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Pulsar/Supernova Remnant Associations

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Abstract. We review proposed pulsar/supernova remnant associations, summarize recent highlights, including searches for young pulsars, searches for remnants, studies of previously proposed associations, and attempts at pulsar/remnant association syntheses. We argue that most proposed associations require additional investigation before they can be considered secure. Existing evidence from secure associations implies pulsars are born with large magnetic fields and short periods, but do not necessarily have particularly large radio luminosities. We argue that the evidence for large space velocities from associations is ambiguous.

1. Introduction

No review of pulsar/supernova remnant (PSR/SNR) associations should begin without praising Baade & Zwicky (1934), who, long before neutron stars were discovered, hypothesized they are born in supernova explosions of massive stars[1]. The Crab pulsar's discovery made the Baade & Zwicky hypothesis seem visionary; but after we scrape our amazed jaws off the floor, the task of putting such hypotheses to careful scientific scrutiny for general cases remains.

PSR/SNR associations can potentially prove the Baade & Zwicky hypothesis. Their study can also constrain the distribution of birth magnetic fields, spin periods, luminosities, beaming fractions, and space velocities of neutron stars, as well as ages. From the SNR point of view, associations help constrain remnant distances, ages, and elucidate unusual remnant morphology or evolution. This can be done by considering individual associations (§2.,§3.3.), or using population syntheses (§4.). The study of associations begins with the discovery of candidates; recent searches are summarized in §3.1. and §3.2.

In this review, the discussion is limited, somewhat arbitrarily, to SNR associations involving radio pulsars. Notable omissions are: SS433 and 1E2259+586, probably binary neutron stars in SNRs (Clark & Murdin 1978; Fahlman & Gregory 1981); probable pulsar-driven plerions and point sources in remnants which show no pulsations (e.g. Vasisht et al. 1996; Petre et al. 1996); and soft gamma repeaters (SGRs), which may be young neutron stars, as inferred by the presence of an SNR in the SGR error box (e.g. Kulkarni & Frail 1993). For an excellent and broader, albeit somewhat out-of-date, review see Helfand & Becker (1984).

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[1] With similar vision, Wheeler (1966) suggested, before the discovery of the first rotation-powered neutron star, that the Crab SNR is powered by a neutron star's rotational energy.

2. Review of Proposed Associations

Table 1 presents a list of 28 proposed PSR/SNR associations. Similar compilations can be found elsewhere (e.g. Caraveo 1993; Frail et al. 1994b; Allakhverdiev et al. 1996). In the Table, the remnant type T is "P" for a plerion, "S" for a shell, and "C" for a composite, in general according to Green's catalog[2]. The pulsar distances are obtained from the dispersion measure (Taylor & Cordes 1993), or from HI observations when available. The remnant distances are best estimates from the literature, in general from the $\Sigma - D$ relation or from apparent interactions with nearby objects. The pulsar ages are the characteristic ages (obtained assuming braking index $n = 3$ and initial spin period P_0 much less than the current spin period, P.) If $P_0 \simeq P$, the age is overestimated, while if $n < 3$, it is underestimated. Some age corroboration may be provided by the presence of timing noise and/or glitches. Remnant ages in the Table are the best available estimates from the literature, but in general are highly uncertain; they depend on the assumed phase of the shell expansion, the distance to the remnant, the energy of the explosion, and strongly on the typically unknown ambient ISM density. The parameter β is the angular pulsar displacement from the SNR centre (θ) in units of the SNR angular radius, and $v_t = d\theta/\tau$ is the implied pulsar transverse velocity, where we adopt the most conservative τ and d from columns 4 and 5 respectively. The column "G" is described below.

Proposed associations may be merely a result of coincidental projection of the pulsar and SNR on the sky. The probability of such an occurrence can be evaluated in a statistical way, by comparing the surface density of pulsars and SNRs in different parts of the Galaxy. Such considerations are not very useful in assessing any particular proposed association, but are crucial in PSR/SNR association syntheses, discussed in §4. To assess the evidence for each proposed association objectively, as well as to illustrate the reasoning used in the literature in evaluating associations, we consider the following questions:

- **Do independent distance estimates agree?** In most cases, meaningful comparisons of the pulsar and remnant distances can be made. For example independent distance estimates for PSR B1853+01 and W44 are in good agreement, while for PSR B1758−23 and W28, they disagree. In many cases, however, the strongest conclusion that can be made is that the distances do not disagree (e.g. PSR J1341−6220 and G308.8−0.1).

