Luminous Supernovae

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ABSTRACT

Supernovae (SNe), the luminous explosions of stars, were observed since antiquity, with typical peak luminosity not exceeding $1.2 \times 10^{43}\,\mathrm{erg\,s^{-1}}$ (absolute magnitude > -19.5 mag). It is only in the last dozen years that numerous examples of SNe that are substantially super-luminous ($> 7 \times 10^{43}\,\mathrm{erg\,s^{-1}}$; < -21 mag absolute) were well-documented. Reviewing the accumulated evidence, we define three broad classes of super-luminous SN events (SLSNe). Hydrogen-rich events (SLSN-II) radiate photons diffusing out from thick hydrogen layers where they have been deposited by strong shocks, and often show signs of interaction with circumstellar material. SLSN-R, a rare class of hydrogen-poor events, are powered by very large amounts of radioactive ⁵⁶Ni and arguably result from explosions of very massive stars due to the pair instability. A third, distinct group of hydrogen-poor events emits photons from rapidly-expanding hydrogen-poor material distributed over large radii, and are not powered by radioactivity (SLSN-I). These may be the hydrogen-poor analogs of SLSN-II.

1. Introduction

Supernova explosions play important roles in many aspects of astrophysics, being sources of heavy elements, ionizing radiation and energetic particles; driving gas outflows and shock waves that shape star and galaxy formation; and leaving behind compact neutron star and black hole remnants. The study of supernovae in general has thus been actively pursued for many decades.

The discovery of super-luminous supernova (SLSN; Figure 1) events in the past decade is now focusing attention on these extreme explosions. The study of SLSNe is motivated, among other things, by their likely association with the deaths of the most massive stars; their potential contribution to the chemical evolution of the Universe and, at early times,

to its reionization; and since they may be manifestations of physical explosion mechanisms that differ from those of their more common and less luminous cousins.

With extreme luminosities extending over tens of days (Fig. 1) and, in some cases, copious ultra-violet (UV) flux, these events may become useful cosmic beacons to study distant star-forming galaxies and their gaseous environments; their long duration, coupled with the lack of long-lasting environmental effects, as well as the fact that they eventually disappear and allow their hosts to be studied without interference, offer some advantages over other probes of the distant universe such as short-lived gamma-ray burst (GRB) afterglows, and luminous high-redshift Quasars.

Accumulated observations suggest that SLSNe can be naturally grouped into three distinct subclasses. In analogy to lower-luminosity explosions, we split SLSNe into hydrogenrich events (SLSN-II) and events lacking spectroscopic signatures of hydrogen (SLSN-I). The latter group is further divided into a minority of events whose luminosity is dominated by radioactivity (SLSN-R) and a distinct majority that require some other source of luminosity, which we simply refer to as SLSN-I. A detailed discussion of these three classes follows in section § 3 below.

Supernovae have been traditionally classified mainly according to their spectroscopic properties (see Filippenko 1997 for a review), while the luminosity of SNe does not play a role in the currently used scheme. In principle, almost all luminous SNe belong to one of two spectroscopic classes: Type IIn, hydrogen-rich events with narrow emission lines which are usually interpreted as signs of interaction with material lost by the star prior to the explosion; or Type Ic, events lacking hydrogen, helium, and strong silicon and sulphur lines around maximum, presumably associated with massive star explosions. However, as will be discussed below, the physical properties implied by the huge luminosities of SLSNe suggest they arise, in many cases, from progenitor stars that are very different from those of their much more common and less luminous analogs; we will propose a provisional extension of the classification scheme that can be applied to super-luminous events.

We consider below SNe with reported peak magnitudes $M < -21 \,\text{mag}$ in any band as being superluminous (Fig. 1). See Supplementary Online Material (SOM) section § 7 for considerations related to determining this threshold.

As will be shown below, modern studies based on large SN samples and homogeneous, CCD-based luminosity measurements, show that SLSNe are very rare in nearby, luminous and metal-rich host galaxies (with the possible exception of luminous SNe IIn). One would therefore expect that older SN surveys, mainly conducted by monitoring nearby galaxies drawn from galaxy catalogs (dominated by luminous, metal-rich objects, we will refer to these

as "targeted surveys" for short) would find very few luminous events. Indeed, Richardson et al. (2002) find no solid detections of super-luminous events resulting from the older targeted surveys (SOM § 8). A handful of events are determined to be "genuinely overluminous" (based on full, modern studies); Richardson et al. list SN 1997cy and SN 1999as; we will add SN 1999bd for which we present here new data. These events, found by the first generation of wide-field non-targeted surveys, are indeed the harbingers of the classes of SLSNe we can finally define today. We note that even the brightest SNe associated with cosmological Gamma-Ray Bursts (GRBs, e.g., the nickel-rich SN 1998bw) fall well below our SLSN threshold.

The structure of this review is as follows: we begin by a brief summary of the observational work leading to the discovery of superluminous SNe in section 2, and we synthesize the accumulated information and define classes of superluminous SNe in 3. We review open questions and controversies in 4, and conclude with a summary in 5.

2. New surveys and the discovery of the first SLSNe

We now know that superluminous SNe are intrinsically rare. Their discovery therefore requires surveys that cover a large volume. The first generation of surveys covering large volumes were designed to find numerous distant Type Ia SNe for cosmological use. These observed relatively small fields of view to a great depth, placing most of the effective survey volume at high redshift. Possible early discoveries of SLSNe by such surveys and their modern counterparts are discussed in the SOM (section § 8).

An alternative method to survey a large volume is to use wide-field facilities to cover a large sky area with relatively shallow imaging. With most of the survey volume at low redshift one can conduct an efficient untargeted survey for nearby SNe. Such surveys provided the first well-observed examples of SLSNe. Prominent initial discoveries were made by the cosmology group at Lawrence Berkeley Labs (Regnault et al. 2001), e.g., SN 1999as (Knop et al. 1999), which turned out to be the first example of the class of extremely ⁵⁶Ni-rich Type I SNe (Gal-Yam et al. 2009) and SN 1999bd (Nugent et al. 1999; Fig. 2), which is probably the first well-documented case of a superluminous SN IIn. The study of the peculiar SN 1997cy by Germany et al. (2000) is perhaps the first modern study of a supernova which is substantially more luminous than the norm, though the absolute peak magnitude of this event (-20.1 mag) as well as those of similar objects discovered since (e.g., SN 2002ic, Hamuy et al. 2003) fall below our fiducial limit defined above, and we do not discuss them any further.

Perhaps the most significant breakthrough in our observational knowledge about the most luminous SN explosions resulted from the operation of the Texas Supernova Survey (TSS) by Quimby and collaborators (Quimby 2006). On 2005 March 3 this survey discovered a hostless transient at mag 18.13, its redshift was z=0.2832, indicating an absolute magnitude at peak around $-22.7\,\mathrm{mag}$, marking it as the most luminous SN discovered until that time (Quimby et al. 2007). SN 2005ap is the first example of the class we will define below as SLSN-I. On 2006 September 18 TSS discovered a bright transient located at the nuclear region of the nearby galaxy NGC 1260 (SN 2006gy; Smith et al. 2007). SN 2006gy suffered substantial host extinction; correcting for this effect, the measured peak magnitude was extreme ($\sim -22\,\mathrm{mag}$; Ofek et al. 2007; Smith et al. 2007). Spectroscopy of SN 2006gy clearly showed hydrogen emission lines with both narrow and intermediate-width components, leading to a spectroscopic classification of SN IIn; this is the prototype and best-studied example of the SLSN-II class. TSS went on to discover additional luminous SNe, as described in the SOM.

During the last few years, several untargeted surveys have been operating in parallel, and now discover and report most SN events (Gal-Yam & Mazzali 2010). The large volume probed by these surveys and their coverage of a multitude of low-luminosity dwarf galaxies have led, as expected (Young et al. 2008) to the discovery of numerous unusual SNe not seen before in targeted surveys of luminous hosts; indeed, it was shown that the SN population in dwarf galaxies is different than that observed in giant hosts (Arcavi et al. 2010). As will be discussed below, luminous SNe generally tend to prefer dwarf hosts (e.g., Neill et al. 2011) and indeed numerous such events are being discovered by this new generation of untargeted surveys. The Catalina Real-Time Transient Survey (CRTS) reported numerous SLSN events including SN 2008fz, an extremely luminous member of the SNLS-II family (Drake et al. 2010). Results from the Palomar Transient Factory (PTF; Law et al. 2009, Rau et al. 2009) include the discovery of SN 2007bi (Gal-Yam et al. 2009), the first extensively-observed example of the radioactively-powered superluminous SN variety (SLSN-R) during a "dryrun" initial phase of the project in 2007, while the more recent PTF discovery of several members of the class of SLSN-I allowed Quimby et al. (2011) to define this class and derive its main properties. The Panoramic Survey Telescope and Rapid Response System 1 (Pan STARRS 1; hereafter PS1, Kaiser et al. 2010) appears to be an efficient program to detect numerous SLSNe at high redshifts (out to $z \sim 1$ and beyond, e.g., Chomiuk et al. 2011; Pastorello et al. 2010). More details about these surveys and their results are provided in the SOM.

3. Emerging classes of superluminous SNe

A total of 18 SLSNe have been discussed in the literature (Table 1). These objects can be grouped into three classes that share observational and physical attributes. We now describe each of these classes in detail.

