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THE COMPLEX RELATIONS BETWEEN SUPERNOVA REMNANTS AND NEUTRON STARS

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RESUMEN

Se espera que la mayoría de las supernovas (SN) produzca una estrella de neutrones (EN) observable como pulsar en ondas de radio. Las observaciones, sin embargo, muestran escasas coincidencias entre restos de supernovas (RSN) y EN. Se presenta una puesta al día de resultados de observaciones multiespectrales llevadas a cabo para investigar este aspecto. El trabajo se focaliza en la comprensión actual de las nebulosas de viento de pulsares, así como en las diferentes formas en que puede manifestarse una estrella de neutrones, tales como pulsares anómalos en rayos X, estrellas de neutrones radio-quietas y repetidores en rayos γ blandos.

ABSTRACT

Most supernovae (SNe) are expected to produce a neutron star (NS) observable as a radio-loud pulsar. The observations, however, show very few SNRs/NS associations. This review summarizes recent multiwavelength observations carried out to investigate this issue. The work is focused on the current understanding of pulsar wind nebulae (PWN), and the different ways in which a NS can manifest, like anomalous X-ray pulsars (AXPs), radio-quiet neutron stars (RQNS) and soft gamma-ray repeaters (SGRs)

Key Words: **ISM: SUPERNOVA REMNANTS — STARS: NEUTRON STARS — STARS: PULSARS**

1. INTRODUCTION

Supernovae (SNe) and their remnants (SNRs) play a vital role in the evolution of galaxies. They supply huge amounts of energy, accelerate cosmic rays, and represent almost the only way to feed the interstellar medium (ISM) with the heavy elements processed in the hot interior of the stars.

Supernovae can be broadly classified in two groups, types I and II, based on their spectra near the maximum of light, with a further subdivision giving types Ia, Ib, Ic, II-P and II-L. The differences among the diverse types are essentially related to the mass of the progenitor star, which determine the mechanism of explosion and subsequent evolution (see Wheeler & Harkness 1990). Basically, supernovae type Ia are the product of thermonuclear collapse of white dwarf stars which are pushed over the Chandrasekhar limit by mass transfer from a binary companion. These explosions, the most luminous events, lead to the complete destruction of the star. Types Ib, Ic and II are believed to be the outcome of gravitational core-collapse of massive stars, either with important mass loss of the precursor star (in the cases of types Ib and Ic), or without previous mass loss (for type II). These SNe, although less luminous than SN Ia at the maximum of light, bring greater consequences on the dynamics of the ISM because they leave a compact core (neutron star or black hole) that will inject relativistic particles and magnetic fields into the surrounding plasma for thousands of years. The central neutron star (NS) can be detected as a pulsar. The appearance of the remnant of a supernova explosion will depend on its age, on the density distribution of the circumstellar and interstellar matter, and on the presence of such central compact object providing continuous source of energy in the interior.

This review will focus on SNRs with neutron stars in the interior, summarizing the current understanding in the light of recent observational results spanning the electromagnetic spectrum.

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2. SUPERNOVA REMNANTS/NEUTRON STARS ASSOCIATIONS

In our Galaxy there are 225 catalogued SNRs[2]. On the other hand, until very recently the number of identified pulsars in the Milky Way has been 732[3]. If we consider the number of supernovae that can leave a compact source (mainly SNe type Ib and II), then about 85% of SNRs should contain a neutron star observable as a pulsar (PSR) in the interior. This means that about 170 galactic SNRs might have an associated PSR. However, until 1986 the number of known SNR/PSR associations was only three: Crab Nebula/PSR B0531+21, Vela/PSR B0833-45 and MSH 15-5*2*/PSR B1509-58 (see Taylor & Stinebring 1986 for a review).

A number of facts have been usually invoked to explain the large disagreement between the expected and the observed number of PSR/SNR associations. Briefly: 1) a rotating neutron star can be observed as a PSR only if the beam crosses the observer's line of sight; 2) the lifetime of a typical PSR ($\tau \sim 10^{6-7}$ yrs) largely exceeds the lifetime of a SNR ($\tau \sim 10^{4-5}$ yrs); 3) the large transverse velocity of PSRs (between $\sim$ 100 and $\sim$ 400 km s^{-1}), can kick them off the parent SNR in less than 10^5 yrs.

Different research paths have been followed to face the problem, like new more sensitive search for PSRs inside SNRs and conversely of faint/incomplete SNRs around PSRs, search for compact sources which manifest themselves in different ways apart from the canonical radio pulsars, search for synchrotron nebulae created by the relativistic particles injected by a (pulsating or not) neutron star, etc.