- **Do independent age estimates agree?** Remnant ages are difficult to estimate and so comparisons here are not usually constraining. Nevertheless, disagreements in estimated ages sometimes cast doubts on proposed associations (e.g. PSR B1509−58 and MSH 15–52; see §3.).

- **Is the implied transverse velocity reasonable?** Instead of asking if the pulsar appears to be inside the remnant, we ask if the pulsar's implied transverse velocity, assuming its birth at the remnant centre and the most conservative age estimate, is consistent with the Lyne & Lorimer (1994)

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[2] http://www.phy.cam.ac.uk/www/research/ra/SNRs/snrs.data.html

velocity distribution, derived from proper motion studies. Identifying the remnant centre, however, is often difficult and subjective.

- **Is there evidence for any interaction between the pulsar and SNR?** This question is often subjective, but associations have been proposed from morphological evidence only (Shull et al. 1989; Kundt & Chang 1992). Pulsars have relativistic particle winds that likely "rejuvenate" SNRs, making them brighter. However, a pulsar-driven nebula is not necessarily related to a previous supernova (§3.1.). Additional evidence for interaction can come from spatial radio spectral index variations in composite remnants (e.g. Frail et al. 1994a).
- **Does the proper motion vector of the pulsar point away from the remnant centre?** In general, young pulsar proper motions are best measured via interferometry, since timing parameters are usually contaminated by red noise and glitches. The direction of proper motion may also be inferred from the morphology of a pulsar wind nebula (e.g. Cordes et al. 1993). A proper motion measurement has the potential to disprove an association regardless of the answers to the other questions.

The above questions can be used to classify associations by how much evidence exists in their favor. Associations for which the answers to all questions are affirmative are secure, and are classified "group" 1; successively less secure associations, as determined by the number of affirmative answers to the above questions, are classified in increasing group number, with group 5 associations being unlikely. This classification scheme is meant as an objective, overall guide to the credibility of an association, but should not substitute for a detailed study in individual cases. The column "G" in Table 1 shows the classification for each proposed association. Note that associations in group 3 or 4 most often suffer from a lack of relevant observations, rather than evidence against the association. They should simply be considered uncertain.

Several conclusions can be drawn from Table 1. First, of the 28 proposed associations, only 7 are compelling, with only 3 certain, in contrast to other authors who have suggested that as many as 17 associations are probable. Indeed it is remarkable that of the 22 pulsars having characteristic ages under 100 kyr, 18 are included in the Table. (The exceptions are PSRs J0631+10, B1046−58, B1727−47, B1737−30, and B1916+14). However this may also simply be the effect of young pulsars being given preferential attention; we discuss this disagreement further in §4. Associations proposed since 1994 are indicated in the Table with an asterisk; three that have yet to be published have not been classified and are at the bottom. No association that has been proposed since 1994 falls in either our group 1 or 2. If we consider only the most secure associations (groups 1 and 2), we find that all have magnetic fields at the high end of the distribution and periods at the low end (Taylor et al. 1993) and so there is clear evidence from PSR/SNR associations that pulsars are born with large magnetic fields and short periods. By contrast, several of those in the same sample have radio luminosities at the low end of the distribution (e.g. PSR B1951+32), so there is less evidence that pulsars are born with preferentially large radio luminosities (see also Kaspi et al. 1996b). With the same sample (omitting PSR B0540−69 for which v_t is poorly constrained), $\bar{v_t}$ = 500 km/s. However, none of the proposed associations involving $v_t > 260$ km/s has been verified independently by a proper motion measurement. Indeed, if only PSR B1757−24, the "Swan" pulsar, is excluded from the estimate, we find $\bar{v}_t = 280$ km/s, less than previous estimates, and less than the Lyne & Lorimer (1994) mean pulsar transverse velocity. Thus, PSR/SNR associations do not unambiguously provide evidence for large pulsar velocities.

