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Neutron Star/Supernova Remnant Associations

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Abstract. The evidence for associations between neutron stars and supernova remnants is reviewed. After summarizing the situation for young radio pulsars, I consider the evidence from associations that young neutron stars can have properties very different from those of radio pulsars. This, though still controversial, shakes our simple perception of the Crab pulsar as prototypical of the young neutron star population.

The prediction by Baade & Zwicky (1934) that neutron stars are formed in supernova explosions remains one of astronomy's boldest assertions and greatest triumphs. Indeed the discovery in 1968 of the young radio pulsars in the Vela and Crab supernova remnants both established the neutron-star nature of radio pulsars, and confirmed the neutron star/supernova remnant connection. One may well ask why, over 30 years later, there is still a need to review the subject.

Young neutron stars are interesting for many reasons: they provide one of the few means of studying the equation of state of nuclear-density matter, they allow probes of neutron star internal structure from the study of glitches, they facilitate the study of the magnetospheric emission mechanism via X-ray and γ-ray observations, and have large enough spin-down energies that magnetospheric marvels such as toroidal relativistic winds and jets can be observed. On the other hand, the study of supernova remnants (SNRs) illuminates the composition and structure of the progenitors, the physics of core collapse and of strong shocks, the sites of cosmic ray acceleration, and the evolution of the interstellar medium. By associating neutron stars with SNRs, we obtain information about each class that is unavailable from either separately. Associations provide means of obtaining independent age and distance estimates, which can more accurately constrain the birth properties of neutron stars, namely, their period, magnetic field, luminosity and velocity distributions, as well as help interpret remnant spectra, morphologies, and evolutionary states.

1. Radio Pulsar/Supernova Remnant Associations

There are complicated selection effects against finding radio pulsars and SNRs; both populations are significantly incomplete, and not in an easily quantifiable way. However, since the working hypothesis is that *all* pulsars are born in supernovae, it is fair to consider just the youngest pulsars and ask whether they are associated with SNRs.

Table 1 contains all published radio pulsars having characteristic ages ($\tau_c \equiv P/2\dot{P}$) under 25 kyr. This age cutoff is arbitrary, but the inclusion of only the

Table 1. Known Rotation-Powered Pulsars having $\tau < 25$ kyr.

Name	τ_c kyr	P s	d kpc	B 10^{12} G	found in	SNR
B0531+21	1.3	0.033	2.5	3.8	radio	Crab
B1509−58	1.6	0.151	4.4	15	X-ray	MSH 15−52
J1119−6127	1.6	0.408	8.0	41	radio**	?
B0540−69	1.7	0.050	50	5.0	X-ray	N158A
J0537−6910	5.0	0.016	50	0.92	X-ray**	N157B
B1610−50	7.4	0.232	7.2	11	radio*	-
J1617−5055	8.0	0.069	6.5	3.1	X-ray**	-
B0833−45	11.4	0.089	0.5	3.4	radio	Vela
B1338−62	12.1	0.193	8.7	7.1	radio	G308.8−0.1
B1757−24	15.5	0.124	4.6	4.0	radio	G5.4−1.2
B1800−21	15.8	0.134	3.9	4.3	radio*	G8.7−0.1
B1706−44	17.4	0.102	1.8	3.1	radio*	?
B1853+01	20.3	0.267	2.8	7.6	radio*	W44
B1046−58	20.4	0.124	3.0	3.5	radio*	-
B1737−30	20.7	0.607	3.3	17	radio*	-
B1823−13	21.4	0.101	4.1	2.8	radio*	?
J1811−1926	24.4	0.065	5.0	1.7	X-ray**	G11.2−0.3

youngest pulsars is deliberate: associations involving older pulsars are harder to evaluate. First, evidence suggests that SNRs can fade on time scales of ~20-25 kyr, much shorter than pulsar lifetimes. Second, a young pulsar moves a distance $d \simeq 12(v/450\ \mathrm{km/s})(\tau/25\ \mathrm{kyr})$ pc from its birth place (where τ is its true age). This distance can be far enough to reach or escape the parent remnant shell, depending on the birth velocity distribution, which has been estimated independently (e.g. Lyne & Lorimer 1994). The current version of Green's SNR catalog[1] contains 220 SNRs, 156 of which lie in the range $260° < l < 50°$ and $|b| < 3.5°$. The area these remnants cover is ~32 square degrees, or some 3% of that region of the Galactic Plane. In the same area, the published pulsar catalog[2] reports 280 radio pulsars. Assuming these are distributed randomly in that area, one expects ~8.5 chance coincidences. By contrast, if one restricts oneself to pulsars having $\tau_c < 25$ kyr, one expects only ~0.4 chance coincidences. Thus, very few or none of the entries in Table 1 should be mere chance superpositions.

