RADIO-QUIET X-RAY PULSARS IN SUPERNova
REMnANTS AND THE “MISSING” PULSAR PROBLEM

E. V. gotthelf
NASA/Goddard Space Flight Center, Code 662, Greenbelt, MD 20771

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The paradigm that young neutron stars (NSs) evolve as rapidly rotating Crab-like pulsars requires re-examination. Evidence is accumulating that, in fact, many young NS are slowly rotating ($P \sim 10$-s) X-ray pulsars, lacking in detectable radio emission. We present new results on three radio-quiet NS candidates associated with supernova remnants, which suggests that alternative evolutionary-paths exist for young pulsars. These include the 12-s pulsator in Kes 73, the 7-s pulsar near Kes 75, and the enigmatic X-ray source in RCW 103. We postulate that such objects account for the apparent paucity of radio pulsars in supernova remnants.

1. Where Are All The Young Neutron Stars?

Neutron stars are thought to be born as rapidly rotating ($\sim 10$ ms) radio pulsars created during a Type II/Ib supernova explosion involving a massive star. Their existence was postulated in 1934 by Baade & Zwicky (1934) based on theoretical arguments, but had to wait until the 1970s for observational support, provided by the remarkable discoveries of the Crab and Vela pulsars in their respective supernova remnants (SNRs).

The properties of these pulsars were found to be uniquely explained in the context of rapidly rotating, magnetized neutron stars emitting beamed non-thermal radiation. Their fast rotation rates and large magnetic fields ($\sim 10^{12}$ G) are consistent with those of a main-sequence star collapsed to NS dimension and density. A fast period essentially precluded all but a NS hypothesis and thus provided direct evidence for the reality of NSs (see Shapiro & Teukolsky 1983 for a brief history and intro to NS physics). Furthermore, their inferred age and association with SNRs provided strong evidence that NSs are indeed born in supernova explosions. These properties were considered typical of all young pulsars, but as we shall see, there is new evidence that suggests that this is unlikely to be the case.

Most supernovae (non Type Ia) are expected to produce a NS, whose unpulsed emission should be easily discernible in the radio-band during the lifetime of a typical SNR ($\gtrsim 10^4$ yrs) as a radio-loud “plerion” (Weiler & Sramek 1988). So it is quite remarkable that, despite detailed radio searches, few of the hundreds of known SNRs have yielded a NS candidate. Furthermore, comprehensive radio surveys suggest that most radio pulsars near SNRs can be attributed to chance overlap (e.g. Lorimer et al. 1998; Gaensler & Johnston 1995; see Kaspi et al. 1996 for a review). With the results of these new surveys, traditional arguments for the lack of observed radio pulsars associated with SNR, such as those invoking beaming and large “kick” velocities, are less compelling.
It is now clear that this discrepancy is an important and vexing problem in current astrophysics.

2. The Revolution Evolution: Slowly Rotating Young X-ray Pulsars

Progress in resolving this mystery is suggested by X-ray observations of young SNRs. These are revealing X-ray bright, but radio-quiet compact objects at their centers. It is now understood that these objects form a distinct class of radio-quiet neutron stars (Caraveo et al. 1996, Gotthelf, Petre, & Hwang 1997; Vasisht et al. 1997; and refs. therein), perhaps born or evolving in a fashion drastically different from that of the Crab.

Some of these sources have been found to be slowly rotating pulsars with unique properties. Their temporal signal is characterized by spin periods in the range of $5 \sim 12$ s, steady spin-down rates, and highly modulated sinusoidal pulse profiles ($\sim 30\%$). They have steep X-ray spectra (photon index $\gtrsim 3$) with X-ray luminosities of $\sim 10^{35}$ erg cm$^{-2}$ s$^{-1}$. As a class, these seemingly isolated pulsars are currently referred to as the anomalous X-ray pulsars (AXP; van Paradijs et al. 1995). Nearly half are located at the centers of SNRs, suggesting that they are relatively young ($\lesssim 10^5$ yr-old). And so far, no counterparts at other wavelengths have been identified for these X-ray bright objects. The prototype for this class, the 7-s pulsar 1E 2259+586 in the $\sim 10^4$ yr old SNR CTB 109, has been known for nearly two decades (Gregory & Fahlman 1980).

These are now about a dozen slow X-ray pulsars apparently associated with young SNRs (originally Gregory & Fahlman 1980; see also Table I, Gotthelf & Vasisht 1998 for a recent summary). These include the four known soft $\gamma$-ray repeaters (SGR), also likely to be associated with young SNRs (Cline et al. 1982; Kulkarni & Frail 1993; Vasisht et al. 1994), which have recently been confirmed as slow rotators (Kouveliotou et al. 1998). In fact, there are currently more known slow, radio-quiet X-ray pulsars in the center of identified SNR than confirmed Crab-like radio pulsars!

