ON THE ASSOCIATION BETWEEN PULSARS AND SUPERNOVA REMNANTS

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The true nature of the association between pulsars and supernova remnants has remained an intriguing and poorly understood problem even after all these years of research on them. We attempt in this review to marshal all the evidence one has on this question, and to see what conclusions we can draw.

The idea that there should be an association at all owes its origin to Baade and Zwicky (1934) who advanced the view that supernovae represent the transitions from ordinary stars into neutron stars - a new and revolutionary concept at that time, just two years after the discovery of the neutron. Following their suggestion, all theories of supernovae for many years afterwards involved a neutron star as an essential member of the cast, and one capable in principle of releasing up to 10^{53} ergs of gravitational binding energy at the time of its formation. But the details of how a part of this energy could be coupled to the infalling envelope of the star to arrest its collapse, and to accelerate it outwards to velocities of thousands of km s^{-1}, have remained a major problem. It is only now that plausible scenarios are being advanced in which the neutron star collapses to greater than nuclear densities and rebounds transmitting energy to the envelope (see Brown et al. 1981 and references therein).

After pulsars were discovered, and when it was suspected that they had to be spinning neutron stars, it was predicted (Woltjer 1968) that they should be found in SNRs, and in particular that there should be one in the Crab Nebula. It should be remembered, however, that in the case of the Crab Nebula, the prediction was motivated at least as much by the need to have a central engine to explain its continuing activity (Pacini 1968), as to find a natural birth place for neutron stars. The discovery of a pulsar in the Vela supernova remnant within months (Large et al. 1968) and one in the Crab soon after (Staelin and Reifenstein 1968), seemed at the time to have answered several questions all at once.

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The extraordinary thing is that the total number of firm associations with supernova remnants remained at these two for over a decade or so although the total number of pulsars and supernova remnants mounted up with time. The fact that no further associations were found in spite of repeated searches was attributed to selection effects like distance, dispersion, interstellar scattering, multi-path propagation, small beaming angle, etc., all of which when put together, "satisfactorily" explained why no more pulsars were seen in SNR. (see Manchester and Taylor 1977). This can also be seen by studying the distribution of observed pulsars and supernova remnants with distance from the Sun. All of the selection effects can be thought of as combining to cut down the distance within which pulsars will be picked up in searches over areas of the sky which may include supernova remnants. Assuming that all SNRs have a pulsar in them, it can be shown that the number of these pulsars expected to be found is of the order of one, quite consistent with the associations we have had.

But apart from the absence of more associations, there are important differences even between the two known cases, the significance of which needs to be understood. We mentioned earlier that in most theories of supernovae, it was the binding energy of the neutron star that was somehow responsible for the motion of the ejecta which subsequently formed the remnant. In the case of the Crab, the optical filaments appear to be the only ejecta ($\sim 1\ M_{\odot}$) whose present velocities - with some little acceleration since 1054 AD - were mainly acquired at the time of the explosion. These filaments seem to lie on the periphery of a bright and centrally concentrated nebula now believed by all to have been created by the pulsar over a period since its formation. There is no canonical shell around this object although such shells are commonly found in both younger and older remnants, most of which have a hollow interior as seen in the radio.

If it is really part of the binding energy of the neutron star which powers the supernova remnant, then there are clearly two completely different ways in which this happens. If energy is imparted to the envelope at the time of the explosion, then it presumably results in a shell remnant whose characteristics will depend on the mass and initial velocity, and whose development will be governed by the density of the medium into which it is expanding. If the energy stored in the rotation of the neutron star is released subsequently through its functioning as a pulsar, then a filled remnant similar to the Crab nebula will be formed, whose characteristics will depend upon the initial spin rate and field of the pulsar as shown by Pacini and Salvati (1973), and whose evolution must also be affected by the interstellar medium.

That the Crab Nebula, although special, is not unique, has been argued by Weiler (and others) in a series of papers over many years. There are a handful of other such objects in the galaxy, with similar characteristics, all presumably powered by a fast spinning pulsar inside (see e.g., Wilson and Weiler 1976; Weiler and Wilson 1977;

Weiler and Shaver 1978; Weiler and Panagia 1978; Weiler 1978; Caswell 1979; Weiler and Panagia 1980; and Wilson 1980).

