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Do we still need to search for supernovae ?

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Abstract. In the last decade a major effort has been devoted to the study of supernovae, in particular those of type Ia for their role in the discovery of the acceleration of the Universe. In this contribution I will briefly review some of the new findings that have significantly advanced our understanding of supernovae of all types. At the same time I will argue that, in the next few years, there is the need and the opportunities to answer some of the fundamental questions that are still open.

Key words. Stars: supernovae: general – Stars: evolution

1. Introduction

Textbook stellar evolution shows how the fate of a star is determined by its mass. While most stars fade out quietly, some end their life in a spectacular explosion, named supernova (SN).

There are three main types of SNe which are linked to progenitors of different masses as follows :

- type Ia: 3 – 8 $M_\odot$, thermonuclear explosion of accreting WD in binary system
- type II: 8 – 40 $M_\odot$, core collapse of massive stars after low/moderate mass loss
- type Ib/c: 30 – 60 $M_\odot$: core collapse of massive stars after strong mass loss. 10 – 20$M_\odot$ stars in binary systems may also explode as SNeIb/c.

In the following I will briefly review some of the recent findings for each SN types and highlight some science projects for the future.

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2. Understanding SNIa for precision cosmology

SNeIa are the best luminosity distance indicators on cosmological scale. Dispersion of SN based distances is currently 0.1-0.2 mag but precision cosmology to explore dark energy needs a factor 5-10 better accuracy. To achieve this we need to *i*) increase the statistics, *ii*) improve accuracy of the measurements, *iii*) control systematics. Hereafter I will focus on the latter.

SNeIa are not standard candles: their magnitudes at maximum span over 1.5 mag. However their absolute magnitudes can be calibrated based on the post-maximum luminosity decline rates: bright SNeIa have a slower decline than faint ones. This was already suspected 30 yr ago (Barbon et al. 1973; Rust 1974; Pskovskii 1977) but was definitely established only with the improved photometric accuracy of CCD measurements (Phillips 1993; Hamuy et al. 1996). At some point is was believed that the dispersion of the calibrated absolute magnitude could be reduced to less than

0.1 mag (Sandage & Tammann 1993) but it is now clear that even excluding obvious outliers and objects with uncertain extinction correction the remaining dispersion is larger than that expected from photometric errors only (eg. Altavilla et al. 2004; Prieto et al. 2006).

To exclude possible evolution of SN Ia properties with redshift, which would threaten their use as cosmological distance indicators, it is crucial to understand the physical reasons for SN Ia diversity.

The standard scenarios for SNeIa calls for a C-O WD which, after accreting mass from a close companion, reaches the Chandrasekhar limit (about 1.4 $M_{\odot}$) and explodes due to carbon deflagration. While the nature of the companion star is still strongly debated, either a low mass star in the red giant phase (single degenerate scenario, SD) or another WD (double degenerate scenario, DD) (Greggio 2005, and references therein), a parameter space study by Nomoto et al. (1984) showed that a particular explosion model (labelled W7) produces ejecta velocity profile and nucleosinthesis yields that are consistent with the observed light curve and spectrum (Branch et al. 1985). Recently, this comparison has been refined by means of spectral synthesis fit of the evolution of SNeIa beginning soon after explosion and extending to the nebular phases. This allowed to reconstruct the abundance stratification in the ejecta (Stehle et al. 2005). By comparison with the predicted W7 abundance stratification it was confirmed that an optimal fit of the observation requires a high degree of mixing in the outer ejecta, with Ni extending up to the surface. The detailed comparison of abundance stratification in different SNeIa can give important hints on the physical origin of SN Ia diversity (Mazzali et al. 2008).

Another approach to study SN Ia diversity is to search for correlation (or lack of) among different observable parameters. I already mentioned that the correlation between absolute magnitudes and luminosity decline rates, usually measured by the Δm_{15}[1], shows a significant residual dispersion. This may be related to a second parameter determining the phenomenology of the events. In particular Benetti et al. (2005) show that the temporal derivative of the ejecta expansion velocity, $\dot{v}$(SiII) which is a measure of the abundance stratification in the ejecta, does not correlate with Δm_{15}. Actually in the plane Δm_{15} vs. $\dot{v}$(SiII), SNeIa appear to cluster into three separate groups.

