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Supernova searches and rates

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Abstract. Supernova statistics, establishing a direct link between stellar populations and explosion scenarios, is a crucial test of stellar evolution theory. Nowadays, a number of SN searches in the local Universe and at high redshifts are allowing observational probes of long standing theoretical scenarios. I will briefly review some of the most interesting results in particular for what concern the evolution with cosmic time of the SN rate, which is one of the topic that in the last few years had a most rapid development.

Keywords. supernovae: general, stars: evolution, galaxies: stellar content

1. Introduction

The use of supernova (SN) statistics to constrain the progenitor scenarios and explosion mechanisms began 50 yr ago with the basic observations that different SN types are linked to different stellar populations (Minkowki 1964). For a long time, the progresses were limited by the small number statistics until, with the progress of instrumentation and of the tools for data mining, searching for SNe has become a routine process that, nowadays, is producing several hundred events per year (Fig. 1). The best known outcome of these efforts is the discovery of the accelerated expansion of the Universe but, as a by product, we could obtain accurate measurements of the SN rates as a function of parent stellar population, at least in the local Universe, and cosmic age. In the following I will briefly review some of the most significant results and their implications.

2. Modern supernova searches

The rich SN harvest of modern SN searches has minimized the problem of the sample size, but we should be aware that using SN statistics is not only a question of sample numerosity, it requires also a careful consideration of the search and selection biases. Indeed, while each search has different characteristics, all have biases. One basic distinction is between targeted and un-targeted SN searches.

Typically, a targeted SN search monitors a well defined sample of bright, nearby galaxies, preferentially giant spirals which are known to have a higher SN rate. The most successful experiment of this sort is probably the Lick Observatory SN search (LOSS, Leaman *et al.* 2011) but in this category are also to be included the many SN searches conducted by amateur astronomers that today contribute with a significant number of SN discoveries in the local Universe.

Un-targeted SN searches make use of wide field imagers to monitor large sky areas, e.g. the Sloan Digital Sky Survey II (SDSSII) surveyed 300 sq. deg. in five filters (Frieman *et al.* 2008), but we should be aware that, contrary to a usual assumption, this does not guarantee that they are unbiased. In many wide field surveys the candidate selection algorithm is designed to strongly reduce the number of false detections, e.g. favoring the candidates associated with galaxies or neglecting those in the nucleus of bright galaxies.

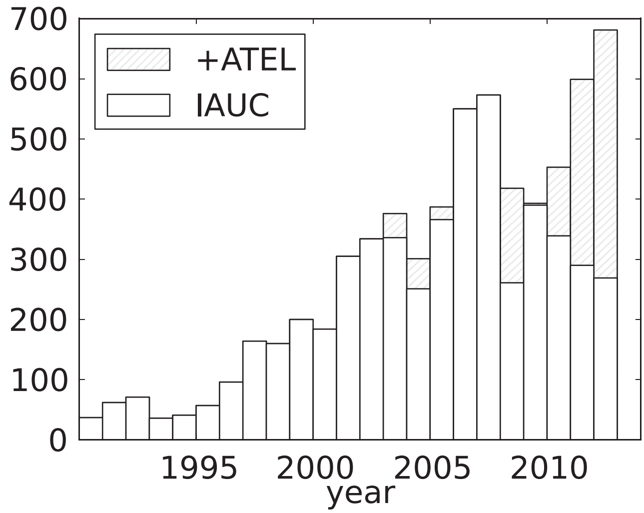

Figure 1. Number of SN discoveries per year (updated at 2012 Dec 31). The white histogram are the SNe reported through the *IAUC/CBET* ((`www.cbat.eps.harvard.edu`) that, to date, are over 6100, whereas the hatched histogram shows those reported **only** via ATEL, The Astronomer's Telegram (`www.astronomerstelegram.org`), that are just over 1100. The ATELs are allowing the community for immediate dissemination of reports and comments upon new astronomical observations that is crucial to assure prompt follow-up. On the other hand because ATELs are not filtered or edited the reports are not standardized and there are more chances for duplications and typos. The fraction of SNe reported only in ATELs is growing, being over 50% in the last two years.

