

## **A New View on Young Pulsars in Supernova Remnants: Slow, Radio-quiet & X-ray Bright**

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**Abstract.** We propose a simple explanation for the apparent dearth of radio pulsars associated with young supernova remnants (SNRs). Recent X-ray observations of young remnants have revealed slowly rotating ( $P \sim 10$ s) central pulsars with pulsed emission above 2 keV, lacking in detectable radio emission. Some of these objects apparently have enormous magnetic fields, evolving in a manner distinct from the Crab pulsar. We argue that these X-ray pulsars can account for a substantial fraction of the long sought after neutron stars in SNRs and that Crab-like pulsars are perhaps the rarer, but more highly visible example of these stellar embers. Magnetic field decay likely accounts for their high X-ray luminosity, which cannot be explained as rotational energy loss, as for the Crab-like pulsars. We suggest that the natal magnetic field strength of these objects control their subsequent evolution. There are currently almost a dozen slow X-ray pulsars associated with young SNRs. Remarkably, these objects, taken together, represent at least half of the confirmed pulsars in supernova remnants. This being the case, these pulsars must be the progenitors of a vast population of previously unrecognized neutron stars.

### **1. Where Are All The Young Neutron Stars?**

For the last 30 years it has been understood that young neutron stars (NSs) are created during Type II/Ib supernova explosions involving a massive star. Common wisdom holds that these neutron stars are born as rapidly rotating ( $\sim 10$  ms) Crab-like pulsars. Furthermore, pulsars and their accompanying supernova remnants are thought to be highly visible for tens of thousands of years, the former via radio-loud, Crab-like “plerionic” (Weiler & Sramek 1988) pulsar nebulae, the latter as distinctive X-ray and radio shell-type remnants. So where are all the young ( $< 10^4$  yr) neutron stars? Of the 220 known Galactic SNR (Green 1998) and over 1100 detected radio pulsars (Camilo et al., this volume), few associations between the two populations have been identified with any certainty.

The current paradigm rests on the discoveries in the 1960’s of the Crab and Vela pulsars in their respective supernova nebulae. These were taken as spectacular confirmation for the existence of neutron stars postulated much earlier

by Baade & Zwicky (1934) based on theoretical arguments. The connection seems firm as the properties and energetics of these pulsars could 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. Furthermore, their inferred age and association with SNRs provided strong evidence that NSs are indeed born in supernova explosions.

So it is quite remarkable that, despite detailed radio searches, few Galactic SNR have yielded a NS candidate over the years since the initial discoveries. A recent census tallied only 10 SNRs with pulsed central radio sources (Helfand 1998). Furthermore, comprehensive radio surveys suggest that most radio pulsars near SNRs shells can be attributed to chance overlap (e.g. Gaensler & Johnston 1995). 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, become less compelling, and perhaps even circular.

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 and refs. therein). Often these objects have been labeled “cooling neutron stars”, mainly because of their lack of optical counterparts.

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 – 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 pulsars are currently referred to as the anomalous X-ray pulsars (AXP; see refs. in Gotthelf & Vasisht 1997). Nearly half are located at the centers of SNRs, suggesting that they are relatively young ( $\lesssim 10^5$  yrs-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  $\sim 10^4$  yrs-old SNR CTB 109, has been known for nearly two decades (Gregory & Fahlman 1980).

There are now almost a dozen slow radio-quiet X-ray pulsars apparently associated with young SNRs. These include the four known soft  $\gamma$ -ray repeaters (SGR) which have recently been confirmed as slow rotators (Kouveliotou et al. 1998), and likely associated with young SNRs (e.g. Cline et al. 1982; Kouveliotou et al. 1998). The census of these radio-quiet objects now approach in number those estimated for those candidate young radio-bright objects connected with SNRs.

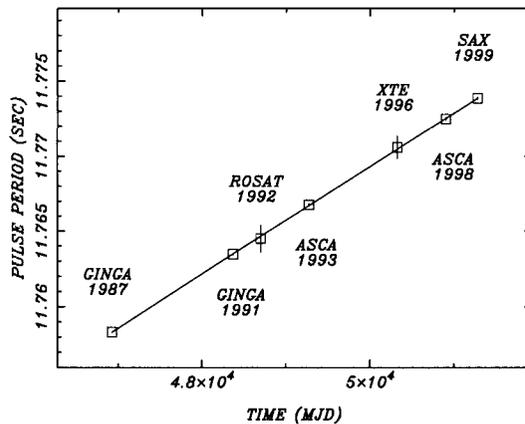


Figure 1. Spin history of the 12-s central pulsar in the Galactic SNR Kes 73. The rapid but steady spin-down, spanning over a decade, provides the strongest evidence yet for a magnetar.

