the ELSNs discovered since 2005 have come from surveys covering large areas of sky (rather than bright nearby galaxies), including ROTSE (Quimby et al. 2007), the SNfactory (Gal-Yam et al. 2009), and CRTS (Drake et al. 2009a). In most cases, these have been discovered in intrinsically faint, low-mass galaxies. This is interesting, as Kauffmann et al. (2003)

found that only $\sim 13\%$ of the stellar mass in galaxies resides in galaxies less massive than $10^9 M_{\odot}$, low-mass galaxies appear to have much higher SN rates than expected for their baryonic content (Mannucci et al. 2005). One likely reason for this observation is the elevated star formation rate in such galaxies (Zheng et al. 2007). Furthermore, such low-mass galaxies tend to have low metallicity (Spolaor et al. 2009), which is believed to favor the formation of the massive stars that led to bright supernovae and hypernovae (Heger et al. 2003). Hypernovae exhibit broad-line type Ic supernova spectra (Sahu et al. 2009) and are linked to the long-timescale GRBs that occur during the deaths of massive stars (Paczynski 1998). Modjaz et al. (2008) found that hypernovae are preferentially observed in low-mass, low-metallicity, star-forming galaxies. However, not all broad-line type Ic events have been associated with GRBs, nor do they all exhibit extreme luminosities. Nevertheless, recent ELSN discoveries are being made in environments like those of hypernovae.

2. DATA REDUCTION AND DISCOVERY

The Catalina Real-time Transient Survey (CRTS; Drake et al. 2009a) is a synoptic survey that searches for optical transients (OTs) in data taken by the Catalina Sky Survey (CSS; Larson et al. 2003). The survey was initially based on unfiltered Catalina Schmidt telescope observations, which covered the same 1200 deg^2 of the sky four times per night with images reaching magnitude $V \sim 20$ at $2''.5$ pixel resolution. All CSS data are automatically processed in real time, and OT discoveries are immediately distributed publicly as VEvents.⁷

Unlike most current surveys for nearby supernovae, which target between a few hundred and a few thousand bright nearby galaxies (KAIT/LOSS, Pucket/POSS, CHASE), the CRTS survey covers the sky irrespective of targets. However, as transient detection is performed using catalogs, rather than image subtraction, CRTS is not currently sensitive to detecting OTs associated with extended bright sources. This bias increases the likelihood that CRTS supernova discoveries are either very bright, such as ELSNe (e.g., SN 2006gy; Smith et al. 2007), or of normal luminosity in a faint host galaxy (e.g., SN 2009aq; Mahabal et al. 2009). Both circumstances are of interest as such events are largely undetected by surveys covering only bright nearby galaxies.

SN 2008fz was first discovered by CRTS on 2008 September 22 (Drake et al. 2008a) and is located at $\alpha = 23^{\text{h}}16^{\text{m}}16^{\text{s}}.57 (\pm 0^{\text{s}}.02)$, $\delta = +11^{\circ}42'47''.4 (\pm 0''.2)$ (J2000). Photometric follow up of this event was taken with the Palomar 1.5 m telescope on 2008 September 23 and 24. As no host galaxy was visible, the object was first classified as either a CV or a supernova (Drake et al. 2008b). A noisy spectrum was obtained on September 23 with the 1.82 m Plaskett Telescope (range 390–703 nm, resolution 0.3 nm) and the supernova was initially classified as a type Ic event (Hsiao et al. 2008). A third spectrum was obtained on October 1 with the Palomar 5 m telescope and DBSP (Mahabal et al. 2008). Subsequently, Benetti et al. (2008) took a spectrogram on October 9 using the TNG 3.5 m telescope and DOLORES and found the object as a type IIn SN at redshift $z = 0.133$ with magnitude $M_R = -22.1$.

3. SPECTRA

In addition to the October 1 Palomar 5 m spectrum of SN 2008fz, spectra were obtained on October 25 with the