3.1. SLSN-R

Of all classes of super-luminous SNe, this seems to be the best understood. SLSN-R events are powered by large amounts (several M_{\odot}) of radioactive ⁵⁶Ni (hence the suffix "R"), produced during the explosion of a very massive star. The radioactive decay chain $^{56}\text{Ni}\rightarrow^{56}\text{Co}\rightarrow^{56}\text{Fe}$ deposits energy via γ -ray and positron emission, that is thermalized and converted to optical radiation by the expanding massive ejecta. The luminosity of the peak is broadly proportional to the amount of radioactive ⁵⁶Ni, while the late-time decay (which in the most luminous cases begins immediately after the optical peak) follows the theoretical ^{56}Co decay rate (0.0098 mag day⁻¹). The luminosity of this "cobalt radioactive tail" can be used to infer an independent estimate of the initial ^{56}Ni mass.

The first well-observed example of this group was SN 2007bi, discovered by the PTF "dry run" experiment. An extensive investigation of this object and its physical nature is presented in Gal-Yam et al. (2009). The most prominent physical characteristic of this group, the large ⁵⁶Ni mass, is well-measured in this case using both the peak luminosity ($R = -21.3 \,\mathrm{mag}$) and the cobalt decay tail, followed for > 500 days. Estimates derived from the observations, as well as via comparison to other well-studied events (SN 1987A and SN 1998bw) converge on a value of $\mathrm{M}_{^{56}\mathrm{Ni}} \approx 5 \,\mathrm{M}_{\odot}$. The large amount of radioactive material powers a long-lasting phase of nebular emission, during which the optically thin ejecta are energized by the decaying radio nucleides. Analysis of late-time spectra obtained during this phase (Gal-Yam et al. 2009) provides independent confirmation of the large initial ⁵⁶Ni mass via detection of strong nebular emission from the large mass of resulting ⁵⁶Fe, as well as the integrated emission from all elements, powered by the remaining ⁵⁶Co.

Estimation of other physical parameters of the event, in particular the total ejected mass (which provides a lower limit on the progenitor star mass), its composition, and the kinetic energy it carries, is more complicated. There are no observed signatures of hydrogen in this event (either in the ejecta or traces of CSM interaction) so the ejecta mass directly constrains the mass of the exploding helium core, which is likely dominated by oxygen and heavier elements. Gal-Yam et al. (2009) use scaling relations based on the work of Arnett (1982), as well as comparison of the data to custom light-curve models, and derive an ejecta

mass of $M \approx 100 \,\mathrm{M}_{\odot}$. Analysis of the nebular spectra provides an independent lower limit on the mass of $M > 50 \,\mathrm{M}_{\odot}$, with a composition similar to that expected from theoretical models of massive cores exploding via the pair-instability process. Moriya et al. (2010) postulate a lower ejecta mass ($M = 43 \,\mathrm{M}_{\odot}$); this difference becomes crucial to the controversy about the explosion mechanism of these giant cores (see below). In any case there is no doubt these explosions are produced by extremely massive stars, with the most massive exploding heavy-element cores we know. The same scaling relations used by Gal-Yam et al. (2009) also indicate extreme values of ejecta kinetic energy (approaching $E_k = 10^{53} \,\mathrm{erg}$). Finally, the integrated radiated energy of this event over its very long lifetime is high (> $10^{51} \,\mathrm{erg}$).

SN 1999as was one of the first genuine SLSNe discovered (Knop et al. 1999, see above) and was initially analyzed by Hatano et al. (2001). As shown in Gal-Yam et al. (2009; see also Fig. 3) this object was similar to SN 2007bi during its photospheric phase (reaching –21.4 mag absolute at peak), while the analysis of Hatano et al. (2001) suggests physical attributes (⁵⁶Ni mass, kinetic energy, and ejected mass) that are close to, but somewhat lower than, those of SN 2007bi. Unfortunately, no late-time data have been collected for this object, so it is impossible to conduct the same analysis carried for SN 2007bi, but the similarities suggest this was another member of the SLSN-R class.

Recently, the Lick Observatory Supernova Survey (LOSS; Filippenko et al. 2001) using the 0.75m Katzman Automatic Imaging Telescope (KAIT) discovered the luminous Type Ic SN 2010hy (Kodros et al. 2010; Vinko et al. 2010); Following the discovery by KAIT this event was also recovered in PTF data (and designated PTF10vwg). It is interesting to note that while the LOSS survey is operating in a targeted mode looking at a list of known galaxies, by performing image subtraction on the entire KAIT field of view it is effectively running in parallel also an untargeted survey of the background galaxy population (as noted by Gal-Yam et al. 2008 and Li et al. 2011). It is during this parallel survey that KAIT detected this interesting rare SN, residing in an anonymous dwarf host. While final photometry is not yet available for this event, preliminary KAIT and PTF data indicate a peak magnitude of -21 mag or brighter, and it is spectroscopically similar to other SLSN-R (Fig. 3) suggesting it is also likely a member of this class.

Objects of this sub-class are exceedingly rare (this is observationally the rarest class among the SLSN classes reviewed here; I discuss relative volumetric rates below), and thus additional examples are scarce. During the last two years, the PTF survey has discovered another likely member (PTF10nmn; Gal-Yam 2011; Fig. 3) with similar properties to SN 2007bi, while PS1 may have discovered another similar object at a higher redshift (Smartt 2011). Assembling a reasonable sample of such events may thus be a time-consuming process.

Young et al. (2010) present additional observations of SN 2007bi during the decline

phase, as well as a detailed study of its host galaxy. They find the host is a dwarf galaxy (with luminosity similar to that of the SMC), with relatively low metallicity ($Z \approx Z_{\odot}/3$) - somewhere between those of the LMC and SMC. So, while the progenitor star of this explosion probably had sub-solar metal content, there is no evidence that it had very low metallicity. The host galaxy of SN 1999as is more luminous (and thus likely more metal-rich) than that of SN 2007bi, but still fainter than typical giant galaxies like the Milky Way (Neill et al. 2011), while the host of PTF10nmn seems to be as faint or fainter than that of SN 2007bi. It thus seems this class of objects typically explode in dwarf galaxies.

Considering all available data, it seems there is agreement about the observational properties of this class and their basic interpretation: very massive star explosions that produce large quantities of radioactive 56 Ni. A controversy still exists about the underlying explosion mechanism that leads to this result, either very massive oxygen cores ($M > 50 \,\mathrm{M}_{\odot}$) become unstable to electron-positron pair production and collapse (Gal-Yam et al. 2009), or else slightly less massive cores ($M < 45 \,\mathrm{M}_{\odot}$) evolve all the way till the common iron-core-collapse process occurs (Moriya et al. 2010). We will return to this question below. Assuming, for the sake of the current discussion, that these explosions do arise from the pair instability, a clear prediction of the relevant theoretical models (e.g., Heger & Woosley 2002, Waldman 2008) is that for each luminous, 56 Ni-rich explosion (from a core around $100 \,\mathrm{M}_{\odot}$) there would be numerous less luminous events with smaller 56 Ni masses but large ejecta masses ($M > 50 \,\mathrm{M}_{\odot}$). These should manifest as events with very slow light curves (long rise and decay times) and yet moderate or even low peak luminosities (SOM; Fig. 6).

3.2. SLSN-II

This is probably the most commonly observed class of SLSN. While some examples have been identified early on (e.g., SN 1999bd discussed above; Fig. 2), these objects only became a focus of attention with the discovery of SN 2006gy (Ofek et al. 2007; Smith et al. 2007). Since then, several additional examples have been studied in some detail. SLSN-II show strong hydrogen features in their spectra; these explosions therefore typically occur within thick hydrogen envelopes, making investigations of their nature more complicated, as all information carried by electromagnetic radiation from the exploding core is reprocessed by the outer envelope. For this reason, our knowledge about the energy source (or sources) of these explosions is still mostly speculative. On the other hand, the physics responsible for converting the explosion energy into the observed radiation is better understood.

Two main physical processes have been invoked to explain the conversion of explosion energy to emitted radiation in SLSN-II. The first process assumes the explosion launches a

powerful shock wave expanding outwards from the center of the star; this shock heats the material it traverses until it eventually escapes from the effective outer edge of the star, where this effective edge is the radius around which the material in no longer optically thick to radiation. Note that this effective edge does not necessarily coincide with the physical edge of the star, which we can define here as the radius inside which material is gravitationally bound to the star. The energy deposited by the shock is then slowly re-emitted by the hydrogen-rich material as photons diffuse out, in analogy to the more common and much less luminous Type II-P SNe where this process occurs within the envelope of a red supergiant star. In order to achieve the much higher luminosities observed for SLSN-II, the radius of the effective edge of the star must be substantially larger compared to radii of even the largest red supergiants; deposition of shock energy into more compact stars is radiatively inefficient as the deposited energy is quickly drained by adiabatic expansion. The observed luminosities probably require also an energetic explosion shock. The shape of the light curve is determined mostly by the density structure and composition of the material into which the energy was deposited. In order to explain the large effective radii ($> 10^{15}$ cm) required for this mechanism to work, several options have been suggested. These include very large (bloated) stars (e.g., Gezari et al. 2009), energy deposited into massive (unbound) opticallythick shells ejected by previous eruptions of the exploding star that have expanded to the required radius (e.g., Smith & McCray 2007; Miller et al. 2009) or energy deposited into an optically-thick massive stellar wind (e.g., Ofek et al. 2010; Chevalier & Irwin 2011; Moriya & Tominaga 2011) extending out to the required radius.