When the Vela pulsar was discovered by Large et al. (1968) it was immediately associated with the large shell remnant whose age as deduced by the standard method was in reasonable agreement with the characteristic age of the pulsar ($P/2\dot{P} \sim 12{,}000$ years). The rough agreement in the rotation measures obtained for both pulsar and SNR was taken to add further support to the association although the dispersion measure of this pulsar when coupled with the average electron density ($0.03\ cm^{-3}$) in the interstellar medium would have led to a distance (2.3 kpc) four to five times that estimated independently for the SNR. This discrepancy is now understood as due to the presence of a large HII region in the line of sight.

The major difference from the case of the Crab is the form of the associated SNR which clearly calls for an explanation. The position of the pulsar, unlike that in the Crab, is substantially displaced from the apparent centre of the large shell remnant and is in fact located in a centrally concentrated nebulosity at the edge of the shell. It has been pointed out by Weiler and Panagia (1980) that the spectral index, general form and polarization characteristics of this nebulosity were reminiscent of the Crab nebula, and very different from that of the shell. It should also be noted that if the pulsar had been born close to the centre of the present shell, it would require an unlikely space velocity in excess of 1000 km s^{-1} to reach its present position, or the shell would have had to expand in a very non-uniform way. That the nebulosity at the position of this pulsar is not just a piece of the shell against which the pulsar is superposed on the sky, is confirmed by the non-thermal X-radiation from it, which resembles that of the Crab nebula. Thus the association of the pulsar with the radio and X-ray source surrounding it seems beyond doubt, while the connection with the shell remnant is less well established. (Weiler and Panagia 1980; Radhakrishnan and Srinivasan 1980).

If we assume that the Vela *shell remnant* is also definitely associated with the pulsar, this will imply that both features of this remnant can be produced by the same neutron star, with the energy to one being delivered at birth, and to the other over a characteristic time determined by the initial period and field of the pulsar. Observational evidence in support of such duality has been (until recently) very meagre however. Only one other shell remnant (G326.3-1.8) shows a radio concentration within the shell, and the half-a-dozen or so remnants like 3C58 display the fried-egg morphology of the Crab, and a similar lack of any shell around them. This led to the hypothesis advanced by Radhakrishnan and Srinivasan (1980) that the two types of remnants were perhaps exclusive. Following Ostriker and Gunn (1971), we proposed that the energy for the expansion of shell-type remnants came from the rotational energy of those neutron stars which (for some reason) did not function as pulsars at birth; if they did, they would produce pulsar - nebulae (plerions) like the Crab.

Our contention was that the neutron stars that should be there in the young classical shell remnants like Cas A, Kepler and Tycho, did not function as pulsars at all. The absence of emission from a central nebula in either radio or X-ray supported our hypothesis, which however left several awkward questions unanswered. One of them was why very little ejected mass is observed associated with bright plerions like the Crab and 3C58. This is not easily explained, unless strong pulsar activity at birth is itself associated with a very low mass for the envelope. We shall return to this possibility at the end of this review.

While the absence of X-ray nebulae within most shells supported the picture mentioned above, the absence of point X-ray sources in most SNRs was a source of embarrassment. If neutron stars were left behind by every supernova explosion as we had assumed, some fraction of them should have been detectable by their thermal emission in X-rays. The fact that very few such compact X-ray sources were found, either meant that there were no neutron stars in most remnants, or that neutron stars cooled much faster than generally believed as Radhakrishnan and Srinivasan (1980) had suggested. (See discussion by Helfand in this volume).

The former point of view was taken by supporters of theories of supernova explosions which did not leave behind any neutron star. It was claimed that given the right conditions, some stars could suffer thermo-nuclear detonation in their degenerate carbon cores and disintegrate completely leaving no collapsed remnant. It was suggested that these were type I supernovae associated with stars in the mass range 1.4-6 $M_\odot$; stars of greater mass caused type II supernovae which left behind neutron stars which could function as pulsars. (See Tinsley 1977 and references therein). Lack of the expected amount of iron peak elements in the spectra of type I supernovae, was one of the observational facts that did not support this point of view. Another was the high mass ($\sim$ 15 $M_\odot$) estimated for the shell of Cassiopeia (Fabian et al. 1980) which apparently has no pulsar in it, and the low mass ($\sim$ 1 $M_\odot$) found around the Crab pulsar.