Table 1. Table 1: Proposed PSR/SNR associations, arranged by group, and by pulsar τ within each group. Those not yet in press are at the bottom and remain unclassified. Asterisks indicate associations proposed since 1994. Columns τ and d show values for pulsar/SNR.

PSR	SNR	T	τ (kyr)	d (kpc)	β	v_t (km/s)	G	Refs
B0531+21	Crab	P	1.3/0.9	2/2	$\sim$0	125	1	1
B0540−69	SNR0540−693	P	1.7/0.6	-/50	$\sim$0	$\sim$0	1	2
B0833−45	Vela	C	11/18	0.6/0.5	0.3	120	1	t
J1341−6220	G308.8−0.1	C	12/32	8.7/7	0.35	600	2	3,4
B1757−24	G5.4−1.2	C	16/14	4.6/5	1.2	1600	2	5,6
B1853+01	W44	S	20/$\sim$10	3/3.1	0.6	250	2	7
B1951+32	CTB 80	C	107/96	2.4/3	$\sim$0	300	2	8
B1509−58	MSH 15–52	C?	1.7/10	5.7/4.2	0.2	3000	3	t
B1800−21	G8.7−0.1	S	16/15-28	4/3.2-4.3	$\sim$0	$\sim$0	3	t
B1643−43*	G341.2+0.9	S	33/-	6.9/8.3-9.7	0.7	500	3	t
B2334+61	G114.3+0.3	C	41/10-100	2.4/1.8	0.1	<50	3	9
B1758−23	W28	C	58/35-150	13.5/2	1.0	200	3	10,11
B1610−50*	Kes 32	S	7.5/5	7/3-7	1.5	1600	4	12,13
B1706−44	G343.1−2.3	S	17.5/-	2.4-3.2/3	1.0	800	4	t
B1727−33*	G354.1+0.1	?	26/-	4.2/-	$\sim$0	460	4	t
B1830−08*	W41	S	148/<50	4-5/4.8	1.6	200	4	14,15
B1855+02	G35.6−0.5	?	160/-	9/4 or 12	0.4	100	4	16
J1627−4845*	G335.2+0.1	S	2700/-	6.8/6.5	0.4	70	4	17
B1930+22	G57.3+1.2	?	40/-	9.6/4.5	0.5	750	5	18
B0611+22	IC 443	S	89/65	4.7/1.5	1.7	110	5	19
B0656+14	Monogem	S?	110/60-90	0.8/0.3	0.5	200	5	20
B1832−06	G24.7+0.6	C	120/12	6.3/4.4	1.6	360	5	15
J2043+2740*	Cygnus Loop	S	1200/20	1.1/0.6	2.5	1500	5	21
B1154−62	G296.8−0.3	S	1600/25	10/4	1.4	550	5	22
B0458+46	G160.9+2.6	S	1800/30-100	1.8/1-4	0.3	<300	5	23,24
J1105−6107*	G290.1−0.8	S	63/-	7/>4	2.9	650	-	25
J0538+2817*	S147	S	600/100	1.6/1–1.6	0.4	30	-	26

Refs: [t] see text §2. [1] Staelin & Reifenstein (1968) [2] Seward et al. (1984) [3] Kaspi et al. (1992), [4] Caswell et al. (1992) [5] Frail & Kulkarni (1991) [6] Manchester et al. (1991) [7] Wolszczan et al. (1991) [8] Kulkarni et al. (1988) [9] Kulkarni et al. (1993) [10] Kaspi et al. (1993) [11] Frail et al. (1993) [12] Caraveo (1993) [13] Johnston et al. (1995) [14] Clifton & Lyne (1986) [15] Gaensler & Johnston (1995a) [16] Phillips & Onello (1992) [17] Kaspi et al. (1996a) [18] Routledge & Vaneldik (1988) [19] Davies et al. (1972) [20] Thompson & Cordova (1994) [21] Ray et al. (1996) [22] Large & Vaughan (1972) [23] Damashek et al. (1978) [24] Leahy & Roger (1991) [25] Kaspi et al. (1996b) [26] Anderson et al. (1996)

3. Recent Highlights

We now consider highlights of recent work on particular PSR/SNR associations.