The second mechanism invoked in order to convert large explosion energies into optical emission is strong interaction between the expanding ejecta and massive circum-stellar material (CSM), previously lost from the progenitor star. This mechanism converts the kinetic energy carried by the expanding ejecta into radiation via strong shocks, and is commonly invoked for Type IIn SNe. Note that there is no conflict between this process (converting kinetic energy to radiation) and the previous one (converting shock energy stored as internal heat energy into radiation) and both can contribute in any given object; there are some debates in the literature which is dominant for particular cases. Since CSM envelopes can be extremely extended, this process can in principle remain active for many years, and is thus more attractive to explain very long-lived events (e.g., SN 2006tf, Smith et al. 2008; SN 2003ma, Rest et al. 2011). On the other hand, conversion of kinetic energy into radiation should manifest in an observed decline in expansion velocities; this process is therefore disfavored for events showing high expansion velocities that do not decrease significantly with time (e.g., SN 2008es, Gezari et al. 2009). Possible mechanisms invoked to eject large quantities of mass from the star prior to explosions include LBV-like activity (e.g., Smith et al. 2007; 2008) and the pulsational pair instability (e.g. Woosley et al. 2007).

Regardless of the conversion mechanism, the total emitted energy in several recently observed objects ($> 10^{51}$ erg) is challenging to produce in regular iron-core-collapse explosions (where > 99% of the initial explosion energy, $\sim 3 \times 10^{53}$ erg, is carried away by neutrinos). This led several authors to speculate about additional energy sources contributing to these powerful explosions. Pair instability explosions can provide large kinetic energies and synthesize large amounts of radioactive ⁵⁶Ni; however, SLSN-II studied at late time did not follow the expected ⁵⁶Co radioactive decay rate, in contrast to SLSN-R; the derived limits on the amount of initial radioactive nickel generally argue against SLSN-II resulting from energetic pair-instability explosions. Spin-down of nascent magnetars (rapidly spinning neutron stars with strong magnetic fields) has been proposed as an alternative energy source (Woosley 2010, Kasen & Bildsten 2010), this process may be relevant at least for some SLSN-II (e.g., SN 2008es). One can also consider the so-called "collapsar" scenario where energy is extracted from material rapidly accreting onto a newly-formed black hole; this process may be driving cosmological γ -ray bursts (Macfadyen & Woosley 1999). When occurring within a massive star with a thick hydrogen envelope, this process may deposit the energy in the expanding envelope, where it may be thermalized and reemitted in the optical (Young et al. 2005; Quimby et al. 2007). Unfortunately, the fact that any energy injected by such processes at the deep layers of the exploding stars is then reprocessed by the outer, optically thick hydrogen layers, makes investigations of such exotic processes in SLSN-II difficult, and mostly speculative so far.

In any case, it is clear that SLSN-II are explosions of massive stars that retained their hydrogen envelopes until they exploded. For some objects spectroscopy indicates these stars have lost substantial amounts of mass prior to explosion (e.g., SN 2006gy, Smith et al. 2007; SN 2006tf, Smith et al. 2008), suggesting perhaps the progenitor stars are similar to massive luminous blue variables (LBVs) which are known to undergo episodic eruptions involving extreme mass loss (e.g., Humphreys & Davidson 1994); a similar relation has been established in the case of a lower-luminosity SN IIn (SN 2005gl, Gal-Yam et al. 2007a; Gal-Yam & Leonard 2009).

The observational characteristics of SLSN-II are quite diverse. The peak luminosities of the brightest events are impressive, reaching well above $-22 \,\mathrm{mag}$ absolute (e.g., SN 2008fz, Drake et al. 2010). However, these seem to be the top of a broad distribution, with examples of luminous Type IIn events reported with peak magnitudes smoothly extending from these extreme values down to luminosities typical of the general SN population (e.g., SN 2010jl, Stoll et al. 2011, Smith et al. 2011; see Kiewe et al. 2011 for a review of older events). The light curve shapes are quite diverse, with some SLSN-II showing a rapid rise and decline (e.g., SN 2008es, Gezari et al. 2009), some showing light curves with a slow rise (> 50 days) to a broad peak (e.g., SN 2006gy, Smith et al. 2007, Ofek et al. 2007; SN 2008fz,

Drake et al. 2010), and some with rapid rise and very slow decline (e.g., SN 2003ma, Rest et al. 2011; SN 2008am, Chatzopoulos et al. 2011; and probably also SN 2006tf, Smith et al. 2008). Spectra (Fig. 2) also show diversity, with most objects showing narrow hydrogen Balmer lines, and SN 2008es uniquely not. Narrow Balmer lines arise from a slow wind blown by the progenitor star prior to its explosion, assumed to have been photoionized by the explosion and to then recombine. The lack of such narrow lines in the spectra of SN 2008es suggests the progenitor star was not blowing massive winds for an extended period prior to its explosion; any substantial mass loss must have been episodic (e.g., Miller et al. 2009) or otherwise time-variable (Moriya et al. 2011).

The environments of SLSN-II are also quite diverse. This is the only SLSN subclass that has been detected also in luminous, Milky-Way-like galaxies (e.g., SN 2006gy, Ofek et al. 2007, Smith et al. 2007; CSS100217:102913+404220, Drake et al. 2011). Still, like other SLSNe, most SLSN-II events reside in dwarf star-forming hosts (Neill et al. 2011). It is interesting to note that published SLSN-II events in giant host galaxies seem to have been discovered very close to their host nuclei, suggesting that perhaps specific conditions that are unique to this environment (e.g., in circumnuclear star-forming rings) somehow mimic the conditions in star-forming dwarf galaxies. A review of SLSN-II events from the PTF survey confirms that five additional unpublished events reside either in dwarf hosts or in nuclei of giant hosts, supporting this interesting trend. Since several SLSN-II have exploded in the high-metallicity cores of luminous galaxies, it seems that these events do not require low-metallicity progenitors.

3.3. SLSN-I

This final group of SLSNe was initially the most difficult to understand, with the two first reported events, SN 2005ap (Quimby et al. 2007) and SCP 06F6 (Barbary et al. 2009) rather sparsly observed. It was only following the discovery of additional members of this class by the PTF survey, bridging the redshift gap between the relatively nearby SN 2005ap (z=0.2832) and the high-redshift SCP 06F6 (z=1.189) that a comprehensive view of this class of objects could be formed (Quimby et al. 2011; including spectroscopic redshifts based on MgII absorption lines, and the first correct identification of the redshift of SCP 06F6; Fig. 4). A major reason for the initial difficulties was that early spectra of these objects are quite featureless and the absorption lines that do appear are mostly of high-excitation low-mass elements (Fig. 4), while the elements commonly observed in most SN classes (neutral oxygen, magnesium, iron and the ubiquitous ionized calcium) appear only much later (Pastorello et al. 2010; SOM Fig. 5).

Observationally, these events are characterized by extreme peak luminosities (often brighter than $-22\,\mathrm{mag}$ absolute), very blue spectra with significant ultra-violet (UV) flux persisting for many weeks, and (compared to other classes of SLSNe) relatively fast-evolving light curves with rise times below 50 days and post-peak slopes that decline substantially faster than radioactive cobalt decay rates (Pastorello et al. 2010; Quimby et al. 2011). Contrary to early reports (e.g., Quimby et al. 2007, Miller et al. 2009, Gezari et al. 2009), these events do not show hydrogen in their spectra (Quimby et al. 2011; Pastorello et al. 2010; SOM Fig. 5), and thus do not belong to the spectroscopic class of Type II SNe. Technically, these events should be classified as Type Ic SNe (as they also do not show strong He features in spectra taken around peak); since the class of Type Ic SNe is not positively defined and a physical connection between the events we consider here and more common SN Ic events has not been firmly established (see below), we refer to this class as SLSN-I.

Quimby et al. (2011) provide extensive discussion about the physical nature of these objects based on the accumulated observational data. They show that the observed luminosity requires the deposition of significant amount of internal energy, taking place at large radii (10¹⁵ cm, approximately ten times the size of the largest red supergiants), into material expanding at high velocities (10⁴ km s⁻¹). The data can rule out traditional mechanisms discussed above (radioactivity; photon diffusion, interaction with massive hydrogen-rich CSM). Viable options for the energy conversion mechanism include interaction with expanding shells of hydrogen-free material (Chevalier & Irwin 2011), perhaps ejected by the pulsational pair-instability (e.g., Woosley et al. 2007); or reemission of energy injected by an internal engine, such as magnetar spin-down (Woosley 2010; Kasen & Bildsten 2010) or a "collapsar"-like accreting black hole (e.g., Quimby et al. 2007); further discussed by Pastorello et al. (2010), Chomiuk et al. (2011) and Leloudas et al. (2012). Frustratingly, at this time, and even though these events are not enshrouded by massive, opaque hydrogen shells, the physical nature of the energy source remains speculative, and the energy conversion mechanism is also not clearly understood.

