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Three Proposed Pulsar/Supernova Remnant Associations and Their Possible Origin in Close Binary Systems

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Summary. An attempt is made to establish associations between pulsars and supernova remnants based not only on their distances, ages and position but also on pulsar radio polarization information. Of three pulsars investigated, a supernova remnant (G 193.3−1.5) is visible near one (PSR 0525+21) but the estimated ages of the remnant and the pulsar are discrepant. Possible ways of removing this discrepancy are discussed. Two further associations are proposed on the basis of position and distance estimates alone. They are PSR 0153+61 with G 132.4+2.2 (HB3) and PSR 1927+18 with G 53.9+0.3.

Key words: pulsar — supernova — binary systems — polarization

1. Introduction

Early attempts to find associations between pulsars and supernova remnants were based on rough positional agreement alone (Prentice, 1970; Tsarevsky, 1972). Large and Vaughan (1972) have shown that these associations were statistically insignificant, and more recent attempts have involved consideration of distance and age estimates for both the pulsar and supernova remnant (Large and Vaughan, 1972; Davies et al., 1972). In most of these latter cases, the pulsars have been relatively young and the errors in the age estimates are believed to be unimportant. On the other hand, the age estimates for older pulsars derived from their rate of change of period are suspected to be gross overestimates (Lyne et al., 1975; Anderson et al., 1975; Manchester et al., 1974). Furthermore, recent observations of neutral hydrogen shells around several older supernova remnants (Assousa and Erkes, 1973; Knapp and Kerr, 1974) have suggested that their ages (Jones, 1975a,b) are much greater than previously thought. Shklovskii (1974) has also pointed out that large variations in the apparent lifetime of supernova remnants can be expected on account of the dependence of lifetime on the density of the interstellar medium at the site of the explosion. Thus age criteria cannot be given great weight in establishing associations between old pulsars and old supernova remnants.

In this paper, we report on an initial attempt to establish associations between pulsars and supernova remnants based not only on their distances, ages and position, but also on polarization information.

Three pulsars were investigated in this manner, and a supernova remnant was visible near one. However, the estimated ages of pulsar and supernova remnant are discordant. If this is really a physical association, then the age discrepancy may be understood if the special conditions discussed above are assumed for the supernova explosion. Alternatively, if some pulsars are formed in close binary systems which subsequently undergo a second supernova explosion, the age difference may also be accounted for.

During the course of this study, two further possible associations were noticed on the basis of position and distance estimates alone.

2. The Intrinsic Polarization Angle Criterion

For those pulsars with measured proper motion Morris et al. (1976) have shown that the intrinsic angle of polarization ϕ_I of the radio emission at the center of the pulse is correlated with the direction of motion V. They found that for the majority of pulsars the values of $\phi_I - V$ cluster around 90 degrees with a possible secondary concentration at 0 degrees. From a study of a slightly different sample Tademaru (1977) has concluded that the distribution is bimodal with peaks at $\phi_I - V = 0$ and 90 degrees. Hence on this basis, when V is not known for a pulsar, the direction perpendicular, or parallel, to ϕ_I can

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be used instead to trace the pulsar back to its point of birth. There is of course an ambiguity of 180 degrees in the direction of motion derived thus, and its precision will depend on the intrinsic scatter of the distribution of $\phi_I - V$ about 0 or 90 degrees. At present the measurement errors in ϕ_I are sufficiently large, that it may be difficult to estimate this intrinsic scatter. Helfand and Tademaru (1977) have discussed some of the factors influencing the scatter in the framework of the theory of the acceleration of pulsars by the asymmetric radiation reaction (Harrison and Tademaru, 1975). For the purpose of this paper we assume that the intrinsic scatter is negligible in comparison with the measurement errors. The technique may be particularly useful for those distant pulsars for which no accurate proper motion is available.