In addition, a specific observing strategy may be adopted to maximize the detection of selected transients: in most cosmological SN searches observations were spaced by 15 days to maximise the detection of type Ia SNe near maximum. Indeed many of the breakthroughs of the Palomar Transient Factory (PFT, Rau *et al.* 2009) are the result of the monitoring of un-explored time domain, with either very frequent cadence or otherwise long term survey duration.

The presence of specific biases affecting different searches was emphasised by Quimby *et al.* (2012) by comparing the SN discovery list of LOSS, SDSSII and their own SN search based on the ROTSE experiment (`www.rotse.net`). It turns out that the luminosity function of the SN Ia found by LOSS includes a higher fraction of faint events than either SDSS II and ROTSE, while the latter is peculiar with respect to the luminosity function of SN host galaxies, with an excess of faint galaxies compared with both SDSS II and LOSS. None of these two biases have an obvious explanation though likely they are the result of a combination of many different search features, including the instrument characteristics (field of view, pixel scale), search strategy (depth, frequency of monitoring) and detection/selection algorithms.

Despite the presence of biases, the plain statistics of SN discoveries can still lead to fundamental conclusions for what concern the origin of SNe. A good example in this respect is the statistics of the SN types as a function of the host galaxy properties, in particular the galaxy morphological type. Fig. 2 shows the number of supernovae of type Ia against the number of those of type II grouped according to the Hubble type of their host galaxies. It is well known that the Hubble sequence in the Local Universe is also a sequence of stellar population ages (eg. Buzzoni 2005): early type galaxies (*E, S0*) have completed their stellar assembly long time ago and therefore they host only low mass stars with an average age of several billion years. At the other extreme, in the late

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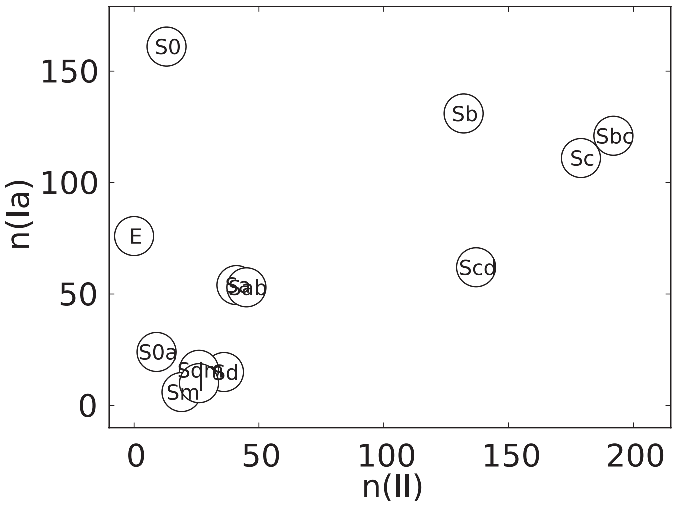

Figure 2. Number of SN Ia vs. number of SN II grouped according to the morphological type of the host galaxies. The sample is limited to host recession velocities $< 10000\,\mathrm{km}\,s^{-1}$ and the numbers where **not** normalized to the relative fraction of different type of galaxies in the Universe. Data were extracted from the Asiago Supernova Catalogue (`http://graspa.oapd.inaf.it`).

spirals (*Sc,Sd,Sm*) star formation is still ongoing and the luminosity is dominated by young massive stars. Intermediate Hubble types host a mixed stellar population with a comparable fraction of old, low mass stars and of young, massive stars.