With the purpose of discovering new radio pulsars in the southern hemisphere, a pulsar survey, the Parkes Multibeam Pulsar Survey (http://www.atnf.csiro.au/research/pulsar/pmsurv/pmpsrs.db), is being conducted since mid 1997. This is a project designed for pulsar searches with good sensitivity and high observing frequency that provides very good conditions for finding fast, distant pulsars which may have been missed in previous searches. The high success of this survey allowed to almost duplicate the number of catalogued pulsars in our Galaxy, from the 730 PSRs known up to 1997, to over 1300 in 2001 (Manchester et al. 2001). This new study allowed the discovery of new members of binary systems, four new millisec PSR, several PSR younger than a thousand of years, various possible identifications with EGRET sources, and, what is especially relevant for this report, this pulsar survey allowed the discovery of a number of very likely associations between SNRs and PSRs. Examples of possible associations are SNR G292.2-0.5/PSR J1119-6127 (Pivovaroff et al. 2001, Crawford et al. 2001), SNR G352.2–0.1/PSR J1726–3530 (Manchester et al. 2001) and SNR G284.3–1.8/PSR J1016-5857 (Camilo et al. 2001).

[2]catalogue at http://www.mrao.cam.ac.uk/surveys/snrs/
[3]catalogue at http://pulsar.princeton.edu/

2.1. *Pulsar wind nebulae (PWN)*

It is known that all pulsars accelerate particles to relativistic velocities. When a pulsar is still inside its parent SNR, the high pressure of the surrounding plasma can confine the pulsar's relativistic wind (formed by pairs e^-/e^+ and/or unspecified ions, with strong magnetic fields) generating synchrotron emission observable as a pulsar wind nebula (PWN). This fact has the important consequence that observation of a central synchrotron nebula implies the existence of a central pulsar even if a central NS is not detected like a radio pulsar (for example because the beam is not oriented towards the Earth). Because of the short lifetime of the wind particles, it is more likely to find synchrotron nebulae associated with young neutron stars. Plerions powered by synchrotron emission have been detected around five of the six classical young pulsars (Chakrabarty et al. 2001).

A PWN can be detected in radio and/or in X-rays, and sometimes even in γ–rays (like is the case of the PWN around PSR B1706-44, Kifune et al. 1995). In radio wavelengths, a PWN is characterized by a flat spectum and high polarization.

The nebulae are confined by inertia or by the pressure of the interstellar or circumstellar medium. Sometimes they have associated conical outflows, that is precesing jets emanating from the magnetic poles of the pulsar (e.g. in PSR B1508-58, Gaensler et al. 2002). In other cases they have a cometary shape, like it is the case for the PWN associated with PSR B1643-43 (Figure 1, from Giacani et al. 2001).

When pulsars move through the ambient medium, the wind of the pulsar interacts with it, eventually forming a steady flow, with a bow shock in the direction of the stellar motion, e.g. in Vela pulsar (Helfand et al. 2001). Also, recent observations carried out with *Chandra* and *XMM-Newton* X-ray Observatories, revealed the existence of a cometary-shaped PWN in the SNR IC443 (Olbert et al. 2001, Bocchino & Bykov 2001).

3. EXOTIC CENTRAL COMPACT OBJECTS

The properties of "normal" radio PSRs have been found to be uniquely explained in the context

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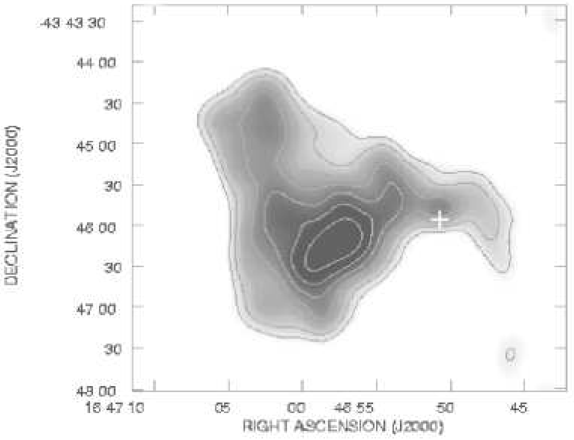

Fig. 1. Synchrotron nebula powered by the relativistic wind from the pulsar PSR B1643-43. The pulsar position is indicated by a white cross (from Giacani et al. 2001).

of rapidly rotating, magnetized (B$\sim$ 10^{12} G) NS beamed non-thermal radiation. There is, however, evidence that suggests that this is not the only possibility. There are three classes of compact objects associated with SNRs whose nature is still an open question: radio-quiet (or radio-silent) neutron stars (RQNSs), anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). They can be the clue to solve the basic question whether all SNRs believed to result from gravitational collapse produce a compact neutron star or not.

