The supernova rate: a critical ingredient and an important tool

Filippo Mannucci

INAF-OAA, Largo E. Fermi 5, 50125 Firenze, Italia

Abstract. In this review I summarize the role of supernova rate as a critical ingredient of modern astrophysics, and as an important tool to understand SN explosions. Many years of active observations and theoretical modeling have produced several important results. In particular, linking SN rates with parent stellar populations has proved to be an important strategy. Despite these advances, the situation is far from clear, in particular for the SNe Ia.

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1. WHY BOTHER WITH HOW MANY SNE ARE EXPLODING

SN rate has two distinct roles in modern astrophysics. On one side, it is a critical ingredient to be used in any model of galaxy formation and chemical enrichment. On the other side, SN rates are also a tool to investigate the nature of the exploding stars.

1.1. An ingredient

There are many fields were SNe play a key role. 1. Both core-collapse and thermonuclear SNe are the main producers of heavy elements (e.g., [78]). The chemical enrichment of each galaxy is determined by the SN rate as a function of galaxy age, while the cosmic SN rate as a function of redshift is leading the chemical evolution of the universe as a whole [79, 105]. 2. Core-collapse (CC) SNe are believed to be the main producer of dust at high redshifts [64, 65, 96]. 3. Both types of SNe could contribute and even dominate the feedback processes needed for galaxy formation and to explain the ubiquitous presence of outflows in star forming galaxies (e.g., [87]). 4. If a reasonable calibration can be obtained, and if dust extinction can be estimated and controlled (e.g., [70]), then the CC rate can also be used to estimate to star formation (SF) density and its evolution with redshift. Many indicators are now available (see, for example, [51, 68]), each one with different uncertainties and biases, and it is therefore important to compare different, independent result [25, 24, 10].

Summarizing, many fields of astrophysics need to know how many SNe are exploding at each redshift, in what environments, and what are the properties of the ejected material. The importance of a good modeling of SN rate should not be underestimated. Naive approximations, such as that all SN Ia explode after 1 Gyr, are likely to produce completely wrong results.
1.2. A tool

In the same time, SN rates are also an important tool to investigate the nature of the exploding systems. While the evolution of SN photometry and spectra and the stratification of the chemical elements can constrain the explosion mechanism, SN rates are crucial to constraint the progenitors. For example, soon after the introduction of the distinction between “type I” and “type II” SNe [84], van den Bergh [122] used the frequency of type I and type II SNe to investigate the progenitors.

CC SNe are considered to be due to the gravitational collapse of very massive stars, $M > 8 \text{M}_\odot$, although how massive is still to be defined. In principle, this uncertainty in the mass range can be solved or reduced by measuring good rates and the initial mass function (IMF) of the parent population [10, 43].

The situation for SNe Ia is more complex. These SNe are considered to be due to the thermonuclear explosion of a C/O white dwarf (WD). Such a conclusion follows from a few fundamental arguments: the explosion requires a degenerate star, such as a white dwarf; the presence of SNe Ia in old stellar systems means that at least some of their progenitors must come from old, low-mass stars; the lack of hydrogen in the SN spectra requires that the progenitor has lost its outer envelope; and, the released energy per unit mass is of the order of the energy output of the thermonuclear conversion of carbon or oxygen into iron. Considerable uncertainties about the explosion model remain within this broad framework, such as the structure and the composition of the exploding WD (He, C/O, or O/Ne), its mass at explosion (at, below, or above the Chandrasekhar mass) and flame propagation (detonation, deflagration, or a combination of the two).

Large uncertainties also remain on the nature of the progenitor system. Usually, a binary system is considered, with the WD dwarf accreting mass either from a non-degenerate secondary star (single-degenerate model, SD) or from a secondary WD (double-degenerate model, DD). The evolution of the binary system through one or more common envelope phases, and its configuration at the moment of the explosion are not known (see [126] for a review). Single-stars models are also possible [119, 75], and current observations are unable to solve the problem [77].

