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Supernova Taxonomy - New Types

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Abstract. A number of transients have been recently discovered showing unprecedented properties that do not fulfill the traditional supernova classification scheme. Their light curves span a wide range of peak magnitudes, and the ejected ^{56}Ni masses range from the 10^{-4}-10^{-3} $M_{\odot}$ observed in the intrinsically faintest objects to many solar masses in the brightest events. The explosion mechanisms producing transients with such extreme properties are still controversial. This article will provide an updated observational review on the most debated cases.

Key words. Stars: supernovae: general

1. Introduction

The discovery of unusual optical transients is one of the goals of modern surveys. Focused supernova searches or all-sky surveys (e.g. the Texas Supernova Search, Pan-STARRS 1, the Palomar Transient Factory, the Catalina Reatime Transient Survey) are expected to discover new types of transients that can revolutionize our knowledge of stellar explosions. Ultra-bright supernovae (SNe), usually associated with faint and, presumably, metal-poor host galaxies, and faint transients lying in the magnitude gap that separates luminous novae from faint SNe, are among the most spectacular recent discoveries. However, their collocation in a traditional SN classification scheme is sometimes problematic.

The usual classification criteria are based on the identification of selected features in early-phases spectra and -more marginally- in the characteristics of the light curves. Type I SNe have spectra that do not show H lines, while type II SNe have spectra showing H features. SNe I (Figure 1, left) are then subclassified as follows:

- **type Ia**, when the spectra are characterized by the presence of Si II and S II lines, and no evidence for H and He I;
- **type Ib**, when the spectra are dominated by He I features (and no evidence of H);
- **type Ic**, when the spectra show prominent Ca II and O I lines, and no evidence for the presence of H, He I and S II features. Some of them, sometimes dubbed hypernovae (Iwamoto et al. 1998), have broadlined spectra and are occasionally associated with long gamma-ray bursts (GRBs, Galama et al. 1998).

Type II SNe are classified in different subtypes using both spectroscopic and photometric criteria. Main sub-types are:

- **type II-plateau (IIP)**, when the light curves are characterized by a long-lasting phase of almost constant luminosity, called

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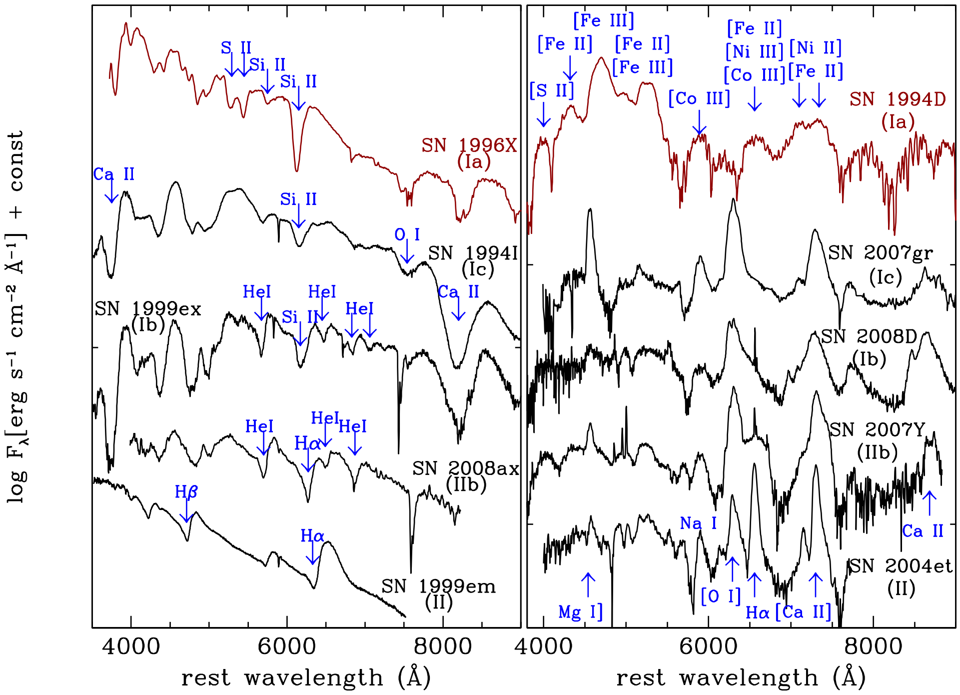

Fig. 1. Comparison of spectra of different SN types. Left: photospheric spectra. Right: nebular spectra.

