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On the Relationship Between Pulsars and Supernova Remnants

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Abstract. We propose that single stars in the mass range 4–6·5$M_\odot$, that explode as supernovae of Type I, are totally disrupted by the explosion and form shell-type remnants. More massive single stars which explode as supernovae of Type II also give rise to shell-type remnants, but in this case a neutron star or a black hole is left behind. The first supernova explosion in a close binary also gives rise to a shell-type supernova remnant. The Crab-like filled-centre supernova remnants are formed by the second supernova explosion in a close binary. The hybrid supernova remnants, consisting of a filled centre surrounded by a shell, are formed if there is an active neutron star inside the shell.

Key words: pulsars—supernovae—supernova remnants

1. Introduction

On the basis of their radio observations, supernova remnants (SNRs) have been divided into two classes (Casewell 1979). Most of the SNRs are shell-type, in which radio emission comes from a shell. The filled-centre, Crab-like plerions are characterized by radio emission which has a peak at the centre and falls steadily to the periphery with no enhanced shells. Plerions have flat spectra ($\alpha \simeq 0{\cdot}0$–$0{\cdot}3$, $S_\nu \sim \nu^{-\alpha}$) while the shell-type have steep spectra ($\alpha \simeq 0{\cdot}5$).

In both the types, radio emission is synchrotron in nature, but while in the shell sources the magnetic field and the relativistic electrons are most probably swept up from the interstellar medium, the relativistic electrons in Crab-like SNRs come from a central pulsar, as is suggested by the observed spatial distribution of the radio emission. X-ray spectrum of shell sources is thermal as evidenced by profuse line emission while the Crab Nebula X-ray spectrum is a featureless power law with $\alpha \simeq 1{\cdot}15$ and a continuation of synchrotron radio emission. Absence of thermal emission from the Crab Nebula implies that the SN 1054 produced at most a very weak shock wave (Schattenberg *et al.* 1980) unlike the shell SNRs which require strong shock waves for their formation.

Examples of shell-type SNRs are Cas A, Tycho, Kepler and SNR 1006. Crab and 3C 58 are two well known examples of plerions. Then there are hybrid SNRs which exhibit the characteristics of both the types. The SNR G 326·3 — 1·8 has a weak but well defined shell ($\alpha \simeq 0{\cdot}4$) surrounding the central feature ($\alpha \simeq 0{\cdot}0$) (Weiler and Panagia 1980). A similar object is CTB 80 (G 68·9+2·8) which has a Crab Nebula-type central radio source inside a weak extended broken shell (Angerhofer, Wilson and Mould 1980). This object is probably the remnant of SN 1408. Weiler and Panagia (1980) have argued that while the SNR Vela XYZ is shell type, the part Vela X which contains the pulsar is Crab-like. The SNR W 50 around SS 433 also perhaps belongs to this category (Weiler and Panagia 1980). It has the sharp outer edge and the integrated spectral index ($\alpha = 0{\cdot}45$) typical of shell-type remnants but its central regions are plerionic.

From among the 120 or so SNRs known, only two, the Crab and the Vela SNRs are known to contain pulsars. Significantly, the Einstein Observatory has failed to find any evidence for pulsed or unpulsed X-ray emission from a neutron star at the centre of any of the historic SNRs, Cas A, Tycho, Kepler or 1006. Either, only some SN leave behind neutron stars, or else a cooling mechanism more efficient than neutrino cooling—pion cooling for example—may make the neutron star so cold that they are not detectable at X-ray wavelengths (Helfand, Chanan and Novick 1980). Since the cold neutron star at the centre of SNR 1006, if present, would be as old as the Crab pulsar, which is a source of thermal X-rays, it would then seem that pulsar radiation mechanisms heat up the neutron stars so that if a neutron star is not a radio pulsar, it would also not be a source of thermal X-rays.

Attempts have been made to relate the type of the SN, the morphology of the SNR and the presence or otherwise of pulsars in it. Weiler and Panagia (1978) suggested that plerions come from SN II and shell-type SNRs from SN I. According to Radhakrishnan and Srinivasan (1980), although shell-type SNRs do have neutron stars in them, their magnetic fields are such that pulsar activity does not take place (Shukre and Radhakrishnan 1980). Similarly Shklovsky (1980) feels that shell-type SNRs do have neutron stars which do not manifest themselves as pulsars and ‘somehow X-ray astronomy fails to detect them’.