2. THE DELAY TIME DISTRIBUTION

The key quantity to relate type Ia SN rate to the parent stellar population is the delay time distribution (DTD), i.e., the distribution of the delays between the formation of the progenitor system and its explosion as a SN. In general, deriving an expected DTD from a progenitor model is not an easy task because many parameters are involved, such as the initial distribution of orbital parameters in the binary system, the distribution of the mass ratio between primary and secondary star, the efficiency of mass loss during the common envelope phase, the efficiency of mass transfer from one star to the other, the amount of mass retained by the primary star during accretion. Also the uncertainties in the explosion model play a key role: for example, it is not known if it is necessary to reach the Chandrasekhar mass to start the explosion, or if it is enough to be in the sub-Chandrasekhar regime.

Starting from the ’80s, several authors have computed the expected DTD for SD and
DD systems [42, 117, 116, 120, 100, 49, 127, 80, 7, 41, 126, 18, 59, 46, 45]. Different models often obtain very different results. In some cases, all the explosions are concentrated in a very narrow range of delay time (for example, in the SD Chandrasekhar-mass model by Yungelson & Livio [127] all the SNe explode between 0.6 and 1.5 Gyr). In other cases, the explosion occurs at any delay time (from 25 Myr to 12 Gyr, in the DD model by Yungelson & Livio [127]); in some models, all happens soon after the formation (within 1 Gyr for the SD model by Belczynski et al. [7]); in other cases the first SNe explode after a very long time (more than 10 Gyr for the semidetached double white dwarf model by Belczynski et al. [7]); some distributions are smooth [41], some others have multiple peaks [7].

The observed SN rate is the convolution of the DTD with the past SF history of the galaxies. This latter function also determines the stellar population. As a consequence, studying the SN rates in different parent galaxies can put strong constraints on the DTD.

3. 50 YEARS OF OPTICAL OBSERVATIONS

The measured rates of SNe both at low and at high redshifts are based on optical observations because only at these wavelengths the current instrumentation has sufficient field coverage, spatial resolution, and sensitivity to detect large numbers of SNe within a reasonable observing time.

In the local universe ($z<0.1$), the rates most commonly used have been computed by Cappellaro et al. [15] and Mannucci et al. [71]. Both works are based on a SN sample defined by Cappellaro et al. [17] from a a compilation of a few visual and photographic searches. The ongoing LOSS SN search is expected to produce a new set of SN rates in a short time (W. Li et al., in preparation), based on a homogeneous set of several hundreds of SNe detected in ten years of CCD searches.

Many past and ongoing searches have been designed to discover distant SNe, up to $z \sim 1.5$, and measure the evolution of the SN rate [92, 72, 50, 91, 63, 115, 8, 25, 110, 16, 6, 88, 109, 112, 94, 10, 60, 24, 52, 40, 28]. Despite this large effort, significant uncertainties remain. On one hand, the rates observed by some groups are not consistent with other results within the estimated errors, meaning that at least part of them are affected by systematic errors that are not well understood. On the other hand, rates are derived from the observed number of SNe after a long list of assumptions (luminosity, light curve, dust extinction, sensitivity, spatial distribution of SN within their parent galaxy, colors, and so on). Usually, it is assumed that these parameters have no evolution with redshift, and this can introduce large uncertainties. For example, several searches for Ia SNe at high redshift assume that the moderate average extinction observed locally remains the same at any redshift. If, as it is expected, average extinction actually increases with distance, this is likely to introduce an underestimate of the rates at high redshifts. Also, the above-mentioned assumptions are calibrated on the local sample of SNe, dominated by relatively quiescent galaxies. At high redshifts, dusty starburst like LIRG and ULIRG become the dominant contribution to star formation, and SNe might have different properties [70].

The rates observed at high redshifts, produced by the convolution of the DTD with the cosmic SF history, can in principle be used to constrain the DTD. Actually, large
uncertainties are present both in the observed rates and in the cosmic star formation history, and the combination of these two uncertainties makes it impossible to derive meaningful DTDs [31, 90, 9]. The redshift evolution of the rates can still be used to put additional constraints, but only when other observations are considered [69], as explained below.

