Superluminous Supernovae

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Abstract. Not long ago the sample of well studied supernovae, which were gathered mostly through targeted surveys, was populated exclusively by events with absolute peak magnitudes fainter than about -20. Modern searches that select supernovae not just from massive hosts but from dwarfs as well have produced a new census with a surprising difference: a significant percentage of supernovae found in these flux limited surveys peak at -21 magnitude or brighter. The energy emitted by these superluminous supernovae in optical light alone rivals the total explosion energy available to typical core collapse supernovae ($> 10^{51}$ erg). This makes superluminous supernovae difficult to explain through standard models. Adding further complexity to this picture are the distinct observational properties of various superluminous supernovae. Some may be powered in part by interactions with a hydrogen-rich, circumstellar material but others appear to lack hydrogen altogether. Some appear to be powered by large stores of radioactive material, while others fade quickly and have stringent limits on 56-Ni production. In this talk I will discuss the current observational constrains on superluminous supernova and the prospects for revealing their origins.

Keywords. supernovae: general

Until nearly the turn of the century, the sample of supernovae discoveries with peak absolute magnitudes brighter than about -19 in the optical was dominated by Type Ia events, only a handful of supernovae connected to the deaths of massive stars were observed to cross this threshold, and there were no well studied supernovae brighter than -21 magnitude. Richardson *et al.* (2002) studied the peak magnitude distributions of supernovae including events listed in the Asiago Supernova Catalog (Barbon *et al.* 1999) for which only minimal discovery reports were available. A few events were noted as possibly brighter than -21 magnitude, although most of these can likely be explained by calibration errors†.

The absolute magnitude distribution expected for a local, *volume* limited survey is shown in Fig. 1. None of the supernovae in the volume limited samples of the Lick Observatory Supernova Search (LOSS) have peak magnitudes brighter than -20 (Li *et al.* 2011). A flux limited survey was conducted by the Supernova Cosmology Project in the Spring of 1999, which perhaps netted the first high luminosity ($M < -21$) supernova discovery, SN 1999as (Deng *et al.* 2001). However, it would be several more years before the first unambiguous superluminous supernova (SLSN) was detected and confirmed by multiple research groups.

SN 2006gy proved to be a rather surprising event. At just 72 Mpc, this supernova was observed to peak at about 14th magnitude–bright enough to be studied with even small aperture telescopes or photon hungry instruments on the larger ones–or an absolute

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† For example, the reported magnitude for SN 1988O places it near -22 mag absolute, but it was spectroscopically connected to the subluminous Type Ia class (Branch *et al.* 1993), and the magnitude given in IAUC 4601 was likely incorrect (J. Mueller, priv. comm.).
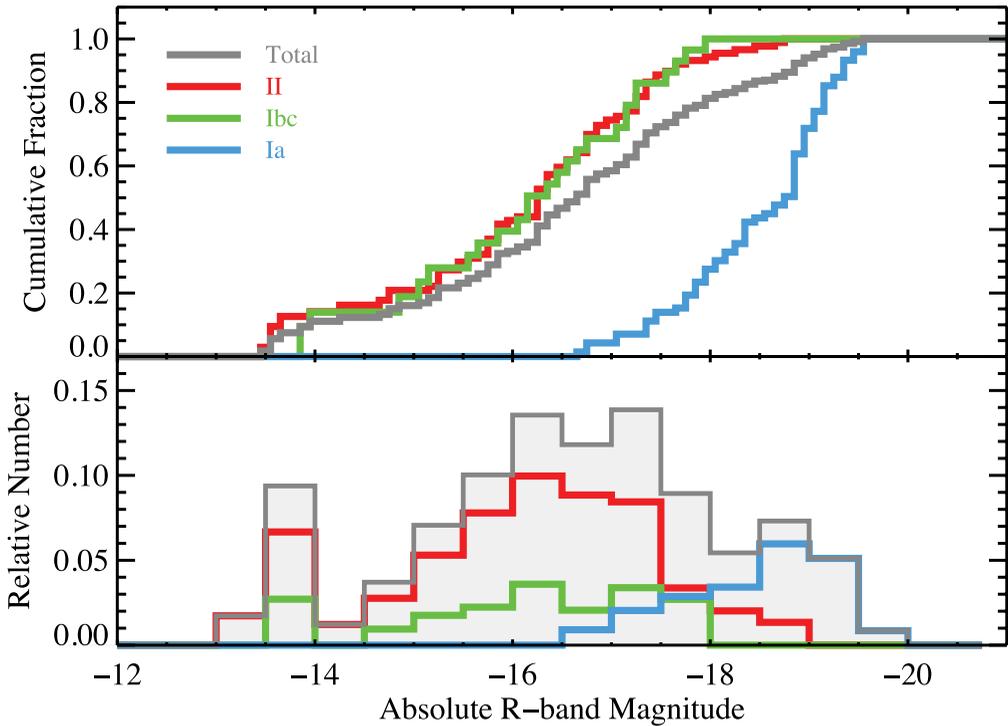
Figure 1. Peak R-band magnitude distribution for supernovae in an local, volume limited sample. Based on data from the Lick Observatory Supernova Search (Li *et al.* 2011).

