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Pulsar Activity and the Morphology of Supernova Remnants

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Abstract. We use the recently introduced concept of a 'window' of magnetic field strengths in which pulsars can be active to explain the variation in morphology of supernova remnants. The striking difference between shell-type and filled-type remnants is attributed to differences in the magnetic field strengths of the neutron stars left by the respective supernovae. Field strengths of a value permitting pulsar activity result in particle production and Crab-like centrally concentrated remnants. Other field values lead to strong magnetic dipole radiation and consequent shell formation (*e.g.* Cas A). Several apparent inconsistencies concerning pulsar-supernova associations appear to find a logical explanation on the basis of this hypothesis.

Key words: pulsars—supernova remnants—magnetic window

1. Introduction

It is generally accepted that supernova explosions are unlikely without the formation of neutron stars. According to this picture there must be a neutron star associated with all supernova remnants (SNR). Because the observed proper motions of pulsars are very much less than the velocity of supernova ejecta, the neutron stars must be inside the SNR while the latter are still young. Since the typical age of pulsars is much larger than the life-time of SNRs, it is to be expected that old pulsars will show no association with SNRs; on the other hand we find it surprising that a radio pulsar has been detected in only 2 of the 120 or so known SNRs. This question has been asked many times in the literature and several arguments have been advanced to explain why a pulsar is not seen inside more, if not all SNRs.

The main arguments are (a) the pulsar may not be beamed at us; (b) a low flux density and large dispersion measure make it difficult to detect; (c) in addition, if it is in a binary system the pulsar may be 'smothered' by the stellar wind from the companion star (see Manchester and Taylor 1977 for a discussion of these effects). These three arguments would reduce the number of pulsars that one would expect to detect from 120 to a much smaller number. However, even if they do explain the absence of *pulsed* radio radiation from the centres of the majority of SNRs, they do not concern themselves with other possible manifestations of a rotating neutron star inside the SNRs.

If the newly born neutron star was functioning as a normal young pulsar (short period and high magnetic field), there should be a copious outflow of relativistic particles (Goldreich and Julian 1969; Sturrock 1971; Ruderman and Sutherland 1975). These should radiate either in the interstellar magnetic field or the field of the low frequency magnetic dipole radiation (Rees and Gunn 1974), giving rise to a central concentration of radio brightness around the neutron star. The Crab Nebula is a classic example of such a central concentration, and Shklovskii (1977) has argued very convincingly that the relativistic particles responsible for the radiation must be produced by the central pulsar.

In recent years, 9 more SNRs resembling the Crab Nebula, and showing no evidence of shell structure, have been reported by various authors and have been compiled by Caswell (1979). All the hundred or so other remnants are of the so-called shell-type, although in several cases the structure is not well delineated in the available radio maps. With one exception (G 326·3—1·8), central concentrations are not found in shell-type remnants and are conspicuously missing in the three youngest known remnants, Cas A, Tycho and Kepler which are among the best examples of well-defined shells with hollow interiors. The non-observability of radio pulsars in these three young remnants could be due to one of the factors such as beaming referred to above, but their distinctly non-Crab-like appearance cannot be a result of the direction from which they are viewed. It is an explanation of this difference in remnant morphology that we are attempting in this paper.

2. Field strengths and pulsar activity

Very reasonable arguments have been advanced that filled-centre supernova remnants may be expected to have lifetimes of ~10,000 years (Weiler and Panagia 1978). Since Cas A, Tycho and Kepler are all less than ~400 years old, the absence of such a nebula in each of them is consistent with the absence of a pulsar at their centres. To reconcile this with our earlier premise that a neutron star must have been formed in each explosion, we advance a new hypothesis relating the activity of neutron stars as pulsars with remnant morphology.

It has been argued recently (Radhakrishnan 1979) that for a neutron star to be active as a pulsar, the surface magnetic field must lie within a small range $2\text{–}3\times10^{12}$G, and its rotation period must be less than a few seconds. The latter condition will need to be satisfied for the production of a sufficiently high voltage to sustain the sparks which generate the energetic particles which then radiate (Ruderman and Sutherland 1975). In addition, the former condition has to be satisfied to enable reinitiation of the sparking process each time the gap has been re-formed after the previous breakdown. According to this picture, the observed spread in the magnetic fields *derived* from period and period derivative measurements on the assumption of dipole braking and a constant radius, is a reflection of the presence of multipole components and the spread in radii of the neutron stars in question (Shukre and

Radhakrishnan 1980). For the purpose of this paper we shall assume the above picture and explore the consequences for supernova remnants.