A different point of view from which this problem can be looked at, is in regard to the birthrates of supernovae, supernova remnants and pulsars. Starting with SN, the best estimate from extragalactic observations is one in 20 years (Tammann 1977) with an uncertainty of a factor of two. A similar estimate has also been made by Clark and Stephenson (1977) who studied historical records and arrived at a not too different figure of 1 in 30 years or less. One can also derive a birthrate for SNRs, which should be the same, unless a fraction of SN did not leave remnants. This exercise has been done in various ways, leading to estimates of one in 50 $\pm$ 25 y (Ilovaisky and Lequeux (1972), $\sim$ 80 y (Caswell and Lerche 1979), and $\sim$ 150 y (Clark and Caswell 1976). A recent attempt by Srinivasan and Dwarakanath (1982a) gives 1 in 25 y, and a similar number has been derived by Higdon and Lingenfelter (1980). Both papers have argued that the ages of shell SNRs have been much overestimated previously. (Even more recently, Mills - this volume - has derived a birthrate of 1 in 30 years). It is seen that within the errors, all these recent estimates of the birthrate of SNRs agree with the occurrence rate of SN, and for our purposes we shall assume a birthrate of 1 in 25-30 years for both.

The birthrate of pulsars is a more touchy number, involving as it does, numerous selection effects both known and unknown. Among the well-known estimates in the literature are those of Taylor and Manchester (1977), Phinney and Blandford (1981) and Lyne (1981) all of the order of 1 in 10 years, or more frequently. However, a more recent estimate obtained by studying the current in the P-$\dot{P}$ diagram and allowing for luminosity selection effects gives 1 in 21^{+6}_{-5} y (Vivekanand and Narayan 1981), where the errors are 95% confidence limits. This last estimate of the pulsar birthrate is significantly lower than previous ones and is, within the errors, compatible with the SNR birthrate adopted above.

All of the above estimates of the pulsar birthrate assume a beaming factor of 5, and this has long been a weak point frequently pounced upon by theorists. The observational astronomers, working with longitude scans, and resigned to the impossibility of obtaining a latitude scan through pulsar beams, have become accustomed to thinking of them as circular. Very recently, however, the equivalent of a latitudinal scan has been achieved by a statistical analysis (Narayan and Vivekanand 1982) of the polarization angle sweep obtained from new high quality observations (Backer and Rankin 1980). The surprising result of this analysis is that pulsar beams are found to be elongated in latitude by a factor of $3^{+0.5}_{-0.4}$ over the longitudinal width, but that the elongation appears to be a function of the pulsar period. Because of this dependence on period, the effective value of the average beaming factor is somewhat uncertain; but whatever the magnitude of the change from the previously assumed value, it can only decrease the birthrate. Incorporating a new determination of the distribution of dispersing electrons (Vivekanand and Narayan 1982), the birthrate estimate is expected to be even further reduced.

While all these developments reduce the urgency of manufacturing neutron stars in less spectacular events than supernovae, it would still appear that practically every SNR has a neutron star in it. In any case, even if only some SNRs have neutron stars inside, why do we not see evidence of their activity as radio and X-ray nebulae around them? As pointed out by Radhakrishnan and Srinivasan (1980) this is independent of beaming angle and viewing geometry. We are thus forced to conclude that the majority of neutron stars that may exist in shell remnants are not functioning like the Crab and Vela pulsars. This could be due to an absence of particle and field production as we conjectured, or perhaps because of a greatly reduced output due to slower initial rotation of the pulsar. The possibility that shell-type remnants leave behind a slow pulsar has also been suggested by Weiler (1978) in a discussion which however involved the different types of supernovae.