Starting from this knowledge interpreting the distribution of points in Fig. 2 is straightforward. Type Ia SNe that strongly dominate in early type galaxies need to be associated to low mass progenitors and instead type II that are most frequent in late spirals are to be linked to young massive stars. We may notice that the number of SN Ia is high also in late spirals where old stars are rare. If we maintain that the type Ia progenitor mass range is the same in all galaxies, the similar rate of events in early and late spirals indicates a wide range of progenitor ages at explosions, from few 10^9 yr in ellipticals to few 10^5 yr in late spirals. The latter however are not the dominant fraction: for the same global on-going star formation rate, measured from the number of detected SN II, the number of type SN Ia in intermediate *Sb* spirals is much higher that in late *Scd* spirals arguing in favour of a significant fraction of SN Ia progenitors with intermediate ages. As shown in the next section, these qualitative conclusions based on the plain event statistics, are confirmed by the results of the detailed quantitative analysis.

3. SN rates and galaxy types

For a quantitative statistical analysis first of all we need to compute SN rates, that is not just count the discovered events but also account for the surveillance time and for the observational biases, at least the known ones, and normalise to the size of the stellar population under investigation. This approach requires a detailed knowledge of the SN search characteristics which usually limits the analysis to the SNe discovered by a specific search, then reducing the available SN statistics. The obvious solution, i.e. to combine the data of different searches, was attempted only in one case (Cappellaro *et al.* 1999). With this approach, by comparing the SN rate per unit blue luminosity (SNu) to the star formation rate (SFR) for galaxies of different colours (as derived by galaxy evolutionary model, Kennicutt 1998) it was possible to constrain the masses for core collapse SN

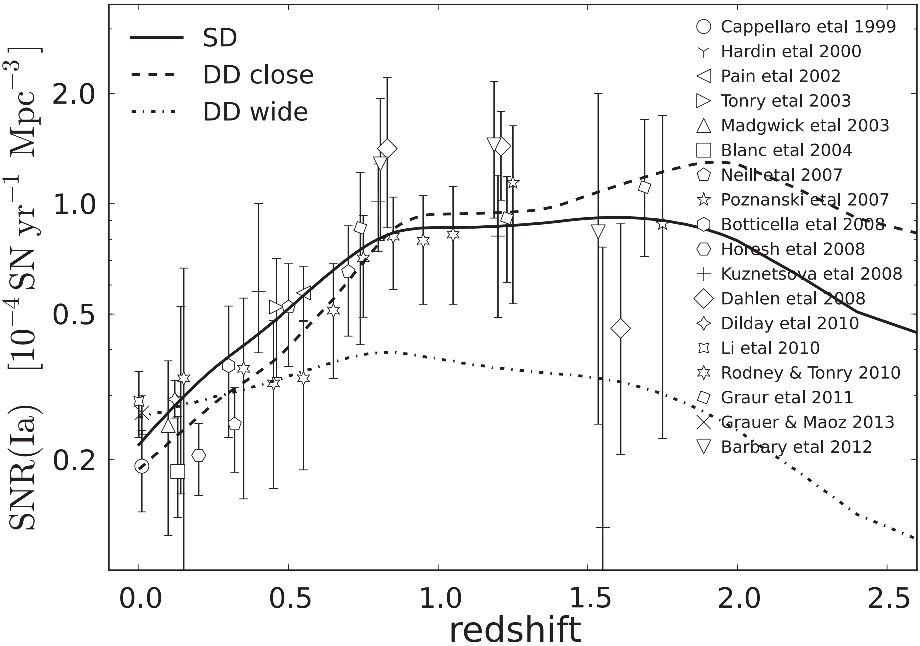

Figure 3. Evolution with redshift of the type Ia SN rate per unit volume. All measurements available in literature have been collected excluding early estimates that later have been revised and a few measurements at low redshift with very large error-bars. The predicted rate evolution assuming the current estimate of SFR (Cucciati *et al.* 2012) and three different SN Ia progenitor scenarios, namely single degenerate (SD), and two flavors of double degenerate (DD) with close and wide distribution of the binary separation (Greggio 2005) are also shown.