plateau. Typically, type IIP SN spectra show broad H Balmer lines with prominent and quasi-symmetric P-Cygni profiles;

- **type II-linear (IIL)**, when the light curves show a linear post-maximum decline. In general, the spectra are dominated by prominent and broad H lines, usually with the emission components dominating over the absorptions;
- **type II-narrow (IIn)** constitute a rather heterogeneous group defined by Schlegel (1990), whose spectra are blue and show narrow H emission lines superimposed on broader components. Normally, the photometric evolution of SNe IIn is slower than that of other SN types;
- **type IIb** SNe are transitional between II and Ib SNe, with spectra showing simultaneously He I and (sometimes weak) H lines (Figure 1, left). The photometric evolution is fast and similar to that of type I SNe.

It is worth noting that this classification scheme does not provide any direct information on the SN explosion mechanism, that can be instead constrained from the study of the late-phases (nebular) spectra. At these phases the outer ejecta become transparent and the composition of the inner material can be unveiled. While type Ia SNe have nebular spectra dominated by iron-group elements, all other SN types show strong lines of intermediate-mass elements (plus H in type II SNe) and only weak [Fe II] features (Fig. 1, right). Type Ia SNe are thought to be produced in the thermonuclear explosion of a white dwarf that belongs to a close binary system, and that accretes mass by stripping the companion star up to reach the Chandrasekhar mass limit. All other SN types (II and Ib/c) result from the gravitational collapse of the core of massive stars (above 7-8 $M_{\odot}$) at the end of their sequence of nuclear burnings.

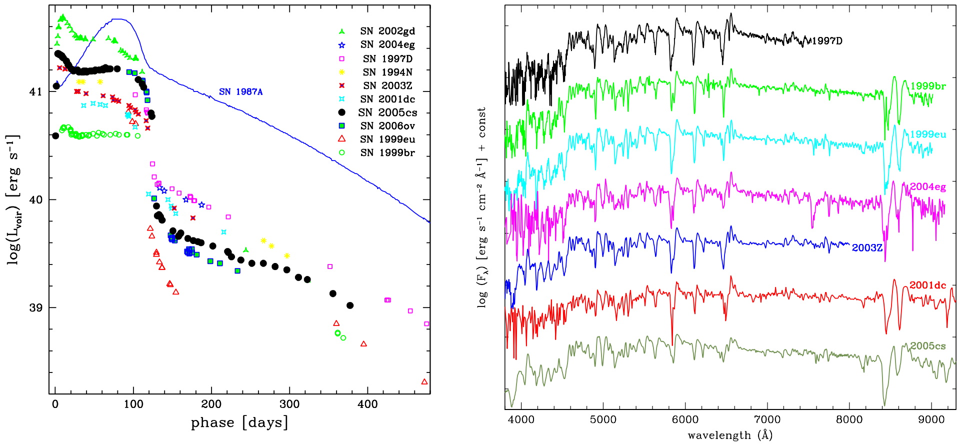

Fig. 2. Left: quasi-bolometric light curves of sub-luminous SNe IIP are compared with that of SN 1987A (see Whitelock et al. 1989, and references therein). Right: selected spectra of under-luminous type II-P SNe obtained at the end of the plateau phase. The spectra of faint SNe IIP are from Turatto et al. (1998); Benetti et al. (2001); Pastorello et al. (2004, 2006, 2009); Spiro & Pastorello (2009).

One can note that a number of SNe discovered recently have observed properties that do not comfortably match the traditional classification scheme detailed above. In this contribution, I will describe a few of these new types of transients.

2. Ultra-faint supernovae

One of the most interesting results of recent SN searches is the detection of intrinsically faint transients. Kulkarni et al. (2007) noted the existence of a poorly-populated area (*gap*) in the luminosity vs. event duration diagram separating traditional core-collapse SNe ($M_V \lesssim$ -15) from the brightest, fast-evolving novae ($M_V \gtrsim$ -10). In this zone we can find unusual transients, including ultra-faint SNe, giant eruptions of luminous blue variables (LBVs), luminous red novae (LRNe) and other exotic outbursting objects. In this section we will describe a few interesting transients that we suggest to be sub-luminous SNe populating the *gap* in the Kulkarni et al. diagram.

