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SUPERNOVA REMNANTS: A LINK BETWEEN MASSIVE STARS AND THE SURROUNDING MEDIUM

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RESUMEN

Las estrellas de gran masa mueren explotando como supernovas (SNs) tras sufrir un catastrófico colapso gravitacional. Dicha explosión origina poderosos frentes de choque que modifican irreversiblemente la materia circundante, creando grandes burbujas, comprimiendo nubes circundantes, etc. Este trabajo repasa los mecanismos que conducen al colapso y explosión de las estrellas de alta masa y las posibles conexiones entre la estrella precursora, los mecanismos de explosión y los remanentes de supernovas (RSN). Se discute el desacuerdo existente en nuestra Galaxia entre el número esperado y el observado de RSN y de estrellas de neutrones asociadas.

ABSTRACT

Massive stars end their lives exploding like supernovae (SNe) after a catastrophic gravitational collapse. Powerful shock fronts originated after the explosion irreversibly modify the surrounding matter creating large bubbles, compressing nearby clouds, etc. This work reviews the mechanisms that lead to the collapse and explosion of massive stars and the possible connections between the precursor star, the explosion mechanism and the supernova remnant (SNR). The disagreement between expected and observed numbers of SNRs and of associated neutron stars in our Galaxy, is discussed.

Key Words: stars: massive stars — supernova remnants

1. INTRODUCTION

The fate of the stars is essentially governed by their mass and composition at birth, and by the history of mass loss. Low mass stars can die quietly or can explode as supernovae type Ia (SN Ia) when they undergo a thermonuclear collapse. Standard models conjecture that a SN Ia is the result of the complete disruption of a carbon-oxygen white dwarf that has been accreting matter from a non-degenerate companion star, a donor that survives the explosion (see Branch 2001 for a review of current models for low mass SNe).

Massive stars, on the other hand, presumably evolve from the main sequence to red giants and have a series of nuclear burning stages producing ever heavier elements in the core. When the star has built up a large enough iron core, exceeding its Chandrasekhar mass, collapses to form a neutron star (NS) or a black hole (BH). Such star ends its life exploding as a SN Type II or Type Ib/c.

The first question is how massive has to be a massive star to undergo a core collapse? In the past the minimum initial mass for which core collapse can take place was thought to be approximately 10 $M_\odot$. In recent years, theoretical and observational considerations favour smaller masses, of about 8 $M_\odot$. In either case, the range of masses spanned is huge, from $8 \sim 100$ $M_\odot$ or more (Young & Arnett 2004).

The second big question is how to convert a collapse into an explosion. Quoting Colgate (2004) *"it is a weird circumstance that a collapse SNe should explode"*. Understanding the physical processes that drive the explosion is crucial for linking stellar progenitors to supernova remnants as well as to predict many observable properties, like explosion energies, masses of NSs and BHs, nucleosynthesis yields, anisotropies and pulsar kicks.

2. EXPLOSION OF MASSIVE STARS

When the stellar core collapses, the radius of the star shrinks from thousands of km to little more than 10 km, forming an extremely dense compact remnant. For progenitors with main-sequence masses of less than $\sim 20 - 25 M_\odot$ and solar metallicity, the compact remnant will be a NS. In the case of more massive stars, a BH is formed.

The huge gravitational energy involved in this process is temporarily stored as internal energy of the compact remnant and probably as rotational energy of the nascent NS or BH (energy from nuclear reactions contributes at a minor level). To produce a successful explosion some fraction of this energy has to be transferred from the compact central object

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to the ejecta. What are the physical mechanisms to mediate this energy transfer and on what timescale? How can positive kinetic energy emerge from a gravitationally bound system? This is a matter of ample debate and a challenge for physics. Currently two basic mechanisms are considered to explain how the collapse of an iron core might be partially reversed to make a SN explosion (Wheeler 2000; Fryer 2003; Janka et al. 2004). One mechanism considers that when the NS forms, the new star overshoots its equilibrium configuration giving a large compression to the neutron core (the core collapses in about 1 sec). This produces a rebound that sends a strong supersonic shock wave in about 0.01 sec that travels through the infalling matter. In a short time a huge explosion should be generated, the outer matter is ejected and a NS is left behind. However, part of the energy of the shock is dissipated by the production and loss of neutrinos, as well as breaking down the infalling iron into lighter elements, protons and neutrons to form the NS. Therefore, the shock wave ends with insufficient energy to reach the outer layers of the star. The conclusion is that with all the infalling matter the NS becomes a BH but the explosion never occurs. In summary, the historical hydrodynamical bounce-shock models do not work. Proposed magnetohydrodynamical models, on the other hand, contain a large number of open variables and are still far from explaining the phenomenon.

