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Weird and wild supernovae

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Abstract. I review the observational status of Supernovae originating from the explosion of massive stars.

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1. Introduction

The beginning of the modern study of Supernovae (SNe) started about ∼ 70 years ago with the pioneristic works of Zwicky (1942) and Minkowski (1942) on SN rates and SN classification. As a consequence of the evolution of astronomical instrumentations during the years (larger telescopes and detectors sensitivity, better spatial and temporal resolution observations, multiwavelnghts approach due to observations from space) the "Supernova story" can be crudely summarized in three different chronological stages. I identify as *"Heroic Times"* the epoch from early 40's to the end of 70's, in which observations were carried out with ground-based telescopes and data were collected on photographic plates. The occurence of SN 1987A in the LMC boosted enormously the interest for SNe, starting a real SN *"Golden Age"*. In those years entirely new classes of SNe have been discovered and the SN taxonomy has been accordingly revised (Filippenko 1997). The use of CCD arrays coupled with 4m class telescopes allowed to increase the rate of SN discoveries by an order of magnitude with respect to the past and to detect SNe up to very faint luminosity levels ($R_{\rm max} \sim 24 - 25$) and up to distance of cosmological interest ($z = 0.83$ (Perlmutter et al. 1998)). In the last ten years (*"Modern Times"*) SN observations have been characterized by fully exploiting new observational opportunities, such as: i) 10m class telescopes, which accomplished the the spectroscopic follow-up of SNe discovered with HST (Riess et al. 2004); ii) gathering multi-wavelengths observations in radio (Weiler et al. 2002); X-ray (Campana et al. 2006) and UV (Panagia 2003; Immler et al. 2007); iii) robotic telescopes for SN searches in the local universe aimed at improving the local SN rate measurements (Weidong et al. 2010); iv) moderately deep surveys ($z < 1$) aimed at measuring the SN rates at different redshifts (Botticella et al. 2008).

The increasing number of SN detections (from about 30/year at the end of 80's to current 600/year) and their systematic spectroscopic and photometric foolow-up has made possible to discover new classes of rare SNe, such as broad-lined SNe-Ibc, a fraction of which is connected with Gamma-ray Bursts

(Guetta & Della Valle 2007), Luminous Blue Variable-SNe (Pastorello et al. 2007a); ultra-faint (Pastorello et al. 2007b) and ultra-luminous (Quimby et al. 2009) SNe, very fast evolving objects such as SN 2002bj (Poznaski et al. 2009) and objects like SN 2005E (Perets et al. 2009) or SN 2005cz (Kawabata et al. 2009) which occur in "unusual" environments, characterized by the lack of trace of recent star formation, although both SNe exhibit properties of core-collapse events. In this paper, I'll go through each "SN age" in some details.

2. The heroic times

The SN classification as proposed by Minkowski (1942) in his seminal paper was spectroscopically based and very simple. Minkowski reported about *"...two types of supernovae. Nine objects form an extremely homogeneous group provisionally called type I. The remaining ve objects are distinctly dierent; they are provisionally designed as type II. The individual dierences in this group are large..."* SNe of type I are defined by the lack of hydrogen in the spectra. Nowadays we designated as type-Ia (SNe-Ia) those type-I SNe that are characterized by a strong absorption observed at $\sim$ 6150Å (attributed to the P-Cyg prole of Si II, $\lambda\lambda$ 6347, 6371) and lack of H. The absence of H, and the fact that these SNe are discovered also in elliptical galaxies, hint that they may arise from the thermonuclear disruption of a white dwarf approaching the Chandrasekhar limit, after accreting material from a binary companion or coalescing with it on time scales of 0.1-10 Gyrs (Mannucci et al. 2006). Their spectroscopic (Filippenko 1987) and photometric homogeneity (Barbon et al. 1973) have justified "sic et simpliciter" for about three decades the use of these SNe as standard candles. Only in the early 90's (e.g. Della Valle & Panagia (1992), Phillips (1993), Hamuy et al. (1996)) was realized that the use of SN-Ia as cosmic yardsticks was much more complicated that previously thought.