Further analysis shows that whereas the mass of ^{56}Ni, and consequently the SN luminosity, can differ significantly, other characteristics of SNeIa are remarkably homogeneous. In particular, a narrow dispersion of the maximum Si velocity indicates a similar extent of the thermonuclear burning region in all SNeIa: SNe that produce less ^{56}Ni synthesize more intermediate mass elements.

This is attributed to the fact that thermonuclear burning consumes similar masses in all SNeIa and support the idea that a single explosion scenario, possibly a delayed detonation, may explain most SNeIa (Mazzali et al. 2007). Three-dimensional explosion simulations support this interpretation. In these models the distribution of burning products inside SN Ia could result from the variation of a single initial parameter, the flame ignition configuration (Röpke et al. 2007).

There are however peculiar objects which do not fit in this scenario. Howell et al. (2006) report the discovery of a high-redshift supernova, SNLS-03D3bb, that combines an exceptionally high luminosity and a low kinetic energy both implying a super-Chandrasekhar-mass progenitor, possibly of the order of 2 $M_{\odot}$.

Because of the many uncertainties of current evolution scenarios and explosion models it would be crucial to obtain observational constraints for the progenitor system of SNeIa, SD or DD. However, SN Ia progenitors are faint, much fainter than the massive progenitors of core collapse SNe, and so far no progenitor system has been directly confirmed.

Recently, some indirect evidences has been claimed to support the SD scenario. In particular, the peculiar spectral evolution of

[1] Δm_{15} is the difference in magnitude between the maximum of the light curve and the magnitude 15 days later. Δm_{15} is found to correlate with the absolute magnitude hence with the ^{56}Ni mass.

SN 2002ic, with an early spectrum consistent with that of a SN Ia and the late time spectrum showing the signature of strong interaction of the ejecta with a dense H-rich circumstellar shell, has been explained with the presence of an asymptotic giant branch star in the progenitor system of a type Ia SN (Hamuy et al. 2003). Actually, it has been argue that the early spectrum is also consistent with that of a bright SN Ic (Benetti et al. 2006). In this case the presence of a dense circumstellar shell is the natural outcome of the evolution of a very massive star which lost all the H (and He) envelope before explosion.

Support for the SD scenarios was also derived from the spectroscopic detection of circumstellar material in the normal SN Ia 2006X (Patat et al. 2007). The expansion velocities, densities, and dimensions of the circumstellar envelope indicate that this material was ejected from the progenitor system. In particular, the relatively low expansion velocities suggest that the WD was accreting material from a companion star that was in the red-giant phase at the time of the explosion. However, SN 2006X is still a unique case and only the discovery of other SNeIa showing these features can make the case conclusive.

More recently it has been reported the discovery of an object in pre-supernova archival X-ray images at the position of the SNIa 2007on. Deep optical images (also archival) show no sign of this object. From this it was claimed that the X-ray source is the progenitor of the SN again favoring the accretion model for SN Ia (Voss & Nelemans 2008). However, subsequent Chandra X-ray observations and detailed astrometry of the field sources give an offset between the SN and the X-ray source position of 1.18+/-0.27" which casts serious doubts on the identification of the X-ray source with the progenitor (Roelofs et al. 2008).

In conclusion, none of the three cases reported above is definitive and we are still dealing with circumstantial clues.

A most interesting piece of evidence comes from the measurements of the evolution of the SN Ia rate with redshift (Botticella et al. 2008, and reference therein). This appears to increase by a factor $5-10$ up to redshift $0.7-1.0$ and then decrease rapidly and is back to the local rate at redshift $1.5-1.7$.

So far the only explanation proposed to explain the observed low rate of SNeIa at high redshift, taking the current estimates of the star formation rate history, is that for SN Ia progenitors the delay time from formation to explosion is > 2 Gyr (Strolger et al. 2005). However this is in contrast with the observed dependence of the local SN rates on galaxy morphology and colors which instead require that a significant fraction of SNeIa have short delay time ($< 100-200$ Myr) (Mannucci et al. 2005). Actually, it may be fair to conclude that, if we account for the uncertainties in the star formation rate history, at present the diagnostic power of the cosmic SN Ia rate on their progenitor model is relatively weak (Blanc & Greggio 2008).

