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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 could 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

In the year 2000, after decades of surveys for time variable objects, the highest luminosity supernova published was SN 1999cy at $M_V < -20.1$ (Turatto *et al.* 2000; excluding light attributable to the optical afterglows of gamma-ray bursts). At that time, there were a handful of candidates for even more luminous supernovae, but these were still–and largely remain–unvetted by the refereeing process. The true luminosities of these objects are uncertain. Most are based simply on the discovery data presented in IAU Circulars and often include “quick and dirty” magnitude estimates divined from photographic plates in fields lacking reliable comparison stars†.

In 1995, the Supernova Cosmology Project (SCP) announced eleven high redshift supernovae from their ongoing, CCD based, batch discovery search program (Perlmutter *et al.* 1995). Ten of these proved to be Type Ia supernovae, and several of these would be used to reveal the accelerating expansion of our universe (Perlmutter *et al.* 1999; see also Riess *et al.* 1998). The eleventh discovery, the probable Type IIn SN 1995av, is perhaps the first well observed, high-luminosity supernova ($M_R < -20.8$). While a mere footnote to the larger discovery of our accelerating universe, SN 1995av gives the first indication that non-targeted, flux limited searches are sensitive to rare, high luminosity events that could easily have been passed over previously. It also suggested that such discoveries could prove to be a non-negligible contributor to such surveys.

The high redshift oriented SCP spawned a low redshift counterpart in the Spring of 1999 (and later the SNFactory, Aldering *et al.* 2002), tasked with selecting nearby

† For example, for its distance, the reported magnitude of SN 1988O would correspond to an absolute magnitude of about −22, but this source was later classified as a subluminous SN Ia. Given this classification, the magnitude reported in the announcement was likely incorrect (J. Mueller, priv. comm. 2009).

supernovae in a manner equivalent to the distant search. This survey quietly netted two discoveries of unprecedented luminosities: SNe 1999as and 1999bd (Knop *et al.* 1999, Nugent *et al.* 1999). Deng *et al.* (2001) show that the Type Ic SN 1999as reached a peak luminosity of at least $M < -21.5$, and the discovery report for the Type IIn SN 1999bd implies a peak of $M < -21.6$. For comparison, Li *et al.* (2011a) have presented a volume limited sample of supernova discoveries from their targeted LOSS program, and the brightest of these 179 events is the Type Ia supernova SN 2006lf at $M_R = -19.55 \pm 0.12$.

Following in the footsteps of the SCP and SNFactory, the Texas Supernova Search (TSS; Quimby 2006) began patrolling the skies in 2004 with a modified version of the same image subtraction code. The program also had a similar objective of discovering supernovae with as little bias to host environment as possible. The TSS was relatively modest in its scope (the main survey instrument was a 0.45 m telescope, ROTSE-IIIb), but this was not without its advantages. As few discoveries were made and these were all rather bright ($m \gtrsim 18$ mag), spectroscopic confirmation could be carried out for all new supernova candidates selected. The main facilitator for this follow-up was the 9.2 m Hobby-Eberly Telescope, which is queue scheduled and permits low resolution spectroscopic observations to be triggered as needed, even in bright time when most observatories switch to high resolution or NIR instruments. The TSS began finding significant outliers from the established supernova population almost immediately. The fourth supernova discovered by the TSS, SN 2005ap, would prove to be ten times more luminous than most Type Ia supernovae, and at $M = -22.2$, it remains one of the most luminous supernovae ever found.

Since this discovery, several new optical transient searches have come on line including the Catalina Real-Time Transient Survey (CRTS), the Palomar Transient Factory (PTF; now iPTF), Pan-STARRS, La Silla-QUEST (LSQ), Skymapper, and the Dark Energy Survey. Many of these searches have reported supernovae with peak luminosities brighter than $M = -21$.

