NEUTRON STAR/SUPERNOVA REMNANT ASSOCIATIONS

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Abstract

We summarize the current observational evidence for associations between supernova remnants and neutron stars, including radio pulsars, proposed “inactive” young neutron stars, “anomalous” X-ray pulsars, and soft gamma-ray repeaters, and argue that the paradigm that all young neutron stars are Crab-like requires reconsideration.

1. Introduction

When Baade & Zwicky proposed in 1934 that collapsed stars composed of neutrons could be formed in supernova explosions, they had little notion of how such creatures would manifest themselves observationally. The surprise discovery of pulsars, and in particular, of the Crab and Vela pulsars in their respective supernova remnants, heralded the first visual image of the isolated neutron star: that of a compact, highly magnetized (surface field $\sim 10^{12}$ G) star, spinning down slowly due to magnetic braking, emitting a collimated beacon, and exciting its surroundings via the injection of ultra-relativistic particles. However, even the simplest follow-up questions, such as whether all neutron stars form in supernovae, what fraction of supernovae produce neutron stars, and in particular, whether all young pulsars are born with properties like those of the Crab and Vela pulsars remain to this day naggingly unanswered.

Here I summarize observations of neutron stars plausibly associated with supernova remnants. The last similar review was published by Helfand & Becker (1984). Their interesting synthesis of the observational data is beyond the scope of this paper. More recent reviews including only radio pulsar/supernova remnant associations can be found elsewhere (Kaspi 1996; Kaspi 1998).
2. Rotation-Powered Neutron Star/Supernova Remnant Associations

Associations between remnants and neutron stars have traditionally been identified with detections of radio pulsars. The Helfand & Becker (1984) review included only three such objects: the Crab, Vela, and PSR B1509–58. Since then, the number of associations has blossomed to between 7 and 23, depending on the one’s criteria for certainty. The great increase is for several reasons. Many young pulsars were found in radio pulsar surveys of the Galactic plane at observing frequencies near 1400 MHz (Clifton & Lyne 1986; Johnston et al. 1992), where dispersion-measure and scatter-broadening of radio pulses are reduced relative to traditional pulsar survey frequencies, like 430 MHz. Also some, but not all, radio pulsar searches specifically targeting remnants have been successful (Manchester, D’Amico & Tuohy 1985; Kaspi et al. 1996; Gorham et al. 1996; Lorimer, Lyne & Camilo 1998). Finally major advances in the capabilities of X-ray observatories have led to several recent exciting discoveries, discussed further below (§2.1).

Proposed associations may be merely a result of coincidental projection of the pulsar and remnant on the sky; the probability for chance alignment is generally significant, particularly for the inner Galactic plane. The burden of proof therefore rests on the observer. Evidence comes from consideration of whether independent distance and age estimates agree, whether there is an interaction between the pulsar and remnant, whether the transverse velocity implied by the angular displacement of the pulsar from the approximate remnant geometrical center, its (perhaps naively) assumed birthplace, is consistent with the known pulsar velocity distribution, and, even better, if the measured pulsar velocity’s magnitude and direction is as predicted. For most proposed associations, few of these questions have clear answers (see Kaspi 1998 for more detail).

Table 1 summarizes proposed rotation-powered pulsar/supernova remnant associations. In the Table, PSR and SNR are the pulsar and remnant names, T is the remnant type (S is shell, P is plerion, C is composite), \( \tau \) and \( d \) are the best age and distance estimates for PSR/SNR, \( \beta \) is the angular displacement of the pulsar from the apparent remnant center in remnant radii, \( v_t \) is the best-guess transverse velocity assuming the pulsar characteristic age and the most reliable distance estimate, with \( v_t \) in bold actual measurements. \( E \) is a rough figure of merit, where \( E = 1 \) is secure, and \( E = 5 \) dubious. Note that often \( E \) is high for lack of supporting, rather than conclusively damaging, evidence.