A second mechanism takes advantage of the enormous stream of neutrinos leaving the NS. It considers that since NS matter is so dense, it becomes opaque (or semitransparent) to neutrinos, and some of them can be trapped just behind the shock created by the core bounce. The slow (~ 1 sec) accumulation of energy from neutrinos can create a “boiling” NS (i.e. with large convection effects inside the nascent NS). There is a consensus that explosions will not occur without this boiling (Wheeler 2000). Some fraction of these neutrinos can interact with matter beyond the NS but behind the standing shock. This boosts the shock and a successful explosion takes place. It is still discussed if the process is sufficient to cause an explosion. The configuration is probably asymmetric and matter can be ejected more intensily in some directions (because of intrinsic precursor rotation, magnetic fields, etc.). In fact, spherically symmetric models do not yield explosions (see for example the case for SN2004dj, Leonard et al. 2006). Also the presence of a binary companion can affect the final core structure of massive stars with the subsequent consequences on the SN explosion (Podsialowski et al. 2004).

Stars with main sequence masses beyond $20-25M_\odot$ seem to be associated with much more powerful explosions (with energies up to several 10^{52} erg). Such energies are out of reach for the neutrino-driven mechanism as discussed by Janka et al. (2004). The core of such stars probably collapses to a BH, which then continues to accrete the infalling matter of the progenitor star (a “failed supernova”, Woosley 1993).

Even in successful explosions, where a strong outward shock is born, mass may later fall back onto the NS, turning it, within seconds to tens of hours into a BH. Heger et al. (2003) present an interesting plot showing where BH and NS are likely to form and where different types of SNe are produced, as a function of mass and metallicity of the SN precursor.

The few neutrino events discovered in connection with SN 1987A were the first observational prove of stellar core collapse and NS formation, but they were not sufficient to yield a direct insight of the explosion. The hope to solve many of the present theoretical uncertainties is a future SN explosion in our Galaxy.

3. HOW DO THE VARIOUS TYPES OF SNE RELATE TO THE PROGENITOR HISTORY AND TO THE SNR?

After the explosion the information comes from the study of light curves and of early and late times spectra. On these basis, SNe from massive stars can be divided into four categories, depending on the amount of mass lost during the stellar evolution and the radius of the progenitor star. Although the division is not always clear (Chevalier 2005), the four types of core-collapse SNe are basically the following:

(1) SN IIP: they are type II SN whose light curve has a plateau. The presence of a plateau in the light decay implies a massive hydrogen envelope. These SNe are the end point of red supergiants (RSG) with relatively low mass-loss rates; they probably come from a single star with a mass of ~ 10 to 15 $M_\odot$ in the final stages of evolution (Schaller et al. 1992). Because of the low mass-loss rate, the RSG wind extends to a relatively small distance from the progenitor (≤ 1 pc) and is surrounded by a low-density wind bubble created during the main-sequence phase. An example of SN IIP is SN 1999em. The SNRs Crab Nebula and 3C 58 (Figure 1) are very likely the outcome of SNe of type IIP.

(2) SN IIL/Ib: they are type II SN whose light curve decays linearly. They are also the outcome of RSGs but with higher mass-loss rates. The result can be a dense circumstellar region that extends to

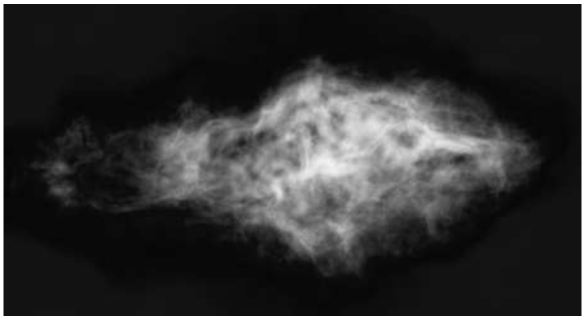

Fig. 1. High-resolution VLA image of the plerionic SNR 3C58 as taken from Bietenholz (2006).