2.1. Under-luminous SNe IIP

Faint SNe IIP form a small group of core-collapse events with homogeneous observed parameters: they are faint at all phases compared with classical SNe IIP (the *V*-band absolute magnitude at peak lies in the range between -13 and -15) and late-photospheric spectra show a forest of narrow lines suggesting expansion velocities of the ejected material of $v_{ej} \sim 1000$ km s^{-1}, or even less (Pastorello et al. 2004). This indicates low kinetic energies ($E_k \lesssim 10^{50}$ erg). Finally, the modest luminosity of the light curve tail in faint SNe IIP suggests the ejection of tiny amounts of radioactive ^{56}Ni (a few $\times 10^{-3}$ M$_{\odot}$).

Although this SN group has been related in the past with the core-collapse death of massive stars with significant mass fall-back (e.g. Zampieri et al. 2003), there are new observational evidences that preferentially link them to lower-mass precursors (see Smartt et al. 2009, and references therein). In particular, one object of this class has been studied in detail in recent years: SN 2005cs in M51 (Pastorello et al. 2006, 2009; Li et al. 2006; Tsvetkov et al. 2006; Brown et al. 2007). This SN is

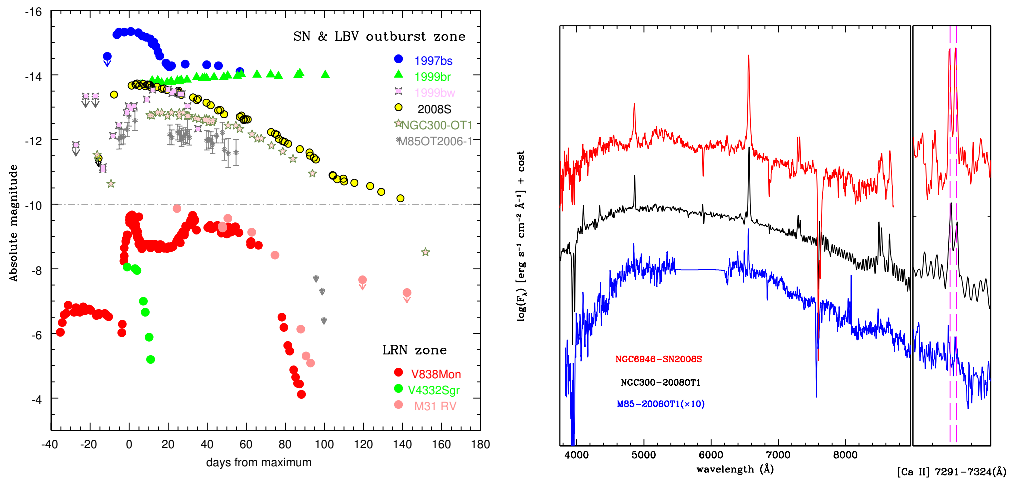

Fig. 3. Left: Absolute light curves of sub-luminous transients. Those with peak magnitudes fainter than ≈ -10 (below the dashed line) are classified LRNe, while in the upper region we can find major eruptions of LBVs (such as (SN) 1997bs, Van Dyk et al. 2000), faint type IIP SNe (e.g. SN 1999br, Pastorello et al. 2004) and the transients described in Section 2.2. Right: comparison of spectra of SN 2008S-like transients, with (on the right) a blow-up of the region of the [Ca II] $\lambda\lambda$7291,7325 emission characterizing this family.

of extreme interest because the progenitor star was detected in pre-explosion Hubble Space Telescope archive images, and was proved to be a moderate-mass (8-10 $M_\odot$) red supergiant star (Maund et al. 2006a; Li et al. 2006).

2.2. SN 2008S-like transients

Another family of transients of recent definition showed hybrid properties between LBV eruptions and type IIn SNe. It is well known than occasionally LBVs can experience luminous outbursts that mimic the spectroscopic characteristics of weak SNe IIn. For this reason they are labeled as *SN impostors* (Van Dyk et al. 2000; Maund et al. 2006b). However, their light curves are erratic, very different from the regular evolution of SNe.

M85 2006-OT1 was the first transient of this group announced by Kulkarni et al. (2007). These authors claimed the progenitor to be a low-mass star (less than 2 $M_\odot$) and found some similarity with nearby LRNe. However, this object was significantly brighter at maximum (by > 2 mags) than LRNe shown in Fig. 3 (left panel). Pastorello et al. (2007b) noted some similarity in the photometric and spectroscopic evolution with faint SNe IIP (see Sect. 2.1) and revised the progenitor mass limit to $\lesssim$8 $M_\odot$, so still consistent with the core-collapse of a moderate-mass star.