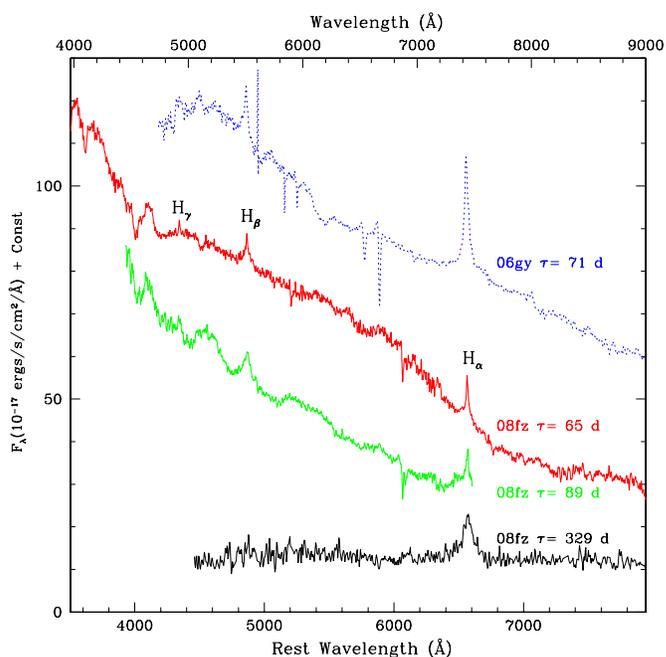


Figure 1. Spectra of SN 2008fz at $\tau = 65$, $\tau = 89$, and $\tau = 329$ days after explosion, obtained with the Palomar 5 m + DBSP, MDM 2.4 m + Modspec, and Palomar 5 m + DBSP, respectively. For comparison, the $t = 71$ day spectrum of SN 2006gy from Smith et al. (2010) is shown with a dotted line. The explosion date for SN 2008fz assumes that the event has the same rise time as SN 2006gy. (A color version of this figure is available in the online journal.)

Modular Spectrograph (modspec) on the MDM 2.4 m, and on 2009 June 22 with the Palomar 5 m telescope using the DBSP (Oke & Gunn 1982). In Figure 1, we present spectra of SN 2008fz along with that of the luminous type IIn SN 2006gy. Here the approximate time of SN 2008fz's explosion was determined assuming the same rise time as SN 2006gy. We estimate that the explosion date is uncertain to ~ 10 days. The Palomar spectrum of SN 2008fz at $\tau = 65$ days exhibits a strong, narrow component to the Balmer lines, firmly placing the redshift at $z = 0.133 \pm 0.003$. The $H\alpha$ profile exhibits an expansion velocity of $\text{FWHM} = 660 \text{ km s}^{-1}$, as well as a broader component with $\text{FWHM} \sim 3100 \text{ km s}^{-1}$. This expansion rate is similar to that of SN 2006gy (Smith et al. 2007; $\text{FWHM} = 2500 \text{ km s}^{-1}$). Indeed, the velocity determined from the $H\beta$ emission of SN 2008fz is 2500 km s^{-1} .

The $\tau = 329$ days spectrum of SN 2008fz shows that the blue continuum has faded and become flat. The broad $H\alpha$ has an expansion rate of 5900 km s^{-1} . Evolution from initial narrow Balmer lines in type IIn supernovae is expected to occur as expanding material interacts with the surrounding circumstellar material (CSM). This material prolongs the event and mediates the conversion of energy to luminosity (Smith et al. 2010). The $H\alpha$ emission is the only remaining strong feature in the 4500–8000 \AA range and likely traces the speed of the blast wave itself. In comparison, a value of 4000 km s^{-1} was observed for late SN 2006gy spectra (Smith et al. 2010).

4. PHOTOMETRY

Following SN 2008fz's discovery, unfiltered observations continued as part of the CSS survey. All CSS photometry is routinely transformed to V magnitudes by using between 10 and 100 G-type dwarf calibration stars measured in each image. These calibration stars are pre-selected using Two Micron All

⁷ CRTS, <http://crts.caltech.edu/> and SkyAlert, <http://www.skyalert.org/>.

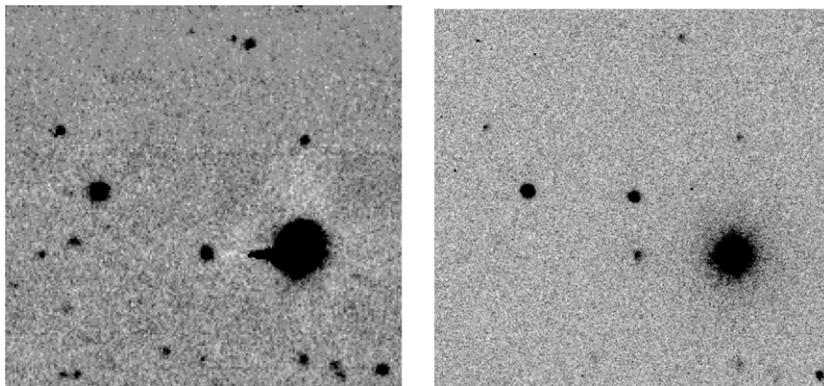


Figure 2. Images of the location of SN 2008fz centered ($3' \times 3'$). Left: Palomar Quest pre-discovery co-added image in the Johnson I -band filter. Right: Palomar 1.52 m follow-up image taken in Gunn- r on 2008 September 23.