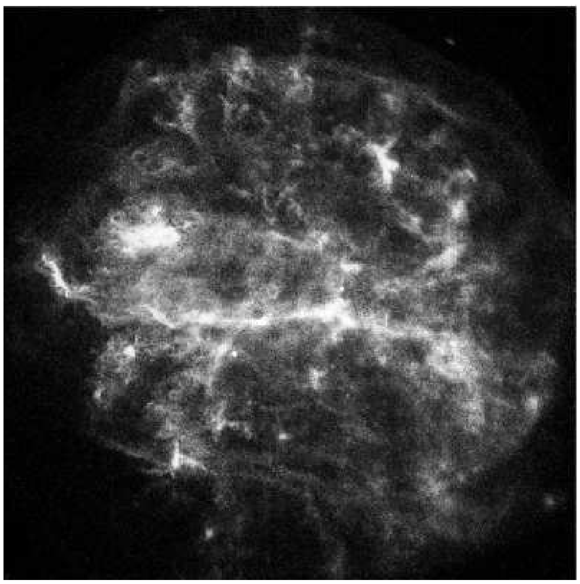

Fig. 2. *Chandra* X-ray image of the SNR G292.0+1.8 as taken from Hughes et al. (2001).

5 pc or more from the star. The best studied case of this type is SN 1993J. The SNR G292.0+1.8 (Figure 2), with O-rich, H-poor filaments, is an example of SNR coming from a SN IIL/b or Ib/c category (Gaensler & Wallace 2003).

(3) SN Ib/Ic: They are similar to the SN IIL/b in the sense that there is little or no hydrogen envelope. These SNe would be the end point of Wolf-Rayet stars. If the star has an earlier phase of RSG, the dense wind from this phase is expected to be swept-up by the fast WR wind. At the time of the SN, the RSG wind matter is in clumps at a radial distance larger than ∼10 pc. The SNR MSH 15–52 (Figure 3) is compatible with a SN Ib/Ic scenario, where material from the RSG wind has been swept up during the WR phase of the precursor star.

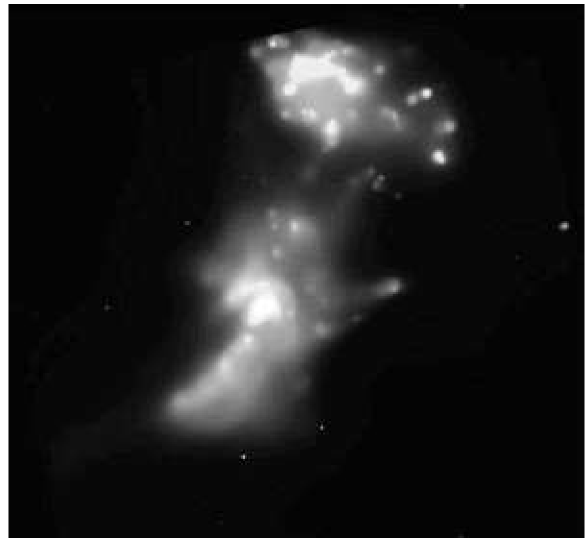

Fig. 3. *Chandra* X-ray image of the SNR MSH15-52 with the pulsar PSR B1509-58 in its interior, as taken from Gaensler et al. (2002).

The young SNR Cas A has been suggested to come from a WR precursor with mass $\leq 60 M_{\odot}$ (Fesen & Becker 1991; García-Segura, Mac-Low, & Langer 1996). However, Young et al. (2006) have demonstrated that all the observational constraints in Cas A can also be matched by assuming a progenitor of 15–25 $M_{\odot}$ which loses its hydrogen envelope to a binary interaction and undergoes an energetic explosion.

(4) SN1987A-like: The famous SN 1987A is the product of the explosion of a blue supergiant (BSG) and became the prototype of the SN 1987A-like class. Models show that the progenitor could have been a $\sim 18 M_{\odot}$ star in which the envelope mass is greater than the core mass, although there has been some mass loss (Chevalier 2005). The BSG circumstellar medium is complex, as can be seen from the current interaction. In a few hundreds of years the interaction should be with the wind of the RSG phase.

4. SUPERNOVA REMNANTS

The transition from SN to a supernova remnant is not well defined and, since it is a fast stage, it is very poorly explored. Besides, the observational study of this stage has only very recently been possible with the last generation high-resolution instruments. The conversion from SN into SNR lasts few to tens of years depending on the density of the surrounding matter. Studies of SN 1987A have been very helpful to witness certain aspects of the identity change.

