Unsolved Problems about Supernovae

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Abstract. A number of unsolved problems and open questions about the nature and the properties of supernovae are identified and briefly discussed. Some suggestions and directions toward possible solutions are also considered.

Keywords: Supernovae
PACS: 97.60.Bw

INTRODUCTION

When I started studying supernovae (SNe) in 1978, I thought that most problems had been solved already and that I could just help clarifying minute details. Actually, there were quite a number of fundamental aspects still to understand and clarify. In the course of many years, I have done my share of work, e.g. establishing multifrequency studies of SNe to clarify the nature of the overall explosion process among the different classes [1], starting systematic radio studies of SNe that enable one to probe the circumstellar medium of the SN progenitors [2], recognizing the existence of different types of type I SNe, which indicated that the absence of hydrogen in their spectra was not telling us the full story [3], finding observational evidence that SNIa are produced by at least two different channels of progenitors [4, 5, 6, 7], and, maybe, a few more items. However, these are a minor part of the problems successfully addressed in the last 30 years, and a tiny number as compared with the ones that still need a solution.

In this talk I will consider a few of the hottest or most intriguing problems yet to solve about the nature and the properties of supernovae.

SNIA PROGENITORS AND PROPERTIES

SNIa Progenitors: Why Binary Systems?

Common wisdom has it that SNIa originate from moderate mass binary systems (e.g. [8]), but what is the evidence for binarity? Let’s see:

- The absence of H and He from SNIa ejecta points in the direction of highly evolved progenitors.
- Judging from SNIa rates in various types of galaxies (e.g. [7, 9]), about 50% of SNIa explosions occur hundreds million or even several billion years after the formation of

the progenitor star.
- It is an experimental fact that Nova explosions are produced in binary system in which matter accreted on a white dwarf from its close companion induces sudden nucleosynthesis in the superficial layer of accreted material.
- In order to produce an energetic explosion (say, $> 10^{51}$ erg) the explosive nuclear burning of a substantial amount of mass (say, $> 1M_{\odot}$) is required, and, therefore, the progenitor star must have mass substantially higher than the Sun and suitably lower than what is believed to give rise to core-collapse explosions, about $8M_{\odot}$.
- Invoking a binary system increases dramatically the physical channels capable to produce a SNIa explosion (through the introduction of more free parameters...) and may help justifying the wide range of properties of different SNIa (e.g. Benetti et al. [10]).

The fact is that we have never seen any such star actually exploding, nor can we expect a detection any time soon because white dwarfs are faint stars and even their companions are not expected to be particularly bright stars. Thus, we cannot identify the progenitor stars before their explosions (e.g. on historical pre-SN images) nor it is going to be easy to detect a possibly surviving companion. We are left with circumstantial evidence, but we have to make it as solid as possible before concluding that *"we know what the progenitors are"* (e.g. Phillips [11], and this Conference).

Stellar Evolution of SNIa Progenitors

As mentioned before, it is most reasonable that SNIa progenitors are stars in the approximate range of 3-8 $M_{\odot}$, i.e. stars that on the Main Sequence belong to spectral types B. Many of these stars are known to display high rotational velocities, and may be expected to have high magnetic fields as a result of intense dynamo activity. Perhaps some of these properties may be THE cause for a given B-type star to end its evolution exploding as a SNIa, whether with or without the help of a companion.

Moreover, stars in the mass range 3-8 $M_{\odot}$ are known to become Cepheid variables when they evolve off the main sequence and to end their *regular* evolution through a Planetary Nebula phase. Perhaps there are important clues to the nature of SNIa progenitors that can be extracted from the study of stars easily identifiable in these characteristic phases. For example, a systematic study of the white dwarf companions of Cepheid variables would permit us to clarify the statistical properties of binary systems that may give origin to a SNIa and help identifying the crucial parameters that lead to a SNIa explosion.

SNIa as Standard Candles for Cosmology

Even if SNIa are commonly referred to as *ideal standard candles* because of their high luminosity at explosion and their relatively narrow range of observational properties, they are not quite *perfect* and, maybe, *not even standard*. Actually, it is widely recognized that their peak luminosities span more than a factor of ten and that their spectral properties do not correlate closely with their photometric properties. Standardization is obtained exploiting the empirical evidence that bright SNIa evolve photometrically more slowly than faint SNIa. However, even if this phenomenon is measured rather accurately in the local Universe so as to lead to accurate empirical corrections, its physical nature is far from understood and, therefore, this standardization rests on unsecure grounds. Moreover, when moving to higher redshifts [7] , i.e. to the past phases of the evolution of the Universe, the balance between fast evolving SNIa progenitors (with lifetimes less than about 100 Myrs) and the “tardy" ones (that typically explode more than 1 Gyr after formation) shifts in favor of the fast component, so that any systematic difference between the two components will bias the observational results.