Here, we present new results on three intriguing radio-quiet, X-ray bright neutron star candidates which we are studying closely. These include the recently discovered 12-s X-ray pulsar in the SNR Kes 73, very likely to be an isolated “magnetar”, a pulsar with an enormous magnetic field ($B \sim 10^{14}$ G); the newly discovered (March 1998), bright 7-s pulsar near Kes 75, AX J1845-03, which displays similar properties; and a follow-up ASCA observation of RCW 103, which helps resolve some long-standing mysteries about this enigmatic object. The study of these and closely related objects are shedding new light on the evolution of young NSs.

2.1. The Remarkable X-ray Pulsar in Kes 73

The recent discovery of pulsed X-ray emission from the central compact source in SNR Kes 73 (Vasisht & Gotthelf 1997) was somewhat surprising, as this unresolved Einstein source, 1E 1841−045, has been studied for some time (Kriss et al. 1985; Helfand et al. 1994). The slow (12-s) period is most unusual for a young pulsar; if this is an “isolated” neutron star, then it is the one having the longest spin period ever observed.

This pulsar was initially detected during a 1993 ASCA X-ray observation of Kes
73 and confirmed with a weak archival ROSAT detection, which indicated a unusually rapid spin-down rate (Vasisht & Gotthelf 1997). We have recently obtained a new ASCA measurement of the pulsator which provides irrefutable confirmation of its remarkable spin-down.

Fig. 1 shows the periodogram for the two ASCA epochs (From Gotthelf & Vasisht 1998, in prep.). The pulsar is apparently spinning down rapidly at a rate of $4.1 \times 10^{-11}$ s/s, orders of magnitude faster than the Crab-like pulsars. This rate is consistent with that found using the ROSAT data and suggests a linear trend. Most importantly, the characteristic pulsar age is consistent with the age derived for the SNR ($\sim 2,000$ yrs). The flux has remained steady between the two ASCA observations, consistent with the ROSAT flux measurement. And the spectrum also remains unchanged, described by a steep power-law of photon index $\sim 3.4$, unlike a typical Crab-like or recycled pulsar.

These properties have important consequences for a young pulsar. The rotational energy of 1E 1841−045 is far too small to power its total X-ray emission of $L_X \sim 3 \times 10^{35} d^2_{7}$ erg/s. The maximum luminosity derivable just from spin-down is $L_X \lesssim 4\pi^2 I \dot{P}/P^3 \sim 10^{34}$ erg/s. On the other hand, the observed luminosity is appreciably low for an accretion powered binary system $\sim 10^{36-38}$ erg/s. However, the derived luminosity, steep spectrum, and lack of stochastic variability makes an accretion scenario all but unlikely. In §3 we discuss the several models to explain the nature of this and other AXPs.

![Fig. 1. The ASCA spin-down history of the Kes 73 pulsar. (Lower panel) The Oct 11 1993 GIS detection of the 12 sec pulsar in Kes 73. (Upper panel) The follow-up March 27 1998 GO observation. The period derivative, assuming a linear trend, is $4.1 \times 10^{-11}$ s/s.](image)

2.2. PSR J1845−0258: A 7 Second Anomalous Pulsar in the Distant Milky Way

A recent automated search through the ASCA archive (Gotthelf & Vasisht 1998; Torii 1998) has revealed another AXP-like slow pulsator. Like the 12 s pulsar in Kes73, this
7 s rotator has a sinusoidal pulse shape and is modulated with a 35% amplitude. The pulsar lies at the edge of the ASCA field containing the SNR Kes 75, but their separation makes an association most unlikely.

Fig. 2. Discovery of a 7 s X-ray pulsar near Kes 75. (Left) The GIS pulsed emission image (contours) overlayed on the phase integrated image (greyscale). Kes 75 is on the left and PSR J1845−0258 on the right. (Right) The folded GIS pulse profile of PSR J1845−0258. Two cycles are shown for clarity.

On the basis of its properties, PSR J1845−0258 is most likely the latest example of an anomalous X-ray pulsar. The period is nearly identical to that of the pulsar in CTB 109. The light curve is consistent with that of a steady source. A preliminary search for variability fails to show Doppler modulation which would signal the presence of a binary companion. In addition, the low frequency spectrum shows no obvious pink noise typical of accretion powered sources. The X-ray spectrum is remarkably steep, with a power law index \( \sim 5 \). The steep index is indicative of the tail of an intrinsically thermal spectrum. An absorbed blackbody also gives a good fit with a temperature of \( kT \sim 0.64 \) keV, similar to that found for other AXPs.