Later on, two other transients (SN 2008S and NGC 300 2008-OT1) were discovered with properties similar to those of M85 OT2006-1: slow SN-like light curve evolution, absolute peak magnitudes in the range between -12.5 and -14, type IIn-like spectra evolving with time to redder colors and showing the characteristic narrow emission of [Ca II] $\lambda\lambda$ 7291,7324 (Fig. 3, right). Remarkably, in the two cases mentioned above, the progenitor stars were not detected at the optical and near-infrared wavelengths, but were recovered in pre-explosion *SPITZER* images, and proved to be dust-enshrouded massive stars (M ~ 10-20$M_\odot$) (Thompson et al. 2009; Prieto et al. 2008, 2009, 2010; Bond et al. 2009; Botticella et al. 2009; Smith et al. 2009; Berger et al. 2009; Gogarten et al. 2009; Wesson et al. 2010). Although the observed parameters of these transients are still consistent with luminous outbursts of massive stars, the core-collapse of the star (forming an electron-capture SN) is still a viable scenario (Pumo et al. 2009).

2.3. SN 2008ha and 2002cx-like SNe

SN 2008ha (Valenti et al. 2009; Foley et al. 2009) is the prototype of a new class of weak, fast-evolving, stripped-envelope SNe that share some similarity with peculiar 2002cx-like type Ia SNe (see Jha et al. 2006, for a review on this SN group). The spectrum of SN 2008ha showed narrow P-Cygni lines indicative of low expansion velocities of the ejecta ($v_{ej} \lesssim 2000$ km s^{-1}), no H and He I features, and only very weak Si II and S II lines (Foley et al. 2010). The light curve was characterized by a faint absolute peak magnitude (M ~ -14.2) and a very rapid luminosity decline. These observed properties suggest a very low kinetic energy ($<<10^{50}$ erg), a small amount of synthesized ^{56}Ni (~3-5 $\times 10^{-3}$ $M_{\odot}$) and a modest total ejected mass (a few $\times$ 10^{-1} $M_{\odot}$, Valenti et al. 2009; Foley et al. 2009). Later on, the identification of other fast-evolving stripped-envelope SNe with narrow-lined spectra was announced (e.g. SNe 2002by, 2005E and 2005cz; Poznanski et al. 2010; Kawabata et al. 2010; Perets et al. 2010). In some of them He I lines were detected during the photospheric phase, while permitted and forbidden Ca II features were prominent in the nebular spectra. However, there was only a marginal evidence for the presences of forbidden Fe lines typical of type Ia SNe at similar phases, and of the [O I] $\lambda\lambda$ 6300,6364 doublet that characterizes late-time spectra of core-collapse SNe.

The interpretation on the nature of these transients and their link with 2002cx-like SNe are controversial. Foley et al. (2010) favored a failed deflagration of a C-O WD for SN 2008ha while, for fast-evolving He-rich events, Poznanski et al. (2010) and Perets et al. (2010) proposed He detonations of WDs. However, the core-collapse of massive stars that had their H envelopes stripped away is a viable alternative (Valenti et al. 2009; Pumo et al. 2009; Kawabata et al. 2010; Moriya et al. 2010b). Remarkably, faint stripped-envelope SNe were hypothesized to produce a class of long GRBs without clear signatures of associated bright SNe (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006).

3. Ultra-bright supernovae

At the other extreme of the SN luminosity distribution we find ultra-luminous events, with absolute peak magnitudes exceeding about -20. Hyper-luminous objects have been found for almost all SN types.

3.1. Super-Chandrasekhar mass SNe Ia?

It is well-known that a handful of peculiar SNe Ia does not follow the relation between peak magnitude and width of the light curve (Phillips 1993) that allows us to use these SNe as standard candles. In particular, a few luminous SNe Ia have absolute peak magnitudes between -19.5 and -20.5, slow-evolving light curves, relatively narrow line spectra, and unusually strong C II features. This group includes SNe 2003fg (Howell et al. 2006), 2006gz (Hicken et al. 2007; Maeda et al. 2009), 2007if (Scalzo et al. 2010; Yuan et al. 2010), 2009dc (Yamanaka et al. 2009; Silverman et al. 2011; Taubenberger et al. 2011). These parameters are usually interpreted as the result of the explosion of super-Chandrasekhar mass WD progenitors ejecting up to about 2.4 $M_{\odot}$ of material, 1.6 $M_{\odot}$ of which is ^{56}Ni (Scalzo et al. 2010), although other works offer alternative explanations, including off-axis explosions (see e.g. Hillebrandt et al. 2007; Sim et al. 2007)