A good summary of the current efforts to address and solve these problems can be found in Andy Howell et al. Astro-2010 White Paper on SNIa [12].

CORE COLLAPSE SUPERNOVA PROGENITORS

Core-collapse supernovae (CC-SNe) are believed to originate from the collapse of the core of massive stars ($M > 8M_{\odot}$) at the end of their nucleosynthetic life when Iron has formed in the core of the star and there is no additional energy source to prevent the star from collapsing onto itself catastrophically.

Evidence that this is the correct scenario for SNe in this class has been provided by the detection of a total production of more than 10^{53} erg in the form of neutrinos from SN 1987A explosion: this was just what theoretical predictions were expecting from the collapse of a massive stellar core (e.g. Arnett et al. 1989 [13]).

However, SN 1987A was exceptional in that it occurred so close to us (a mere 52kpc...) that it was easy to identify the star that exploded and monitor what was left behind after the explosion. At distances of several Mpcs or more it is much harder to separate stars in compact clusters (for example, at 5Mpc even the 0.05" resolution of HST optical imagers corresponds to an absolute size of 1.2pc) and the identification is necessarily of statistical value and can be affected by large uncertainties.

Direct Identification of Progenitors

Nevertheless, when something is hard, it is still possible... And with a judicious/clever observing strategy one can obtain the necessary information on the SN progenitors. Thus, comparing post-explosion high resolution (essentially HST) images with pre-explosion images of the parent galaxies it is possible to recognize which star did explode. And if one has images taken with different filters one can determine the stellar properties of the progenitor.

In this way, the heroic efforts of the Belfast Group (Steve Smartt and collaborators) and California Group (Schuyler Van Dyk, Avishai Gal-Yam and collaborators) have provided clear measurements of the properties of Type IIP SN progenitors, leading to the identification of red supergiant progenitors and to explicit mass determinations for about a dozen SNe, which fall in the range $\sim 8M_{\odot}$ to $\sim 16M_{\odot}$.

Trying to do the same for SNIb/c has not been as successful, mostly because these events are more rare and, therefore, are likely to be discovered in more distant galaxies so that even HST resolution is not enough to provide an unambiguous identification of the progenitor star. In the cases in which a positive identification has been possible, the progenitors seemed to be early type stars, as expected in the scenario that calls for WR stars to produce SNIb/c. However, just because of being high effective temperature stars, photometric measurements in few optical bands do not allow one to determine pre-explosion bolometric luminosities and/or stellar masses. The few lower limits indicate that the targeted SNIb/c had progenitors with masses above $\sim$20 $M_\odot$.

While these results seem to be consistent with theoretical and statistical expectations, one has to consider that a lower limit is hardly good enough to clarify the issues but can at best reduce the parameter space within which one has to look for THE correct answer.

The SNII zoo: What are SNIIb, SIIn, SNIIL?

Still we don't know much about the remaining multiplicity of CC-SNe, such as SNIIb, SIIn, SNIIL. The progenitor mass estimates for SNIIP and SNIb/c leaves unanswered the question "are the progenitors masses of SNIIn, SNIIL, SNIIb falling in the apparent gap 16-20 $M_\odot$ or are these SN explosions mostly determined by some other parameter, such as binarity, rotation, etc?" As usual, it looks as if ALL of these parameters may enter crucially into the game: for instance, radio observations have shown that the SNIIL 1979C exploded in a detached binary system with a primary star around 20 $M_\odot$ and a companion of at least 5 $M_\odot$ [14], SNIIb 2001ig displayed radio light curves highly suggestive of interactive winds as seem in systems composed of massive early stars, and possibly containing a WR star [15], and the progenitors of both SNIIb 1993J and SN200igd had mass loss rates that were strongly decreasing in the last 10,000 years before their explosions [16, 18].

Ultra-faint Supernovae

While the luminosities of most type Ia SNe are believed to be confined in a relatively narrow interval, it is well known that the luminosities of CC-SNe can vary by large factors, more than a factor of 100. It is intuitive that if there is a category of faint CC-SNe, one may miss many, or most of them unless looking very hard. The studies championed by Benetti, Pastorello, and their group have shown that some SNII can be really faint, as faint as $M_B \simeq -14$ and perhaps even fainter [17]. Despite their valuable efforts and results (many of them presented at this Conference), we are seeking quantitative answers the the questions: *“How faint can “faint" SNe be?"*, *“Where is the boundary between Nova and Supernova phenomena fall?"*, *“How many “faint" SNe are there?"*, and *“How many “unexpected SN explosion channels exist?"*

Ultra-bright Supernovae

At the other end of the scale, it is clear that exceptionally bright SNII do occur, starting with “my" first SN, 1979C, which at maximum was at least as bright as a SNIa ($M_B < -19.5$) [1], to the very recent SN 2005ap [19] and 2006gy [20]. These events pose a number of question, such as *“How bright can “ultra-bright" SNe be?", “What are they?", “Why do they occur?"*, etc. One of the “simple" suggestions is that they are the result of a pair-annihilation event which is predicted for ultramassive stars (M$>$ 140M$_\odot$) of extremely low metallicities (Z$<$ $1/1000$Z$_\odot$). This is an interesting possibility that is worth considering and pursuing, but I find it hard to imagine that such stars may exist in the local Universe, after more than 13 billion years of chemical evolution.