A high foreground absorption suggests that the pulsar is distant and likely highly absorbed. Uncertainty in the distance to the pulsar makes the luminosity difficult to estimate. Our best guess is 15 kpc, an estimate likely to be accurate to within a factor of two. The isotropic X-ray luminosity is then \( L_X \sim 2 \times 10^{35} d_{15}^2 \) erg s\(^{-1}\). Note that like for the Kes 73 pulsar, the spectrum of PSR J1845−0258 is unlike that of any accreting high-mass neutron star binary.

We await further multi-wavelength observations of PSR J1845−0258 necessary to fully describe this source and gauge its importance. There is evidence in the MOST radio survey data for an underlying shell-type SNR (B. M. Gaensler, Priv. Comm.). If verified, this would be a spectacular endorsement of the AXP hypothesis. Although only a future \( \dot{P} \) measurement can help determine its spin-down age.
2.3. The Neutron Star Candidate 1E161348−5055

The central X-ray source in RCW 103, 1E161348−5055, has also been known for some time (Tuohy & Garmire 1980), but unlike Kes 73, so far no pulsar has been identified. Nevertheless, several other properties of this source identify it as AXP-like object. Located in the center of a young SNR, the compact source has an unexpectedly steep spectral signature (photon index $\sim 3$) with an X-ray luminosity of $\sim 10^{35}$ erg cm$^{-2}$ s$^{-1}$ (Gotthelf, Petre & Hwang 1997). But the lack of detected pulsations leave the nature of 1E161348−5055 ambiguous and so far no clear interpretation of the origin of the X-ray emission has emerged.

Progress on this front is suggested by a recent follow-up ASCA observation of RCW 103. The flux from 1E161348−5055 was seen to decrease by a factor of $\sim 10$ compared to the 1993 observation 3.5 yrs earlier (see Fig. 1, Petre & Gotthelf 1998, this Proceedings). This was quite unexpected as the count rates for the HRI detections at two epochs spanning 16 yrs agreed to within $\sim 10\%$. The spectral fits to the original ASCA data only allowed a flux, at most, $< 3$ times higher that predicted by the HRI measurements.

Our new result, the detection of significant variability from 1E161348−5055, strongly rules out a simple cooling NS origin, as originally postulated by Tuohy et al. (1993). A fuller account of this result is presented elsewhere in this Proceedings (Petre & Gotthelf 1998). In the next section, we present several models which may help to elucidate the aforementioned objects, and discuss their significance.

3. Interpretation and Discussion

The spectral and temporal properties of 1E 1841−045 and PSR J1845−0258 are similar to each other and to the other seemingly isolated, young AXPs. And these objects appear related to the SGRs. Similarly, although no pulsation have been found from central source in RCW 103, its spectral properties suggest a relation to these slow pulsars.

If these and other NS candidates like them were indeed born as fast rotators, then a mechanism must be found to slow them down to their currently observed rates. The rapid but steady spin-down of the Kes 73 pulsar suggests a possibility. The equivalent magnetic field for a rotating dipole is $B_{\text{dipole}} \approx 3.2 \times 10^{19} (P\dot{P})^{1/2} \approx 8 \times 10^{14}$ G, one of the highest magnetic fields observed in nature. Theory describing a NS with such an enormous field, a “magnetar”, has been worked out by Duncan & Thompson (1992). Vasisht & Gotthelf (1997) suggest that the Kes 73 pulsar was born as a magnetar $\sim 2 \times 10^3$ yrs ago and has since spun down to a long period due to rapid dipole radiation losses. This would then be the first direct evidence of such a magnetar (see Vasisht & Gotthelf 1997 for a detail discussion). In the context of the above theory, 1E161348−5055 may have been born a magnetar which has subsequently spun down.

Alternatively, some NSs may be born as slow ($\sim 2$ s) rotators as considered by Spruit & Phinney (1998), resulting from strong physical coupling between the progenitor’s slowly rotating envelope and its pre-collapse core.

The enormous magnetic field postulated for these slow pulsars may provide a natural explanation for their radio-quiet nature. It has been argued that for supercritical
fields, magnetic pair creation $\gamma \to e^+e^-$, the source of electrons for radio emission, is suppressed (Baring & Harding 1998).

In now seems likely that the Crab and Vela pulsars are in fact rare, but highly visible, examples of young NS evolution. They might have obtained their rapid initial spins through some impulsive mechanism that imparts both kicks and spins to young neutron stars (Spruit & Phinney 1998). Slow AXP pulsars, exemplified by Kes73, are likely to be more common, but observationally less obvious manifestations of young NSs. The SGRs may represent an evolutionary stage during which young NSs are likely to be produce bursts. Under this scenario, the AXPs and SGR phenomena are closely related, linked by their strong magnetic field.

The discovery of new examples of slow pulsars is revolutionizing our understanding young NS evolution – it suggests that an alternative evolution scenario for young NSs, is not only possible, but most probable. We consider that many of the young NSs “missing” in radio surveys can be accounted for by the above discussed radio-quiet NSs.

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