The most interesting new pulsar-supernova association is the recently discovered PSR 1509+58 in the shell remnant MSH 15-52 (Seward and Harnden 1982). These authors discovered both X-ray pulses from this object and also an X-ray nebula around it. Radio measurements (McCulloch et al., 1982; Manchester et al. 1982) have confirmed that this is indeed a regular pulsar, and not an accreting X-ray system, thus making it the third firm PSR-SNR association. From the strength of the X-ray nebula around the pulsar it has recently been concluded that this pulsar must have had an "intermediate" value of initial period of $\gtrsim$ 70 ms (Srinivasan et al. 1982). Otherwise, given the exceptionally high magnetic field of this pulsar ($\sim 4\ B_{Crab}$), a short initial period would have resulted in an optical and X-ray nebulosity even more spectacular than the Crab nebula.

That objects like the Crab nebula are rare, with a birthrate of $\sim$ 1 in 350 years, can be shown simply by considering the age, luminosity and expected evolution of the nebula, together with the number of such objects seen in the galaxy (Srinivasan and Dwarakanath 1982b). But because it represented 50% of the known associations for over a decade, the temptation to use it as a proto-type to understand the properties of pulsars in supernova remnants has been irresistible. Much of the difficulty we have had in understanding these objects can, we believe, be attributed to this reason.

Completely independent evidence, not connected with SNRs in any way, that the initial periods of the majority of pulsars may be much longer than generally believed was provided by the same analysis of the current in the P-$\dot{P}$ diagram referred to earlier (Vivekanand and Narayan 1981). This analysis suggested that the majority of pulsars were either born with, or turned on at, a period of around 0.5 seconds. This estimate of the "injection" into the P-$\dot{P}$ diagram has been refined somewhat taking into account new selection effects (Vivekanand et al. 1982) and the latest figure is $\gtrsim$50%. This result is certainly in accord with the absence of central concentrations in shell-type remnants, even though there may be neutron stars within. But it cannot be used to choose unambiguously between a long period for the neutron stars at birth, or an interval of quiescence after birth until they have slowed down through dipole radiation.

We return finally to a question concerning the Crab which was touched upon earlier but not elaborated. It was mentioned that one of the extraordinary features of this nebula is that there is no shell around the object. The possibility that a greater amount of mass (than seen in the filaments) was ejected, but is invisible because of expansion in a very low density medium, has been suggested by several authors (Chevalier 1977; Murdin and Clark 1981). The latter authors have found a weak optical halo surrounding the nebula, and have argued that this may originate in such a shell. However, Wilson and Weiler (private communication, Weiler) find no radio emission to support this interpretation. Pending X-ray observations of the optical halo found by Murdin and Clark (1981), it appears to us that the evidence for any substantial amount of ejected matter beyond the present boundary is weak.

If the mass ejected were in fact low, it is very tempting to think that it might be connected with the powerful activity of the pulsar. We have already discussed the need for a short spin period at birth to produce the particles and field that would form a bright nebula. If a high spin-rate at birth was, say, a consequence of a low mass for the envelope to which the core would be magnetically connected during collapse, we might have an explanation.

To speculate further, it should be noted that if such a mechanism could be shown to work, the envelope would extract a fraction of the rotational energy of the neutron star, which would otherwise reside in it for later use; also, the more massive the envelope, the greater the fraction. It is not clear whether a low-mass envelope accelerated in this fashion would fragment, as the mass in the Crab nebula seems to have done; but the kinetic energy can certainly be accounted for without requiring any 'bounce' at all. As an illustration, if angular momentum conservation had given the Crab pulsar an initial period of 10 ms, then slowing it down to 16 ms provides the $\sim 10^{50}$ ergs of kinetic energy now found in the ejecta.

To summarize, all the facts put together seem to point to the following conclusions:

1. In spite of the errors in all such estimates, it seems reasonable to believe that the birthrate of pulsars is not higher than the birthrate of SNRs.

2. If all SN leave behind neutron stars, there is no need to look for alternative ways of producing them.

3. If there are neutron stars inside shell remnants, the majority were either born spinning slowly, or are not functioning as pulsars even if spinning fast.

4. The Crab phenomenon is relatively rare and not a prototype of either young pulsars or young supernova remnants.

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