Sky Survey near-IR data.⁸ The magnitudes for each calibration star are transformed to V following Bessell & Brett (1988), and the zero point for each field is derived. The scatter in the V magnitude for the calibration stars is typically <0.05 (Larson et al. 2003).

In order to check the accuracy of the routine calibrations for SN 2008fz, we used observations of the nearby standard star GD 246. This star lies within a degree of SN 2008fz and has a V magnitude of 13.09 ± 0.01 (Landolt 2009). GD 246 was observed 16 times within minutes of observing SN 2008fz during four nights. This standard star, being a hot white dwarf, has a color closer to that of SN than the G-type dwarfs used in the routine calibration. The average V magnitude for GD 246 from the four overlapping nights was 13.07 ± 0.04 . As an additional check, we transformed the Palomar 1.5 m g, r, i, z photometry of SN 2008fz to V magnitude, following Jordi et al. (2006). These values agree with the CSS photometry to better than 0.1 mag. We have also considered how the spectral features of SN 2008fz might affect the measured magnitudes. Near the peak, SN 2008fz does not exhibit very strong features that might affect the transformed CSS V magnitudes relative to true V magnitudes (see Figure 1). However, at late times ($\tau = 329$ days) the spectrum becomes dominated by $H\alpha$ emission. This clearly lies within the range of our unfiltered photometry, but outside the bandpass of a V -band filter.

To determine the absolute V -band magnitude of SN 2008fz, the CSS photometry was corrected for a Galactic extinction of $A_V = 0.136$ from Schlegel et al. (1998) reddening maps. However, no correction was applied for intra-galaxy extinction within the host. We applied a K -correction of 0.14 mag to account for the effective rest-frame bandwidth of the redshifted supernovae (Oke & Sandage 1968). However, as the photometry of both SN 2006gy and SN 2008fz was taken unfiltered, we did not apply corrections for the redshift of the spectral energy distributions. Such corrections are expected to be small because of the relatively flat flux distribution and low redshift of these supernovae. The peak absolute magnitude of SN 2008fz is found to be $V = -22.28 \pm 0.07$ for redshift $z = 0.133 \pm 0.003$, assuming $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_m = 0.27$. This value is in very good agreement with the synthetic luminosity derived by Benetti et al. (2008).

5. THE HOST GALAXY

In Figure 2, we present a pre-SN Palomar-Quest (PQ) co-added image and a September 23, Gunn- r , Palomar 1.5 m observation at the location of SN 2008fz. The PQ image was constructed from nine, 140 s, Johnson I -band exposures of the 1.2 m Oschin Schmidt telescope taken on eight nights between 2003 August 31 and 2006 September 24. The limiting magnitude of the image is approximately 22.5. A similar PQ R -band image with a limiting magnitude of 22 was also constructed and shows no sign of a host galaxy. The image presented is $3'$ wide, corresponding to 550 kpc at the redshift of the supernova. The nearest detected object (which appears to be a galaxy) is offset by $17''$. This offset corresponds to roughly 10 half-light radii for the object. Therefore, this object is very unlikely to be the host galaxy of SN 2008fz. Based on the SN redshift, the unseen host galaxy is fainter than $M_r \sim -17$. For comparison, the Small Magellanic Cloud (SMC) has magnitude $M_V = -16.2$ and would have a radius of $\sim 1''/8$ at this distance. Therefore, it is possible for a galaxy like the SMC to host SN 2008fz and go unseen.

The DSS-2 image (DSS2-B) of this region appears to show a small elongated source at the location of SN 2008fz. This was suggested as a possible host galaxy (Drake et al. 2008a). However, close inspection of the image revealed this to be either a photographic or scan artifact. A PQ B -band co-added image reaching a similar depth to DSS-2 shows no object.

6. COMPARISON WITH SUPERNOVA 2006gy

As noted earlier, a number of ELSNe have recently been discovered. These include highly luminous, rapidly declining supernovae, such as SN 2005ap (Quimby et al. 2007) and 2008es (Gezari et al. 2009), as well as energetic long-timescale events, such as SN 2007bi (Gal-Yam et al. 2009) and 2006gy (Smith et al. 2007). Among these discoveries, the most optically energetic event known is 2006gy (Smith et al. 2010).