We have considered the pulsars PSR 0525+21, PSR 0628−28 and PSR 2045−16 since they are the only candidates which at present have uncertainties of 10 degrees or less in the intrinsic polarization angle at the centre of the average pulse profile. For PSR 0525+21, we have used the published value of ϕ_I from Manchester (1974). Values of ϕ_I have been derived for the remaining pulsars from the 11 cm measurements of Morris et al. (1970) using published rotation measures (Manchester, 1974). Catalogues of supernova remnants and maps of the background radiation were searched for remnants lying within sectors of angular width $\pm\sigma$ centred on the pulsar position and parallel or perpendicular to ϕ_I. In only one case was a known supernova remnant to be found within a distance of 15° from the pulsar. For each pulsar studied, Table 1 lists ϕ_I and V, the position angle of the pulsar with respect to the centre of the candidate supernova remnant. It also serves to compare the distances and ages of the members of the possible associations. From their transverse separations a transverse velocity has been calculated for the pulsar assuming two possible flight times. One is the pulsar spin down age and the other is the estimated supernova remnant age. Ages for the supernova remnants have been derived from the measured diameter given by Clark and Caswell (1976), using the model calculations of Mansfield and Salpeter (1974). For the purpose of this paper, we have assumed $E/n = 5 \times 10^{51}$ erg cm^3 as suggested by Clark and Caswell (1976). According to Clark and Caswell, the errors in diameter (or distance) may amount to ±30% corresponding to an extreme range of 2:1 observed in the Magellanic clouds. The errors propagated in the ages then correspond to an extreme range of about 5:1.

(a) PSR 0525+21—G 193.3−1.5

Prentice (1970) and Tsarevsky (1972) suggested the association of this pulsar with S147 (G 180.0−1.7), however, the pulsar distance of 2.0 kpc (Taylor and Manchester, 1975) is in disagreement with that of the supernova remnant (0.9 kpc) (Clark and Caswell, 1976). Furthermore, as the relation $\phi_I - V = 90°$ (or 0°) is not satisfied, there seems little to support this suggested association.

Gott et al. (1970) have argued that PSR 0525+21 and PSR 0531+21 are both run-away remnants of a binary system in the I Gem. association which was disrupted by

Table 1

PSR	SNR	ϕ_I (°)	V (°)	Distance (kpc)		SNR Diam.	Age (y)		Transverse Separation		Pulsar vel. (km s^{-1})	
		(1)		PSR (2)	SNR (3)	(pc) (3)	PSR (4)	SNR (5)	(°)	(pc)	(6)	(7)
0153+61	HB 3 G 132.7+1.3		259 ±5	2.0	1.9	41	2.0×10^5	1.6×10^4	2.6	90	450	5400
0525+21	G 193.3−1.5	40 ±10	121 ±2	1.9	1.9	45	1.5×10^6	2.0×10^4	11.5	400	270	20000
0628−28	non detected	36 ±10			1.4		7.9×10^6					
1927+18	G 53.9+0.3		292 ±30	3.7	3.1*	34*		10^4	≈0.2	≈10		≈1000
2045−16	non detected	172 ±10		0.43			2.8×10^6					

Notes
(1) From Manchester, 1974
(2) From dispersion measure, Taylor and Manchester, 1975
(3) From Clark and Caswell, 1976
(4) From spin down, Taylor and Manchester, 1975
(5) Using Equation (6) of Mansfield and Salpeter (1974) with $E/n = 5\ 10^{51}$ erg cm^3
(6) Using the pulsar spin down age $P/2\dot{P}$
(7) Using SNR age
* Estimated in Section 3a

the supernova explosion leading to the formation of PSR 0525+21 about 3 million years ago. On this basis, they predict a proper motion for PSR 0525+21 of 0".011 per year in position angle 90 ± 15 degrees. The measured intrinsic angle of polarization for PSR 0525+21 is 40 ± 10 degrees (Manchester, 1972). This leads to a value $\phi_I - V = 50 \pm 18$ degrees, which fails to fulfil the criterion $\phi_I - V = 90$ (or 0) degrees. Although the disagreement is only by twice the quoted error, the polarization information does not support the association suggested by Gott et al. It has also been criticized by Trimble and Rees, (1971).

We have searched for other supernova remnants near PSR 0525+21 closer to the directions defined by the observed polarization angle. Two were found, one of which, the Origem loop (Berkhuijsen, 1974), seems to be excluded by its small distance (1.1 kpc) in comparison with that of the pulsar (2.0 kpc). The other, G 193.3−1.5 (PKS 0607+17), fulfils both distance and polarization criteria. From Table 1 it can be seen that $\phi_I - V = 81 \pm 10$ degrees. There are difficulties, however, in reconciling the estimated ages of G 193.3−1.5 and PSR 0525+21.

The pulsar spin down age of 1.5×10^6 years is about 75 times the age of the supernova remnant (2×10^4 years) as estimated from its diameter. Furthermore, if this age for the remnant is accepted then the pulsar transverse velocity must be about 2×10^4 km s^{-1}. This is about 40 times the largest known pulsar velocity (≈ 500 km s^{-1}) and suggests that for the association with G 193.3−1.5 to be valid, the remnant age must be larger than estimated by a similar factor.