3. The fate of massive stars

Stars with mass $> 8\ M_{\odot}$ end their life as core collapse supernovae. Hot issues are the association between stripped envelope SNe and GRBs, the dependence of the explosion outcomes on the progenitor mass and the effects of mass loss history.

3.1. SNe and GRBs

This link between SNe and GRBs is a strongly debated, hot issue for which we only remind a few basic observational facts which are most interesting from the point of view of SN researches.

– A few long GRBs have been definitely linked to highly energetic SN Ic, in particular SN1998bw-GRB98042 (Galama et al. 1998), SN2003dh-GRB030329 (Stanek et al. 2003) SN2003lw-GRB031203 (Malesani et al. 2004).

– There are high energy SNeIc with no associated GRBs (eg. SNe 1997ef, 2002ap, 2003jd, 2004aw). Late time spectra of SN 2003jd revealed double-peaked profiles in the nebular lines of neutral oxygen and magnesium. These profiles can be understood if the SN was an aspherical axisymmetric explosion viewed from near the equatorial plane. If SN

2003jd was associated with a gamma ray burst, it would be missed because it was pointing away from us (Mazzali et al. 2005).

– There are long GRBs which do not show a SN. The most compelling case is that of GRB060614 for which it was estimated an upper limit V=-12.6 for the absolute magnitude of a possible SN (Gal-Yam et al. 2006)

– GRB/XRF can be associated to *normal* SN Ib/c. Two such examples have been discovered recently, namely SN 2006aj-XRF060218 (Pian et al. 2006) and SN 2008D-XRF080109 (Soderberg et al. 2008). Whether X-ray flashes-analogues of GRBs are intrinsically 'weak' events or typical GRBs viewed off the axis of the burst, is unclear. In particular it has been suggested that XRF 060218 is an intrinsically weak and soft event, rather than a classical GRB observed off-axis. This extends the GRB-supernova connection to X-ray flashes and fainter supernovae, implying a common origin. Events such as XRF 060218 may probably be more numerous than GRB-supernovae.

At present the observational link between SNe and GRbs have still to result from a coherent scenario and a few different alternatives are still being considered.

3.2. SN II: hydrogen-rich core collapse explosions

After the discovery and study of SN 1987A it may appear that most of the fundamental questions on SN II explosion has been understood and the main ingredients determining the SN display well identified. On the other hand, .. *the mechanism for core collapse supernova explosions remains unknown. ... one-, two-, and three-dimensional simulations performed thus far have shown that (1) neutrino transport, (2) fluid instabilities, (3) rotation, and (4) magnetic fields, together with proper treatments of (5) the sub- and super- nuclear density stellar core equation of state, (6) the neutrino interactions, and (7) gravity will be important* (Mezzacappa 2005, see also Burrows et al. 2006).

From the observational point of view, after SN 1987A much of the effort was spent to understand the physical origins of SN II diversity.

For instance, it is now clear how the stellar radius at the time of explosion, the ejecta and Ni mass and the ejecta kinetic energy determines the light curve. The main parameter determining the early light curve is the pre-supernova radius: the observed 5 mag range in absolute magnitudes corresponds to 1 order of mag in progenitor radii (Turatto et al. 1990). A similar range of variation in the ejecta masses determines the evolution soon after maximum. If the ejecta mass is small (< 1 $M_\odot$) the luminosity declines quite rapidly (Linear SNeII) whereas for large ejecta mass($5 - 10$ $M_\odot$) the luminosity remains almost constant for $2 - 3$ months (Plateau SNeII).

Contrary to early belief it is now clear that there is a large spread in the late (~ 1 yr) luminosity of SN II. The late luminosity gives a direct measure of the Ni mass produced in the explosion which is found to vary in the range $0.002 - 0.3$ $M_\odot$ (Pastorello et al. 2004). It appears that the explosion energy and the Ni yield are directly related both depending on the mass cut for the fall-back on the central compact object. It was suggested that the faint SNeII originate from the explosion of massive progenitors, $25 - 40$ $M_\odot$, in which the rate of early infall of stellar material on the collapsed core is large. Events of this type could form a black hole remnant, giving rise to significant fallback and late-time accretion (Zampieri et al. 2003).