3.1. Searches for SNRs near Young Pulsars

One technique for finding new PSR/SNR associations is to search for extended non-thermal radio emission near young pulsars. Recently, Frail et al. (1994b) made deep 20 and 90 cm VLA images of the fields near three young pulsars, PSRs B1643−43, B1727−33, and B1706−44. All three were found to have nearby extended non-thermal emission. Images of the field around PSR B1643−43 reveal an arc of emission consistent with a partial shell morphology. The coincidence of the partial shell with the pulsar position suggests an interaction, and is consistent with the pulsar's motion away from the best-guess remnant centre. Images of the field near PSR B1727−33 reveal emission near the pulsar that extends mainly northward. Its interpretation in terms of an SNR is problematic, as unlike that for PSR B1643−43, the morphology of the "partial shell" is inconsistent with the inferred motion of the pulsar. The emission may be pulsar-powered, but is not necessarily the remnant of a supernova explosion (see §4.). Extended emission near PSR B1706−44 was first detected by McAdam et al. (1993); Frail et al. (1994b) confirm the detection. They discuss some problems with an association, namely the absence of any interaction despite this pulsar's particularly large spin-down luminosity.

3.2. Searches for Young Pulsars near SNRs

Historically many young pulsars that were later plausibly associated with SNRs have been discovered in untargeted searches (e.g. Damashek et al. 1978; Clifton & Lyne 1986; Johnston et al. 1992). The success of a search targeting SNRs by Manchester et al. (1985) made similar, more sensitive searches attractive. Recent searches for pulsars in the direction of SNRs have met only limited success. Gorham et al. (1996) searched for radio pulsations from 18 SNRs using the Arecibo telescope, but found no new pulsars. Biggs & Lyne (1996) searched 29 SNRs at Jodrell Bank, but found no new pulsars. Kaspi et al. (1996a) searched 40 Galactic remnants, and found two new pulsars, one of which is almost certainly not associated with its target remnant. The other, PSR J1627−4850, is at a position well within the remnant boundaries, and distance estimates to the two agree, but the pulsar characteristic age is well over the expected lifetime of SNRs. The association is plausible only if $P_0 \simeq P$ or $n > 3$. Kaspi et al. conclude that the primary limiting factor against finding pulsars in SNRs is luminosity, suggesting deeper searches of remnants are warranted.

3.3. New Results on Previously Proposed Associations

Vela: Addressing previous concerns (Bignami & Caraveo 1988) regarding the association of the Vela pulsar with the Vela SNR, Aschenbach et al. (1995), obtained a ROSAT image of the region. They project the apparent trajectories of six extended features outside the remnant backward, and, with the known pulsar proper motion, find a consistent origin for all objects, the location of the supernova. They estimate the explosion occurred ~18 kyr ago, though larger ages are also consistent. Independently, from timing, Lyne et al. (1996)

conclude that the age of the pulsar may be greater than its characteristic age of 11 kyr, because of evidence for a surprisingly small braking index, $n = 1.3$. They note that if such small braking indexes are standard for Vela-like pulsars, their transverse velocities implied by β in possible SNR associations are overestimated.

PSR B1509−58: Although PSR B1509−58 and its surroundings have recently been studied in detail, in contrast to Vela, this association is not yet clear. The region is complex, and the large radio SNR, MSH 15–52, appears to be much older than the pulsar (Seward et al. 1983); evidence suggests MSH 15–52 is not associated with the pulsar, and that the system comprises more than one SNR. A proper motion limit for the pulsar (Kaspi et al. 1994) makes an association with the large radio SNR MSH 15–52 difficult; additional evidence against it is presented by Strom (1994) and Du Plessis et al. (1995). Yet, the pulsar is almost certainly associated with some component of this complex system. Thorsett (1992) proposed that the "guest star" of 185 A.D. was the historical supernova that produced PSR B1509−58, possibly clarifying the situation by establishing a firm age for the pulsar, however a recent rereading of the records suggests the guest star was a comet (Chin & Huang 1994).

PSR B1800−21: Kassim & Weiler (1990) proposed an association between the 134-ms pulsar PSR B1800−21 and SNR G8.7−0.1, which was problematic since an association implied an extremely large v_t. Frail et al. (1994a) made new VLA images of the area that suggested the association is not real, since no remarkable emission was found near the pulsar. However, Finley & Ögelman (1994) observed the region using ROSAT and concluded an association is plausible if the supernova occurred near the present pulsar position (thus precluding a large v_t) and expanded into a nearby molecular cloud.