Type II SNe display a completely different behaviour: the spectra are definitely different from each other and characterized by the presence of H-Balmer lines (Filippenko 1997). SNe of type II (SNe-II) have been always discovered in Spirals and never in Ellipticals which are essentially formed by an old stellar populations. Both these facts have consolidated the general consensus that SNe-II originate from the collapse of the core of massive stars $> 8 - 10 M_{\odot}$ (Iben & Renzini 2000). The photometric behaviour shows a broad range of luminosity at maximum, spanning more than a factor 1000 in luminosity (see paragraphs on ultra-faint and ultra-bright SNe) and complex lightcurve morphology (e.g. Patat et al. 1994). The idea is that much of this variety in the luminosity at maximum and in the lightcurve morphologies is due to the mass of the H envelope of the progenitors at the time of the collapse of the core and the properties of the circumburst medium.

The first hint that the Minkowski's classification was an over-simplified version of SN taxonomy came from Bertola's observations (1962) of SN 1961V. The lack of H in the spectra hinted for a type I SN, but the simultaneous absence of the absorption feature at 6150Å was clueing Bertola to conclude that *"....supernova in NGC 1058...must be considered of a new type...'.'* Today we know that these SNe belong to the SN-Ibc class, related with core-collapse events rather than exploding WDs.

3. The golden age

The criteria to classify the members of this subclass of type-I SNe just as "peculiar" objects were adopted in the literature for the following 20 years. Only in the mid-1980s (Panagia 1985; Elias et al. 1985; Uomoto & Kirshner 1985; Wheeler & Levreault 1985)) it was realized that sufficient observational differences did exist to justify having two separate classes of objects. Type-Ib SNe are characterized by spectra with no presence of H or very weak lines (Branch et al. 2002) and strong He I lines at 4471, 5876, 6678 and 7065 Å. When even He lines are no prominent (if not totally absent) a new class, Ic, has been advocated (Wheeler & Harkness 1986). Spectra of Ic SNe show Ca II H & K, NIR Ca II triplet and O I lines with P-Cyg proles. Type-Ib/c

SNe have been so far observed only in late type galaxies and their most outstanding spectroscopic feature is the lack of H in the spectra. Both facts suggest that their progenitors are massive stars, possibly in binary systems (Maund et al. 2004) which undergo the collapse of their cores after they have lost the respective H or He envelopes, via strong stellar wind or transfer to a binary companion via Roche overflow. This scenario is fully consistent with observations at radio wavelengths that reveal the existence of a strong radio emission due to the interaction of the ejecta with a dense pre-explosion stellar wind ($10^{5\div6} M_{\odot} yr^{1}$) /established circumstellar medium, produced by the progenitor (Weiler et al. 2002). In the same years the discovery of SN 1987K showed that some SN could undergo a "trasgender" behaviour. Initially classified as SN-II for the presence of H in its spectrum, SN 1987K evolved into type Ib/c (lack of H) during the nebular stages. The neat interpretation of this behaviour was that the massive progenitors still retained a "thin" H envelope prior to exploding. The H layer was still detectable at early stages but it becomes optically thin at later stages as soon as the ejecta expanded. This class of SNe, labeled as SN-IIb represent the physical link between SNe-II with H-rich envelopes ($M_H \sim 10 M_{\odot}$) and H-deficient Ib/c SNe ($M_H \sim 0.1 - 10^{-3} M_{\odot}$) (Elmhamdi et al. 2006). In 1990 (Schlegel 1990) suggested that the spectra of some SNe-II were characterized by a broad H_{α} line ($\sim 10,000$ km/s) sometimes superimposed by a narrow emission component (FWHM $\sim 200/300$ km/s). In this case the SN is dubbed as II-n, "narrow". SNe belonging to this class show strong H lines in emission without absorptions. Chugai (1997) pointed out that these SNe undergo a strong interaction with a dense wind generated by the progenitor during repeated episodes of mass loss prior to exploding (Benetti et al. 1998).