In order to compare SN 2008fz with the energetic SN 2006gy, we transformed the KAIT R -band magnitudes given by Smith et al. (2007) to V magnitudes. The KAIT photometry for SN 2006gy, like the CSS data for SN 2008fz, was taken unfiltered and transformed to a standard system. However, photometry for SN 2006gy must be corrected for the very high internal extinction from SN 2006gy's host galaxy (Smith et al. 2007), $A_R = 1.25$, as well as the moderate line-of-sight Galactic extinction, $A_R = 0.43$. This high total extinction for SN 2006gy

⁸ <http://www.ipac.caltech.edu/2mass/releases/allsky/doc/exlsup.html>

is justified by the presence of a red continuum relative to typical type II_n supernovae as well as deep Na I D absorption lines. Smith et al. (2007) assumed the standard Galactic extinction law when deriving the reddening for SN 2006gy. Using this same extinction law the total *V*-band extinction of SN 2006gy is 2.1 mag. As SN 2006gy is a type II_n SN, some of the observed extinction could come from the surrounding CSM. Therefore, it is not clear how accurate Smith et al.'s (2007) value is. At peak brightness the (*V* − *R*) color of SN 2006gy is 0.57 ± 0.14 (Agnolotto et al. 2009). We therefore shift the transformed *R*-band magnitudes by the measured *V* − *R* color difference to obtain approximate *V* magnitudes. Again we note that, although the color of SN 2006gy would clearly evolve, both KAIT and CSS images were taken unfiltered and neither data set is corrected for evolution of the supernova's color. After the color transformation, the KAIT *V*-band peak is 0.06 mag brighter than measured by Agnoletto et al. (2009; well within the 0.13 mag measurement uncertainty).

As noted above, the CSS photometry of SN 2008fz does not constrain the exact explosion time (other than that the SN was not visible three months prior to discovery to a limit of $V = 20$). Based on the similarity of the light curve to SN 2006gy, we assume that the rise times were similar. However, the time of peak brightness is well constrained. In Figure 3, we present the light curves of SN 2008fz in relation to the two ELSNe, SN 2006gy (transformed to *V*) and SN 2007bi (Gal-Yam et al. 2009). For comparison, we also display two supernovae with normal luminosities, the type II_n SN 1999E (Rigon et al. 2003) and the type Ia SN 1999ee (Stritzinger et al. 2002). By integrating the flux from 2008fz over the 88 days of observations, while correcting for time dilation ($1 + z$) but not applying a bolometric correction, we calculate a total radiated energy of $E_{\text{rad}} = (1.4 \pm 0.2) \times 10^{51}$. As this is based on a partial light curve, the value provides a firm lower limit on the total energy emitted by SN 2008fz. Smith et al. (2007) found that SN 2006gy radiated $(1.2 \pm 0.2) \times 10^{51}$ erg over their full light curve. Over the same 88 day time window about maximum light, we find that SN 2006gy radiated 1.0×10^{51} erg.

During the first 65 days after the maximum light SN 2006gy declined at an average rate of 0.020 ± 0.001 mag day^{−1}, whereas SN 2008fz declined at 0.018 ± 0.001 mag day^{−1} (corrected for the time-dilation stretch). The combined optical energy and decline rates suggest that SN 2008fz was more energetic in total optical emission. However, there is some evidence that SN 2006gy may have had a slightly longer rise time than SN 2008fz. Nevertheless, SN 2008fz was ~ 0.5 mag more luminous than SN 2006gy at peak and continually brighter during the entire period that it was observed by CSS. As noted above, the peak luminosity of SN 2006gy was derived assuming a significant reddening correction. Although there is little evidence of a significant reddening in the spectrum of 2008fz, the presence of extinction within the host galaxy would mean that SN 2008fz's absolute luminosity is underestimated. Thus, SN 2008fz may have been even more luminous and energetic. An exact comparison of the luminosity and energy of SN 2008fz and SN 2006gy is not possible without knowing the difference in the response of the KAIT and CSS systems. Such a comparison may be possible in the future using observations of common standard stars.