In Table 1, the columns are τ_c, period P, distance d, inferred surface magnetic field B, the discovery band (items with asterisks were discovered in the past 15 yr, double asterisks in the past 5 yr), and associated SNR. Some caveats are necessary: τ_c is only an estimate of the true age τ; τ_c is calculated assuming a birth spin period $P_0/P << 1$ and braking index $n = 3$ and is an overestimate of τ if $P_0 \simeq P$; the reverse is true for $n < 3$. Similarly, B is estimated assuming a dipole braking model, incorrect for objects with $n < 3$, and is dependent on the stellar radius and mass.

[1] http://www.mrao.cam.ac.uk/surveys/snrs/

[2] http://pulsar.princeton.edu/pulsar/catalog.shtml

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Note that of the 4 associations discovered in the past 5 yr, 3 were found at X-ray energies. This is in stark contrast to the situation in the previous 25 yr, in which only 2 of the 13 discovered young pulsars were found at X-ray energies, the rest being found at radio wavelengths. This is due to major advances in X-ray telescopes. Also, of the 8 pulsars found at radio wavelengths in the past 15 yr, only one was found by looking for pulsations in a SNR. This is not for lack of trying. Indeed the three major radio pulsar search efforts targeting SNRs (Kaspi et al. 1996, Gorham et al. 1996, Lorimer et al. 1998) collectively searched 91 targets and found precisely zero young pulsars. By contrast, untargeted surveys of the Galactic plane for radio pulsars (Johnston et al. 1992, Clifton & Lyne 1986, Lyne et al. 2000) collectively discovered 6 radio pulsars having $\tau_c < 25$ kyr. This suggests that the best way to find young radio pulsars is to look everywhere in the Galactic Plane *but* in SNRs! One explanation for this quandary is that bright SNRs reduce radio pulsar survey sensitivity; for example, the mean radio flux of the SNRs in Green's catalog (omitting the bright Cas A) roughly doubles the system temperature of the Parkes Multibeam survey. The quandary also underscores how incomplete the SNR catalog is. Indeed, PSRs B1610−50 and J1617−5055 ($\tau_c = 7$ and 8 kyr, respectively) appear very young but do not have any observable associated SNR (Pivovaroff et al. 2000, Kaspi et al. 1998). The absence of visible SNRs around these pulsars suggests that remnant fading time can be much shorter than has been suggested (e.g. Braun et al. 1989).

2. Evidence for New Classes of Neutron Stars

There is now significant evidence that young neutron stars do not all manifest themselves as radio pulsars. There has been only a modest hint that this is true from population statistics. The supernova rate in the Galaxy has been estimated to be $0.025^{+0.008}_{-0.005}$ yr^{-1} (Tammann et al. 1994). Of these, some 85-90% are likely to be of Type Ib and II (i.e. producing compact stellar remnants). The black hole formation rate is thought to be small, at most a few percent (Fryer 1999). The pulsar birth rate for radio luminosities greater than 1 mJy kpc^2 is 0.010 ± 0.007 yr^{-1} (Lyne et al. 1998). Given that there must be some low luminosity pulsars, the agreement in the pulsar birth rates and the neutron-star-producing supernova rate is reasonable, though a pulsar dearth is possible. There has been, however, a long-recognized puzzle that most SNRs do not contain visible pulsars. There are significant selection effects against finding radio pulsars in SNRs, but this is less true of finding Crab-like plerions at the centers of shell SNRs, as those radiate isotropically. Yet roughly 85% of Green's catalogued SNRs have pure shell morphologies. In fact, independent evidence is mounting that a significant fraction of young neutron stars have properties very different from Crab-like radio pulsars; just how large that fraction has yet to be determined, as is the cause of the diversity. To summarize, there are three classes of unusual high-energy sources have been compellingly argued to be young, isolated neutron stars:

Anomalous X-Ray Pulsars (AXPs): The properties of AXPs can be summarized as follows (see Mereghetti & Stella 1995, Gotthelf & Vasisht 1998): they exhibit X-ray pulsations in the range ~5–12 s; they have pulsed X-ray luminosities in the range $\sim 10^{34}$-10^{35} erg/s; they spin down regularly within the limited

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timing observations available (e.g. Kaspi et al. 1999); their X-ray luminosities are much greater than their $\dot{E}$'s; their X-ray spectra are characterized by thermal emission with $kT \sim 0.4$ keV, with evidence for a hard component; and they are in the Galactic Plane. Currently there are 5 confirmed AXPs and one strong AXP candidate (see Table 2). Of these 6 sources, 3 lie at the apparent centers of SNRs: 1E 2259+586 in CTB 109 (Fahlman & Gregory 1981), 1E 1841−045 in Kes 73 (Vasisht & Gotthelf 1997), and AX J1845−0258 in G29.6+0.1 (Gotthelf & Vasisht 1998, Torii et al. 1998, Gaensler et al. 1999). The association of these objects with SNRs is arguably the most compelling reason to believe they are isolated neutron stars. The leading models explaining their large X-ray luminosity invoke the large stellar magnetic field as inferred from the spin down (hence the name "magnetars"), either using field decay (Thompson & Duncan 1996) enhanced thermal emission (Heyl & Hernquist 1997).