The host galaxies of these events are again typically dwarf galaxies, though at higher redshifts luminosity upper limits on undetected hosts are less constraining (Neill et al. 2011, Quimby et al. 2011). The most natural explanation for these objects not occurring in more luminous galaxies is that a lower metallicity is required to form the progenitor stars of these events, but other explanations are also possible (e.g., different star formation modes or a top-heavy IMF in dwarf galaxies). The extreme intrinsic luminosity and plentiful UV flux of these sources make them ideal probes of dwarf galaxies at high redshifts; prospects for detecting numerous such events by deep surveys such as the PS1 medium-deep survey (Chomiuk et al. 2011) seem bright.

4. Open questions and controversies

4.1. The explosion mechanism of SLSN-R: pair instability vs. iron-core-collapse

While the observations of SLSN-R strongly indicate these events are powered by massive-star explosions that synthesize several solar masses of radioactive 56 Ni, the physical nature of the explosion is a matter of some controversy. Theoretical works suggest two options. The first is an extreme version of the iron-core-collapse model that is generally assumed to take place in explosions of massive stars that manifest as common Type II SNe (Umeda & Nomoto 2008; Moriya et al. 2010). The second is the pair-instability mechanism (e.g., Rakavy & Shaviv 1967; Barkat, Rakavy & Sack 1967; Bond et al. 1984; Heger & Woosley 2002; Scannapieco et al. 2005; Waldman 2008). The pair instability occurs during the evolution of very massive stars that develop oxygen cores above a critical mass threshold ($\sim 50\,\mathrm{M}_\odot$); these cores achieve high temperatures at relatively low densities; significant amounts of electron-positron pairs are created prior to oxygen ignition; loss of pressure support, rapid contraction, and explosive oxygen ignition follow, leading to a powerful explosion that disrupts the star. Extensive theoretical work indicates this result is unavoidable for massive oxygen cores; when the core mass in question is large enough ($\sim 100\,\mathrm{M}_\odot$, as inferred for SN 2007bi) many solar masses of radioactive nickel are naturally produced.

Umeda et al. (2008) and Moriya et al. (2010) show that if one considers a carbon-oxygen core with a mass of $\sim 43\,\mathrm{M}_\odot$ (just below the pair-instability threshold), which explodes with an ad-hoc large explosion energy (> $10^{52}\,\mathrm{erg}$), one can produce the required large amounts of nickel (Umeda & Nomoto 2008), as well as recover the light curve shape of the SLSN-R prototype, SN 2007bi (Moriya et al. 2010). Since both the pair-instability model and the massive core-collapse model fit the light curve shape of SN 2007bi equally well; and progenitors of pair-instability explosions have larger cores and thus larger initial stellar masses, which are, assuming a declining initial mass function, intrinsically more rare, Yoshida & Umeda (2011) favor the core-collapse model.

The two models (pair instability vs. core-collapse) agree about the nickel mass, but strongly differ in their predictions about the total ejected mass. Total heavy-element masses above the $50\,\mathrm{M}_\odot$ threshold would indicate a core that is bound to become pair unstable, and will rule out the core-collapse model. Gal-Yam et al. (2009) estimated the total ejected heavy-element mass of SN 2007bi in several ways, including modelling of the nebular spectra of this event. The core-collapse model of Moriya et al. 2010 does not fit these data (Gal-Yam 2011); this model assumes a similar amount of radioactive ⁵⁶Ni and lower total ejected mass (to avoid the pair-instability) leading to very strong nebular emission lines that are

not consistent with the data. Thus this model is not viable for this prototypical SLSN-R object, supporting instead a pair instability explosion as originally claimed. It remains to be seen whether the massive core-collapse model does manifest in nature (the prediction would be for SLSNe showing large amounts of radioactive nickel but relatively small amounts of total ejecta). As a final note, it should be stressed that while the stellar evolution models considered by Yoshida & Umeda (2011) require stars with exceedingly large initial masses (> $310\,\mathrm{M}_\odot$) to form pair-unstable cores at the moderate metallicity indicated for SN 2007bi (Young et al. 2010), alternative models (Langer et al. 2007) predict that stars with much lower initial masses ($150-250\,\mathrm{M}_\odot$) explode as pair-instability SNe at SMC- or LMC-like metallicities, though they may have to be tweaked to explain the lack of hydrogen in observed SLSN-R spectra.

4.2. Rates of SLSNe

The only measurement of the rate of SLSNe is a rough estimate provided by Quimby et al. (2011) based on TSS statistics, which, normalizing the rate of SLSN-I at $z\approx 0.3$ relative to that of SNe Ia, yields a rate of $\sim 10^{-8}\,\mathrm{Mpc^{-3}\,y^{-1}}$. This rate is substantially lower than the rates of core-collapse SNe ($\sim 10^{-4}\,\mathrm{Mpc^{-3}\,y^{-1}}$), and is also well below those of rare sub-classes like broad-line SNe Ic ("hypernovae"; $\sim 10^{-5}\,\mathrm{Mpc^{-3}\,y^{-1}}$) or long Gamma-Ray Bursts (> $10^{-7}\,\mathrm{Mpc^{-3}\,y^{-1}}$; Podsiadlowski et al. 2004; Guetta & Della Valle 2007). Both the reported discovery statistics as well as unpublished PTF counts suggest that the rate of SLSN-II is comparable of larger than that of SLSN-I, while SLSN-R are rarer by about a factor of five, correcting for their slightly lower peak luminosities. I believe this suggests that SLSN-R are indeed the rarest type of explosions studied so far, and quite possibly arise from stars that are at the very top of the IMF.

4.3. The connection between SLSN-I and broad-line Type Ic SNe

Pastorello et al. (2010) emphasize the similarity between late-time spectra of SN 2010gx (SLSN-I) and spectra of broad-line Type Ic SNe (see also Quimby et al. 2011; SOM Fig. 5). They suggest this may be indicative of a physical connection between all SLSN-I and SNe Ic. However, there are several physical differences between SLSN-I and SNe Ic.

Detailed modelling of SNe Ic (e.g., Sauer et al. 2006; Mazzali et al. 2007; 2010) indicate the luminosity is dominated by radioactive ⁵⁶Ni decay, and these objects show a correlation between the peak luminosity and the synthesized ⁵⁶Ni mass (e.g., Perets et al. 2010; Drout et

al. 2011). The same is true for SLSN-R (Gal-Yam et al. 2009), but not for SLSN-I (Quimby et al. 2011) in the sense that the nickel mass required to power the observed luminous peaks is in conflict with the later evolution of the light curve (e.g., Quimby et al 2011; Pastorello et al. 2010). The luminosity of SLSN-I must therefore come from a different source.

It is interesting to note in this context a small group of very luminous broad-line SNe Ic (SN 2007D, Drout et al. 2011; SN 2010ay, Sanders et al. 2011) with peak luminosities approaching those of SLSN-R (-20.6 mag and -20.2 mag absolute for SN 2007D and SN2010ay, respectively), but with significantly less 56 Ni ($\sim 1 \, \mathrm{M}_{\odot}$). Other processes may be contributing to the large observed peak luminosity of these events (e.g., an internal "engine"; Sanders et al. 2011). Perhaps these are intermediate events between the class powered purely by radioactivity (normal SNe Ic and SLSN-R) and SLSN-I for which the contribution from 56 Ni is negligible, and which must be powered by some other process, as discussed above.

Another important physical distinction between SLSN-I and SNe Ic is the size of the emitting region. As shown by Quimby et al. (2011), the energy radiated by SLSN-I must have been deposited at large initial radii, $\sim 10^{15}$ cm. On the other hand, early observations of SNe Ic indicate the progenitor stars had an initial radius an order of magnitude smaller, (< 10^{11} cm; Corsi et al. 2011; Sauer et al. 2006) and both the explosion shock energy and and radioactivity must therefore be contained within a much smaller initial radius.

It thus seems that the observed spectroscopic similarity between SLSN-I (at late time) and broad-line SNe Ic suggests similar ejecta composition and a large kinetic energy (evident as significant amount of mass at high velocities), but other physical properties (energy source, physical size) are substantially different and argue for a different physical mechanism powering these two classes of objects.

4.4. Forbidden line emission during the photospheric phase of SLSN-R

As a final curiosity, some photospheric spectra of SLSN-R (Gal-Yam et al. 2009; Young et al. 2010; Gal-Yam 2011; Fig. 3) show forbidden line emission, notably [Ca II] and probably also [Mg II]. Such lines are usually only observed during the nebular phase of SNe, when the ejecta are optically thin - this is clearly not the case here. The superposition of this nebular-like emission on an underlying photospheric spectrum may hint at a complex geometry of the emitting region (motivating spectropolarimetric studies), but no explanations for this phenomenon have been put forth so far.

5. Summary

During the last dozen years, numerous super-luminous SN events have been discovered and studied. The accumulated data suggest these can be grouped into three distinct subclasses according to their observational and physical attributes. Radioactively-powered SLSN-R seem to be the best understood (and rarest) class, while hydrogen-rich SLSN-II and the most luminous hydrogen-poor SLSN-I are more common, but the physical origins of the extreme luminosity they emit is not clear at this time. With several ongoing surveys efficiently detecting additional examples, the amount of information about these objects, their rates and diversity, is likely to increase substantially in the coming few years.