4. Syntheses of PSR/SNR Associations

Here we discuss recent attempts at synthesizing data on PSR/SNR associations.

- Frail et al. (1994b), after finding extended emission near three young pulsars (see §3.1.) and compiling a list of proposed PSR/SNR associations, conclude that of all young pulsars, "the majority are associated with supernova remnants." Their main argument is that a much larger fraction of young pulsars has nearby extended emission compared with the general pulsar population. They cautiously suggest that the number of associations is as high as 17, a conclusion also arrived at by Caraveo (1993). They find that $\bar{v}_t \simeq 500$ km/s for young pulsars on the basis of the associations, and discuss the implications.

- By contrast, Gaensler & Johnston (1995a,b,c), using a creative Monte Carlo simulation, argue that most proposed associations are actually false. In their analysis, they seed the Galaxy with 35,000 supernovae, allowing every explosion to produce both a pulsar and a shell expanding independently into a warm or hot ISM. They then simulate untargeted 1 GHz radio surveys in order to "discover" SNRs, as well as targeted and untargeted radio pulsar searches. To model the pulsar population, they assume the Lyne

& Lorimer (1994) birth velocity distribution, the Lorimer et al. (1993) pulsar luminosity function, the Biggs (1990) beaming law, and the Taylor & Cordes (1993) DM-distance-scattering model. They compare their simulation's "observed" PSR/SNR associations with those in the literature, and arrive at interesting conclusions: only $\sim$2% of pulsars with $\tau < 25$ kyr should have $\beta > 1$, although $\sim$30% of pulsars with $100 < \tau < 200$ kyr can have $\beta > 1$, in contrast to the percentages of the proposed PSR/SNR associations (Table 1). From their results, they conclude that, statistically speaking, only $\sim$7 of those in Table 1 are real.

The assessment of most PSR/SNR associations in this review is less optimistic than that expressed by Frail et al. (1994b). We see several reasons for this. In some instances (e.g. PSR B1727−33), although they find extended nonthermal emission near young pulsars, its identification as a remnant is unclear, and its interpretation is necessarily subjective. Of interest might be a study of the chances of finding extended emission in *any* direction, given a deep VLA image. Also, young pulsars have had less time to migrate from the Galactic plane, and so are more likely to be found near a remnant, associated or not. In addition, if, as suggested by Shull et al. (1989), pulsars can "rejuvenate" remnant shells, SNRs containing fast pulsars may be easier to detect, estimates of large $\bar{v}_t$ may be artificially inflated, and some SNRs might not be observable without pulsar rejuvenation (c.f. Braun et al. 1989). Even with these considerations, Gaensler & Johnston's conclusions stand in striking opposition. This could be because several phenomena that may have important impacts on the discovery of new PSR/SNR associations were not modeled in their simulation. As discussed above, pulsars may "rejuvenate" shells, so the assumption that the pulsar and shell evolve independently may be incorrect. Second, Gaensler & Johnston simulated only untargeted searches for remnants, rather than the sorts of searches done by Frail et al. (1994b), which may reveal low surface brightness remnants. Third, PSR/SNR X-ray studies were not considered even though two well-studied associations are direct results of X-ray discoveries (PSRs B1509−58 and B0540−69). Finally, in simulating searches for pulsars, Gaensler & Johnston made necessary, but uncertain, assumptions about the pulsar population and the evolution of SNRs; their results are particularly sensitive to the filling factor of the different ISM phases, which governs shell evolution.

5. Conclusions

The study of PSR/SNR associations holds the key to fundamental issues in neutron star astrophysics. Much progress has been made in recent years owing to tenacity and hard work, yet most proposed associations require further investigation before they can be considered certain. Nevertheless, the present evidence argues strongly that young pulsars have larger magnetic fields, shorter spin periods, but not obviously larger radio luminosities than the typical pulsar. Also, the evidence from PSR/SNR associations for high pulsar velocities is ambiguous; proper motion measurements for young pulsars are crucial for deciding this issue, and indeed for determining whether many of the associations listed in Table 1 are genuine. Synthesis analyses accounting for previously unmodeled factors, like those discussed at the end of §4., should also prove valuable.

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