4. The modern times

The modern era for SN studies has been marked by the discovery of a "peculiar" SN of type Ib/c (SN 1998bw) which was found to be associated with the Gamma-Ray Burst (GRB) 980425, (Galama et al. 1998). GRB-SNe are characterized by: i) lack of H and He in the ejecta; ii) very broad features, which implies large expansion velocity of the order of $0.1c$; iii) the non-relativistic ejecta are characterized by a very high kinetic energy content of $\sim 10^{52}$ erg, that is about 10 larger than observed in "standard" CC-SNe; iv) the explosions are strongly aspherical as derived from profile of nebular lines O vs. Fe (Maeda et al. 2008) and from polarization measurements (Gorosabel et al. 2008); v) they are very luminous at maximum light, which implies that a large amount of ^{56}Ni mass ($\sim 0.5 M_{\odot}$) has been produced. GRB-SNe are very rare phenomena compared to SN explosions without GRBs. Only << 1% of all CC-SNe produce GRBs (Guetta & Della Valle 2007), which implies that very special conditions are requested to stars to become GRB progenitors: i) to be massive $> 30 - 40 M_{\odot}$ (Raskin et al. 2008); ii) H envelopes to be (mostly) lost before the collapse of the core; iii) low metallicity star forming environments seem also necessary (Fruchter et al. 2006; Modjaz et al. 2008); iv) high rotation of progenitor stars (Yoon & Langer 2005; Campana et al. 2008); v) binarity (Mirabel 2004; Smartt 2009).

To date five clear cases of associations between SNe and GRBs have been discovered SN 1998bw & GRB 980425 (z=0.0085) (Galama et al. 1998); SN 2003dh & GRB 030329 (z=0.17) (Hjorth et al. 2003); SN 2003lw and GRB 031202 (z=0.1) (Malesani et al. 2004); SN 2006aj and GRB 060218 (z=0.033) (Campana et al. 2006; Pian et al. 2006); SN 2008hw & GRB 081007 (z=0.53) (Della Valle et al. 2008), plus another three cases, up to $z \sim 1$ which show SN signatures in the spectra of the GRB afterglows (Della Valle et al. 2003; Soderberg et al. 2005; Della Valle et al. 2006a).

4.1. New types of stellar explosion

Intensive SN searches characterized by daily/weekly temporal sampling (Weidong et al. 2010) and recent surveys characterized by thousands deg^2 footprint (Law et al. 2009;

Rau et al. 2009) have increased, by a full order of magnitude, with respect to past surveys, either the number of SN discoveries and the patrolled volume suitable for transients search. These facts have made possible to discover new classes of rare stellar explosions which could not be discovered in the past due to their very low frequency of occurence, $\sim 10^{-2/-4}$ the rate of "standard" core-collapse SNe.

4.2. SN 2006jc: a supernova from a luminous blue variable star?

The peculiar type Ib supernova SN 2006jc is spatially coincident with a bright optical transient that occurred in 2004. Spectroscopic and photometric monitoring of the supernova leads Pastorello et al. (2007a) to suggest that the progenitor was a carbon-oxygen Wolf-Rayet star embedded within a helium-rich circum-stellar medium. There are different possible explanations for this pre-explosion transient, none really conclusive. It appears similar to the giant outbursts of luminous blue variable stars (aka "Hubble-Sandage" variable) of $\sim 100 M_{\odot}$ solar masses. On the other hand the progenitor of SN 2006jc was helium- and hydrogen-deficient unlike LBVs. One can call for an LBV-like outburst of a Wolf-Rayet, and this would be the first observational evidence of such a phenomenon. Alternatively, one can assume a massive binary system composed of an LBV, that erupted in 2004, and a Wolf-Rayet star exploding as SN 2006jc.