These hypotheses have many unsatisfactory features. Cas A is a shell-type SNR and a result of a SN II (Woltjer 1972). It is an obvious counter example to the above hypothesis that SN II form plerions. It is not clear where sources like G 326·3 — 1·8, which have a weak shell surrounding a Crab-like feature, fit in this scheme. On the basis of the detection by the Einstein Observatory of an X-ray nebulosity, 80 arcsec in diameter, around the Vela pulsar (Harnden *et al.* 1979), Radhakrishnan and Srinivasan (1980) and Shklovsky (1980) have concluded that the Vela SNR is a plerion. In our view such a conclusion is erroneous. The radio sources Vela X, Y and Z are all parts of an incomplete and rather asymmetrical shell, about 5° in diameter (Milne 1968); the circular outline of the nebula is clearly visible in the ultraviolet light (Miller 1973). The soft X-ray emission also comes from the shell and is interpreted as thermal emission from a (mostly interstellar) plasma heated to about 4×10^6 K by shock waves (Moore and Garmire 1976). Thus the Vela SNR is characterized by radio emission from a shell and X-rays from shock heated plasma—features which are independent of the embedded pulsar. This is in contrast to the Crab Nebula, which owes its structure to the central pulsar. The non-thermal X-rays from a small region around the Vela pulsar and the thermal X-rays from the pulsar itself are the signatures of a 10^4 yr old pulsar and *not* the defining characteristics of a SNR. We, therefore, conclude that Vela is a shell-type SNR and the Crab-like activity around the pulsar (Harnden *et al.* 1979, Weiler and Panagia 1980) is due to the pulsar. We thus have two morphologically distinct SNRs each containing a pulsar. We now discuss a hypothesis which attempts to relate the type of the SN with the morphology of the SNR and with the presence or otherwise of a compact star.

2. Shell-type supernova remnants

It has been suggested that SN come from short lived stars—SN I from stars in the mass range 4–6·5 $M_\odot$ and SN II from the more massive stars (Oemler and Tinsley 1979, Kochhar and Prabhu 1981a). Thus a typical elliptical galaxy, in which stars are atleast 10^{10} yr old, will not produce SN; only those will that went through a burst of star formation a few times 10^7 yr ago so that the stars formed then are exploding now. The stars formed would be of masses $< 6{\cdot}5\ M_\odot$; to form more massive stars the presence of density waves is essential (Kochhar and Prabhu 1981b).

It is well known that SN II are confined to the spiral arms whereas SN I belong to the interarm region (Maza and van den Bergh 1976). Since massive close binaries are confined to the spiral arms, it follows that SN occurring in massive close binaries should be of Type II. Moreover, since it is not possible to reproduce the light curve and the spectra of a SN II without a hydrogen envelope around the exploding star (Falk and Arnett 1977), it follows that the pre-SN star in a close binary should have a hydrogen envelope around it. Such an envelope could have survived the mass transfer phase. Or else, it could be transferred back and forth between the two stars if their masses are approximately the same. Alternatively, the matter lost from the system could form a shell around the binary to give a SN II light curve.

We now propose that stars in the mass range 4–6·5 $M_\odot$ exploding as SN I, are totally disrupted by carbon detonation (Arnett 1973) and form a shell-type SNR. More massive stars which explode as SN II also give rise to a shell-type SNR; but in this case a compact core—a neutron star or a black hole—is formed. The first SN explosion in a close binary in most cases is of Type II. Once again a shell SNR forms and a compact star is left behind. If the exploding star in a close binary is totally disrupted, the companion would become a runaway star (Kochhar 1978). Thus the SN explosion of a single star and the first SN explosion in a close binary would give rise to a shell-type SNR. If in the process a neutron star is formed, it would result in a Crab-like activity inside the shell. On the other hand, if no core is left behind by the SN explosion, or else a blackhole forms, the SNR will be a ‘ pure ’ shell-type.

W 50 is an example of a shell-type SNR formed as a result of the first supernova explosion in a close binary. The central filled-centre activity is attributed to the neutron star in the binary SS 433 which is exactly at the centre of W 50. We have here an example of Crab-like activity due to a neutron star which is not a pulsar.

We now propose that the shell SNR Cas A has a black hole inside it. A similar conclusion has been reached by Shklovsky (1979) by different arguments. In this context it should be noted that the X-ray emitting gas in Cas A, which must have been ejected from the pre-supernova star, has a mass exceeding 15 $M_\odot$ (Fabian *et al.* 1980) implying a very large mass for the progenitor star.