To be considered "superluminous," a supernova should be both brighter than the brightest normal (non-interacting) SNIa and significantly brighter than peak magnitude distributions of normal thermonuclear and core-collapse events. Figure 1 shows the pseudo-absolute magnitude distributions of core-collapse and Type Ia supernovae from the LOSS volume limited sample (Li et al 2011a). Pseudo-absolute magnitudes are the observed magnitudes corrected for distance and Galactic extinction, but not corrected for any absorption by the host environment. We have scaled the distributions to the volumetric rates derived from the LOSS search (Li *et al.* 2011b) to give the cumulative rate of events fainter than a given magnitude (top panel), and the rates per half magnitude bin (lower panel). The distribution of core collapse supernovae is reasonably well approximated by a Gaussian distribution with $M_{\rm peak} = -16.4$ and $\sigma = 1.0$ mag (dotted line in the figure), ignoring the surplus of events between $-13.5 < M_{\rm peak} < -14.0$. The resemblance to a Gaussian is surprising given that the sample is not corrected for host absorption (we would expect an intrinsically Gaussian distribution to be skewed to fainter magnitudes by dust).

The most luminous SN Ia published so far, SN 2007if, reached a peak optical magnitude of about $M = -20.4$ (Scalzo *et al.* 2010, Yuan *et al.* 2010). Yasuda & Fukugita (2010) have calculated the intrinsic luminosity function from the SN Ia discovered by the SDSS-II. They find a Gaussian distribution with $M_B = -19.423$ (roughly $M_R = -19.5$ assuming a normal spectrum) and $\sigma = 0.237$.

We define superluminous supernovae to be events with peak absolute magnitudes in the optical that are brighter than any known, non-interacting Type Ia supernova, or $M_{\rm peak} \leqslant -20.5$. The most luminous interacting SN Ia published so far, SN 2005gj (Aldering *et al.*

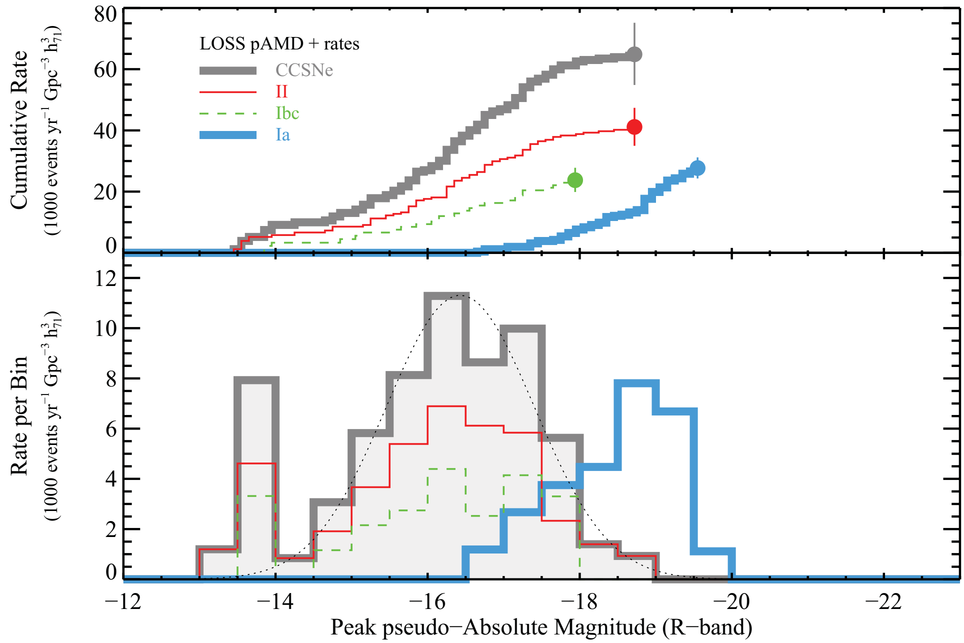

Figure 1. Peak pseudo-absolute R-band magnitude distribution for supernovae in an local, volume limited sample demonstrating that normal supernovae do not get brighter than about $M = -20$ mag. Based on data from the Lick Observatory Supernova Search Li *et al.* 2011a.