4.3. Ultra-faint supernovae

The discovery of SN 1987A as an unusually dimmed SN-II in the LMC, has opened a new line of research in the SN field (Woltjer 1997; Turatto et al. 1998). More recently, the detection of another half a dozen of events (Pastorello et al. 2007b) suggests that very faint CC-SNe do exist, and their contribute to the global CC-SN rate, should of the order of $< 10\%$ (Pastorello et al. 2004), which is smaller than previously estimated (Woltjer 1997). All ultra-faint SNe so far reported were classified of type II "plateau". Two very recent papers have enriched the ulta-faint SN variety. SN 1999ga appears to be the first "linear" type II SN belonging to the ultra-faint family (Pastorello et al. 2009). Even more interesting is the case of SN 2008ha (Valenti et al. 2008). This SN classified of Ib/c type, is the first H-deficient SN detected at so faint luminosity levels ($M_R \sim -14$). The existence of similar SNe has been hypothesized by Della Valle et al. (2006b) to explain the class of long γ-ray bursts that do not show evidence of associated bright SNe.

4.4. Ultra-bright supernovae

Thanks to robotic surveys over large areas of the sky, an increasing number of exceptionally bright SNe such as SN 2005ap (Quimby et al. 2007), SN 2006gy (Smith et al. 2007; Ofek et al. 2007; Agnoletto et al. 2009) and SN 2008es (Gezari et al. 2009; Miller et al. 2008) and bright transients (Quimby et al. 2009) have been discovered. Spectroscopic similarities exhibited among these objects suggest that all of them may belong to a class of ultra-bright CC-SNe ($M_R \sim -23$) for which the explosion trigger may be the so called "pulsational pair-instability" mechanism devised by (Woosley et al. 2007) to explain the exceptional brightness of SN 2006gy. However see Agnoletto et al. (2009) for a more conventional interpretation, in terms of the production of a relatively large amount of ^{56}Ni and strong interaction of the ejecta with a dense circumstellar medium.

4.5. CC-SNe in unusual environment

SN 2005cz appears to be a unique supernova (Kawabata et al. 2009). The early-phase spectrum of this supernova is similar to those of "SNe-Ib" (helium-rich) that originate from the explosion of massive stars. The peculiarity is its place of occurence: NGC 4589 is indeed an elliptical galaxy. This fact is puzzling enough because the stellar population in elliptical galaxies are normally formed by old low-mass stars rather than young and massive stars.

The theoretical modeling of the photometric and spectroscopic data found a number of interesting results: i) it is faint ($M_R \sim -16.5$), producing a tiny amount of radioactive ^{56}Ni, about 0.018 $M_\odot$ (cfr. 0.07 $M_\odot$ of ^{56}Ni for SN 1987A); ii) its light curve evolves very rapidly, suggesting a small ejecta mass; iii) the oxygen emission line in late-phase spectra is much weaker than those of calcium, contrary to what is observed in other core-collapse SNe from envelope-stripped progenitors. All of this may suggest that SN 2005cz originated from a progenitor at the low-mass end of stars undergoing Fe-core collapse, i.e. a star of initially $\sim 10 M_\odot$ possibly in a close binary system. We note that Della Valle & Panagia (2003) and Della Valle et al. (2005) have predicted the occurrence of a few CC-SNe in elliptical radio-galaxies as a consequence of their merging activity. NGC 4589 has a significant (admittedly not overwhelming) radio luminosity, which is about 10 times larger than it is measured in radio-quiet systems.