magnitude of nearly -22 after extinction correction. And SN 2006gy did not just peak at 100 times the optical luminosity of a typical supernova, it remained brighter than normal Type Ia supernovae for 5 months, and brighter than any other well studied supernovae for 3 months (e.g. Smith *et al.* 2007; Ofek *et al.* 2007). Integration of the light curve shows the energy radiated in photons exceeds 10^{51} erg. Just how this energy was generated and how such a massive star (likely $M_{MS} > 100 M_{\odot}$) came to be in the core of a giant, metal rich galaxy, remain active research topics.

In any case, SN 2006gy clearly demonstrated that high luminosity supernovae can exist in the local universe, and this realization helped in the discovery of additional SLSNe. In particular, SN 2005ap had (obviously) been detected earlier, but it was difficult to accept the consequences of its spectroscopically determined redshift. At $z = 0.28$, SN 2005ap was possibly even more luminous than SN 2006gy (Quimby *et al.* 2007; a definitive statement remains difficult given the unfiltered nature of the light curve). The spectra (see Fig. 2) are similar to SN 2006gy in the sense that the strong P-Cygni profiles evident in normal supernova are lacking, leaving mainly featureless blue continua, but with an important difference: SN 2006gy shows a complex Hα profile (Smith *et al.* 2010), while SN 2005ap appears to lack hydrogen all together. SN 2005ap also shows a series of broad absorption dips near rest frame 4200Å (identified as OII; Quimby *et al.* 2011), which are not present in the spectra of SN 2006gy.

Another SLSN detected by the Robotic Optical Transient Search Experiment (ROTSE-IIIb; Akerlof *et al.* 2003) supernovae searches shows further spectroscopic differences. Spectra of SN 2008es shows a broad HeII λ4686 line early on and broad Hα develops later, but the narrow emission lines such as those present in SN 2006gy are not observed
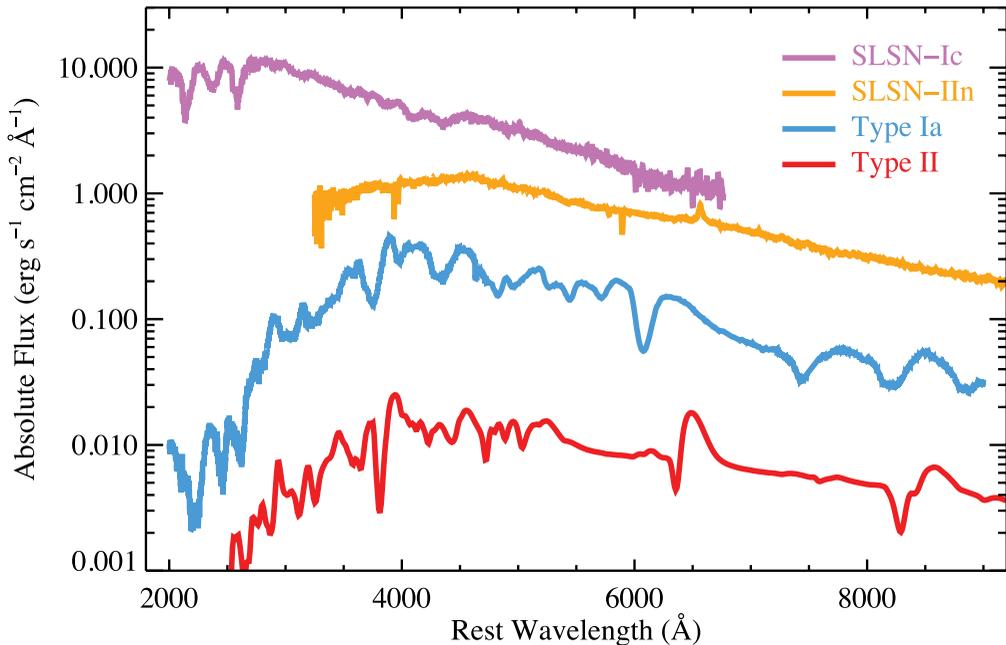
Figure 2. Spectra of normal and superluminous supernovae taken near peak (optical) bright-ness. The SLSN-Ic spectrum is a composite of SCP06F6 (Barbary *et al.* 2009), PTF09cnd (Quimby *et al.* 2011), and SN2005ap (Quimby *et al.* 2007), the SLSN-IIn is SN 2006gy from Smith *et al.* (2007), the Type Ia is a combination of SN 1992A (Kirshner *et al.* 1993) and SN 2003hv (Leloudas *et al.* 2009), and the Type II is a Nugent template (see supernova.lbl.gov/∼nugent/nugent_templates.html). Flux values have been scaled to typical val-ues for each class. SLSNe are about 10 times brighter than typical Type Ia supernovae in the optical, but in the UV, they can be a thousand times more luminous.