2006), reached roughly this limit, and it is possible that some higher luminosity Type IIn events may have a similar physical origin (cf. Dilday *et al.* 2012; Silverman *et al.* in prep.). This cutoff is about 4σ brighter than either the CCSNe distribution from LOSS or the SN Ia distribution from the SDSS-II sample (Li *et al.* 2011a, Yasuda & Fukugita 2010).

We have searched the literature for all known supernovae with peak magnitudes brighter than $M_{\rm peak} \leqslant -20.5$. Table 1 lists the 22 supernovae brighter than this cut-off that have so far been published, and Table 2 lists 28 further events that have been announced. Note that we exclude from this list objects with lower intrinsic luminosities that have been magnified via gravitational lensing even when this raises the effective luminosity above our defined threshold (e.g. the normal Type Ia supernova, PS1-10afx; Chornock *et al.* 2013, Quimby *et al.* 2013b).

Although the sample is relatively small, some events share certain characteristics that distinguish them from the others. The most basic division is that the spectra some SLSNe do not show obvious hydrogen features (SLSN-I), but others do (SLSN-II). Figure 2 shows representative spectra of SLSN-I and SLSN-II compared to examples of the more familiar SNIa and SNII classes. The light curves of the published SLSN sample are shown in figure 3. It is evident from this sample that there is significant dispersion in both rise and decay time scales. These differences could indicate some diversity in the progenitors of SLSNe.

Some SLSNe, like SN 2007bi for example, may be powered mainly by radioactive decay ^{56}Ni, but others (e.g. PTF09cnd, SN2010gx) reach peak luminosities too great to be explained exclusively by the ^{56}Ni production allowed by their late time photometric limits (Pastorello *et al.* 2010, Quimby *et al.* 2011, Chen *et al.* 2013). Some SLSNe, like SN 2006gy for example, may be powered mainly by interactions of the SN ejecta with pre-SN winds (e.g. Smith *et al.* 2007), but others (e.g. SN 2008es; Miller *et al.* 2009, Gezari *et al.* 2009) show no obvious signs of such ongoing interactions. It may therefore