Detailed studies of the remnants in different spectral regimes would ideally allow to connect the SNR with the type of SNe explosion and hence with the history of the pre-SN. For most young SNRs (except Kepler) the precursor can be successfully identified (at least the type of SN explosion). After the SN shock swept up ~8 times the ejected mass, their parentage is more difficult to determine (Dickel 2006).

A SNR includes one or more of the following ingredients: ejected stellar debris, a shell of shocked ISM and swept-up material, a central compact object (NS or BH) if the precursor was a massive star, a synchrotron nebula around the NS created by the pulsar wind, thermal X-ray emission from the hot interior and optical filaments from stellar ejecta and from interaction SN shock/surrounding clouds. The SNR G292.0+1.8 (Figure 2) is the only Galactic SNR that shows all of these characteristics (Hughes et al. 2001; Gaensler & Wallace 2003).

The appearance of a SNR depends on the type and energy of the explosion, on the age and on the density distribution in the environs. Three different phases can be broadly recognized along the several thousands of years that spans the life of a SNR. Namely, **free expansion**, which lasts less than 200-300 years, **adiabatic**, about 20,000 years in duration, and **radiative**, up to ~500,000 to ~700,000 years. The SNR disappears when the expansion velocity of the swept-up matter becomes comparable to the random motions of the interstellar clouds and it merges with the surrounding gas. The onset and end of each phase is strongly dependent on the density distribution in the environs. In fact, if the surrounding matter has density inhomogeneities more than one evolutionary phase can co-exist in the same SNR (see for example the case of Tycho's SNR, Reynoso et al. 1997).

According to their radio morphology SNRs have traditionally been divided into three different classes: **(a) Shell-type:** with the appearance of a hollow shell or ring. In this case the particles responsible for the observed synchrotron emission are accelerated at the shock front. The vast majority of SNRs have this morphology. It is typical of remnants from type Ia SNe. When the remnant comes from a core-collapse SN, in addition to the bright shell, it can include a central compact object (e.g. the SNR Cas A); **(b) Crab-like or plerions:** where the appearance is of a filled center nebula. In this case the accelerated particles and magnetic fields responsible for the synchrotron emission are injected by the central NS (e.g. the SNR 3C 58 shown in Figure 1, or the Crab Nebula, prototype of this class). In these cases, the shell is absent and only the pulsar wind nebula is observed; **(c) Composites:** which include a shell plus a central component (like in G292.0+1.8, Figure 2). These SNRs can have a plerionic component (the pulsar wind nebula) surrounded by a shell, both emitting sinchrotron radiation, observable in radio wavelengths, or sometimes they have a radio shell, but the center is filled with thermal X-rays.

5. THE PROBLEM OF THE MISSING SNRS AND MISSING NS IN SNRS

Statistics of extragalactic SNe suggest that a galaxy like the Milky Way should have a SN outburst every 30 to 50 yr on average (Cappellaro et al. 1999). Therefore, at least ~40 stellar explosions are expected to occur in the last twenty Centuries (of which we are aware of 7 "more or less safe" SN events, Stephenson & Green 2002). Also, taking into account the duration of a SNR, there should be more than a thousand SNRs in our Galaxy. Currently there are 265 SNRs catalogued in the Milky Way (Green 2006). The question is where are the missing SNRs? Is this a problem of insufficient technical resources to discover new SNRs or the incomplete census has more profound causes and there are more aborted SNe than expected? A recent sensitive search for new SNRs conducted by Brogan et al. (2006) at low radio frequencies, resulted in the discovery of 35 new Galactic SNRs in the inner Galaxy, suggesting that the "missing SNRs" problem can be attributed, to some extent, to selection effects. Massive stars exploding in low-density ambients (as expected if the massive precursor swept up most of the surrounding gas through powerful winds) are unlikely to create bright expanding shells.