(Miller *et al.* 2009; Gezari *et al.* 2009). SN 2008es was also the first SLSNe to be studied in the UV with the *Swift* (Gehrels *et al.* 2004) Ultraviolet/Optical Telescope (UVOT; Roming *et al.* 2005). These data constrain the broad band spectral energy distribution and its time evolution, which can be fit relatively well with a cooling black body. The temperatures derived from this fit show that SN 2008es stayed rather hot for over a month even as the photosphere expanded at $\sim 10000\,\mathrm{km\,s^{-1}}$. The lack of adiabatic cooling thus suggest a large initial radius at (or beyond) the limits of super red giant envelopes.

The Palomar Transient Factory (PTF; Law *et al.* 2009; Rau *et al.* 2009) began dis-covering a steady supply of SLSNe from its commissioning in 2009. Some of the first of these, PTF09atu, PTF09cnd, SN 2009jh, and SN 2010gx were found to be hydrogen poor SLSNe similar to SN 2005ap (SLSN-Ic; Quimby *et al.* 2011; see also Pastorello *et al.* 2010). These supernovae were also followed-up in the UV using *Swift*. Like SN 2008es, there is only slow cooling over time even as the ejecta expand at $> 10000\,\mathrm{km\,s^{-1}}$. Unlike SN 2008es, however, these events lack hydrogen. There are no stripped envelop progenitor systems known (to the author at least) with bound, hydrogen poor material distributed at $\sim 10^{15}$ cm, which suggests an unbound configuration.