Table 1. Published SLSNe

Name	RA	Dec	z	Type	Peak Mag[a]	Reference
SN 2003ma	05:31:01.9	−70:04:15.9	0.289	IIn	$M = -21.6$	Rest *et al.* 2011
SN 2005ap	13:01:14.8	+27:43:31.4	0.283	Ic	$M = -22.2$	Quimby *et al.* 2007
SN 2005gj	03:01:12.0	+00:33:14	0.0616	IIna	$M = -20.5$	Aldering *et al.* 2006
SN2213-1745	22:13:39.970	−17:45:24.486	2.0458	?	$M_{\rm UV} \sim -21.2$	Cooke *et al.* 2012
SCP 06F6	14:32:27.4	+33:32:24.8	1.189	Ic	$M = -22.1^b$	Barbary *et al.* 2009
SN1000+0216	10:00:05.872	+02:16:23.621	3.8993	?	$M_{\rm UV} \sim -21.4$	Cooke *et al.* 2012
SN 2006gy	03:17:27.1	+41:24:19.5	0.019	IIn	$M = -20.7$	Smith *et al.* 2007
SN 2006oz	22:08:53.6	+00:53:50.4	0.376	Ic	$M = -21.7?$	Leloudas *et al.* 2012
SN 2006tf	12:46:15.8	+11:25:56.3	0.074	IIn	$M = -20.5$	Smith *et al.* 2008
SN 2007bi	13:19:20.2	+08:55:44.3	0.1279	Ic	$M = -21.0$	Galyam *et al.* 2009
SN 2007va	14:26:23.24	+35:35:29.1	0.1907	II?	$M_{\rm IR} = -24.2$	Kozlowski *et al.* 2010
SN 2008am	12:28:36.2	+15:34:49.1	0.2338	IIn	$M = -21.8$	Chatzopoulos *et al.* 2011
SN 2008es	11:56:49.1	+54:27:25.7	0.205	II	$M = -22.0$	Miller *et al.* 2009, Gezari *et al.* 2009
SN 2008fz	23:16:16.6	+11:42:47.5	0.133	IIn	$M = -21.9$	Drake *et al.* 2010
PTF09atu	16:30:24.5	+23:38:25.0	0.501	Ic	$M = -21.6$	Quimby *et al.* 2011
SN 2009jh	14:49:10.1	+29:25:10.4	0.349	Ic	$M = -21.7$	Quimby *et al.* 2011
PTF09cnd	16:12:08.9	+51:29:16.2	0.258	Ic	$M = -21.9$	Quimby *et al.* 2011
CSS100217	10:29:13.0	+40:42:20.0	0.147	IIn?	$M = -22.8$	Drake *et al.* 2011
SN 2010gx	11:25:46.7	−08:49:41.4	0.230	Ic	$M = -21.5$	Pastorello *et al.* 2010, Quimby *et al.* 2011
PS1-10ky	22:13:37.8	+01:14:23.6	0.956	Ic	$M = -21.9$	Chomiuk *et al.* 2011
PS1-10awh	22:14:29.8	−00:04:03.6	0.908	Ic	$M = -21.9$	Chomiuk *et al.* 2011
PS1-11bam	08:41:14.192	+44:01:56.95	1.566	Ic	$M_{\rm UV} \sim -22.3$	Berger *et al.* 2012

[a] Peak magnitudes are in the rest-frame, unfiltered ROTSE-IIIb system except for SN2213-1745, SN1000+0216, and PS1-11bam, which are in the rest frame UV, and SN 2007va, which is in the rest frame IR.
[b] Observed with filters that do not overlap well with the rest frame ROTSE-IIIb system.