3.1. *Radio-quiet (/radio-silent) neutron stars (RQNS)*

The "first-light" observations of the *Chandra Observatory* revealed the presence of a non-pulsating X-ray point source near the center of the young SNR Cas A (Tananbaum 1999; Chakrabarty et al. 2001) (Figure 2). This intriguing source shares characteristics with at least three other X-ray point sources discovered near the centers of the SNRs Puppis A, RCW 103 and PKS 1209-5*2* (see Brazier & Johnston 1999 for review and discussion). They are X-ray point sources with extreme spectrum: very bright in X-rays and/or $\gamma-$rays, very faint in optical wavelengths and absent in radio. They are found in the interior of SNRs or in isolation (like Geminga). Their X-ray spectra are consistent with young, cooling neutron stars (Caraveo et al. 1996). In particular, the beaming factor seems to be smaller in radio than at higher energies, making it more likely to miss the radio beam than the X and/or the $\gamma-$ray one (like it is the case for Geminga, whose γ beam intersects the Earth and the radio one does not, Caraveo et al. 1996).

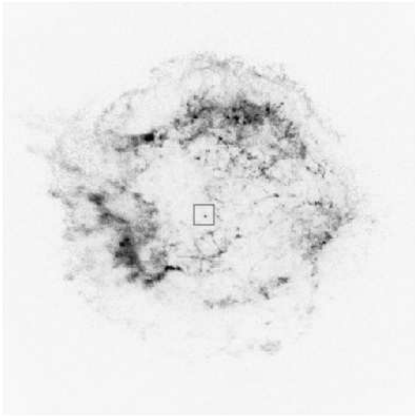

Fig. 2. *Chandra* image of the SNR Cas A. The square surrounds the X-ray point source detected in the interior (from Chakrabarty et al. 2001)

Sometimes radio-quiet neutron stars are differentiated from radio-silent. RQNSs would be NSs that do radiate, but the emission is not detected because it is faint, the object is too far, or the beam is wrongly oriented; while RSNSs would not radiate at all. According to Baring & Harding (1998), they would be neutron stars where the e^-/e^+ pair (essential for radio emission) production in the magnetospheres is efficiently supressed in ultrastrong magnetic fields (B$\geq 4\times10^{13}$ G) by the action of photon splitting.

3.2. *Anomalous X-ray pulsars (AXPs) and Soft Gamma Repeaters (SGRs)*

AXPs and SGRs are neutron stars which share similar period (6 - 12 sec), similar characteristic age ($3\times10^3 - 4\times10^5$ yrs), and comparable X-ray luminosity (L_X $\sim$ $3\times10^{34} - 10^{36}$ ergs/sec), well in excess of the spin-down luminosities. They are almost certainly young and without binary companion. SGRs are sources of brief ($\sim$ 0.1 sec) intense outbursts of low-energy gamma radiation, which occur in bunches, with active periods lasting between few weeks and several months at time intervals of years (see Mereghetti 1999 and Hurley 2000 for a review of properties).

Examples of claimed associations between AXPs and SNRs in our Galaxy are 1E 1841-045/Kes 73 (Gotthelf & Vasisht 1997), and 1E 2259+586/CTB 109 (Rho & Petre 1997). Examples of SGRs proposed to be associated with SNRs: SGR 1900+14 /G42.8+0.6 (Vasisht et al. 1994), SGR 1627-41 /G337.0-0.1 (Corbel et al. 1999).

It has been proposed that AXPs and SGRs are magnetars: neutron stars with extremely high magnetic field (B$\geq 10^{15}$ G). These high magnetic fields can account for the $\gamma-$ray activity seen from the SGRs, and also for the observed P and $\dot{\rm P}$.

According to Kouveliotou et al. (1998), SGRs would represent the earliest phase in the evolution of magnetars, followed by a phase in which they appear as AXPs. According to Gaensler et al. (2001), AXPs and SGRs must represent two discrete populations: SGRs would be magnetars and AXPs accreting systems. Alternatively, they could be two kinds of magnetars: SGRs with extreme ($\sim 10^{15}$ G) magnetic fields and high velocities, and AXPs, with lower ($\sim 10^{14}$ G) fields and lower velocities. The general consensus seems to be that the proposed associations between AXPs and SNRs is better established than between SGRs and SNRs.

4. CONCLUSIONS

In summary, the recent multiwavelength observations have demonstrated that the presence of neutron stars can manifest in a variety of ways: pulsars, X-ray and/or radio PWN, X-ray point-sources, exotic compact objects, etc. After taking into account all these different manners, then the current census of NS/SNR associations rise from 3 to 56 (Helfand 2002). This fact means that about 30 % of the cases expected in our Galaxy have been discovered at present. All these new studies, however, call the attention to parts of the puzzle. A broad synthesis of the properties of neutron stars, and the consequences of their interaction with the SNRs, as well as of the SNR/ISM interaction, is still needed.

A short list of important theoretical problems to be addressed in the future is: the theory of the interior of NS (equation of state for the neutron fluid in the core), the physical coupling between PWN and the surrounding SNR plasma, the dynamical evolution of the PWN, the true nature of the exotic objects, etc. From the observational point of view, it is important to search for more cases of SNR/NS associations, to explore the connection with $\gamma-$ray sources, to carry out accurate spectral analysis of radio and X–ray emissions, and to investigate in detail the consequences of the interactions NS/SNR and SNR/ISM.

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