Soft Gamma Repeaters (SGRs): SGRs, of which 4 are known (see Table 2), are sources that occasionally and suddenly emit bursts of soft γ-rays having super-Eddington luminosities. That 3 of them lie in the Galactic Plane, and the 4th is in the LMC, argues that they are a young population. The detection of AXP-like X-ray pulsations from 2 of these sources (e.g. Kouveliotou et al. 1998), with evidence for pulses from the other two, also argues strongly that they are isolated neutron stars. Their burst properties and observed spin-down are well explained in the magnetar model (Thompson & Duncan 1995, but see Marsden et al. 1999). The association between SGR 0526−66 and the SNR N49 in the LMC (Cline et al. 1982) first suggested the SGRs might be young neutron stars, however since then the SGR/SNR association picture has grown a bit murky. First, SGR 0526−66 is located near the edge of the N49 shell; this is problematic as it requires a very high transverse velocity ($v_t > 1000$ km/s) for the SGR (Rothchild et al. 1994). SGR 1806−20 has been suggested to be associated with the plerionic radio nebula G10.0−0.3 (Kulkarni & Frail 1993), although a recent relocalization of the γ-ray source calls the association into question (Hurley et al. 1999). SGR 1900+14 has been associated with SNR G42.8+0.6 (Vasisht et al. 1994), however the γ-ray source lies well outside the shell, demanding a distressing $v_t > 3000$ km/s. Smith et al. (1999) suggest that the newly discovered SGR 1627−41 may be associated with the shell SNR G337.0−0.1; the large SGR positional uncertainty precludes a firm conclusion.

"Quiescent" Neutron Stars: There are currently 4 cases of X-ray point sources in SNRs that may be "quiescent" neutron stars having low $\dot{E}$ – they exhibit neither magnetopsheric emission nor obvious Crab-like plerions. These are: 1E 1207.4−5209 in PKS 1209−52 (G296.5+10.0, Helfand & Becker 1984, Vasisht et al. 1997), 1E 161348−5055 in RCW 103 (Tuohy & Garmire 1980), 1E 0820−4250 in Puppis A (Petre et al. 1996) although claimed 75 ms X-ray pulsations, if confirmed, imply that it is an ordinary rotation-powered pulsar (Pavlov et al. 1999), and the newly discovered point source in Cas A (Tananbaum 1999). That these sources are only seen in X-rays suggests they could be thermally cooling neutron stars, still hot following their formation. Problematic in the neutron star interpretation for 1E 161348−5055 is that its X-ray luminosity is apparently variable (Gotthelf et al. 1999). In Cas A, a preliminary look shows that the point source spectrum may be harder than expected for a cooling neutron star (M. Pivovaroff, pers. comm.). Deep searches for pulsations (enough

Table 2. Proposed Magnetars and Their Properties.

Type	Name	P	$\dot{P}$	τ_c	B	SNR
		s	$\times 10^{-11}$	kyr	10^{14} G	
AXP	4U 0142+615	8.69	0. 23	60	2.9	-
AXP	1E 1048−5937	6.45	2.2	4.6	3.8	-
AXP	RXJ 170849−400910	11.0	1.9	9.2	4.6	-
AXP	1E 1841−045	11.8	4.1	4.0	7.5	Kes 73
AXP	AX J1845−0258	6.97				G29.6+0.1
AXP	1E 2259+586	6.98	0.048	210	0.59	CTB 109
SGR	0526−66	8				N49
SGR	1627−41	6.41?				G337.0−0.1?
SGR	1806−20	7.47	8.3	1.4	8	G10.0−0.3?
SGR	1900+14	5.16	12	0.68	8	G42.8+0.6?

to see few percent modulation, as in the known thermally cooling neutron stars like Vela) and/or high-resolution X-ray spectroscopy to detect predicted absorption lines in the stellar atmospheres are the most promising ways of determining the nature of these objects.

In conclusion, although radio pulsars first confirmed the neutron star/supernova remnant connection, it now appears clear that they represent only a part of young neutron star phase space. The origin and full extent of the diversity are not yet clear, however the problem appears tractable, particularly given the Parkes Multibeam survey and new and upcoming X-ray missions, including *Chandra*, *XMM*, and *ASTRO-E*.

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