As for Tycho, Kepler and SNR 1006, which are all SN I (Woltjer 1972) we propose that they are the result of a total disruption of their progenitors caused by explosive carbon burning in degenerate cores (Arnett 1973). The major objection to the carbon detonation model for SN is that it produces too much of iron peak nuclei (Arnett 1973). The chemical composition of the gas in the star before the explosion is determined by the conditions after the helium burning phase in the stellar core. The gas consists of equal parts of ^{12}C and ^{16}O and two per cent of ^{22}Ne which arises in the following manner: all initial CNO nuclei (which have solar abundances) are converted into ^{14}N during hydrogen burning which in turn is converted into ^{18}O during helium burning. It is then assumed that all of the ^{18}O is burnt to ^{22}Ne before helium gets exhausted in the core (Arnett 1973).

Recently the ^{18}O (α, γ) ^{22}Ne reaction has been studied experimentally and the reaction rate compared with that of the competing ^{18}O (α, n) ^{21}Ne (Trautvetter *et al.* 1978). The results indicate that at temperatures $\leqslant 6 \times 10^8$ K helium burning of ^{18}O proceeds predominantly through the ^{18}O (α, γ) ^{22}Ne reaction, synthesizing mainly the isotope ^{22}Ne. On the other hand at temperatures $> 1 \cdot 6 \times 10^9$ K the ^{18}O (α, n) ^{21}Ne reaction dominates by three orders of magnitude over the ^{18}O (α, γ) ^{22}Ne reaction and hence the isotopes ^{21}Ne and ^{22}Ne are produced in a ratio of 10^3:1 (Trautvetter *et al.* 1972).

It would thus seem that the assumption that the pre-explosion gas contains two per cent of ^{22}Ne may not be valid and ^{18}O may be the main product of secondary nucleosynthesis in helium burning. Simulation of explosive-carbon-burning nucleosynthesis with an initial neutron rich mass fraction of two per cent of ^{18}O is found to yield much better agreement with solar system abundances than simulation with an initial two per cent of ^{22}Ne as hitherto used (Harris 1979). Thus after all the carbon detonation supernovae may not be producing too much of iron peak nuclei.

The elemental abundances in SNR can be deduced from their X-ray spectra. Cas A, Tycho and Kepler all show strong line emission from helium-like species of Si, S and Ar (Becker *et al.* 1979, 1980a, b). If it is assumed that the emitting plasma is in collisional ionization equilibrium (CIE) the above observations imply that Si, S and Ar are greatly overabundant. However, there are enough indications that the emitting plasma is not in CIE (Pravdo and Smith 1979, Pravdo *et al.* 1980). In such a plasma, the line emission corresponds to a temperature much lower than the electron temperature, giving the impression of a two-temperature plasma in which both the high temperature lines and the low temperature continuum are missing. Consequently, the state of ionization is much lower than that predicted by CIE with the result that the intensities of some of the lines may differ from the predicted values by more than an order of magnitude (Itoh 1977). Thus the HEAO 1 and 2 X-ray spectra can be understood in terms of non-equilibrium line emission from a plasma with normal abundances and one need not invoke abnormal abundances (Pravdo and Smith 1979, Pravdo *et al.* 1980). Similarly the X-ray data on SNR 1006 (Becker *et al.* 1980c) can be interpreted in terms of thermal bremsstrahlung from a non-equilibrium plasma rather than as synchrotron emission from a pulsar which is not there (Helfand, Chanan and Novick 1980).

3. Crab-like supernova remnants

The Crab Nebula is characterized by an overabundance of helium without a corresponding excess of heavy elements (Woltjer 1972). Furthermore, as already mentioned, the absence of X-ray line emission implies that the SN 1054 did not produce any shock waves (Schattenberg *et al.* 1980). Kochhar (1979) has suggested that the Crab Nebula is the debris of a helium star in a close binary containing a neutron star. The helium star was totally disrupted by the spiralling-in of the neutron star which in the process was spun up and is identified with the Crab pulsar. The spiralling-in would occur in cases where the separation between the neutron star and the helium star is sufficiently small (if the separation is large, the helium star would evolve as a single star and explode leaving behind a compact star).

We now suggest that all filled-centre SNRs without outer shells are disrupted helium stars. Thus all plerions should have a chemical composition appropriate to a helium star. Since the progenitors of such systems have already undergone a SN explosion, their mean $|z|$ would be about 200 pc (Kochhar 1978).