Galaxy clusters play a special role for the study of galaxy evolution and SNe. These regions are particularly overdense, and most of the galaxies are early-type. Their stellar populations are usually considered to be simpler than in the field and dominated by old stars. Constraints on the DTD of Ia SNe at late times can be obtained by measuring cluster SN rates. Clusters are also very important to derive information on the chemical evolution of the universe, because they retain all the metals lost by the individual galaxies. For this reason, the measured SN rate can be compared with the total amount of SNe ever exploded in the cluster as measured by the integrated metallicity [105, 79, 14, 26]. Finally, the large number of galaxies present in a relatively small volume can increase the efficiency of SN detection. For all these reasons, a significant effort was put in looking for SNe in galaxy clusters [22, 5, 13, 89, 35, 33, 76, 39, 107, 101, 74, 34]. The number of detected SNe is still low, and more observational work is needed in this field.

4. OBSERVATIONS AT LONGER WAVELENGTHS

In the last few years several attempt were made to avoid the limitations of the optical observations and detect SNe in dusty environments. Several searches targeted the near-IR range, up to 2.2$\mu$m [121, 44, 11, 81, 85, 66, 73, 1, 82, 83, 23, 56] and obtained a few detections. The rates measured by Mannucci et al. [73] show that IR observations can detect many more SNe in starburst than optical observations, but also that most of the expected SNe are still missing. This is probably due to the presence of high dust column densities, preventing the detection of many SNe, or by the dominance on nuclear starburst. Ongoing and future projects, based on the ESO instruments HAWK-I and VISTA, are expected to produce a larger sample of IR-detected SNe, and study their properties.

Significant results, albeit for a small number of galaxies, have been obtained at radio wavelengths [108, 62, 99, 61, 93]. At these frequencies, interferometry allows for very high spatial resolutions, and even the inner parts of the starburst are transparent. As a result, SNe can be detected in deep images even if they explode in the nucleus of the parent galaxy and are completely enshrouded in dust. It is difficult to use these results to obtain rates, as the properties of SNe in such dense environments are not well known. Nevertheless, these observations show that a significant fraction of SNe are missing from any existing searches. These SNe could be a small fraction (\(\sim 10\%\)) in the local universe, but are expected to dominate the rates at \(z>1\) [70].

The IR space-based telescope Spitzer is actively used to study young SNe and SN remnants. Probably it will play an important role also in detecting new SNe, as the large difference in sensitivity with previous instruments is expected to compensate the limited spatial resolution.
FIGURE 1. *Strong* and *weak* bimodality are confronting each other. The Cappellaro et al. [15] sample supports the strong bimodality, and the LOSS sample is the referee. Actually, strong bimodality includes the weak one.

5. OPEN PROBLEMS WITH SNE Ia

5.1. The weak bimodality in type Ia SNe

Most computations of the DTD for Ia SNe have shown that binary star models naturally predict that these systems explode from progenitors of very different ages, from a few $10^7$ to $10^{10}$ years. The strongest observational evidence that this is the case was provided by Mannucci et al. [71] who analyzed the SN rate per unit stellar mass in galaxies of all types. We found that the bluest galaxies, hosting the highest star formation rates (SFRs), have SN Ia rates about 30 times larger than those in the reddest, quiescent galaxies. The higher rates in actively star-forming galaxies imply that a significant fraction of SNe must be due to young stars, while SNe from old stellar populations are also needed to reproduce the SN rate in quiescent galaxies. This lead Mannucci et al. [71] to introduce the simplified two component model for the SN Ia rate (a part proportional to the stellar mass and another part to the SFR). These results were later confirmed by Sullivan et al. [112], while Scannapieco & Bildsten [105], Matteucci et al. [79] and Calura et al. [14] successfully applied this model to explain the chemical evolution of galaxies and galaxy clusters. A more accurate description is based on the Delay Time Distribution (DTD), which is found to span a wide range of delay time between a few $10^7$ to a few $10^{10}$ years [69]. At least 10% of the SNe must explode on short timescales ($\sim 10^8$ yr) to follow the SFR, and the rest must follow on much longer timescales. This is the so-called “weak” bimodality. Recently, Pritchet et al. [95] have shown that SN rate and white dwarf formation rate have the same dependence on the SFR, confirming a close link between the two effects and the wide distribution of delay times.