Table 2. Announced SLSNe

Name	RA	Dec	z	Type	Peak Mag[a]	Reference
SN1995av	02:01:36.75	+03:38:55.2	0.30	II?	$M_R < -20.8$	IAUC 6270
SN1999as	09:16:30.86	+13:39:02.2	0.1270	Ic	$M_V < -21.5$	IAUC 7128; Deng *et al.* 2001
SN1999bd	09:30:29.17	+16:26:07.8	0.151	IIn	$M < -21.6$	IAUC 7133
SN 2000ei	04:17:07.2	+05:45:53	0.60	II?	$M_R < -19.9$	IAUC 7516
SN 2007bt	14:27:47.73	+12:48:47.1	0.04	IIn	$M < -20.8$	CBET 941
SN 2007bw	17:11:01.99	+24:30:36.4	0.14	IIn	$M < -21.8$	CBET 941
2007-Y-155	01:07:56.083	+00:17:41.51	0.797	Ic	$M_R < -21.3$	Garnavich *et al.* 2010
SN 2009ca	21:26:22.20	−40:51:48.6	0.090	Ic	$M < -20.9$	CBET 1787
SN 2009nm	10:05:24.54	+51:16:38.7	0.21	IIn	$M < -21.3$	CBET 2106
PTF10heh	12:48:52.0	+13:26:24.5	0.338	IIn	$M_R < -21.1$	ATel 2634
PTF10nmn	15:50:02.79	−07:24:42.1	0.123	Ic	$M_R \sim -20.8$	Gal-Yam 2012
PTF10vqv	03:03:06.8	−01:32:34.9	0.452	Ic	$M_R < -21.8$	ATel 2979
SN 2010hy	18:59:32.89	+19:24:25.9	0.19	Ic	$M < -20.7$	CBET 2461, 2476
SN 2010jk	01:12:35.63	+15:28:28.5	0.28	IIn	$M < -20.6$	CBET 2534
SN 2010kd	12:08:01.1	+49:13:32.8	0.101	Ic	$M = -21.1$	CBET 2556; Vinko *et al.* 2012
SN 2011af	02:25:54.36	+10:23:11.1	0.064	IIn	$M < -20.6$	CBET 2659
SN 2011cp	07:52:33	+21:53:30	0.39	IIn	$M_V = -21.7$	ATel 3340, CBET 2733
CSS110406	13:50:57.77	+26:16:42.8	0.143	Ic	$M_R < -21.4$	ATel 3343, 3344, 3351
PTF11dsf	16:11:33.55	+40:18:03.5	0.385	IIn	$M_R < -22.2$	ATel 3465
SN 2011ep	17:03:41.78	+32:45:52.6	0.28	Ic	$M < -21.8$	CBET 2787
PTF11rks	01:39:45.51	+29:55:27.0	0.19	Ic	$M_R < -20.7$	ATel 3841
CSS120121	09:46:13	+19:50:28	0.175	Ic	$M_g = -21.1$	ATel 3873, 3918
CSS111230	14:36:58	+16:30:57	0.245	Ic	$M_V < -21.5$	ATel 3883
LSQ12byu	12:16:05.88	+09:38:07.1	0.34	I?	$M \sim -20.5$	ATel 4063
PTF12dam	14:24:46.20	+46:13:48.3	0.107	Ic	$M_R < -21.2$	ATel 4121
LSQ12dlf	01:50:29.78	−21:48:45.4	0.23?	Ic	$M_V < -21.5$	ATel 4299, 4329
SSS120810	23:18:01.82	−56:09:25.7	0.18	Ic	$M_V < -21.6$	ATel 4313, 4329
CSS121015	00:42:44	+13:28:27	0.286	Ic?	$M_V < -22.5$	ATel 4498, 4512
MLS121104	02:16:43	+20:40:09	0.14	Ic	$M_V < -21.3$	ATel 4599

[a] Peak absolute magnitudes are estimated from the observed magnitudes and redshift only; K-corrections are not applied.

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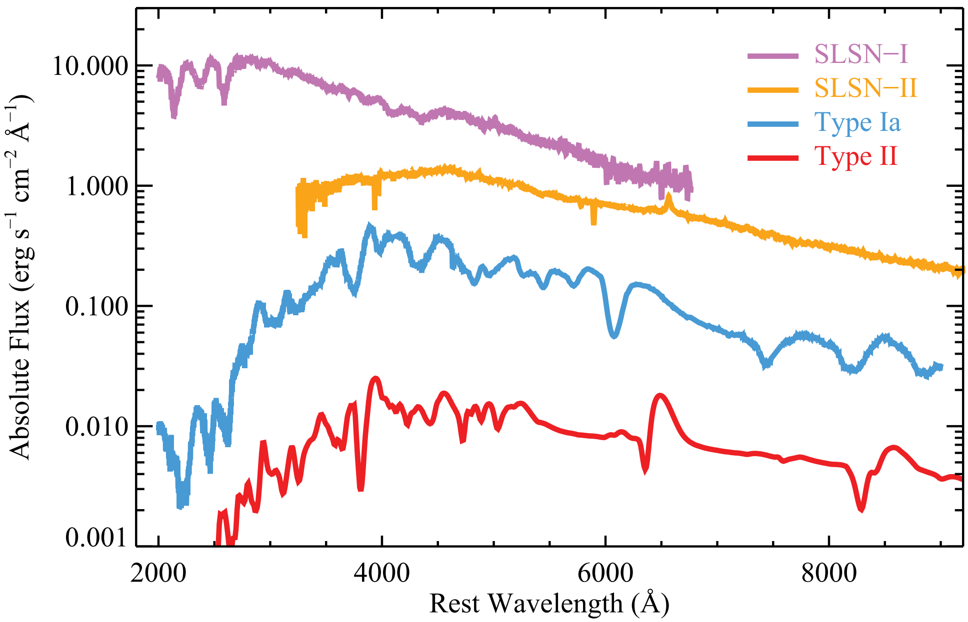