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Supplementary Online Material

7. Defining the threshold cut for superluminous events

Richardson et al. (2002) conducted a thorough study on the luminosity of supernovae (SNe) discovered until mid-2001. The most luminous among the common types of SNe are Type Ia events; Richardson et al. therefore identified a "SN ridgeline" at absolute blue magnitude $M_B = -19.5 \,\mathrm{mag}$ (f= $1.2 \times 10^{43} \,\mathrm{erg \, s^{-1}}$; equal to the peak luminosity of a normal SN Ia) as the location where the peak luminosities of cataloged events cluster, and defined "overluminous SNe" as those being significantly more luminous than this value.

To avoid confusion due to possible errors in measured peak luminosities (arising, e.g., from distance uncertainties to nearby events), and due to the high-luminosity tail of the scatter around the ridgeline value, it is useful to set the arbitrary threshold defining truly super-luminous supernovae (SLSNe) well away from the ridgeline; examining figure 2 of Richardson et al. (2002) the value of $M_B = -21 \,\mathrm{mag}$ ($f = 7.6 \times 10^{43} \,\mathrm{erg \, s^{-1}}$) seems appropriate. Since the objects discussed below were discovered over a large redshift range and peak luminosities are reported in a variety of observed bands, we consider below SNe with reported peak magnitudes $M < -21 \,\mathrm{mag}$ in any band as being superluminous. This is justified since the typical bolometric or cross-filter corrections for SNe around peak are below 1 mag, and our fiducial threshold is well above the SN ridgeline. It would probably be better to use the time-integrated luminosity (the total radiated energy) rather than the peak value as an observational manifestation of unusually powerful explosions; however, the total energy is more difficult to measure and is unknown for some objects. Samples of events coming from future surveys may be better observed and allow the use of this alternative criterion.

SLSN events were not, so far, detected as luminous sources in wavelengths other than the optical-UV; for example, see non-detection reports by Gezari et al. (2009) or Chomiuk et al. (2012). This is not surprising in view of the distance to most SLSNe discovered so far. The nearby SLSN-II event SN 2006gy is an interesting exception as its proximity makes detection of, e.g., radio or X-ray emission feasible. Ofek et al. (2007) report non-detection of this object both in radio and in X-rays. In contrast, Smith et al. (2007) claimed a weak X-ray detection of this event. In my opinion, the analysis of Ofek et al. (2007) as well as recent theoretical considerations (Chevalier & Irwin 2012; Svirski et al. 2012) suggest this event was not detected in X-rays.

8. Historical review

8.1. Cosmological surveys: contaminants

We now know that superluminous SNe are intrinsically rare. Their discovery therefore requires surveys that cover a large volume. Such surveys have been conducted in the past two decades. The first generation of surveys covering large volumes were designed to find numerous distant Type Ia SNe for cosmological use. They therefore observed relatively small fields of view to a great depth, placing most of the effective survey volume at high redshift. These cosmological surveys indeed found mostly high-redshift SNe Ia (the most luminous type of common SNe) but they also discovered some "contaminants" - other types of luminous explosions at high redshifts (e.g., SN 1995av, Deustua et al. 1995; SN 2000ei, Schmidt et al. 2000, See also Neill et al. 2011). No published investigations of these objects beyond the initial reports exist, but they may well have been examples of the super-luminous events we discuss below.

A more recent similar narrow-deep cosmological survey using the Hubble Space Telescope (HST) indeed uncovered one of the first bona-fide super-luminous SNe (SLSN-I; SCP 06F6, Barbary et al. 2009). Another recent survey, the Canada-France-Hawaii Supernova Legacy Survey (CFH SNLS), also uncovered unusually luminous events. Among those was the first example of the "super-chandra" Type Ia events (SNLS-03D3bb; Howell et al. 2006), a class of SNe Ia that are substantially more luminous than the SN Ia ridgeline, though not super-luminous according to the criteria defined above. In addition, the SNLS also detected events that, in retrospect, were very high-redshift ($z \sim 1.5$) members of the SLSN-I class (Howell et al. 2010).

Finally, re-inspection of data collected as part of the SDSS-II cosmological SN survey uncovered another fine example of an SLSN-I (Leloudas et al. 2012); SDSS photometry captures the rising light curve of this object and reveals an initial short plateau that may reflect the breaking of the initial explosion shock from a dense envelope.

8.2. SN factory and the first non-targeted wide-field surveys

An alternative method to survey a large volume is to use wide-field facilities to cover a large sky area with relatively shallow imaging. In this way, most of the survey volume is at low redshift, and one can conduct an efficient untargeted survey for nearby SNe. Such surveys were initially more difficult to conduct since wide-field CCD cameras were challenging and expensive to construct (while the narrow-deep surveys could be carried out with smaller

focal-plane arrays); analyzing the large data volumes from shallow-wide surveys was also a computational challenge. However, shallow-wide surveys were eventually undertaken and provided the first well-observed examples of super-luminous SNe.

The cosmology group at Lawrence Berkeley Labs pioneered large-scale shallow-wide surveys, initially during the "1999 spring campaign" (Regnault et al. 2001) and later on running the "SN factory" project (Copin et al. 2006), which used the Palomar 48" Schmidt telescope. These surveys were designed to study SNe Ia, but the fact that the discovered targets were relatively bright allowed high S/N spectroscopy and other follow-up data to be collected, leading to the discovery of the first relatively well-studied superluminous events. The first notable event was SN 1999as (Knop et al. 1999), which turned out to be the first example of the class of extremely ⁵⁶Ni-rich SLSN-R (Gal-Yam et al. 2009; Fig. 3). During the same campaign, the extremely luminous SN 1999bd was discovered (Nugent et al. 1999; Fig. 2), which is probably the first well-documented case of a superluminous SN IIn.

Interestingly, the Mount Stromlo Abell Cluster Supernova Survey (MSACSS; Reiss et al. 1998) a similar wide-field shallow survey carried out at the southern hemisphere around the same time discovered SN 1997cy (Germany et al. 2000) the other luminous event considered by Richardson et al. (2002) to be a bona-fide superluminous event. This event was technically a Type IIn event, but arguments about its real nature persist (e.g., Hamuy et al. 2003; Benetti et al. 2006). Regardless, the absolute peak magnitude of this event (-20.1 mag) as well as those of similar objects discovered since (e.g., SN 2002ic, Hamuy et al. 2003) fall below our fiducial limit defined above, and we do not discuss them any further.

8.3. Breakthrough: the Texas Supernova Survey

Perhaps the most significant breakthrough in our observational knowledge about the most luminous SN explosions resulted from the operation of the Texas Supernova Survey (TSS) by Quimby and collaborators (Quimby 2006). This survey was unique in that the survey telescope, the 0.45m ROTSE IIIb instrument at McDonald Observatory, had a small aperture, and thus a shallow survey depth, typically 18.5 mag, while the large aperture of the main follow-up telescope, the 9.2m Hobby-Eberley Telescope (HET) at the same observatory, enabled high S/N spectroscopic follow-up. While the number of ROTSE discoveries was modest, it had a high spectroscopic completeness, and in particular did not select against either "hostless" events (transients without a visible host galaxy) or events located at galactic nuclei. Previous surveys, which typically suffered from a shortage in spectroscopic resources, preferred transients clearly offset from well-resolved galaxies to minimize the chances to observe variable-star or active galactic nuclei (AGN) contaminants. This search strategy led

to several important new discoveries.

On 2005 March 3 this survey discovered a hostless transient at mag 18.13; follow-up spectroscopy with HET and the 10m Keck telescope at Mauna Kea revealed its redshift was z=0.2832, indicating an absolute magnitude at peak around -22.7 mag and making it the most luminous SN discovered until that time (Quimby et al. 2007). The interpretation of broad SN features detected was initially difficult (since this was the first event of its kind) and was limited by the availability of only two spectra covering a short temporal baseline, with limited coverage in the red. Retrospective analysis informed by additional events (Quimby et al. 2011), as well as additional spectroscopic data we present here (Fig. 5) show that early spectra can be explained almost exclusively by high-excitation lines of intermediate-mass elements (mostly OII; Quimby et al. 2011), while later spectra evolve to broadly resemble Type Ic supernova spectra of the broad-line subclass (Fig. 5; see also Pastorello et al. 2010); thus SN 2005ap is the first published example of a SLSN-I.

On 2006 September 18 TSS discovered a bright transient located at the nuclear region of the nearby galaxy NGC 1260 (SN 2006gy; Smith et al. 2007). The close proximity of this event to the galactic nucleus (300pc; e.g., Ofek et al. 2007) initially led to suspicion that it was an outburst related to the active galactic nucleus, but high angular resolution imaging confirming the slight offset from the galaxy center eventually indicated its supernova nature. Events of this nature would have probably been missed by most surveys as likely related to AGN; the TSS inclusive approach, as well as the fortunate proximity of this event, allowed its recognition as a stellar explosion. SN 2006gy suffered substantial host extinction; correcting for this effect, the measured peak magnitude was extreme ($\sim -22\,\mathrm{mag}$; Ofek et al. 2007; Smith et al. 2007). Spectroscopy of SN 2006gy clearly showed hydrogen emission lines with both narrow and intermediate-width components, leading to a spectroscopic classification of SN IIn. The initial studies by Ofek et al. (2007) and Smith et al. (2007) were followed by numerous additional studies (e.g., Woosley et al. 2007, Agnoletto et al. 2009; Kawabata et al. 2009; Smith et al. 2010, Miller et al. 2010), and this object became the prototype and best-studied example of the SLSN-II class. TSS went on to discover additional luminous SNe, including the luminous SNe IIn 2006tf (Smith et al. 2008; $\sim -21 \,\mathrm{mag}$ at peak) and SN 2008am (Chatzopoulos et al. 2011; $-22.3 \,\mathrm{mag}$ at peak) and the unique luminous Type II SN 2008es (Gezari et al. 2009; Miller et al. 2009).