progenitors to the range $10 < M < 40\,\mathrm{M}_\odot$. Instead the rate of type Ia in SNu was found approximately constant in galaxies of different Hubble type. Because the M/L ratio is significantly lower in late spirals compared with early type galaxy, this implies that the SN Ia rate per unit mass is much higher in star forming galaxies, supporting the presence of a significant fraction of relatively young stars among SN Ia progenitors. This finding was confirmed by a direct calculation of the SN rate per unit mass, where the galaxy mass was derived from the K-band infrared luminosity and the B-K colours (Mannucci *et al.* 2005). More recently a detailed analysis of the data of LOSS (Li *et al.* 2011) lead to the identification of the dependence of the SN rate per unit mass on the galaxy mass: galaxies with higher mass have a lower SN rate per unit mass. In the context of galaxy evolution, this can be understood considering the downsizing effect for which, in the local Universe, the SFR per unit mass is higher in galaxies of lower mass. This effect is found also for SN Ia that again is an evidence for a significant fraction of SN Ia having young progenitors. Eventually, the direct evidence that the SN Ia rate increases with the specific SFR, that is the SFR per unit mass, has been derived by Smith *et al.* (2012) using the SDSS-II SN database.

The fact that SN Ia show a wide range of progenitor ages or, how it is usually refereed to, of delay time from star formation to explosion, is consistent with the consolidated stellar evolution paradigms. Indeed, while there are still fundamental uncertainties in the standard scenarios for SN Ia explosions, double degenerate or single degenerate or both, in all cases it is expected that the delay times distribution ranges from few 10^5 yr to several 10^9 yr, with more power at young ages (Greggio 2005, 2010).

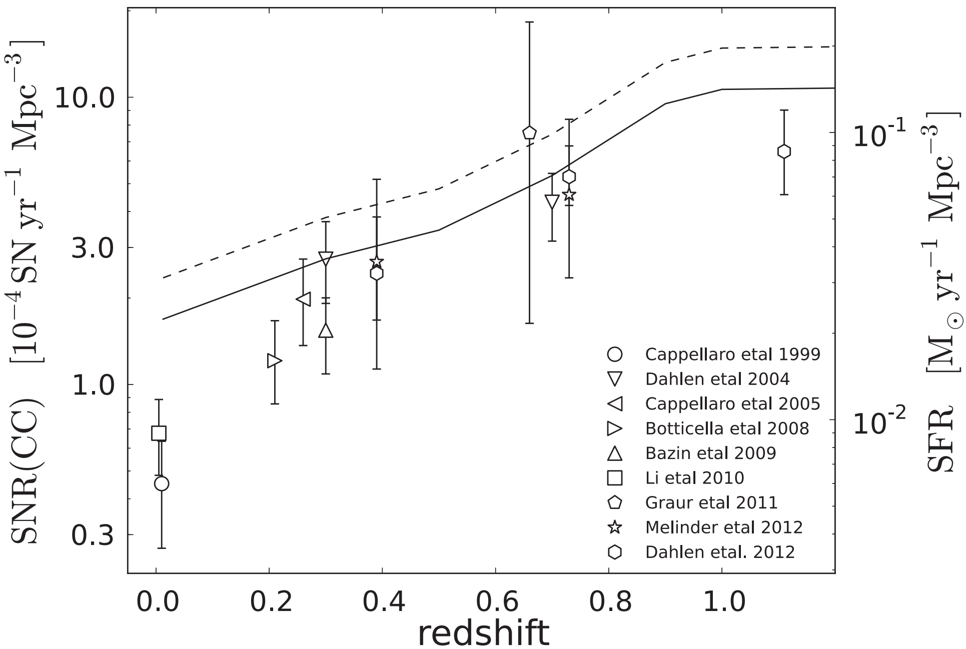

Figure 4. The evolution with redshift of the core collapse SN rate per unit volume is compared with the predicted evolution assuming the current estimate of the SFR (Cucciati *et al.* 2012) and assuming $10 < M < 40\,M_{\odot}$ for the progenitor mass range (solid line) or adopting a lower limit of $8\,M_{\odot}$ (dashed line). The measurements shown in the plot do not include the correction for the core collapse SNe that remain hidden in the nucleus of starburst galaxies (cf. Mattila *et al.* 2012).