As stressed in the introduction, there are large uncertainties in these age estimates and we therefore cannot exclude completely that the ages of pulsar and supernova remnant coincide. The pulsar age is almost certainly an overestimate and the remnant age may very well be an underestimate. There is evidence (Lyne et al., 1975; Anderson et al., 1975; Manchester et al., 1974) from the distribution of pulsars with respect to the Galactic plane and their measured proper motions that on the average the older pulsars are considerably younger than is indicated by their spin down age $P/2\dot{P}$. By way of explanation it has been suggested for example that their effective magnetic moment decays with a time constant of about 1.4×10^6 years (Lyne et al., 1975). A similar result follows if the inclination of the magnetic axis to the rotational axis changes with time (Jones, 1976; Flowers and Ruderman, 1977). If such a time constant applies to PSR 0521+25 then its age estimate is reduced by about a factor 2 to 7.5×10^5 years.

The errors in the age of the supernova remnant stem from numerical uncertainties in the input data for the blast wave theories, and from doubts as to the applicability of such theories to the later stages of the evolution of supernova remnants. In the first place the assumption of a constant value $E/n = 5 \times 10^{51}$ erg cm^3 for all outbursts makes no allowance for variations in the energy of the explosion (E) or in the interstellar density (n) at the site of the explosion (Shklovskii, 1974). To judge from the scatter of the observed properties of supernova remnants in the Magellanic clouds, this error is at least a factor 5 (Clark and Caswell, 1976). In the second place the observed structure of the remnants is open to several interpretations. Jones (1975a,b) has identified the expanding shells of neutral hydrogen surrounding several supernova remnants as "fossil blast waves". On this basis he derives ages of 8×10^5 years and 7×10^6 years for the remnants HB 21 and W 44. (Their diameters are 39 and 52 pc respectively.) An alternative explanation by Cornett and Hardee (1975) leads to an age of 1.4×10^5 years for W 44. All these estimates are in excess of the value obtained from simple blast wave theory which gives for example 3×10^4 years for W 44.

Such discussions suggest that the age of PSR 0525+21 and G 193.3−1.5 may perhaps be reconciled. However for G 193.3−1.5 there is as yet no evidence for either a neutral hydrogen shell, or for enhanced density in its neighbourhood ($Z = -50$ pc). The low resolution survey of Weaver and Williams (1973) shows no obvious neutral hydrogen shell around this remnant. A detailed survey of this region is in progress (Assousa et al., 1973) and better age estimates may be possible when it is complete. In the meantime, accepting the large age discrepancy as real, an alternative possibility is discussed in Section 4.

(*b*) PSR 0628−28 *and* PSR 2045−16

No supernova remnant has been catalogued near PSR 0628−28 (within 15°). Since PSR 2045−16 is relatively nearby (430 pc), the angular size of the search area is large and the expected angular size of the remnant is about 5 degrees. The recognition of any associated SNR is therefore difficult.

3. Two Possible Associations from Position and Distance Data Alone

(*a*) PSR 1927+18—G 53.9+0.3

In projection this pulsar lies within the contours of the supernova remnant G 53.9+0.3 (HC 40) as determined by Velusamy and Kundu (1974). No spectral data exist for this supernova remnant but if a spectral index of −0.5 is assumed, then the surface brightness given at 11 cm by Velusamy and Kundu can be converted to a 1 GHz value. When substituted into Ilovaisky and Lequeux's (1972) relation between surface brightness and diameter, this leads to a diameter of 34 pc, and hence a distance of 3 kpc. Within the considerable uncertainties this value is not in conflict with the pulsar distance of 3.7

kpc as determined by Taylor and Manchester (1975) from the dispersion measure. We suggest this as a possible association to be investigated further on the basis of age, polarization and/or proper motion data, none of which exists now.

(*b*) PSR 0153+61—G 132.7+1.3

This pulsar lies 2.5 degrees from the supernova remnant HB 3 (G 132.7+1.3) and at their common distance of 2 kpc this corresponds to a transverse separation of 90 pc. The spin down age of PSR 0153+61 is relatively small ($2\ 10^5$ y) and thus may be a good estimate of the pulsar's age. In this case the transverse motion of the pulsar must be 450 km s^{-1}, which although high is certainly not impossible. The estimated age of HB 3 (1.6×10^4 y) is an order of magnitude less than the pulsar spin down age $P/2\dot{P}$. However, this discrepancy might be accounted for by the intrinsic scatter in the apparent supernovae ages ($\approx$5:1, see Sec. 2). For example, if a lower value of $E/n = 10^{50}$ erg cm^3 is assumed for the explosion, as has been used by Large and Vaughan (1972) then the ages of pulsar and supernova remnant agree.