One of these consequences is that all neutron stars born with initial fields lying outside the magnetic window referred to above will spend part or all of their lives in ‘silence’. Neutron stars with initial fields below the window can never become pulsars. Those born with a true field very much higher than $2{\cdot}5\times10^{12}$G will also never be pulsars no matter how short their initial rotation period; braking due to magnetic dipole radiation will lengthen the period beyond the limit referred to above by the time the field decays to around $2{\cdot}5\times10^{12}$G. Those with initial fields just above this value may become pulsars depending on the timescale of the decay of the magnetic field. If pulsar dipole fields decay through the formation of multipole components as discussed by Flowers and Ruderman (1977), the characteristic surface magnetic field and its value on the polar cap will not diminish greatly while the dipole component relaxes to a very small value. As discussed by Shukre and Radhakrishnan (1980) such a field will permit pulsar operation even though the dipolar field is below the window value. If the evolution of the field as proposed by Flowers and Ruderman (1977) is sufficiently rapid, we may expect a significant number of neutron stars born with fields above the window to turn on as pulsars with some intermediate value of period, and remain observable until the period lengthens to beyond the cut-off value referred to earlier.

Irrespective of whether the initial field is above or below the magetic window, we propose that in either case this is precisely the reason for the hollow appearance of most shell-type remnants, and in particular Tycho, Kepler and Cas A. We suggest that inside each of these remnants, there is in fact a rapidly spinning neutron star with a surface magnetic field outside the window, and from which pulsed radio radiation would therefore not be observed from any direction or distance; and that the only outlet for the rotational energy of these stars is magnetic dipole radiation as discussed by Pacini (1967) and Gunn and Ostriker (1969).

It is interesting that Woltjer (1974) has suggested that the hollow interior of objects such as Cas A may perhaps be understood as due to the very strong electromagnetic wave field of a pulsar in the centre. In his picture, low frequency electromagnetic waves sweep the relativistic electrons out from the immediate vicinity of the pulsars, which must be spinning very fast but may not be beaming at us. According to our picture, there are no relativistic particles put out by the neutron stars in these remnants, but only a strong low frequency wave field. Depending on the initial strength and decay time of their fields these neutron stars may manifest themselves as pulsars in due course as discussed above. By this time the remnants will almost certainly have dissipated themselves; for them to remain observable would require that the decay time of neutron star magnetic fields be much shorter than generally believed, and of the order of the lifetime of shell-type SNRs ($\sim10^5$ years). In any case, one would not expect to see central concentrations around such ‘turned on’ pulsars, since these nebulae can be sustained only by rapidly spinning young pulsars.

3. Filled remnants

The centrally concentrated remnants listed by Caswell (1979) can now be understood as resulting from those cases where the initial magnetic field of the neutron star lay within the 'magnetic window' (Radhakrishnan 1980; Shukre and Radhakrishnan 1980) at birth. The rotational energy of such pulsars goes into the production of relativistic particles and pulsed radiation. The central concentration of radio brightness is the evidence for the operation of the neutron star as a pulsar, and the absence of radio pulses from any of them can now be attributed to one or more of the factors mentioned earlier, namely beaming direction, low flux density, large dispersion measure etc. The smaller number of such centrally concentrated remnants makes these arguments, in our view, more acceptable now than when applied to all the 120 or so observed supernova remnants in the galaxy.

The SNR Vela X associated with the pulsar PSR 0833 — 45 also has a filled interior as seen in the radio emission (Lerche and Milne 1980). Recent observations by HEAO-B (Harnden *et al.* 1979) have revealed an X-ray nebula of angular size $\sim 1'$ and centred on the pulsar. Together with the Crab, we thus have two pulsars seen in $\sim$10 such remnants, all presumably powered by pulsars. This is in reasonable accord with the 20 per cent factor usually associated with pulsar beaming.