Such a wide distribution of DTD is consistent with recent results based on the Subaru SN search by Totani et al. [118]. Usually, DTDs are investigated by convolving them with the SF history to reproduce the observed rates. Totani et al. invert the process and obtain the DTD by deconvolving the SF history from the rates. The resulting DTD shows...
a wide power-law distribution from \(10^8\) to \(10^{10}\) years, fully consistent with the results by Mannucci et al. [71]. The DTD in Totani et al. [118] depends critically on a severe approximation used, i.e., that the rate observed in a galaxy is related to the DTD at the mass-weighted mean stellar age of that galaxy. This is a risky hypothesis that should be tested: the system is intrinsically non-linear, i.e., galaxies with similar mean age but with different age distributions can have SN rates that differs by orders of magnitude. For example, as little as 0.3% of young \((10^8\) yr) stars added to an old \((10^{10}\) yr) galaxy can easily boost the rate by a factor of two (assuming the “classical” DTD by Matteucci \\& Recchi [80]). The galaxy remains old-looking, the mass weighted mean age does not change much, and in any case the observed rate is not due to the DTD at that age. More sophisticated procedures of deconvolution of galaxy spectra [98, 114, 32] are needed to check this result.

5.2. The strong bimodality in type Ia SNe

Della Valle et al. [27] studied the dependence of the SN Ia rate in early-type galaxies on the radio power of the host galaxies, and concluded that the higher rate observed in radio-loud galaxies is due to minor episodes of accretion of gas or capture of small galaxies. Such events result in both fueling the central black hole, producing the radio activity, and in creating a new generation of stars, producing the increase in the SN rate. The difference between radio-loud and radio-quiet galaxies can be reproduced by the model of early-type galaxy where most of the stars are formed in a remote past, about \(10^{10}\) years ago, while a small minority of stars are created in a number of subsequent bursts. A galaxy appears radio-loud when is observed during the burst, radio-faint soon after, and radio-quiet during the quiescent inter-burst period (see [67]). The amount of mass produced during the bursts can be constrained by using the (B–K) color observed in both populations. The results show that the last burst created no more that 0.3% in mass of new stars, assuming negligible extinction, or 0.5% when assuming an average extinction of the new component of \(A_V = 1\). This model is consistent with several recent works showing the presence of mergers, dust, neutral gas, molecular gas and recent star formation in local early-type galaxies [19, 125, 123, 104, 86, 98, 3, 58, 106, 55, 20, 57], see Sarzi et al. [103] for a recent review.

As the timescale of the radio activity is known to be less than \(10^8\) yr, the rate in early-type radio-loud galaxies can be used to constrain the DTD on short timescales. Other recent, independent results by Aubourg et al. [4] have confirmed the presence of a significant fraction of Ia SNe exploding on short timescales. These evidences are best reproduced by introducing a “strong” bimodality: a “prompt” component, comprising 20-60% of all the Ia SNe, explodes within \(10^8\) yrs, while the “tardy” SNe explode on much longer timescale, up to an Hubble time.

From a theoretical point of view, it is not difficult to create a bimodal DTD, especially if different channels of production are considered [59, 45, 124]. Nevertheless, it should be noted that the empirical basis of this “strong” bimodality [27, 4] are not as strong as for the “weak” bimodality [71, 112], and additional observations are needed to confirm the result.
5.3. Evolution of the properties of Ia SNe

It is well known that the average properties of local Ia SNe depend on the host galaxy (e.g., [47, 36, 2, 27]), and this is also observed at high redshifts [54, 53]. This dependence could be due to both age and metallicity of the progenitor system, and could be mediated by the amount of $^{56}$Ni produced [48, 113, 37, 53]. The relative fractions of Ia SNe produced by young and old systems are expected to change with redshift as the universe becomes younger and the SF activity increases. As a consequence, the average properties of the observed SNe could change with cosmic time, and this could be of extreme importance for the cosmological studies [97, 102]. The presence and the importance of such an effect can be tested by comparing nearby and distance SNe, looking for differences and similarities. Current results show that the differences are not large [21, 38, 12, 29, 30, 111], nevertheless systematic differences at 10 percent level could be present [30].

In conclusion, linking SN rates and stellar populations is a valuable tool to obtain significant results in both fields of galaxy evolution and SN progenitor. Oncoming improvements in the SN sample are expected to provide a much clearer picture. Nevertheless, the real limiting factor now is the poor knowledge of the properties of the galaxies usually targeted by the SN searches. Much more accurate conclusions will be reached when the parent stellar population can be accurately identified, but this will probably need a new class of “galaxy-driven” SN searches.

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