8.4. Current surveys

During the last few years, several untargeted surveys have been operating in parallel, and now discover and report most SN events (Gal-Yam & Mazzali 2010). The large volume

probed by these surveys and their coverage of a multitude of low-luminosity dwarf galaxies have led, as expected (Young et al. 2008) to the discovery of numerous unusual SNe not seen before in targeted surveys of luminous hosts; indeed, it was shown that the SN population in dwarf galaxies is different than that observed in giant hosts (Arcavi et al. 2010). Luminous SNe generally tend to prefer dwarf hosts (e.g., Neill et al. 2011) and indeed numerous such events are being discovered by this new generation of untargeted surveys.

The Catalina Real-Time Transient Survey (CRTS) is employing telescopes in Arizona and Australia to search for optical transients (Drake et al. 2009). As this survey utilizes a catalog-based search method (comparing object catalogs from new imaging with reference catalogs) it is more sensitive to transients that either have no visible host galaxy, or reside in a host that is much fainter than the transient. This makes this survey biased in favor of discovering very luminous SNe, and indeed many such discoveries have been announced. Prominent results from this survey include the discovery of SN 2008fz, an extremely luminous member of the SNLS-II family (Drake et al. 2010), as well as of the Type IIn SN 2008iy (Miller et al. 2010) which did not achieve a bright peak magnitude, but its unprecedented extended light curve implies a large integrated luminosity, suggesting it may be related to the SNLS-II group.

The Palomar Transient Factory (PTF; Law et al. 2009, Rau et al. 2009) is a wide-field variability survey using the 48" Oschin Schmidt Telescope at Palomar Observatory and the refurbished CFHT 12k camera. The survey employs image subtraction and is thus sensitive to transients regardless of their host luminosity. The PTF has been running since 2009, and has discovered and spectroscopically confirmed over 1300 SNe, including numerous luminous events. The first significant result from PTF was obtained during a "dry-run" initial phase of the project in 2007 conducted using the SN factory infrastructure. This was the discovery of SN 2007bi (Gal-Yam et al. 2009), the first extensively-observed example of the radioactively-powered superluminous SN variety (SLSN-R). The PTF discovery of several members of the class of SLSN-I allowed Quimby et al. (2011) to connect the previously disjoint objects SN 2005ap (Quimby et al. 2007) and SCP 06F6 (Barbary et al. 2009), define the class of SLSN-I, and derive its main properties from the accumulated data.

The Panoramic Survey Telescope and Rapid Response System 1 (Pan STARRS 1; hereafter PS1, Kaiser et al. 2010) project employs a new 1.8m telescope at Haleakala Observatory to conduct wide-field sky surveys. So far, results have been reported mainly from the medium-deep survey, which covers relatively narrow sky areas to deep limits (i.e., most of its survey volume is at high redshift), using image subtraction techniques. This appears to be an efficient program to detect numerous SLSNe at high redshifts (out to $z \sim 1$ and beyond); initial results include discovery of two high-redshift SLSN-I (Chomiuk et al. 2011),

as well as analysis emphasizing the potential relation between SLSN-I and less luminous SN Ic varieties (Pastorello et al. 2010).

9. Sources of data presented in Figure 1

The data presented in Figure 1 are take from the following sources. The light curve of SLSN-I PTF09cnd is taken from Quimby et al. (2011). The data are not corrected for host galaxy extinction, and the distance modulus is calculated from the SN redshift z = 0.258, assuming the standard $\Lambda {\rm CDM}$ cosmology with ${\rm H_0}=71\,{\rm km\,s^{-1}\,Mpc^{-1}}.$ R-band observations of SLSN-II SN 2006gy are taken from Smith et al. (2007) and Agnoletto et al. (2009), are corrected for extinction assuming $A_R = 1.68 \,\mathrm{mag}$ (Smith et al. 2007) and assuming the distance to NGC 1260 from the NASA Extragalactic Database (NED; 76.65 Mpc, distance modulus of 34.42 mag). r-band observations of SN 2007bi are taken from Gal-Yam et al. (2009), are not corrected for host galaxy extinction, and use a distance modulus derived from the host galaxy redshift z = 0.1289 assuming the same cosmology as above. R-band observations of Type IIn SN 2005cl are taken from Kiewe et al. (2011), assuming the host extinction estimated by these authors, and the distance modulus to the host galaxy provided by NED. The Type Ia SN light curve is a template R-band light curve of a normal SN Ia provided by Nugent (http://supernova.lbl.gov/\$\sim\$nugent/nugent\$_\$templates.html). The Type Ib/c light curve is the "average" extinction-corrected light curve from Drout et al. 2011. R-band Observations of Type IIb SN 2011dh are taken from Arcavi et al. (2011); these are not corrected for host galaxy extinction (which these authors argue is negligible) and assume the distance modulus to M51 reported there. The light curve of the prototypical SN 1999em is taken from Leonard et al. 2002, adjusted to match the absolute plateau luminosity reported by these authors ($M_R = -15.9 \,\mathrm{mag}$).

REFERENCES

Agnoletto, I., Benetti, S., Cappellaro, E., et al. 2009, ApJ, 691, 1348

Arcavi, I., Gal-Yam, A., Kasliwal, M. M., et al. 2010, ApJ, 721, 777

Arcavi, I., Gal-Yam, A., Yaron, O., et al. 2011, ApJ, 742, L18

Arnett, W. D. 1982, ApJ, 253, 785

Barbary, K., Dawson, K. S., Tokita, K., et al. 2009, ApJ, 690, 1358

Barkat, Z., Rakavy, G., & Sack, N. 1967, Physical Review Letters, 18, 379

Benetti, S., Cappellaro, E., Turatto, M., et al. 2006, ApJ, 653, L129

Bond, J. R., Arnett, W. D., & Carr, B. J. 1984, ApJ, 280, 825

Chatzopoulos, E., Wheeler, J. C., Vinko, J., et al. 2011, ApJ, 729, 143

Chevalier, R. A., & Irwin, C. M. 2011, ApJ, 729, L6

Chevalier, R. A., & Irwin, C. M. 2012, arXiv:1201.5581

Chomiuk, L., Chornock, R., Soderberg, A. M., et al. 2011, arXiv:1107.3552

Copin, Y., Blanc, N., Bongard, S., et al. 2006, New Astronomy Reviews, 50, 436

Corsi, A., Ofek, E. O., Gal-Yam, A., et al. 2011, arXiv:1110.5618

Deustua, S., Goldhaber, G., Groom, D., et al. 1995, IAU Circ., 6270, 1

Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870

Drake, A. J., Djorgovski, S. G., Prieto, J. L., et al. 2010, ApJ, 718, L127

Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2011, ApJ, 735, 106

Drout, M. R., Soderberg, A. M., Gal-Yam, A., et al. 2011, ApJ, 741, 97

Filippenko, A. V. 1997, ARA&A, 35, 309

Filippenko, A. V., Li, W. D., Treffers, R. R., & Modjaz, M. 2001, IAU Colloq. 183: Small Telescope Astronomy on Global Scales, 246, 121

Gal-Yam, A., Leonard, D. C., Fox, D. B., et al. 2007a, ApJ, 656, 372

Gal-Yam, A., Cenko, S. B., Fox, D. B., et al. 2007b, The Multicolored Landscape of Compact Objects and Their Explosive Origins, 924, 297

Gal-Yam, A., Maoz, D., Guhathakurta, P., & Filippenko, A. V. 2008, ApJ, 680, 550

Gal-Yam, A., Mazzali, P., Ofek, E. O., et al. 2009, Nature, 462, 624

Gal-Yam, A., & Leonard, D. C. 2009, Nature, 458, 865

Gal-Yam, A. 2011, Presentation at the Stockholm "explosive ideas about massive stars" meeting, http://explosive2011.astro.su.se/Talks_slides/Gal-Yam_20110810.pdf

Gal-Yam, A., & Mazzali, P. 2011, arXiv:1103.5165

Germany, L. M., Reiss, D. J., Sadler, E. M., Schmidt, B. P., & Stubbs, C. W. 2000, ApJ, 533, 320

Gezari, S., Halpern, J. P., Grupe, D., et al. 2009, ApJ, 690, 1313

Guetta, D., & Della Valle, M. 2007, ApJ, 657, L73

Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, Nature, 424, 651

Hatano, K., Branch, D., Nomoto, K., et al. 2001, Bulletin of the American Astronomical Society, 33, 838

Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532

Howell, D. A., Sullivan, M., Perrett, K., et al. 2005, ApJ, 634, 1190

Howell, D. A., Sullivan, M., Nugent, P. E., et al. 2006, Nature, 443, 308

Howell, D. A., & Legacy Survey, S. 2010, Bulletin of the American Astronomical Society, 42, #333.02

Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025

Kaiser, N., Aussel, H., Burke, B. E., et al. 2002, Proc. SPIE, 4836, 154

Kasen, D., & Bildsten, L. 2010, ApJ, 717, 245

Kawabata, K. S., Tanaka, M., Maeda, K., et al. 2009, ApJ, 697, 747

Kiewe, M., Gal-Yam, A., Arcavi, I., et al. 2012, ApJ, 744, 10

Knop, R., Aldering, G., Deustua, S., et al. 1999, IAU Circ., 7128, 1

Kodros, J., Cenko, S. B., Li, W., et al. 2010, Central Bureau Electronic Telegrams, 2461, 1