4. Shell-Type remnants

We shall now discuss the question of the formation of supernova shells. If they are formed by the shock waves and mass ejection which are believed to accompany every supernova explosion, then the absence of shells around the Crab and similar remnants must be due to some other parameter. The presence or absence (at the site of the explosion) of interstellar matter which could be compressed into a shell is one possible reason. Cox and Smith (1974) have in fact proposed that holes in the form of million-degree-bubbles are left in the interstellar medium by previous supernova explosions. The filling factor suggested by them for such bubbles is $\sim$10 per cent. This could be considered to agree with the ratio of filled to shell-type remnants, although the much shorter lifetime of the former would really lead to a much larger filling factor, if this were the true explanation.

However, according to this picture, pulsars should be found in either type of remnant; the presence of a shell should depend only on whether there has been a previous explosion in the vicinity. Of the large number of pulsars known today ($\sim$300), there are only two (the Crab and Vela) believed by all to be definitely associated with remnants. The probability that both these pulsars would be found in centrally concentrated remnants is less than 1 per cent because the latter form less than a tenth of the population of supernova remnants. For this reason it seems to us much more likely that the morphology of a remnant is, in fact, a consequence of the presence or absence of an active pulsar in it.

We have already discussed the intimate connection between the nature of filled remnants and the particle producing pulsars in them. In a similar manner, if shells were produced by the strong low-frequency dipole radiation put out by neutron stars which are not pulsars, the picture would be complete. Such a mechanism was proposed by Ostriker and Gunn (1971). According to them, supernova explosions are powered by the stored rotational energy in the newly formed neutron stars. The intense low-frequency radiation pushes out the outer envelope of the star and the surrounding interstellar matter and accelerates them for long enough to acquire the kinetic energy associated with observed shells. Thus newly born neutron stars which do not immediately function as pulsars could create the shells seen as most supernova remnants. The radio radiation from these shells can arise from one or more of the mechanisms proposed for both field amplification and particle acceleration in supernova shells (Gull 1973; Scott and Chevalier 1975; Bell 1978; Blandford and Ostriker 1978).

5. Hybrid morphology?

In the above discussion we have categorised neutron stars as either pulsars producing filled remnants, or magnetic dipole radiators producing shell-type remnants, as if these two types of behaviour were mutually exclusive. It is an open question as to whether a rotating magnetised neutron star can put its energy into particle production (Goldreich and Julian 1969; Sturrock 1971; Ruderman and Sutherland 1975), and *simultaneously* into low frequency magnetic dipole radiation (Pacini 1967; Gunn and Ostriker 1969). In almost all discussions in the literature of any of these two processes, the other is carefully neglected as if it did not exist. If a rotating magnet were immersed in a highly conducting medium, Lenz's law would lead us to believe that the electric fields generated by the rotation would set up currents whose magnetic fields neutralised the far field magnetic dipole radiation. The rotational energy would go into the acceleration of the charges whose motion forms the currents.

Kaplan, Tsytovich and Eidman (1974) have discussed this problem for a strongly magnetised rotating neutron star but assuming that the conductivity in the magnetosphere is isotropic. They concluded that turbulence in the relativistic circumpulsar plasma will sharply reduce its conductivity with several consequences including the shielding of the magnetic dipole radiation. It is possible that their assumption of isotropic conductivity invalidates their conclusions. If it does not, then neutron stars will operate in only one mode at a time, either as magnetic dipole radiators (with no particle output), or as pulsars putting out pulses and relativistic particles (but with little or no dipole radiation).

The interesting case of G 326·3—1·8 (Caswell 1979), which shows a weak but well-defined shell in addition to a central feature might be evidence to the contrary. It is unlikely that the central feature is due to the recent turning on of the neutron star as a pulsar and that the shell was produced before pulsar activity started. As discussed earlier, the time within which the field would have had to decay is unacceptably short; a rough age estimate of this remnant based on its diameter etc. (see for example Clark and Caswell 1976) leads to approximately 5000 years. G 326·3—1·8 represents perhaps simply a case of ' having a little each way ' in that both low-frequency radiation and pulsar behaviour are present. It is conceivable that the recently discovered class of objects (Ryle *et al.* 1978) wherein very small diameter sources are found at the centres of well-defined shells are also in this special category.