Conclusions to be drawn from Table 1 were discussed by Kaspi (1998). The main points are that observable young pulsars have larger magnetic fields, shorter spin periods, but not always larger radio luminosities, than the typical pulsar. The evidence from associations for high pulsar velocities should as yet
be considered inconclusive; proper motion measurements for young pulsars are crucial for deciding whether many of the associations listed in Table 1 are genuine. The detection of bow-shock nebulae via high-resolution radio and X-ray observations may provide another way to test associations.

2.1. Recent X-ray Discoveries

**N157B**: Marshall et al. (1998) have just discovered a 16 ms X-ray pulsar in the Crab-like supernova remnant N157B in the Large Magellanic Cloud using the Rossi X-ray Timing Explorer. The surprisingly short period makes it the most rapidly rotating neutron star known that has not been spun up. The measured pulsar characteristic age is \( \sim 5 \) kyr old, making it the fourth youngest pulsar known, and suggesting that neutron stars can be born spinning significantly faster than previously thought, possibly as fast as a few milliseconds.

**RCW 103**: Torii et al. (1998) have discovered 69 ms X-ray pulsations from a source 7' north of the center of the well-studied, young shell supernova remnant RCW 103 using ASCA, finally confirming an earlier claim by Aoki, Dotani & Mitsuda (1992) who used GINGA. The spin-down rate implied by the difference in periods indicates that the pulsar is very young, having age \( \sim 8 \) kyr. The existence of so young a pulsar near RCW 103 suggests the two might be related, casting doubt on the famous central point source being the stellar remnant (see §3). An association requires a transverse velocity of \( \sim 800 \) km s\(^{-1}\) for a distance of 3.3 kpc, deduced from HI absorption. The radio-pulsar counterpart has recently been discovered at the Parkes observatory (Kaspi et al. in preparation). The dispersion measure suggests a distance to the pulsar of \( \sim 4.5–7 \) kpc. Thus the association can be considered only tentative, and the nature of the central object remains uncertain.

**PSR J1105−6107**: The 63 ms radio pulsar PSR J1105−6107 lies almost three remnant radii from the approximate center of the supernova remnant G290.1−0.8, also called MSH 11−61A (Kaspi et al. 1997). For an association, under standard assumptions, the pulsar transverse velocity must be \( \sim 650 \) km s\(^{-1}\). The recent detection of the pulsar at X-ray energies (Gotthelf & Kaspi 1998) is best explained as arising from a pulsar wind nebula confined by ram-pressure. High-resolution X-ray imaging can test the association if a bow-shock morphology is found.

**G11.2−0.3**: The supernova remnant G11.2−0.3 is the possible counterpart of the event recorded by the Chinese in AD 386 (Strom 1994). The recent detection of evidence for 65 ms X-ray pulsations (Torii et al. 1997) is exciting, as after the Crab, this is the only pulsar associated with an historic event. From the single ASCA observation, \( P < 8 \times 10^{-13} \). If the pulsar was born in AD 386, and
assuming a short birth spin period, the implied $\dot{P} = 6.4 \times 10^{-13}$, consistent with the upper limit. This implies a spin-down luminosity $\dot{E} < 9 \times 10^{37}$ erg s$^{-1}$, and surface magnetic field $B < 1 \times 10^{13}$ G, reasonable for a young pulsar. Confirmation measurement of $\dot{P}$ are top priorities for the future.