Actually this interpretation seems at odd with the recent *direct* measurement of the progenitor's mass for one faint SN II, 2005cs. This was obtained after the recovery of the SN progenitor on archival images of the nearby parent galaxy, M51. From the observed progenitor magnitude and colors different groups derived consistent estimates that point to the low-end of the mass range for core collapse SNe, that is $7 - 10$ $M_\odot$ (Maund et al. 2005; Li et al. 2006; Eldridge et al. 2007). A lack of correlation between progenitor mass and Ni yield is confirmed by the modelling of light curves and spectral evolution of a sample of SNeII (Zampieri 2007).

A poorly known ingredient which affects both the explosion mechanism and the SN display (i.e. ejecta mass and composition) is the mass loss history of the progenitor. In some cases, at the time of explosion the SN is still surrounded by dense circumstellar material (CSM). In the shock of the high velocity ejecta with the CSM some of the ejecta kinetic energy is converted into radiation and the emission from the shocked regions outshines the typical SN display. On one hand in this situation it becomes often impossible to obtain information on the explosion mechanism, on the other hand the ejecta can be used to probe the mass loss history of massive stars which is a long standing problem in stellar evolution.

One recent spectacular example is that of SN 2005gy one of the brightest SN ever discovered. There is now a general agreement that the exceptional luminosity of this SN originates from the collision of the ejecta with a very massive and dense circumstellar shell ($5-10$ $M_\odot$) (Smith et al. 2008, and reference therein). The presence of the dense circumstellar medium and the estimated ejecta mass call for a very massive progenitor, > 50 $M_\odot$ and possible even > 100 $M_\odot$. However, the explosion engine is completely hidden and therefore many different hypothesis still hold, some quite exotic such as the collision of two massive stars in a dense young cluster, the shock of massive shell ejected due to pulsational pair instability or a quark nova.

One clue may be to look in the sky for objects that may be expected to explode as core collapse producing an optical display similar to SN2005gy. In this respect one interesting case is that of η Carinae, a very massive star which experienced a giant eruptions where huge dense shells are ejected. Because of the short distance, η Carinae can be observed in great detail in one of the spectacular feature of the circumstellar nebula (named the *homunculus*) showing a bipolar shape. It this clear that when η Carinae will explode radiation from the ejecta-CSM shock will dominate the optical emission and that asymmetry will strongly affect the observables. While a detailed modeling is needed, qualitatively the explosion of η Carinae is expected to be very similar to SN 2005gy (Agnoletto et al., in preparation).

4. Conclusions

In this short review I tried to show how the efforts spent in the last decade in the field of SN researches resulted in major advancements but, at the same time, many fundamental questions still remains with no answer.

In the next few years we will continue the efforts to understand the physics of SNeIa that is required to support future space mission aiming to use SNeIa to explore the nature of dark energy. The immediate goal is to obtain detailed spectro-photometric observations and modeling of a large sample of nearby SNeIa to identify the physical reasons of their diversity. This kind of study does not require large telescopes (but for special observations at high spectral resolution, spectropolarimetry or for the monitoring at late phases). Instead it needs flexibility in telescope scheduling and rapid response to alerts. In the short term this can be secured exploiting 2−4m size telescopes which are not over-subscribed (eg. TNG). In the long term one may need to think to a network of automated telescope of this class.

The same observing facilities can also be used to address the questions on the final fate of massive stars and their relation with GRBs. In this case, in addition, we need to complement optical spectrophotometry with observations at shorter and longer wavelengths: X-ray - UV (today SWIFT and GALEX missions) are crucial to explore the shock break-out phase and the CSM-ejecta interaction, whereas near IR is especially interesting at late phase to understand the process of dust formation in the ejecta. In this context, a new opportunity will soon be offered by X-shooter at the VLT which will allow in a single exposure to obtain the full spectrum from near-UV to near IR with an excellent resolution.

To link SN progenitor to their parent population it is especially useful to measure the SN rates as a function of redshift and parent galaxy properties. Waiting for space mission much work need to be done to explore the redshift range 0.5-1.3 which is accessible from the ground. Such study requires an instrument with a large field of view attached at a large telescope. The italian community has the opportunity to play a major role in this field of research with the two prime focus cameras of the Large Binocular Telescope.