### 3. A Key Object: the Radio-quiet Slow X-ray Pulsar in Kes 73

Given the latest X-ray results, it now appears likely that at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar. An understanding of such alternative paths for young NS evolution is suggested by 1E 1841–045, the remarkable 12-s anomalous X-ray pulsar in the center of the SNR Kes 73. This young object has the longest period and most rapid spin-down rate of any known isolated young pulsar. A recent comprehensive study of the long term spin history of 1E 1841–045 indicated steady braking on a timescale of  $\tau_s \simeq 4 \times 10^3$  yrs, consistent with the inferred age of Kes 73 (Vasisht et al. 2000). The similarity in age along with the central location of the pulsar strongly suggests that the two objects are related.

If the Kes 73 pulsar 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  $B_{dipole} \simeq 3.2 \times 10^{19} (PP)^{1/2} \approx 8 \times 10^{14}$  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  $\sim 2 \times 10^3$  years ago and has since spun down to a long period due to rapid dipole radiation losses. The pulsar in Kes 73 provided the first direct evidence for a magnetar through spin-down measurements and the apparent consistency in age between the pulsar and SNR (see Gotthelf, Vasisht & Dotani 1999 for details).

In the magnetar model, the enormous magnetic field provides a natural mechanism for braking the pulsar and spinning it down so quickly. Pulsar spin-down via mass accretion, for any reasonable accretion rate, would require longer than a Hubble time to spin-down to the observed values. Furthermore, the observed luminosities of these slow X-ray pulsars is consistent with them being

powered by magnetic field decay. If the total X-ray emission were powered by rotational energy loss, as it the case for the radio pulsars, the available energy is far too small. The maximum luminosity derivable just from spin-down is  $L_X \lesssim 4\pi^2 I \dot{P} / P^3 \sim 10^{34} \text{ erg s}^{-1}$  well below the measured value of  $L_X \sim 3 \times 10^{35} \text{ erg s}^{-1}$ . On the other hand, the measured luminosity is appreciably low for an accretion powered binary system  $\sim 10^{36-38} \text{ erg s}^{-1}$ . These facts along with a lack of stochastic variability and a steep spectrum makes an accretion scenario all but unlikely.

In conclusion, it now seems likely that at least half the population of young neutron stars in SNR evolve as slow AXP-like pulsars, as exemplified by Kes 73. The Crab-like pulsars, highly visible via their radio nebulae, are thus a less common manifestation of young NS evolution. We note that we do not need to invoke a substantial space velocity for the NSs, as those X-ray pulsars within known SNRs typically lie at their centers. 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. We consider that many of the young NSs “missing” in radio surveys can be accounted for by the above discussed radio-quiet NSs. As their evolution along the  $P - \dot{P}$  diagram cannot intersect the bulk of the aged radio pulsar phase-space, AXP-like pulsars thus require the existence of a vast population of previously unappreciated NSs.

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## References

- Baade, W. & Zwicky, F. 1934, *Phys. Rev.*, 45, 138  
 Caraveo, P. A., Bignami, G. F., Trumper, J. 1996, *AARv*, 7, 209  
 Cline, T. L. 1982, *ApJ*, L255, 45  
 Duncan, R. C. & Thompson, C. 1992, *ApJ*, 392, 9  
 Gaensler, B. & Johnston, S. 1995, *MNRAS*, 277, 1243  
 Gotthelf, E. V. & Vasisht, G. 1997, *ApJ*, 486, L133  
 Gotthelf, E. V., Petre, R. & Hwang, U. 1997, *ApJ*, 487, L175  
 Gotthelf, E. V., G. Vasisht, & Dotani, T. 1999, *ApJ*, 522, L49  
 Gregory, P. C. & Fahlman, G. G. 1980, *Nature*, 287, 805  
 Green D.A., 1998, <http://www.mrao.cam.ac.uk/surveys/snrns>  
 Helfand, D. J. 1998, *Mem. Soc. Astron. Ital.*, 69, 791  
 Kouveliotou, C. et al. 1998, *Nature*, 391, 235  
 Vasisht, G. & Gotthelf, E. V. 1997, *ApJ*, 486, L129  
 Vasisht, G., Gotthelf, E. V., Torii, K., & Gaensler, B. 2000, in press  
 Weiler, K. W. & Sramek, R. A. 1988, *ARA&A*, 26, 29.