Langer, N., Norman, C. A., de Koter, A., et al. 2007, A&A, 475, L19

Law, N. M., et al. 2009, PASP, 121, 1395

Leloudas, G., Chatzopoulos, E., Dilday, B., et al. 2012, arXiv:1201.5393

Leonard, D. C., Filippenko, A. V., Gates, E. L., et al. 2002, PASP, 114, 35

Li, W., Leaman, J., Chornock, R., et al. 2011, MNRAS, 412, 1441

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Mazzali, P. A., Kawabata, K. S., Maeda, K., et al. 2007, ApJ, 670, 592

Mazzali, P. A., Maurer, I., Valenti, S., Kotak, R., & Hunter, D. 2010, MNRAS, 408, 87

Miller, A. A., Chornock, R., Perley, D. A., et al. 2009, ApJ, 690, 1303

Miller, A. A., Silverman, J. M., Butler, N. R., et al. 2010, MNRAS, 404, 305

Miller, A. A., Smith, N., Li, W., et al. 2010, AJ, 139, 2218

Moriya, T., Tominaga, N., Tanaka, M., Maeda, K., & Nomoto, K. 2010, ApJ, 717, L83

Moriya, T. J., & Tominaga, N. 2011, arXiv:1110.3807

Neill, J. D., Sullivan, M., Gal-Yam, A., et al. 2011, ApJ, 727, 15

Nugent, P., Aldering, G., Phillips, M. M., et al. 1999, IAU Circ., 7133, 1

Nugent, P. E., et al. 2011, in preparation

Oke, J. B., & Gunn, J. E. 1982, PASP, 94, 586

Ofek, E. O., Cameron, P. B., Kasliwal, M. M., et al. 2007, ApJ, 659, L13

Ofek, E. O., Rabinak, I., Neill, J. D., et al. 2010, ApJ, 724, 1396

Pastorello, A., Smartt, S. J., Botticella, M. T., et al. 2010, ApJ, 724, L16

Perets, H. B., Gal-Yam, A., Mazzali, P. A., et al. 2010, Nature, 465, 322

Perlmutter, S., Gabi, S., Goldhaber, G., et al. 1997, ApJ, 483, 565

Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17

Quimby, R. M. 2006, Ph.D. Thesis, University of Texas

Quimby, R. M., Aldering, G., Wheeler, J. C., et al. 2007, ApJ, 668, L99

Quimby, R. M., Kulkarni, S. R., Kasliwal, M. M., et al. 2011, Nature, 474, 487

Rakavy, G., & Shaviv, G. 1967, ApJ, 148, 803

Rau, A., et al. 2009, PASP, 121, 1334

Regnault, N., Aldering, G., Blanc, G., et al. 2001, Bulletin of the American Astronomical Society, 33, 1427

Reiss, D. J., Germany, L. M., Schmidt, B. P., & Stubbs, C. W. 1998, AJ, 115, 26

Rest, A., Foley, R. J., Gezari, S., et al. 2011, ApJ, 729, 88

Richardson, D., Branch, D., Casebeer, D., et al. 2002, AJ, 123, 745

Sanders, N. E., Soderberg, A. M., Valenti, S., et al. 2011, arXiv:1110.2363

Sauer, D. N., Mazzali, P. A., Deng, J., et al. 2006, MNRAS, 369, 1939

Scannapieco, E., Madau, P., Woosley, S., Heger, A., & Ferrara, A. 2005, ApJ, 633, 1031

Schmidt, B. P., Suntzeff, N. B., Phillips, M. M., et al. 1998, ApJ, 507, 46

Schmidt, B., Tonry, J., Barris, B., et al. 2000, IAU Circ., 7516, 1

Smartt, S. 2011, Presentation at the Stockholm "explosive ideas about massive stars" meeting, http://explosive2011.astro.su.se/Talks_slides/Smartt_20110813.pdf

Smith, N., Li, W., Foley, R. J., et al. 2007, ApJ, 666, 1116

Smith, N., & McCray, R. 2007, ApJ, 671, L17

Smith, N., Chornock, R., Li, W., et al. 2008, ApJ, 686, 467

Smith, N., Chornock, R., Silverman, J. M., Filippenko, A. V., & Foley, R. J. 2010, ApJ, 709, 856

Stoll, R., Prieto, J. L., Stanek, K. Z., et al. 2011, ApJ, 730, 34

Svirski, G., Nakar, E., & Sari, R. 2012, arXiv:1202.3437

Vinko, J., Wheeler, J. C., Chatzopoulos, E., Marion, G. H., & Caldwell, J. 2010, Central Bureau Electronic Telegrams, 2476, 1

Umeda, H., & Nomoto, K. 2008, ApJ, 673, 1014

Waldman, R. 2008, ApJ, 685, 1103

Woosley, S. E., Blinnikov, S., & Heger, A. 2007, Nature, 450, 390

Woosley, S. E. 2010, ApJ, 719, L204

Yaron, O., et al. 2011, in preparation

Yoshida, T., & Umeda, H. 2011, MNRAS, 412, L78

Young, T. R., Smith, D., & Johnson, T. A. 2005, ApJ, 625, L87

Young, D. R., Smartt, S. J., Mattila, S., et al. 2008, A&A, 489, 359

Young, D. R., Smartt, S. J., Valenti, S., et al. 2010, A&A, 512, A70

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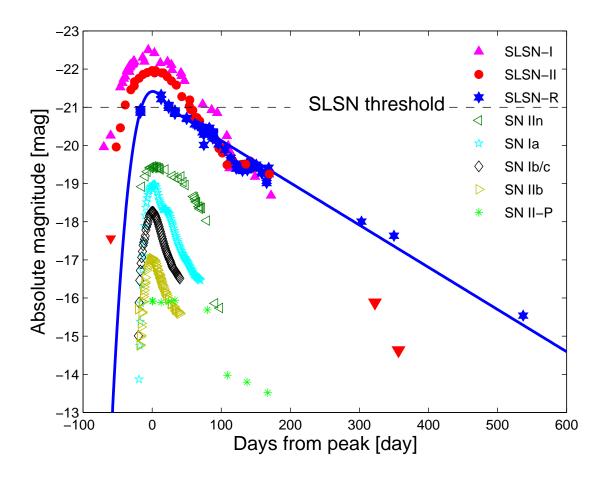


Fig. 1.— The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of $\sim 10^{43}\,\mathrm{erg\,s^{-1}}$ (absolute magnitude > -19.5). The new class of super-luminous SN (SLSN) reach luminosities ~ 10 times higher. The prototypical events of the three SLSN classes (SLSN-I PTF09cnd, Quimby et al. 2011; SLSN-II SN 2006gy, Smith et al. 2007, Ofek et al. 2007, Agnoletto et al. 2009; and SN 2007bi, Gal-Yam et al. 2009) are compared with a normal Type Ia SN (Nugent template), Type IIn SN 2005cl (Kiewe et al. 2011), the average Type Ib/c light curve from Drout et al. (2012), the Type IIb SN 2011dh (Arcavi et al. 2011) and the prototypical Type II-P SN 1999em (Leonard et al. 2002). All data are in the observed R band. See SOM for additional details.

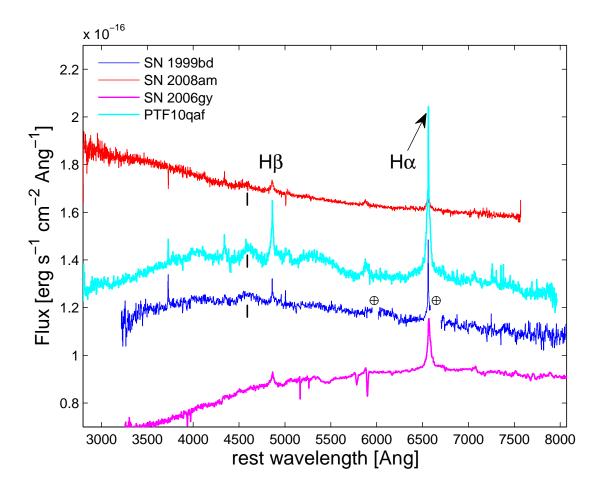


Fig. 2.— Spectra of SLSN-II. A spectrum of SN 1999bd obtained on March 22, 1999 with the 2.5m Dupont telescope at Las Campanas (blue) is compared with spectra of SN 2006gy (from Smith et al. 2007; magenta), SN 2008am (from Chatzopoulos et al. 2011, red) and a luminous SLSN-II from PTF (PTF10qaf, cyan). The Balmer lines show narrow and intermediate-width components (compare with the narrow host oxygen [OII] emission lines). A prominent emission bump around 4600 Å(black tick marks) is also a common feature. At a redshift of z=0.1512, the absolute magnitude at discovery of SN 1999bd was -21.6. Telluric bands are marked and sections of the spectrum of SN 1999bd affected have been excised; the telluric A band strongly absorbs the red wing of the H α line in this spectrum.