3. “Inactive” Neutron Star/Supernova Remnant Associations

Several unidentified X-ray point sources observed in supernova remnants have been hypothesized as being neutron stars emitting X-rays from their initial cooling after formation. To date, the sources that fall in this category are: 1E 1207.4−5209 in G296.5+10.0 (Mereghetti, Bignami & Caraveo 1996), 1E 1613−5055 in RCW 103 (Tuohy & Garmire 1980; but see also §2.1 and Torii et al. 1998), RX J0002+6246 in G117.7+0.6 (Hailey & Craig 1995), and a point source in Puppis A (Petre, Becker & Winkler 1996). The observational properties of these sources that support the neutron star identification are: they are X-ray point sources to within available spatial resolutions, they are coincident with supernova remnants, they have high X-ray to optical luminosity ratios, their spectra are roughly consistent with blackbody emission with temperatures and emitting surface areas roughly as expected for neutron stars, and their X-ray emission does not vary long-term. However they are clearly different from pulsars like the Crab because no X-ray pulsations are seen, no associated radio or $\gamma$-ray emission, pulsed or unpulsed, has been detected, and no evidence for extended pulsar-powered synchrotron nebulae is observed. These objects challenge the conventional paradigm that young neutron stars are born as pulsars, energetic and spinning fast, exciting synchrotron nebulae in their immediate surroundings. An unambiguous conclusion regarding the neutron-star nature of these objects could come from the detection of low-pulsed-fraction X-ray pulsations, expected for magnetized, thermally cooling sources, or through high-resolution spectral X-ray observations, which could reveal absorption features predicted in models of neutron star atmospheres (see Pavlov, this volume).

4. “Anomalous” X-ray Pulsar/Supernova Remnant Associations

The class of objects collectively known as “anomalous” X-ray pulsars is characterized by pulsations long in duration compared with those of the radio pulsar population (5-9 s), and slow but steady spin-down. The members of this class are 4U 0142+61, RX J0720.4−3125, 1E 1048.1−5937, 4U 1626−67, RX J1838.4−0301 and 1E 2259+586. Mereghetti & Stella (1995) summarize the properties of these systems and argue that they are binaries in which the neutron star accretes from so low-mass a companion that the orbital Doppler shift is not
detectable. No optical counterpart has been found for any of the sources except 4U 1626–67, which is certainly an X-ray binary (Middleditch et al. 1981).

It is intriguing that two of the sources, 1E 2259+586 (Fahlman & Gregory 1981) and RX J1838.4–0301 (Schwentker 1994) are associated with supernova remnants. These associations are unexplained in the binary model, although they would not represent the first known X-ray binaries associated with remnants. That honor goes to SS 433, a well-known unusual radio-emitting X-ray binary associated with the supernova remnant W50 (Margon 1984).

The anomalous X-ray pulsars in supernova remnants could be young, isolated, and rotation-powered. However their X-ray luminosities far exceed the implied spin-down luminosities. This demands the introduction of a physical mechanism for the production of X-rays not previously observed in neutron stars. Furthermore, the implied surface magnetic fields are enormous, \( \sim 10^{14} \) G. This has led to them being dubbed “magnetars,” and suggests that the origin of the observed X-rays could lie, for example, in the decay of the magnetic field by diffusive processes (e.g. Thompson & Duncan 1996).

Kes 73: The recent discovery of a 12 s X-ray pulsar in the young supernova remnant Kes 73 (Vasisht & Gotthelf 1997) adds renewed strength to the magnetar hypothesis. The strategic location of the pulsar near the center of the remnant makes a chance coincidence improbable. A weak archival ROSAT detection of the periodicity implies a spin-down rate and hence \( \dot{E} \) and \( B \) that are consistent with the magnetar model. Confirmation of the spin-down rate and long-term timing are important for establishing the nature of this source.

5. Soft Gamma-Ray Repeaters

The class of objects known as “soft gamma-ray repeaters” includes three sources: SGRs 0526–66, 1806–20, and 1900+14. They are characterized by recurrent episodes of soft-spectrum, short-duration \( \gamma \)-ray emission (see Kouveliotou 1996 for a review). Multi-wavelength studies suggest that they represent yet another facet of the young neutron star population, since two of the three (SGRs 0526–66 and 1806–20) are apparently associated with supernova remnants (Cline et al 1982; Kulkarni & Frail 1993). The absence of an obvious remnant host to SGR 1900+14 remains problematic (Vasisht et al. 1996). Thompson & Duncan (1996) discuss SGRs in the context of a magnetar model, suggesting that the SGR phenomenon may represent a phase of evolution in the life of a magnetar, with X-ray pulsations (§4) characterizing a different stage. SGRs are discussed by Kulkarni in more detail elsewhere in this volume.
6. Conclusions