4. Evolution of the SN Ia rate with redshift

Following the early attempts to measure the cosmic evolution of the SFR, Madau *et al.* (1998) were among the first to argue that measurements of the rate of SN Ia with redshift could be used to constrain their delay time distribution and in turn the progenitor scenario. Some time later, the first results based on the Great Observatories Origins Deep Survey (GOODS) lead to a surprising claim (Strolger *et al.* 2004): the SN Ia rate per unit volume shows a rapid increase up to redshift ~ 1 then start to decrease, and by redshift 1.7 the rate is a factor 3/4 lower than at peak. This seemed to imply that the SN Ia delay time distribution is limited to the range 2-4 billion yr.

The need to reconcile this finding with the evidences from the local Universe that a good fraction of SN Ia occurs after a short delay time gave raise to a number of speculations about the possible co-existence of two distinct populations of SN Ia (Scannapieco & Bildsten 2005, Mannucci *et al.* 2006) with very short and very long delay time, respectively. However, not even the two population model could match the GOODS observations: fitting simultaneously the high rate at redshift ~ 1 and the decline at higher redshift would need an ad hoc mechanism to suppress the prompt population at high redshift that otherwise would be dominating. Therefore the debate remained open while a number of groups spent their efforts to add new measurements of SN Ia rate at high redshift. The results of this effort are summarized in Fig. 3 showing that the picture changed significantly with respect to the early claims. First of all the new measurements along with a re-analysis of some of the early data (cf. Dahlen *et al.* 2008, Rodney & Tonry 2010) show that the raise of the SN Ia rate up to redshift ~ 1 is more gentle than initially believed. In addition, the high redshift measurements, while showing a

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significant dispersion and large errorbars, are consistent with a negligible evolution at redshifts > 1.

These observations can be compared with the theoretical predictions based on the known cosmic star formation history and on different evolutionary scenarios. In particular Fig. 3 shows three of the scenarios discussed by Greggio (2005) for SN Ia progenitors. In all cases the SN Ia occurs when a WD in a binary system reaches the Chandraseckhar mass limit either because of accretion from a main sequence or red giant companion (single degenerate scenario, SD) or because of merging with a companion WD (double degenerate scenario, DD). In the latter case, the outcome is strongly dependent on specific assumptions of the common envelope phases that lead to different distribution of binary separation. Two alternatives are shown that corresponds to close (DD-close) and wide (DD-wide) binary separation, respectively. It turns out that both SD and DD-close give an excellent fit of the observations while DD-wide fails because of a shallower evolution with a larger fraction of event with very long delay time compared with the observations.

The result from the analysis of the cosmic evolution of the SN rate is that, consistent with the expectations from the standard astrophysical scenarios, there is evidence for a wide distribution of delay time for SN Ia, with roughly half of the events occurring within 0.5 billion yr and a long tail extending up to an Hubble time and no evidences for two distinct populations. Eventually, the same conclusion was derived, by a refined analysis of the host galaxies of SDSS-II SNe leading to the detection, along with prompt and late components, of an intermediate-delay progenitor population with age $0.4 < t < 2.4\,\mathrm{Gy}$ (Maoz *et al.* 2012).

5. Core collapse SN rate and star formation history

The rate of core collapse SNe (CC SNe) in a given stellar stellar population is a direct measure of the on going SFR, and hence the CC SN rate evolution as a function of redshift can be used to track the cosmic star formation history. This is shown in Fig. 4 where the published estimates of the CC SN rates are compared with the SFR derived from measurements of the FUV galaxy luminosity (Cucciati *et al.* 2012). To match the two scales (SN rate vs. SFR) we need two basic assumptions:

(a) the initial mass function (IMF). While the fraction of massive stars for a given SFR depends from the IMF, the same quantity determines the luminosity/SFR conversion factor. Therefore, the actual choice of the IMF is insignificant as soon as it is consistent in all the comparison. Here we adopt a standard Salpeter IMF as in Cucciati *et al.* (2012).