6. Supernovae in binaries

We turn now to neutron stars born in close binary systems. According to the standard picture (van den Heuvel 1977) the system will not disrupt after the first explosion, and the companion star will remain in the main sequence for a few million years. As the stellar wind of the companion will be weak during this phase, we expect the picture relating to the morphology of remnants described above to remain substantially unmodified.

If the neutron star has the right magnetic field to operate as a pulsar, a nebula centred on the pulsar will be produced as before. If the neutron star is not active as a pulsar, a shell will be formed in the usual way. But as the lifetime of shells is much greater than that of central nebulae, further developments are conceivable in this case. In particular, if within the lifetime of the shell the dipole radiation from the neutron star can be absorbed by the stellar wind in its Roche lobe, this will lead to its heating and subsequent reradiation, *i.e.* to the formation of a source of higher frequency radiation surrounding the neutron star.

In the case of the second explosion in binary systems, we believe that its manifestations will be identical to those accompanying a single star explosion. Even in the unlikely event of the system remaining bound, the first neutron star will have very little influence on the newly formed one. Also, even a moderate proper motion would have moved the binary far from the site of the first explosion in the intervening period of several million years; the development of the remnant will therefore not be biased.

7. Conclusions

We have attempted in this paper to relate pulsar activity in neutron stars with the observed morphology of SNRs. We start with the concept of a window of magnetic field strengths only within which neutron stars will display pulsar activity; neutron stars with fields outside the window will put out only magnetic dipole radiation. The former variety emit large numbers of relativistic particles and create centrally concentrated remnants of which type about 10 are known. Neutron stars emitting only dipole radiation create shells around them characteristic of most of the known supernova remnants.

Among the longstanding inconsistencies relating to pulsar-supernova associations are (a) the fact that in only two of all the known remnants have pulsars been observed, and (b) that neither of these pulsars is in shell-type remnants, which form the vast majority. Both these facts find a logical explanation on the basis of our hypothesis. Only the ten or so Crab-like remnants have active pulsars in them, and the various selection effects in operation make only two of them observable.

We are aware that the present hypothesis appears to further increase the already existing difficulty of reconciling the formation rates of pulsars and occurrence rate of supernovae in the galaxy. Estimates of these two numbers made by different authors are fraught with uncertainties and vary widely, but most of them seem to indicate a higher formation rate for pulsars than if they were produced in supernova explosions (see discussion on p.168 of Manchester and Taylor 1977). If only some of the neutron stars produced by supernovae become pulsars, this discrepancy would obviously be widened. It was mentioned earlier that the lifetime of filled remnants is of the order of 10^4 years, whereas that of shell-type remnants is generally believed to be 10^5 to 10^6 years. As the ratio of these two lifetimes is approximately the same as that of the numbers of observed remnants of the two varieties, this indicates that their production rates are roughly equal. In other words, roughly half of the neutron stars produced in supernovae have initial magnetic fields inhibiting them from functioning as pulsars at birth. If some fraction of these eventually turn on as pulsars after the remnants have dissipated themselves, this would imply that the majority of neutron stars created in supernova explosions do in fact contribute to the pulsar population. Thus, we see that the discrepancy referred to earlier is only marginally affected by the present hypothesis, and the explanation of any serious disagreement must lie elsewhere. We believe in any case, that as more light is thrown on the processes of formation of pulsars and supernovae, the matter will resolve itself without requiring that every neutron star that is created must immediately function as a pulsar.

Finally, we touch upon the possible implications of our conclusions for the direct measurements of neutron star temperatures by X-ray observations (Murray *et al.* 1979; Harnden *et al.* 1979; Helfand, Chanam and Novick 1980). If, indeed, there are neutron stars at the centres of all SNRs as we have assumed, the upper limits imposed by X-ray observations suggest that neutron stars cool much faster than present theories have supposed. Also, if only some neutron stars are active as pulsars as we have proposed, and pulsars operate according to the Ruderman and Sutherland (1975) model, then some difference should be found between the temperatures of the pulsars and of other neutron stars of the same age, due to the extra heating by the particles hitting the surfaces of pulsars.

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