Figure 2. Spectra of normal and superluminous supernovae taken near peak (optical) brightness. The SLSN-I spectrum is a composite of SCP 06F6 (Barbary *et al.* 2009), PTF09cnd (Quimby *et al.* 2011), and SN 2005ap (Quimby *et al.* 2007), the SLSN-II is SN 2006gy from Smith *et al.* 2007, the Type Ia 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 values 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.

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; stochastic differences in the final years of the progenitors may simply color 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 an interaction with slower moving material. This is most clearly evident in SLSNe-II such as SN 2006gy, where the narrow emission features seen in the spectra 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 truncated such that the slow moving material has mostly been overtaken by the SN ejecta by the time the spectroscopic observations begin (Moriya & Tominaga 2012). 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)

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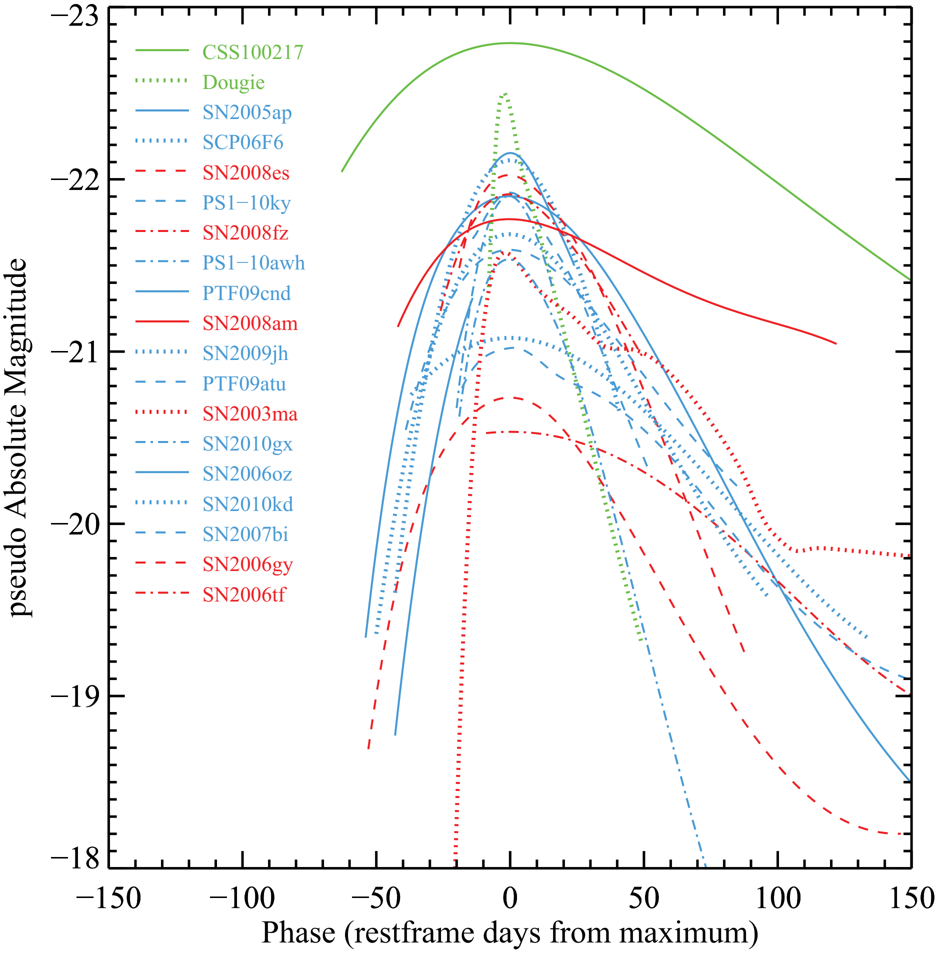