(b) the mass range for core collapse SN progenitors. A good match between CC SN rate and SFR is obtained adopting $10 < M_{CC} < 40\,\mathrm{M}_{\odot}$ (solid line in Fig 4). While the uncertainty on the upper limit has a modest influence (for an upper limit of $100\,\mathrm{M}_{\odot}$ the expected SN rate increases by only $\sim$10%), the choice of the lower limit is more important.

For the latter, we remind that in recent years it has become possible to obtain direct measurements of the mass of CC SN progenitors by the analysis of deep, high resolution pre-discovery images. The method has still large uncertainties but the available data on a dozen events suggest that the lower limit for core collapse explosion is lower than that adopted above, i.e. $8 \pm 1\,\mathrm{M}_{\odot}$ (Smartt 2009). With this number the expected SN rate increases by $\sim 40\%$ (dotted line in the Fig. 4) causing a significant mismatch with respect to the observed rates.

As a possible explanation for the observed discrepancy it has been claimed that the observed rate are lower limit of the true value because a significant fraction of events would remain hidden in the nuclear regions of luminous infrared galaxies due to very high dust extinction (Mannucci *et al.* 2007, Mattila *et al.* 2012). Some support to this idea come from the results of infrared SN searches in starburst galaxies (Miluzio *et al.* 2013) although we would expect that the effect is negligible at low redshift where the fraction of LIRs is small. Instead, as we see in Fig. 4, the discrepancy is significant also at low redshift where SN searches are most complete. We should not forget that the issue of the uncertain extinction correction affects not just SN searches but also galaxy luminosity measurements, in particular in the (rest frame) UV band. Therefore the issue remains open and further more accurate estimates of the CC SN rates are definitely needed not least for a consistent check of more conventional SFR indicators.

6. Conclusion

SN rates as a function of redshift have been measured mainly as a by product of SN searches aimed to measure cosmological parameters. Despite some observational biases they have been able to set useful constraints on the progenitor scenarios and, when extinction biases are fully understood, also on the cosmic star formation history. We may notice however that for a further discrimination among competing scenarios, SN rate per unit volume appears insufficient and what we need now is a detailed investigation of the link between SNe and their parent stellar population as a function redshift. This requires a characterization of the monitored galaxies in term of luminosity, mass and star formation history.

With this in mind we started a new SN search at intermediate redshift using the VLT Survey Telescope (VST) equipped with the OMEGACAM wide field camera (Botticella *et al.* 2013). Differently from other projects, our emphasis is on measuring un-biased SN rates as a function of galaxy properties and, for this reason we focused on two well known sky fields, COSMOS and the Chandra Deep Field South, for which an outstanding amount of ancillary data allows the recovery of the galaxy physical properties. With our project, named SUDARE from Supernova Diversity and Rate Evolution, we aim to provide a first investigation of the statistics of SN diversity as a function of galaxy evolution. While statistics is not expected to be enormous (just few hundred SNe at the completion of the four years search) the project is also intended to prepare the ground for the analysis of future massive transient search, in particular LSST and EUCLID.

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Discussion

Anderson: The discrepancy between IAU and ATEL SN announcements is worrying. Will it be possible to unify these in the future, and how important is this?

Cappellaro: There has been a number of discussion to solve this issue, but not definite solution yet. I agree that this is an important issue. At least nearby events (where nearby is to be defined) should be recorded homogeneously.

Gabici: Which is the best estimate for the supernova rate in the milky way?

Cappellaro: Estimates taken from 1 in 20 year to 1 in 50 year, the later appears to find more support in recent literature.

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