The end of the most massive stars

Another open problem is what happens to the most massive stars, i.e. those stars with initial masses in the approximate range 30-40-up to 100M$_\odot$. They are supposed to end their lives as black holes and, possibly, end in a quite unspectacular event. So, one is presented with the questions: *“Do these stars explode producing very faint events or do they just “disappear"?*, and *“Can we detect such events?"*. One may think that detecting a "non-explosion" (i.e. the lack of an explosion) is a self-contradictory statement because it is the same as detecting “nothing". However, even in the case of a true "non-explosion" there are ways to notice such an event because the star that undergoes a quiet end into its “final nothing", by virtue of being quite massive, was a bright star *before* its end and suddenly it drops in luminosity, essentially dropping forever from sight. Therefore, one should monitor at regular intervals a suitably large number of reasonably nearby galaxies and record which bright stars have disappeared. This is exactly what the project lead by Chris Kochanek [21] is doing and, possibly, in a few years we will have some exciting news about the demise of really massive stars.

THE GRB-SN CONNECTION

It is now well established that a number of Gamma-Ray Burst (GRB) sources have associated SNIc counterparts (e.g. [24]) and that both SNIc and GRBs are most closely associated with active star forming regions than any other type of explosive sources [25].

However, only a handful of GRBs-SNIc associations have been recognized so far and, despite all efforts, there are GRBs that are positively not associated with any SN, e.g. GRB 060614 for which it has been excluded the association with any SN brighter than -13.7 [22, 23], and many SNIc that have not shown evidence of any conspicuous gamma-ray emission (e.g. [24]).

Therefore, we are presented with two complementary and fundamental questions: *“Why many SNe are not GRBs?"*, and *“Why many GRBs are not SNe?"*. Only answering these questions, we could claim that we do understand the GRB-SN connection.

CONCLUSIONS AND RECOMMENDATIONS

My main conclusion from this series of considerations is that there is still a lot to learn about the properties and the nature of most types of SNe, but it appears that we (actually... YOU!) are working hard at it! All the interesting presentations of this week have shown how seriously the existing problems are been addressed, and I am confident that with hard work and perseverance, and a pinch of luck, we will eventually *“see the light at the end of the tunnel"*.

Still, I have a few suggestions and recommendations to make.

First, it seems to me that, since all SNe appear to originate from progenitors with original masses above 3 $M_\odot$, i.e. B-type or O-type stars, both rotation and magnetic fields can be crucially important and should explicitely be folded in the theorical model evolution that leads to a SN explosion.

While studying any type of SN and any aspect of their explosions, one should also consider the cosmic evolution of the SN phenomenon as a function of important parameters such as *(i)* metallicity, *(ii)* stellar population, *(iii)* cosmic age, and *(iv)* environment. With good imagination and a sharp mind you can add here more relevant parameters, but, *please*, do not neglect considering any of the ones listed here. The point is that we are not studying SNe just to understand SNe, but rather because we want to understand how the Universe works and evolve.

In pursuing these noble goals, I have a recommendation for everyone and, especially for the younger generations: *“When aiming at solving a problem try to explore ALL possible solutions"*, or *“Do NOT stop at the first possible solution and call it THE solution"*. Here the point is that declaring success after finding a solution may help along your path to fame (or to tenure...) but could also be a terrible disservice for science if the solution is not unique!

Also, I recommend that the SN community should devise (and enforce...) a classification that is based on Physics rather than pure morphology. Defining new subclasses and/or catchy names every time something different is found may not help much to the understanding of the complex phenomen of SN explosions, and may slow down the progress in some fields by creating the illusion that a problem has been solved.

Finally, I believe that all SN data should be collected in a central database that is properly arranged and open to everyone to search and peruse. A general archive that contains all the observational data would allow one to study all possible connections in a systematic way and compare the results with existing models and theories. Only by accounting for *ALL* aspects of a problem can one claim to have found *THE* solution.

ACKNOWLEDGMENTS

This work was supported in part by STScI-DDRF Grant D0001.82392. I wish to thank Massimo Della Valle, Filippo Mannucci and Kurt Weiler for valuable discussions on various aspects of SN studies, and the organizers of this Conference for giving me an opportunity to participate in it.

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