Prior to the start of the PTF survey proper, a "dry run" was conducted to test the follow-up paradigm that would come to characterize the future survey. This resulted in the intensive follow-up of SN 2007bi (Gal-Yam *et al.* 2009). The spectra of SN 2007bi lack hydrogen (and strong SiII $\lambda6355$), and it can thus be classified as a SLSN-Ic. However,
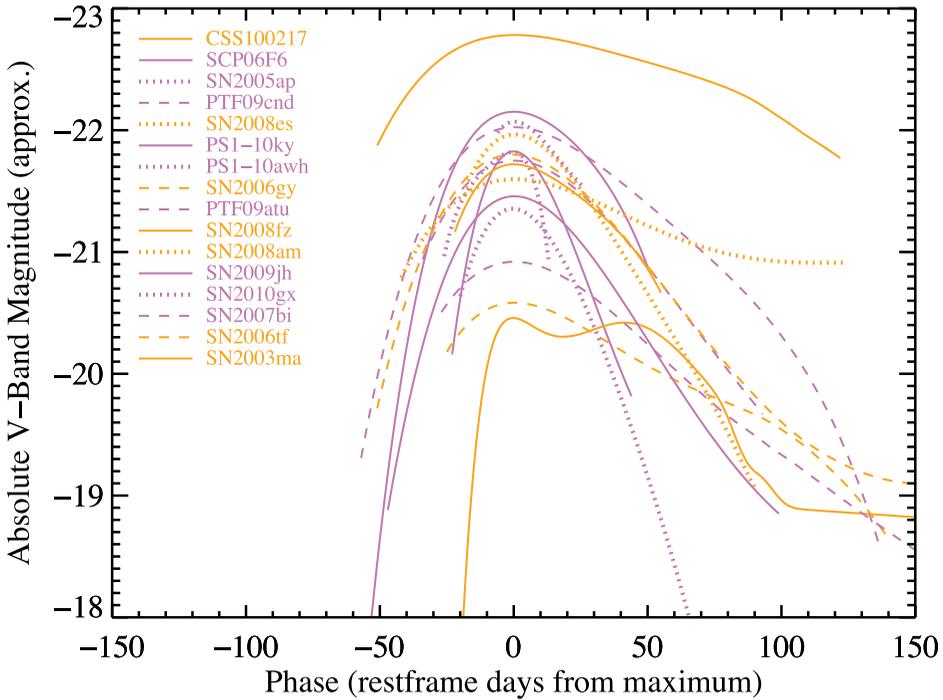
Figure 3. Approximate light curves in the rest frame, absolute V-band magnitudes for a collection of published SLSNe, including the SLSNe candidate, CSS100217. Data adapted from Drake *et al.* 2011, Barbary *et al.* 2009, Quimby *et al.* 2007, Quimby *et al.* 2011, Gezari *et al.* 2009, Miller *et al.* 2009, Chomiuk *et al.* 2011, Smith *et al.* 2007, Drake *et al.* 2010, Pastorello *et al.* 2010, Gal-Yam *et al.* 2009, Smith *et al.* 2008, and Rest *et al.* 2011. The light curve of SN 2006tf is supplemented with unpublished ROTSE-IIIb observations. Note that for some objects (e.g. SN 2005ap) only unfiltered data are available, and for others (e.g. SCP06F6) the available pass bands do not sample the rest frame V-band. This and the simplistic k-corrections used may lead to systematic errors of up to a few tenths of a magnitude.

there is a key difference from the SN 2005ap-like SLSNe-Ic: SN 2007bi shows photometric and spectroscopic evidence for a large ^{56}Ni yield while this is excluded for the SN 2005ap-like events (Quimby *et al.* 2011). In particular, the light curve of SN 2007bi fades by about 1 magnitude every 100 days, as expected from the decay of ^{56}Ni's daughter product, ^{56}Co into ^{56}Fe. Other SLSN-Ic like PTF09cnd fade more rapidly and limit the production of ^{56}Ni to $\lesssim 1 M_\odot$. The light curves of various SLSN-Ic and hydrogen rich SLSN-II are shown in Fig. 3.

Some SLSNe, like SN 2007bi for example, may be powered mainly by radioactive decay ^{56}Ni, but others (e.g. PTF09cnd) reach peak luminosities too great to be explained by the ^{56}Ni production allowed by their late time photometric limits. Some SLSNe, like SN 2006gy for example, may be powered mainly by interactions of the SN ejecta with pre-SN winds, but others (e.g. SN 2008es) show no obvious signs of such ongoing interactions. It may therefore be that there are fundamentally different engines powering these observationally distinct events. On the other hand, the principle sources of power may yet be related and it is stochastic differences in the final years of the progenitors that affect the observations.

A possible process connecting the engines powering at least some SLSNe is the conversion of kinetic energy in the supernova ejecta into radiant energy via interaction with

slower moving material. This is most clearly evident in SLSNe-IIn such as SN 2006gy, where the narrow emission features require slow moving material in the vicinity of the explosion (fast moving material would give rise to broad, not narrow emission features). It is possible that events like SN 2008es also derive some of their power from ejecta/CSM interactions, but in this case the distribution of CSM must be fast moving or truncated such that the slow moving material has mostly been overtaken by the SN ejecta by the time the spectroscopic observations begin. Extending this model further, if the CSM was depleted of its hydrogen (for example, if the progenitor was striped of its hydrogen long before the SN explosion), the ejecta/CSM interaction could in principle provide a similar transfer of kinetic energy into photons. A possible source for such hydrogen poor CSM may be material cast off by instabilities in the cores of very massive stars in their final years (e.g. Woosley *et al.* 2007; Umeda & Nomoto 2008).