3.2. Ejecta-CSM interacting SNe

As mentioned in Sect. 1, SNe IIn display a variety of spectral line profiles, light and color curve evolutions, and peak luminosities. Their overall properties are explained invoking interaction between the material ejected by the SN and the circumstellar medium (CSM) produced in the latest stages of the evolution of the progenitor star. Although pre-SN mass loss occurs in many types of stars, there is increasing evidence linking SNe IIn with massive LBVs (see e.g. Kotak & Vink 2006; Smith et al. 2007; Gal-Yam & Leonard 2009). In recent years the discovery of bright type IIn SNe has bolstered this idea. In particular, SN 2006gy (Ofek et al. 2007; Smith et al. 2007) reached a peak absolute magnitude of about -22 in ~70 days, whilst its spectra showed narrow H lines superimposed on a relatively blue continuum typical of SNe IIn. The extraordinary peak luminosity of SN 2006gy was explained by invoking a huge amount of ejected ^{56}Ni (up to 22 $M_{\odot}$, Smith et al. 2007), pulsational pair-instability and collisions among massive shells (Woosley et al. 2007) or a hybrid scenario with strong ejecta-CSM interaction plus a moderately large ^{56}Ni mass (~ 3 $M_{\odot}$, Agnoletto et al. 2009; Kawabata et al. 2009). Regardless of the mechanism powering the luminosity of SN 2006gy, all authors agree in connecting this SN with the explosion a very massive star (with a main sequence mass of above 100 $M_{\odot}$, Smith et al. 2010) that was losing its H envelope. Other type IIn SNe worth to be mentioned showing high luminosities and/or spectra with clear LBV wind signatures are SNe 2005gj (Trundle et al. 2008), 2006tf (Smith et al. 2008b), 2007rt (Trundle et al. 2009) and 2008fz (Drake et al. 2010).

In the context of transients showing evidence of a pre-existing CSM, SN 2006jc deserves a special mention. The SN explosion was indeed heralded by a major LBV-like eruption on October 2004 (registered by the Japanese amateur astronomer K. Itagaki, Pastorello et al. 2007b). SN 2006jc is the prototype of a new SN type, labeled as **Ibn** (Pastorello et al. 2008a). Type Ibn spectra show at the same time relatively narrow emission lines of He I (v_{FWHM} ~ 2000-2500 km s^{-1}), no H, and broader features commonly observed in SNe Ic (O I, Mg II, Ca II, Fe II). The interpretation is that these SNe are produced in the explosion of WR stars in He-rich circumstellar environments (Pastorello et al. 2007a; Foley et al. 2007; Immler et al. 2008; Tominaga et al. 2008; Anupama et al. 2009). Only a very small number of SNe Ibn have been observed so far, including 1999cq (Matheson et al. 2000), 2000er (Pastorello et al. 2008a), 2002ao (Foley et al. 2007; Pastorello et al. 2008a) and 2005la (although its spectra show some H, Pastorello et al. 2008b). All of them show rather luminous light curve peaks and a subsequent rapid decline in the optical bands.

A remarkable property of SN 2006jc (but not verified so far for other SNe Ibn) is the rapid formation of dust in a post-shock cool dense shell. This likely produces both the fast decline of the optical luminosity and the huge IR excess (Smith et al. 2008a; Mattila et al. 2008). Prompt dust formation was also revealed by other independent studies (Nozawa et al. 2008; Di Carlo et al. 2008; Sakon et al. 2009).

3.3. Ultra-bright stripped-envelope SNe: link to pair-instability events?

We discussed in Sect. 3.2 the cases of some SNe that are probably linked with massive progenitors, and whose high luminosity can be explained invoking a strong ejecta-CSM interaction scenario. However, for other luminous SNe there is no clear evidence for the presence of a conspicuous CSM. This was the case of SN 2007bi, whose early-time spectrum showed prominent P-Cygni lines of Fe II, Na I, Si II, Ca II, O I and Mg II common in photospheric spectra of SNe Ic. However, these lines were relatively narrow and the nebular spectrum showed unusually strong [Fe II] features, similar to those observed in thermonuclear SNe (Gal-Yam et al. 2009; Young et al. 2010). SN 2007bi reached an absolute peak magnitude of about -21.3 and its light curve experienced an extremely slow post-maximum decay. The ejected ^{56}Ni mass was estimated to be 3-11 $M_{\odot}$, while a lower limit for the total ejected mass was 50-60 $M_{\odot}$ (Gal-Yam et al. 2009). These parameters are consistent with those expected in a pair-instability SN produced by the explosion of a 95-110 $M_{\odot}$ core (Gal-Yam et al. 2009), although a core-collapse of a ~40 $M_{\odot}$ C-O core can not be completely ruled out (Moriya et al. 2010a).