4.6. Supernova 2008D: towards a continuum from energetic GRB/XRF to ordinary Ibc SN

Swift detected on 2008 January 9.57 UT a X-ray Flash (XRF 080109) in the galaxy NGC2770 (Berger & Soderberg 2008). Optical follow-up revealed the presence of a supernova coincident with the XRF. Early spectra showed broad absorption lines superposed on a blue continuum and the lack of hydrogen or helium lines, similarly to SN 2006aj although much more reddened $E(B\text{-}V)_{tot} = 0.65$ mag. Since the beginning SN 2008D showed a number of peculiar features: i) the optical light curve had two peaks a first, dim maximum was reached less than 2 days after the XRF. After a brief decline the luminosity increased again, reaching principal maximum at V = 17.4 $\sim$ 19 days after the X-ray trigger. Another unusual feature is the spectral metamorphosis. Unlike SNe 2006aj and other GRB-SNe the broad absorptions did not persist. As they disappeared, He I lines developed (Modjaz et al. 2009). Broad lines require material moving with velocity $v > 0.1c$, therefore their quick disappearance implies that the mass moving at high velocities was small. Mazzali et al. 2008; Tanaka et al. 2009a,b have reproduced the spectral evolution and the light curve of SN 2008D after the first narrow peak using a model with $M_{ej} \sim 7 M_\odot$ and spherically symmetric explosion with $E_K \sim 6 \times 10^{51}$ erg, of which $\sim 0.03 M_\odot$ with energy $\sim 5 \times 10^{50}$ erg, are at $v > 0.1c$. The light curve fits indicate that SN 2008D synthesised $\sim 0.09 M_\odot$ of ^{56}Ni, similarly to the broad-lined SN-Ic 2002ap (non-GRB) but much less than the luminous GRB-SN SN 1998bw. Comparing the derived mass of the exploding He-star with evolutionary models of massive stars, the progenitor had main sequence mass $\sim 30 M_\odot$. A star of this mass is likely to collapse to a black hole, as do GRB/SNe. The X-ray spectrum of SN 2008D can be tted with a simple power-law indicating a non-thermal emission mechanism. This leads naturally to a scenario, which is alternative to the shock break-out model proposed by Soderberg et al. 2008. XRF 080109 might well be the breakout of a failed relativistic jet powered by a central engine as in GRBs. The jet failed because its energy was initially low (due to a small collapsing mass) or because it was damped by the He layer, which is absent in GRB-HNe, or both. This scenario described in (Mazzali et al. 2008) implies that GRB-like inner engine activity exists in all black hole-forming SNe Ibc, but only a small percentage of them, about 0.4% − 3% (Guetta & Della Valle 2007) are able to produce a GRB, while mostly SNe-Ibc do not. I note that SN 2008D has signicantly higher energy than normal core-collapse SNe (although less than GRB/HNe), therefore, it is unlikely that all SNe Ibc, and even more so all core-collapse SNe produce a weak X-ray flash similar to XRF 080109. Future X-ray surveys over thousands deg^2 of the sky (e.g. WFXTM (Murray et al. 2009)) will allow us to measure the rates of events like 080109 and to compare it with SN rates, thus setting a final word on this dispute.

4.7. SN 2009bb: a relativistic supernova

In previous sections we learned that SNe-Ibc mark the gravitational collapse of massive progenitors, i.e. $\sim M > 30M_{\odot}$ (Raskin et al. 2008) propelling a few solar masses of material to velocities of $\sim 10,000$ km/s. The closely-related class of GRB-SNe produce, in addition to this, a relativistic outflow powered by a central accreting black hole. SN 2009bb has been discovered by (Soderberg et al. 2009) as one of the most bright SNe ever observed in the radio, outshining all other SNe-Ibc observed on a comparable timescale.

These observations seem to require a substantial mildly-relativistic outflow ($\Gamma > 1.3$) and indicate that the explosion was powered by a central engine like in the GRBs. The search for a possible gamma-ray counterpart in temporal and spatial coincidence with SN 2009bb was unsuccesfull but it should be noted that the SN position was visible to sensitive satellites for only $\sim 65\%$ of the time in which the SN explosion presumably occurred.

The simple interpretation for this event is that it may represent the first detection of a GRB without the aid of a gamma-ray trigger from space. This conclusion is yet supported by the following argument. Guetta & Della Valle (2007) have shown that only $\sim 0.4\%-3\%$ of SNe-Ibc are able to produce GRBs. On the other hand Soderberg et al. 2009 have carried out an extensive VLA radio survey on 143 local SNe-Ibc, therefore between 0.5 and 4 objects of the sample are expected to be SNe associated with GRBs and to be detected as "relativistic" SNe.

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