References

Altavilla, G., et al., 2004, MNRAS, 349, 1344

Barbon, R., Ciatti, F., & Rosino, L., 1973, A&A, 25, 241

Benetti, S., et al., 2005, ApJ, 623, 1011

Benetti, S., Cappellaro, E., Turatto, M., Taubenberger, S., Harutyunyan, A., & Valenti, S. 2006, ApJ, 653, L129

Branch, D., Doggett, J. B., Nomoto, K., & Thielemann, F.-K., 1985, ApJ, 294, 619

Blanc, G., & Greggio, L., 2008, New Astronomy, 13, 606

Botticella, M. T., et al., 2008, A&A, 479, 49

Burrows, A., Livne, E., Dessart, L., Ott, C. D., & Murphy, J., 2006, ApJ, 640, 878

Eldridge, J. J., Mattila, S., & Smartt, S. J. 2007, MNRAS, 376, L52

Gal-Yam, A., et al., 2006, Nature, 444, 1053

Galama, T. J., et al., 1998, Nature, 395, 670

Greggio, L. 2005, A&A, 441, 1055 Aviles, R., 1996, AJ, 112, 2391

Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., et al., 1996, AJ, 112, 2438

Hamuy, M., et al., 2003, Nature, 424, 651

Howell, D. A., et al., 2006, Nature, 443, 308

Li, W., Van Dyk, S. D., Filippenko, A. V., Cuillandre, J.-C., Jha, S., Bloom, J. S., Riess, A. G., & Livio, M., 2006, ApJ, 641, 1060

Malesani, D., et al., 2004, ApJ, 609, L5

Mannucci, F., Della Valle, M., Panagia, N., Cappellaro, E., Cresci, G., Maiolino, R., Petrosian, A., & Turatto, M., 2005, A&A, 433, 807

Maund, J. R., Smartt, S. J., & Danziger, I. J., 2005, MNRAS, 364, L33

Mazzali, P. A., et al., 2005, Science, 308, 1284

Mazzali, P. A., Röpke, F. K., Benetti, S., & Hillebrandt, W., 2007, Science, 315, 825

Mazzali, P. A., Sauer, D. N., Pastorello, A., Benetti, S., & Hillebrandt, W., 2008, MNRAS, 386, 1897

Mezzacappa, A., 2005, 1604-2004: Supernovae as Cosmological Lighthouses, 342, 175

Nomoto, K., Thielemann, F.-K., & Yokoi, K., 1984, ApJ, 286, 644

Pastorello, A., et al., 2004, MNRAS, 347, 74

Patat, F., et al., 2007, Science, 317, 924

Pian, E., et al., 2006, Nature, 442, 1011

Phillips, M. M., 1993, ApJ, 413, L105

Prieto, J. L., Rest, A., & Suntzeff, N. B., 2006, ApJ, 647, 501

Pskovskii, I. P., 1977, Soviet Astronomy, 21, 675

Roelofs, G., Bassa, C., Voss, R., & Nelemans, G., 2008, ArXiv e-prints, 802, arXiv:0802.2097

Röpke, F. K., Hillebrandt, W., Schmidt, W., Niemeyer, J. C., Blinnikov, S. I., & Mazzali, P. A., 2007, ApJ, 668, 1132

Rust, B. W., 1974, ORNL, Oak Ridge,Tenn.: Oak Ridge National Laboratory (ORNL), Computer Science Division

Sandage, A., & Tammann, G. A., 1993, ApJ, 415, 1

Smith, N., et al., 2008, ArXiv e-prints, 802, arXiv:0802.1743

Soderberg, A. M., et al., 2008, Nature, 453, 469

Stanek, K. Z., et al., 2003, ApJ, 591, L17

Stehle, M., Mazzali, P. A., Benetti, S., & Hillebrandt, W., 2005, MNRAS, 360, 1231

Strolger, L.-G., et al., 2005, ApJ, 635, 1370

Turatto, M., Cappellaro, E., Barbon, R., della Valle, M., Ortolani, S., & Rosino, L., 1990, AJ, 100, 771

Voss, R., & Nelemans, G., 2008, Nature, 451, 802

Zampieri, L., Pastorello, A., Turatto, M., Cappellaro, E., Benetti, S., Altavilla, G., Mazzali, P., & Hamuy, M., 2003, MNRAS, 338, 711

Zampieri, L., 2007, The Multicolored Landscape of Compact Objects and Their Explosive Origins, 924, 358