Another transient discovered in the Hubble Space Telescope Cluster Supernova Survey, SCP 06F6 (Barbary et al. 2009), had unprecedented properties. Its light curve was symmet-

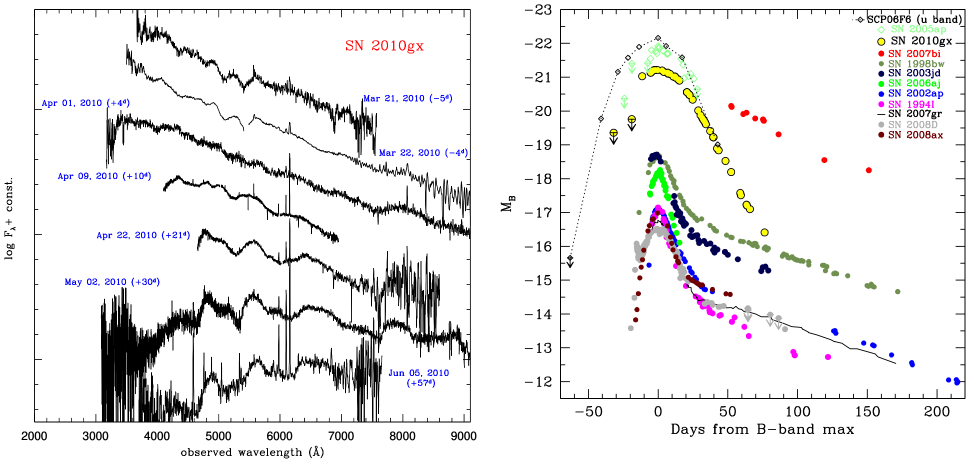

Fig. 4. Left: sequence of spectra of SN 2010gx in the observed frame. Right: absolute light curves of SN 2010gx (Pastorello et al. 2010), SN 2005ap (Quimby et al. 2007) and SCP 06F6 (Barbary et al. 2009) compared with those of a number of normal and broad-lined stripped envelope SNe (see Pastorello et al. 2010, for references).

ric (with a bell-like shape and a ∼100d rise time in the observed frame), the spectrum was extremely blue and with unusual broad absorptions and, finally, the transient was associated with no obvious host galaxy. Since there was no robust constraint on the redshift, even the discrimination between Galactic and extragalactic origin was uncertain. Several scenarios were proposed for SCP 06F6 (Barbary et al. 2009; Gänsicke et al. 2009; Rosswog et al. 2009; Soker et al. 2009), but none of them was fully convincing.

A fundamental impulse to this field was given by Quimby et al. (2009), who noted some similarity of SCP 06F6 (and the ultra-bright SN 2005ap, Quimby et al. 2007) with some objects discovered by the Palomar Transient Factory. Through the detection of narrow interstellar Mg II lines, Quimby et al. (2009) definitely proved that these transients were distant, with redshifts between 0.26 and 1.19. Consequently, they were intrinsically luminous ($M_u \approx$ -22 to -23), being among the brightest stellar explosions ever observed. Later on, the discovery of the relatively nearby SN 2010gx (z=0.23) gave us the unprecedented opportunity to see the spectral transitions of a member of this family from the continuum-dominated spectra shown by Quimby et al. (2009) to those of normal type Ic SNe (Pastorello et al. 2010). The spectral sequence of SN 2010gx is shown in Fig. 4 (left). SN 2010gx and all objects from the Quimby et al. sample have much higher peak luminosities and broader light curves than any other type Ic SN observed so far (Fig. 4, right). However, none of them shows a clear flattening in the light curve at late epochs that one would expect from a ^{56}Ni-powered SN. This led Quimby et al. (2009) to propose a pulsational-pair instability scenario (in which the star survived the eruption) or a magnetar-powered SN, rather than a pair-production SN. Late time observations of one of these events will clarify if (and, in case, how much) ^{56}Ni determines the luminosity of these transients.

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