7. RESULTS AND DISCUSSION

SN 2008fz is possibly the most optically energetic supernova ever discovered. The early and late time spectra clearly show

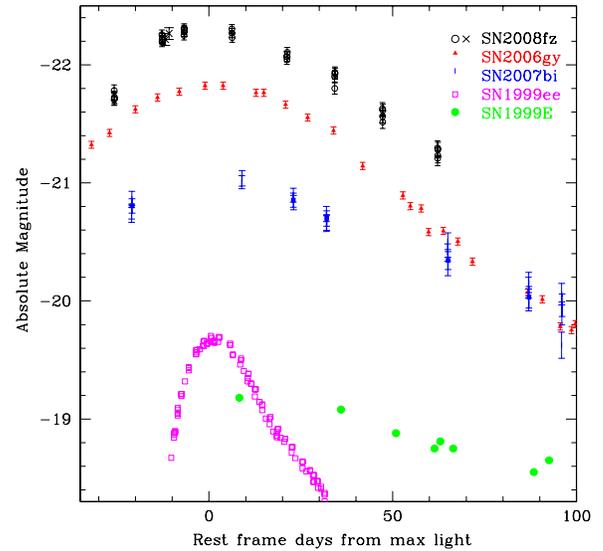


Figure 3. Comparison of the absolute *V*-band magnitudes of SN 2008fz with ELSN and normal-luminosity supernova. Open circles: CSS measurements for SN 2008fz. Crosses: measurements of SN 2008fz made with the Palomar 1.5 m. Triangles: KAIT measurements for ELSN 2006gy from Smith et al. (2007), transformed from the *R* to *V* band (see the text for details). Filled boxes: CSS measurements for ELSN, SN 2007bi (Gal-Yam et al. 2009). Open boxes: measurements for the normal-luminosity type Ia SN 1999ee from Stritzinger et al. (2002). Large dots: measurements for the normal-luminosity type II_n SN 1999E from Rigon et al. (2003).

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

that this was a type II_n event at $z = 0.133$. Our calibrated photometry suggests that this event is significantly brighter than the luminous type II_n SN 2006gy (Smith et al. 2007). SN 2008fz may not be the most luminous event since SN 2005ap had an unfiltered peak absolute magnitude of $M_u = -22.7$ (Quimby et al. 2007). However, based on CSS data the *V*-band absolute magnitude of SN 2005ap was less than SN 2008fz (A. J. Drake et al. 2010, in preparation). The rapidly declining SN 2008es appears to have had a similar peak magnitude to SN 2008fz ($M_V = -22.2$, Gezari et al. 2009; $M_V = -22.3$, Miller et al. 2009).

Additional spectroscopically confirmed ELSNe have also been discovered by CRTS, including two luminous type Ic supernovae, SN 2008iu (Drake et al. 2009b) and the most luminous type Ic event, SN 2009de (Drake et al. 2009c). Both of these events were brighter than the type Ic, pair-instability candidate supernova, SN 2007bi (Gal-Yam et al. 2009).

The similarity of SN 2008fz to SN 2006gy suggests the possible existence of a population of very bright, energetic supernovae that has gone undetected in previous supernova surveys. Prior deep imaging by PQ shows that SN 2008fz must reside within a faint galaxy ($M_V > -17$). This type of environment is expected for pair-instability supernovae with high-mass, very low metallicity progenitor stars (Woosley et al. 2007). However, much more work is required to test whether SN 2008fz was a pair-instability supernova. In the case of SN 2006gy, the event appeared near the bulge or spheroid of the SO/a galaxy NGC 1260 (Bernardi et al. 2002). Although, Ofek et al. (2007) noted that the galaxy is near solar metallicity, Smith et al. (2007) noted the likely presence of ongoing star formation. Given the high level of extinction observed for SN 2006gy, it is also possible that it originated in an associated, low-metallicity dwarf galaxy lying behind NGC 1260. Alternately, both of these energetic supernovae could come from more massive versions

of the LBV star that appears to be responsible for SN 2005gl (Gal-Yam & Leonard 2009).

We thank the anonymous referee for comments that helped significantly to improve this Letter. The CRTS survey is supported by the U.S. National Science Foundation under grants AST-0407448, AST-0909182, and CNS-0540369. The PQ survey is supported by the U.S. National Science Foundation under grants AST-0407448 and AST-0407297. The CSS survey is funded by the National Aeronautics and Space Administration under grant NNG05GF22G issued through the Science Mission Directorate Near-Earth Objects Observations Program. J.L.P. is supported by NSF grant AST-0707982. Support for M.C. is provided by Proyecto Basal PFB-06/2007, by FONDAP Centro de Astrofísica 15010003, and by a John Simon Guggenheim Memorial Foundation Fellowship.

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