At present no polarization or proper motion information is available for PSR 0153+61.

4. Discussion

The present study has led us to suggest associations with observed supernova remnants for 3 out of the 5 pulsars listed in Table 1. For the two remaining pulsars no catalogued remnants which could be considered possible associations were found.

In the case of the two pulsars, PSR 0153+61 and PSR 1927+18, the suggested associations are based, as indicated in the last section, on position and distance data alone. Neither polarization nor proper motion information is available for either of these pulsars, and a spin down age estimate exists for only one of them. It is hoped that measurements of all these observables will be available in the future, it will then be possible on this basis to reassess the validity of these associations.

The association suggested for PSR 0525+21 leads to an order of magnitude discrepancy between the ages of the pulsar and the supernova remnant, unless special conditions are invoked (Section 2a). Faced with this discrepancy, one possible conclusion is that this is a chance association and has no physical basis. With errors of ± 10 degrees in ϕ_I the probability of a chance alignment is about 1/4. While recognizing this possibility, we would like to discuss another explanation which is based on the postulate that some pulsars are formed in close binary systems.

The end results for the evolution of close binary systems are numerous, depending on the initial masses etc. of the stars, but at least in some cases neutron stars are produced (e.g. the binary pulsar and the pulsating X ray stars). (Van den Heuvel, 1975.)

In all there could be two events leading perhaps to the formation of two pulsars. Whether both pulsars are visible will depend upon their age difference and the relative inclination of their individual magnetic axes to their spin axes even though their spin axes will tend to be parallel. Whether the extended remnants of both explosions are visible will also depend on their ages. In general it is believed that pulsars are detectable over a longer lifetime (10^6–10^7 years) than supernova remnants (10^5–10^6 years). Hence if the interval between explosions is more than a few times 10^5 years, only the most recently formed remnant may be detectable at later times. On the contrary, both pulsars may remain visible for much longer. There are two cases to be considered depending on whether the first explosion disrupts the binary system or not.

If the first explosion leaves the system bound, then the pulsar initially formed remains in orbit until the second event occurs to form the second younger pulsar and a second younger remnant. If then the remnant of the first explosion is no longer visible, because of its greater age, we have a situation in which an old pulsar (and perhaps a younger pulsar also) is associated with a young supernova remnant. Furthermore, if the older pulsar is released from orbit by the second explosion, then its angular displacement from the site of this explosion and its proper motion would be consistent with the age of the remnant and not that of the pulsar.

Such a situation could then resolve the age discrepancy in the association of PSR 2021+51 and HB 21 discussed by Jones (1975b). It should perhaps be pointed out that the hypothesis that most pulsars are created in binary systems is not in conflict with the fact that only one out of approximately 150 pulsars known to-date is a binary. If the pulsar remains in orbit after creation, it would be observed only as an X-ray source due to the in-fall of matter from its nearby companion, except in those rare cases where the companion is also a compact object—as has been shown for the only known binary pulsar.

Alternatively, if the binary system was disrupted by the event forming the first pulsar, as suggested for PSR 0525+21 by Gott et al. (1970), then the pulsar may be already at a considerable distance from its companion when it, the companion, later explodes to form the visible remnant. In this case not only will the age of the second remnant be much less than the pulsar age, but using it one would be led to an unreasonably high value for the derived pulsar proper motion.

This second alternative could then account for the discordant ages and large calculated proper motion derived for the association of PSR 0525+21 with G 193.3−1.5.

A final possibility is that the association is "indirect" in the sense that the observed supernova remnant G 193.3−1.5 is merely a marker of the birthplace of PSR 0525+21. There is now evidence that at least four supernovae have occurred in open clusters (Krishna Kumar, 1977; Pauls, 1977). Thus it is possible that supernovae occur repeatedly in the same cluster as stars of various initial masses successively reach the end of their "evolution." The apparent association of a young supernova remnant with an older pulsar then follows naturally. However, we have examined the lists of Hogg (1959) and Becker (1971) and find that none of the catalogued open clusters coincides with G 193.3−1.5.

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