A second problem is that if all core-collapse SNe (Type Ib, Ic, II-L and II-P) leave a compact object after the explosion, it is expected that about 80−85% of SNRs have an associated NS or other form of central compact object. As of October 2006, the ATNF Pulsar Catalogue (Manchester et al. 2005) listed 1772 objects, including rotation-powered pulsars detected through their radio pulsations, pulsars detected only at high energies and the so-called "radio-quiet" NS (Anomalous X-ray Pulsars and Soft Gamma Repeaters) for which coherent pulsations have been detected. This list can be completed with the thermal X-ray point-sources discovered in the interior of SNRs that do not pulse but are supposed to be associated with the SNR (NS whose beams do not point to Earth?), like the objects discovered in the interior of Puppis A and Cas A. Among 265

SNRs identified with certainty in the Galaxy, at least ∼200 SNRs should contain some class of compact object associated. By 1990 only five examples of pulsar/SNR associations were known in our Galaxy, and one in the LMC (Kassim & Weiler 1990). Recent multiwavelength searches for NS (in all its variety of manifestations) associated with SNRs (e.g. Kaplan et al. 2006) have increased the number of certain and probable SNRs/NS associations up to ∼100, but this is still half of expected.

6. CONCLUSIONS

SNe and their remnants play a key role in the galactic ecology. They release the nucleosynthesis products of the massive stars, they mix, process and redistribute the matter in the host galaxies, violently merging stellar material with gas and dust and accelerate particles to relativistic velocities (maybe) giving origin to cosmic rays. They can also compress surrounding clouds and (maybe) initiate new cycles of stars.

Their study is yet far from complete. Some of the pending problems that have to be investigated both theoretically and observationally, are (list far from exhaustive): *(i)* What are the physical mechanisms that produce a SN explosion from a massive star? *(ii)* Is the discrepancy between the expected and observed number of Galactic SNRs a result of our poor knowldge of the explosion mechanisms or simply observational selection effects? And the same question for the case of NSs inside SNRs. *(iii)* What is the role of SNRs in the formation of new stars? *(iv)* What is the role of SNRs as factories of cosmic rays? Deeper radio surveys with high-dynamic range and good angular resolution and high (in the X-rays domain) and very high energy (GeV and TeV) studies, as well as improvements in the theoretical modelization, would be of great help to solve these questions.

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DISCUSSION

Y.-H. Chu - The missing SNR problem is not a real problem. Most massive stars are in OB associations, which form superbubbles. SN explosions in the low-density interiors of superbubbles will not form conventional SNRs.

G. Romero - What is, to your knowledge the best evidence currently available for proton acceleration in SNRs?

G. Dubner - As far as I know, the best case has been found in G347.3-0.5, though it needs more studies (GLAST?) to confirm.

E. Reynoso - Jessica Warren et al. (2005) show evidence of cosmic ray acceleration in Tycho's SNR based on the very short distance between the blast wave and the contact discontinuity.

H. Zinnecker - I am very interested about the question you posed about the role of SNRs in triggering (massive?) star formation. You showed the case of IC 443 with an adjacent YSO. While the SNR may not be the trigger, there are other triggering mechanisms *before* the supernova explodes, i.e., the pressure of HII regions and O-star/WR-star winds. I would like to refer you to a paper by Prebisch & Zinnecker presented at IAU Symp. 240 in Prague, where we discuss the relative role of various trigger star formation mechanisms. We concluded that HII regions and stellar winds may well push molecular material away from the exciting star to distances quite suitable for effective triggering by the ensuing supernova (e.g. the event in Sco-Cen OB association).

G. Dubner - Thanks for the reference. It is very interesting for this case where there are involved both, SNR and HII region. One comment, the case that I showed was W44, not IC443.

N. Walborn - In answer to Zinnecker, there are many examples of triggered star formation from winds/radiation alone, without SN, from large to small regions, e.g. 30 Dor, Eagle Nebula, Monoceros, Cone... There is growing, recent evidence for progenitor mass and SN type. First,several Type II progenitors have been directly identified as $\approx 10\ M_{\odot}$ red supergiants in HST images. Second, GRBs are associated so far with Ic SN and none with Type II, fortunately since the latter is physically impossible in current models (the GRB could not emerge from a RSG atmosphere). Moreover, GRBs and Ic SN are similarly located in the triggered regions of host galaxies, whereas Type II and Ib are similarly located in less bright regions, indicating correlated progenitor populations. Type II may be produced by single stars while Type Ib come from binary evolution. What is the origin of the 10^4 estimate for the number of galactic NS/BH, if all core-collapse SN produce them? I estimate $10^7 - 10^8$.

G. Dubner - 85% of the SN explosions are expected to leave a compact remanent.

Marcelo is scolding LOC members about watering mate all over the place.