Figure 3. Approximate light curves in the rest frame optical band (ROTSE-IIIb unfiltered system) for a collection of published SLSNe. Adapted from Quimby *et al.* (2013a), which includes data from Quimby *et al.* (2007), Smith *et al.* (2007), Smith *et al.* (2008), Miller *et al.* (2009), Gezari *et al.* (2009), Barbary *et al.* (2009), Gal-Yam *et al.* (2009), Drake *et al.* (2010), Pastorello *et al.* (2010), Drake *et al.* (2011), Quimby *et al.* (2011), Chomiuk *et al.* (2011), Rest *et al.* (2011), and Leloudas *et al.* (2012).

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. More exotic compact remnants may similarly inject additional energy into the SN ejecta (Ouyed *et al.* 2012).

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). Chen *et al.* (2013) have studied the

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galaxy hosting the SLSN-I, SN 2010gx, and find its gas phase metallicity to be particularly low.

Looking at the SLSNe samples from ROTSE-IIIb and PTF, there is not an obvious preference among SLSNe-II for dwarf or giant hosts (both surveys find SLSNe-II in hosts of various luminosities, faint to bright). However, the SLSN-I do appear to prefer dwarf host galaxies. There is possibly only one SLSN-I hosted by a giant galaxy in these low-redshift samples out of more than a dozen discoveries. The high-z discoveries reported so far appear to favor low luminosity hosts as well (e.g. the $M > -18$ host of SCP 06F6; Barbary *et al.* 2009, Quimby *et al.* 2011).

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 small ROTSE-IIIb sample, Quimby *et al.* 2013a find that there is one SLSN (of any type) for about every 400 to 1300 core-collapse supernova in the local ($z \sim 0.2$) universe. This rate appears similar to the local rate of sub-energetic gamma-ray bursts (Soderberg *et al.* 2006, although the errors inherent to these small samples remains large.

Cooke *et al.* (2012) have detected likely SLSNe at redshifts as large as $z = 3.90$. As these high redshift discoveries illustrate, it is now possible to discover SLSN out to redshifts of $z = 4$ or greater. This opens the possibility of using SLSNe to gleam 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 (e.g. Tanaka *et al.* 2012). 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. This is already hinted at by the $z \sim 4$ rate inferred from the Cooke *et al.* search, which may be higher than the star-formation corrected ROTSE-IIIb rate. Thus checking if the distant to local SLSN rate differs from the distant to local star-formation rate 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 (e.g. Berger *et al.* 2012).

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Discussion

Kamble: 1. Are there any early features that can be used to distinguish SLSN from other SN? 2. Based on the proposed models would you expect them to take place in the local universe?

Quimby: The fastest way to identify SLSNe is through spectral observations. SLSN-I in particular show spectral features that are unique among SNe, such as the broad OII features (although some normal luminosity type Ic briefly show this soon after explosion). More generally, the spectra may provide a distance (redshift) that combined with the photometry could indicate a SLSN. A slowly rising light curve can also signal a SLSN candidate, but this requires time to collect. 2. From the older models, there was no expectation to find SLSNe in the local universe, but one of the first discoveries, SN

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2006gy, was found just 73 Mpc away. Some of the more modern SLSN models now allow for such local events.

Milisavljevic: Can you comment on the late-time optical emission from SLSN? I am unfamiliar with such spectra outside of SN 2007bi.

Quimby: SN 2007bi had a slow-evolving light curve that could be monitored for ~ 1 year. This permitted late-time optical spectra to be obtained that exhibited strong iron features consistent with large nickel production. Other SLSN, however, have generally exhibited faster-fading light curves, preventing late-time observations. Currently, there is a dearth of late-time spectra for these objects.