Weiler and Panagia (1980) list six SNRs as well established plerions. Out of these, Vela X and the centre of G 326·3–1·8, are surrounded by shells. We have classified them, and W 50, as shell-type SNR with active neutron stars inside. The four 'genuine' plerions G 21·5–0·9, CTB 97, 3C 58 and the Crab have a mean $|z|$ of 240 pc. Of course, all plerions should have neutron stars embedded in them and attempts should be made to identify them.

4. Pulsar birthrates

We have argued that while all stars with $m > M_\odot$ end their lives as SN, only stars with $m > 6{\cdot}5\ M_\odot$ form pulsars. We now show that this is consistent with the recent estimates of pulsar birthrates and of star formation rates.

The computed pulsar birthrate depends on the electron density, n_e, of the interstellar medium which sets the pulsar distance scale and on the beaming factor, f, which specifies what fraction of the total pulsar population is observable. Taking $n_e = 0{\cdot}03$ cm^{-3} and f=0·2, Taylor and Manchester (1977) obtain a pulsar birthrate b_p=0·1 in units of pc^{-2} Gyr^{-1} which in terms of the stellar birthrate of Ostriker, Richstone and Thuan (1974) means that all stars more massive than 2·5 $M_\odot$ must die as pulsars (If n_e is smaller than 0·03 cm^{-3}, b_p would be lower).

Hanson (1979) has pointed out that the proper motion data are very incomplete and strongly biased towards high velocity pulsars which are easily detected. Correcting for this bias reduces the pulsar birthrate by half. Thus for n_e=0·03 cm^{-3} Hanson (1979) obtains b_p=0·05. Recent studies show that the stellar birthrate of Ostriker, Richstone and Thuan (1974) is significantly too low (Miller and Scalo 1979, Shipman and Green 1980). Larson and Tinsley (1978) have noted that this birthrate does not reproduce the position of most galaxies in the *UBV* two-colour diagram.

The most recent pulsar birthrate is due to Shipman and Green (1980). They obtain the deathrate of all stars with $M_L < M < M_U$

$$b = (b_0/x)\,(M_L^{-x} - M_U^{-x}),$$

where $b_0 = 2{\cdot}08$ and $x = 1{\cdot}63$. The birthrate of Ostriker, Richstone and Thuan (1974) corresponds to $b_0 = 4{\cdot}34$ and $x = 2{\cdot}57$. Miller and Scalo obtain $x = 1{\cdot}5$ ($M < 10\ M_\odot$) and $x = 2{\cdot}3$ ($M > 10\ M_\odot$).

We now calculate the birthrates of pulsars and of SN as follows. We assume that all single stars with $M > 4\ M_\odot$ explode as SN. For a SN to occur in a close binary system, the mass of the star should be $M \geqslant 10$–$12\ M_\odot$ (van den Heuvel 1977; Massevitch, Tutukov and Yungelson 1976). Further we assume that 50 per cent of stars with $M < 4M_\odot$ are in binaries. Then following Shipman and Green (1980) we obtain a SN rate $b_{SN} = 0{\cdot}08$. If all single stars with $M > 6{\cdot}5\ M_\odot$ and all double stars with $M > 10\ M_\odot$ become pulsars then the pulsar birthrate is $b_p = 0{\cdot}045$. We thus see that about 45 per cent of SN do not form any compact cores. Our derived pulsar birthrate of 0·045 should be compared with Hanson's (1979) estimates of $b_p = 0{\cdot}05$ for $n_e = 0{\cdot}03\ \mathrm{cm}^{-3}$ and $b_p = 0{\cdot}03$ for $n_e = 0{\cdot}025\ \mathrm{cm}^{-3}$.

5. Conclusions

We have argued that shell-type SNRs form as a result of SN explosion of single stars and the first explosion in a close binary. The Crab-like SNRs are formed by the second SN explosion in a close binary. While a Crab-like SNR owes its existence to the embedded pulsar, the structure of a shell-type SNR is independent of the central pulsar. If at the centre of a shell-type SNR, there is an active neutron star, it will give rise to a Crab-like activity within the shell. On the other hand, if the shell SNR does not contain any neutron star or contains a black hole, we shall get a 'pure' shell-type SNR.

We have further argued that single stars with $4 < M/M_\odot < 6{\cdot}5$ explode as SN I and are totally disrupted while those with mass $> 6{\cdot}5 M_\odot$ exploding as SN II leave behind a neutron star or a black hole. In both cases a shell-type SNR forms.

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