The most striking conclusion following examination of the associations between neutron stars and supernova remnants is that the paradigm that every young neutron star is like the Crab pulsar requires reconsideration. Neutron stars, it seems, come in many flavors, perhaps some yet to be discovered. The continued analysis of valuable archival high-energy data, the upcoming launch of the Advanced X-ray Astrophysics Facility, as well as the ongoing Parkes multi-beam and Nançay Galactic plane survey should ensure significant progress, and even perhaps more surprises in this field in the near future.

7. References

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# Table 1. Proposed Rotation-Powered Pulsar/Supernova Remnant Associations.

| PSR    | SNR      | Type | $\tau$ (kyr) | $d$ (kpc) | $v_t$ (km/s) | $E$ | Refs |
|--------|----------|------|--------------|-----------|--------------|-----|------|
| B0531+21 | Crab     | P    | 1.3/0.9     | 2/2       | ~0           | 125 | 1, 1 |
| B0540−69 | SNR0540−693 | P    | 1.7/0.6     | 50/50     | ~0           | ~0  | 1, 2 |
| J0537−6910 | N157B    | C    | 5/4         | 50/50     | ~0.5         | ~600| 3, 18 |
| B0833−45 | Vela     | C    | 11/18       | 0.6/0.5   | 0.3          | 170 | 1, 32|
| B1509−58 | MSH 15−52 | C    | 1.7/10      | 5.7/4.2   | 0.2          | 3000| 2, 27|
| B1757−24 | G5.4−1.2 | C    | 16/14       | 4.6/5     | 1.2          | 1600| 2, 5, 6 |
| B1853+01 | W44      | C    | 20/~10      | 3/3.1     | 0.6          | 250 | 2, 7 |
| B1951+32 | CTB 80   | C    | 107/96      | 2.4/3     | ~0           | 300 | 2, 8 |
| J1341−6220 | G308.8−0.1 | C    | 12/32       | 8.7/7     | 0.35         | 600 | 3, 34 |
| B1800−21 | G8.7−0.1 | S    | 16/15−28    | 4/3.2−4.3 | ~0           | ~0  | 3, 33, 34 |
| B1823−13 | X-ray nebula | P    | 21/7       | 2.5/?     | ~0           | ~0  | 3, 28 |
| J0538+2817 | S147    | S    | 600/50−200  | 1.8/0.8−1.6 | 0.4       | 30  | 3, 26 |
| B1643−43 | G341.2+0.9 | C    | 33/-       | 6.9/8.9−9.7 | 0.7       | 475 | 3, 29 |
| 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 |
| J1811.5−1926 | G11.2−0.3 | C    | -/-       | -/5−>5   | <1           | ?   | 4, 35 |
| B1610−50 | Kes 32   | S    | 7.5/5      | 7/3−7    | 1.5          | 1600| 4, 12, 13 |
| J1617−5055 | RCW 103 | S    | 8/4        | 7/3.3    | 1.5          | 800 | 4, 36, 37 |
| B1727−33 | G354.1+0.1 | S    | 26/-       | 4.2/-    | ~0           | 460 | 4, 29 |
| J1105−6107 | G290.1−0.8 | S    | 63/-       | 7/7      | 2.9          | 650 | 4, 25 |
| B1830−08 | W41      | S    | 148/<50    | 4/5−4.8  | 1.6          | 200 | 4, 14, 15 |
| B1855+02 | G35.6−0.5 | S    | 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 |
| B1706−44 | G343.1−2.3 | C    | 17.5/-   | 2.4−3.2/3 | 1.0          | <50 | 4, 29, 30, 31 |
| B1930+22 | G57.3+1.2 | C    | 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          | 250 | 5, 20 |
| B1832−06 | G24.7+0.6 | S    | 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        | <150| 5, 23, 24 |

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