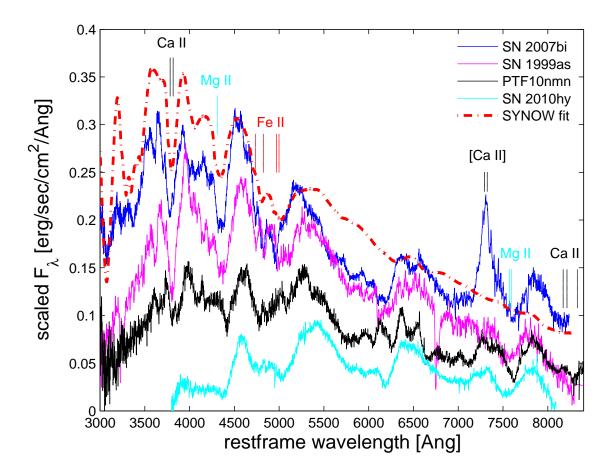


Fig. 3.— Photospheric spectra of SLSN-R events SN 2007bi (blue, from Gal-Yam et al. 2009), SN 1999as (magenta, from Gal-Yam et al. 2009), PTF10nmn (black, from Gal-Yam 2011) and SN 2010hy (cyan; S. B. Cenko, private communication); all spectra were obtained close to peak. Identification of prominent spectral features as well as a synthetic SYNOW fit (red, from Gal-Yam et al. 2009) are also shown.

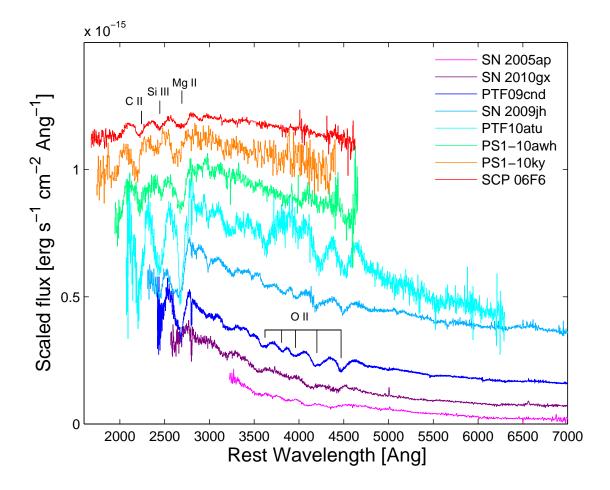


Fig. 4.— Early spectra of all published SLSN-I events: SN2005ap (Quimby et al. 2007); SN 2010gx, PTF09cnd, SN 2009jh, PTF09atu (Quimby et al. 2011); PS1-10awh, PS1-10ky (Chomiuk et al. 2011) and SCP 06F6 (Barbary et al. 2009; combined version from Quimby et al. 2011). The optical OII blends and near-UV CII, Si III and Mg II lines identified by Quimby et al. (2011) are marked. The spectroscopic similarity among these objects is quite striking. All spectra shown are available in digital form from the Weizmann Institute of Science Experimental Astrophysics Spectroscopy System (WISEASS) at http://www.weizmann.ac.il/astrophysics/wiseass/).

Supernova	Redshift	Absolute peak [mag]	Radiated energy [erg]	Reference
SLSN-R		I [- O]	00 [- 0]	
SN 2007bi	0.1289	-21.3	$1 - 2 \times 10^{51}$	Gal-Yam et al. 2009
SN 1999as	0.12	-21.4		Hatano et al. 2001
SLSN-II				
CSS100217	0.147	-23.0	1.3×10^{52}	Drake et al. 2011
SN 2008fz	0.133	-22.3	1.4×10^{51}	Drake et al. 2010
SN~2008am	0.2338	-22.3	2×10^{51}	Chatzopoulos et al. 2011
SN~2008es	0.205	-22.2	1.1×10^{51}	Gezari et al. 2009; Miller et al. 2009
SN~2006gy	0.019	-22.0	$2.3 - 2.5 \times 10^{51}$	Ofek et al. 2007; Smith et al. 2010
SN~2003ma	0.289	-21.5	4×10^{51}	Rest et al. 2011
SN~2006tf	0.074	-21.0	7×10^{50}	Smith et al. 2008
SLSN-I				
SN~2005ap	0.2832	-22.7	1.2×10^{51}	Quimby et al. 2007; 2011
SCP 06F6	1.189	-22.5	1.7×10^{51}	Quimby et al. 2011
PS1-10ky	0.956	-22.5	$0.9 - 1.4 \times 10^{51}$	Chomiuk et al. 2011
PS1-10awh	0.908	-22.5	$0.9 - 1.4 \times 10^{51}$	Chomiuk et al. 2011
PTF09atu	0.501	-22.0		Quimby et al. 2011
PTF09cnd	0.258	-22.0	1.2×10^{51}	Quimby et al. 2011
SN~2009jh	0.349	-22.0		Quimby et al. 2011
SN~2006oz	0.376	-21.5		Leloudas et al. 2012
SN 2010gx	0.230	-21.2	6×10^{50}	Quimby et al. 2011; Pastorello et al. 2010

Table 1: SLSN properties. We list the reported redshifts, absolute peak magnitudes and total radiated energies as taken from the literature. The published post-peak magnitude of SN 2006tf (Smith et al. 2008; $M < -20.7 \,\mathrm{mag}$) is below our fiducial cutoff. However, Smith et al. argue it was probably brighter at peak; this is confirmed by unpublished TSS data that do cover the peak which is around $-21 \,\mathrm{mag}$ absolute (R. Quimby, private communication).

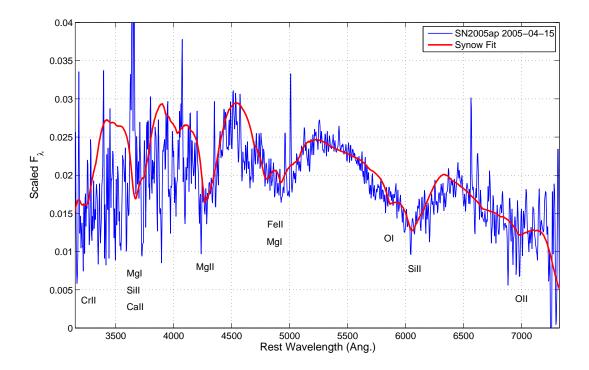


Fig. 5.— A late spectrum of SN 2005ap obtained $\sim 36 \,\mathrm{days}$ after peak magnitude (peak date: March 10.6 2005 UT; quimby et al. 2007) compared to a synthetic SYNOW fit. The spectral features are well explained by common elements (oxygen, magnesium, silicon and iron); the flux decrement on the blue probably results from blends of iron-group elements. The spectrum is overall similar to that of a broad-line Type Ic supernova (the best fits using the superfit software (Howell et al. 2005) are of SN 1998bw and SN 2002ap), as pointed out by Pastorello et al. (2010) for SN2010gx/PTF10cwr. The feature at rest wavelength 6100 Å is well-explained by a blend of Si II and O I lines. A contribution from $H\alpha$ previously considered (Quimby et al. 2007) is disfavored since it would require extreme expansion velocities (> 20000 km s⁻¹); while this was broadly similar to the photospheric velocities seen by Quimby et al. (2007) in early spectra, it is inconsistent with the moderate photospheric velocity we see in this later spectrum ($\sim 15000 \, \mathrm{km \, s^{-1}}$), and would further require the hydrogen velocity to increase with time, which seems unphysical. The spectrum (available in digital form from the Weizmann Institute of Science Experimental Astrophysics Spectroscopy System (WISEASS) at http://www.weizmann.ac.il/astrophysics/wiseass/) was obtained using the Double-Beam Spectrograph (DBSP, Oke & Gunn 1982) mounted on the Palomar Observatory 5m Hale telescope on April 15, 2005 UT, as part of the CCCP project (Gal-Yam et al. 2007b).

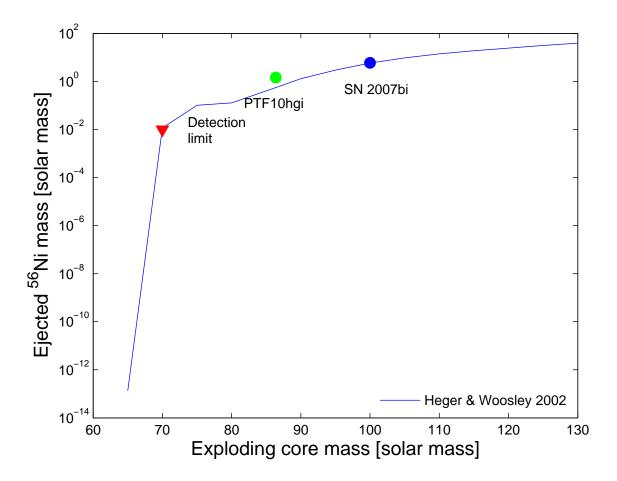


Fig. 6.— The relation between the synthesized 56 Ni mass and the He-core mass (which should roughly equal the total ejected mass for Type I events) based on the (non-rotating and non-magnetic) models of Heger & Woosley (2002). Superposed are the data points for SN 2007bi (Gal-Yam et al. 2009) and PTF10hgi (previously unpublished). We also mark the approximate upper limit on object detectability ($M_{^{56}Ni}=0.01\,M_{\odot}$) below which these events are expected to be too faint to be discovered anywhere except for the nearest galaxies, where the expected rate of these events is probably prohibitively low.