Another possibility is that the high luminosities are achieved by thermalization of energy deposited into an expanding SN envelope by a compact remnant that formed as a result of the core-collapse. In the magnetar model (Kasen & Bildsten 2010; Woosley 2010), rotational energy from the nascent neutron star is transferred (by an unspecified process) to the ejecta mass. Kasen & Bildsten 2010 show that such models can reproduce at least the light curves of events like SN 2008es and even SN 2007bi with plausible initial rotation periods and magnetic field strengths. In this case, the progenitors could be of more modest initial masses.

We can get some insights into the progenitors by studying the broader environments in which these SLSNe explode (e.g. their hosts). Neill *et al.* 2011 have studied the NUV-Optical color vs. Optical magnitude distribution of a number of high luminosity supernovae and they find a preference for fainter, bluer hosts when compared to the broader population of GALEX to SDSS matched galaxies. However, the sample studied is still consistent with the giant to dwarf host distribution of normal luminosity core-collapse supernovae from PTF (Arcavi *et al.* 2010).

Looking at the SLSNe samples from ROTSE-IIIb and PTF, there is not an obvious preference among SLSNe-IIn for dwarf or giant hosts (both surveys find SLSNe-IIn in hosts of various luminosities, faint to bright). However, the SLSN-Ic do appear to prefer dwarf host galaxies. There is possibly only one SLSN-Ic out of more than a dozen discoveries that is hosted by a giant.

The rates of SLSNe can also offer some constraints on the progenitor systems when the birth rates of such progenitors are known. Based on the ROTSE-IIIb sample, *preliminary* results (Quimby *et al.* in prep.) suggest that there is one SLSN (of any type) for about every 1000 core-collapse supernova in the local ($z \sim 0.2$) universe. If we assume that the distribution of SLSN-Ic is skewed brighter than the SLSN-II distribution, as hinted at by the ROTSE-IIIb sample at least, then this would imply that most SLSN have hydrogen, since ROTSE-IIIb has found a roughly equal number of each while the SLSN-Ic would be drawn from a larger volume in this case. The SLSN-Ic rate would then be about one for every 10^4 core-collapse supernovae.

This is still a sufficiently high rate, and the SLSNe are luminous enough that it should be possible with existing instruments to detect SLSNe out to very high redshifts (e.g. $z \sim 4$ with Subaru). This opens the possibility of using SLSNe to glean insights into the distant universe. First of all, if the SLSNe are connected to the most massive stars (as seems to be the case at least for SN 2006gy), then their rates should evolve with redshift with the cosmic star formation history. If there are changes in the IMF such as a "top-heavy" IMF at higher redshifts, then we could expect more SLSNe per unit star formation. Thus checking if the distant to local SLSN rate differs from the distant to local SFR could be one way to search for evolution in the IMF. Additionally, absorption

features imprinted in the otherwise smooth continua of SLSNe could carry information about the chemistry of distant stellar nurseries. Considering the coming suite of wide field cameras on moderate to large aperture telescopes, the future of SLSNe research appears, well, bright.

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Discussion

KATZ: What are the upper limits for X-ray emission from the SLSNe?

QUIMBY: The only SLSN I know of with a reported X-ray detection is SN 2006gy (Smith *et al.* 2007), and not everyone agrees that this is actually a detection. Upper limits exist for an additional number of SLSN-IIn (e.g. Chatzopoulos *et al.* 2011) and SLSN-Ic (e.g. Quimby *et al.* 2011), but these are not often all that constraining given the typically

large distances: the limits near optical maximum are typically around $10^{43}\,\mathrm{erg\,s^{-1}}$ in the *Swift*/XRT band, which is lower than the optical luminosities.

GAL-YAM: I know of no detections in X-ray, including, in my opinion, SN 2006gy.

METZGER: How do the host galaxies of SLSN-Ic compare to those of GRB hosts?

QUIMBY: The sample of SLSN-Ic hosts is still small, but it would appear that SLSN-Ic may favor even lower luminosity hosts than do GRBs.