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CONSTRaining the Evolutionary Fate of Central Compact Objects: “Old” Radio Pulsars in Supernova Remnants

Slavko Bogdanov1, C.-Y. Ng2, and Victoria M. Kaspi3

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Abstract
Central compact objects (CCOs) constitute a population of radio-quiet, slowly spinning (≥100 ms) young neutron stars with anomalously high thermal X-ray luminosities. Their spin-down properties imply weak dipole magnetic fields (∼1010–11 G) and characteristic ages much greater than the ages of their host supernova remnants (SNRs). However, CCOs may possess strong “hidden” internal magnetic fields that may re-emerge on timescales of ≥10 kyr, with the neutron star possibly activating as a radio pulsar in the process. This suggests that the immediate descendants of CCOs may be masquerading as slowly spinning “old” radio pulsars. We present an X-ray survey of all ordinary radio pulsars within 6 kpc that are positionally coincident with Galactic SNRs in order to test the possible connection between the supposedly old but possibly very young pulsars and the SNRs. None of the targets exhibit anomalously high thermal X-ray luminosities, suggesting that they are genuine old ordinary pulsars unrelated to the superposed SNRs. This implies that CCOs are either latent radio pulsars that activate long after their SNRs dissipate or they remain permanently radio-quiet. The true descendants of CCOs remain at large.

Key words: pulsars: general – stars: neutron – X-rays: stars

1. Introduction

In the absence of other means, the age of a rotation-powered pulsar is estimated from its characteristic age, defined as $\tau_c \equiv P/2\dot{P}$, where $P$ is the pulsar period and $\dot{P}$ is the spin-down rate. Although not exact, this value is generally a rough approximation of the true age of a pulsar, provided that the birth spin period was much shorter than the current period. However, Halpern & Gotthelf (2010) and Gotthelf et al. (2013a) have recently measured unusually low spin-down rates of three central compact objects (CCOs), an enigmatic group of young, slowly spinning ($P \gtrsim 100$ ms), radio-quiet but X-ray bright neutron stars at the centers of supernova remnants (SNRs) that indicate unusually low magnetic fields ($\sim 10^{10–11}$ G) and characteristic ages on timescales of ≥10 kyr. A profound implication of this result is that the characteristic age grossly overestimates the true age of these neutron stars. By extension, many supposedly old radio pulsars ($\tau_c \gtrsim 10^5$ yr) may, in fact, be relatively young (a few to tens of kiloyears). This may occur, for instance, if CCOs provide an alternative formation channel that “injects” long-period (>100 ms), low spin-down rate neutron stars into the pulsar population. Such objects may be masquerading as typical pulsars, in which case the conventional picture of pulsar evolution in the $P$–$\dot{P}$ diagram may require substantial revisions (e.g., Faucher-Giguère & Kaspi 2006).

The spin properties of the three CCOs with detected periodicities (PSR J1852+0404 in Kes 79, PSR 0821–4300 in Puppis A, and 1E1207.4–5209 in PKS 1209–51/52) imply relatively weak surface magnetic fields of $\sim 10^{10}$ G. However, the highly non-uniform surface temperature distribution deduced from the thermal pulsations (Gotthelf et al. 2010; Bogdanov 2014) suggest the presence of much stronger subsurface fields. These “hidden” strong fields are expected to re-emerge on timescales of 1–100 kyr (see, e.g., Ho 2011; Viganò & Pons 2012), depending on the submergence conditions, transforming CCOs into neutron stars with stronger external fields ($\sim 10^{12}$ G) at a later evolutionary stage and possibly activating as radio pulsars in the process.

In this evolutionary scenario, some ordinary middle-aged and old radio pulsars with $\sim 10^{12}$ G may in fact be relatively young CCOs, especially those situated within or very near the boundaries of SNRs. These remnants may actually be the pulsar birth sites even though such associations may be dismissed as chance superpositions based solely on the pulsar’s high value of $\tau_c$. One possible manifestation of the youth of these pulsars should be unusually hot thermal emission from the pulsar, resulting in relatively high X-ray luminosity ($L_X \gtrsim 10^{33}$ erg s$^{-1}$) comparable to or in excess of the pulsar spin-down luminosity, as seen in CCOs. To test this possibility, we investigate the X-ray emission from the eight middle-aged/old radio pulsars within 6 kpc that are positionally coincident with Galactic SNRs. This study has important implications for understanding the birth, evolution, and properties of the Galactic population of neutron stars, especially in light of recent discoveries.

2. Sample Selection

To identify radio pulsars that fall within or just outside of the boundaries of SNRs, we have cross-correlated the catalog of Galactic SNRs4 (Green 2009) and the ATNF pulsar catalog5 (Manchester et al. 2005). After filtering out the well-established associations, we have narrowed down the list to a volume-complete sample of eight known old pulsars within 6 kpc. For reference, the chance spatial coincidence probability of a pulsar falling within the confines of any given SNR in the Galactic plane is ∼5%. Although this value is by no means negligible, there is still a strong possibility that at least some of the pulsars and SNRs are truly associated. We have searched the HEASARC archive for serendipitous pointings toward these objects.

4 See http://www.mrao.cam.ac.uk/surveys/snrs/.
5 Available at http://www.atnf.csiro.au/research/pulsar/psrcat/.

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2. SAMPLE SELECTION

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4 See http://www.mrao.cam.ac.uk/surveys/snrs/.
5 Available at http://www.atnf.csiro.au/research/pulsar/psrcat/.
Within 6 kpc, we have targeted the remaining three objects, PSR images. In order to obtain a volume-complete sample of SNRs, only G272.2−05:09 of free electrons (Cordes & Lazio2002). Among the eight combined with the NE2001 model for the Galactic distribution of free electrons, their distances were estimated based on the dispersion measure (DM) representative of the population of ordinary radio pulsars. Their spin-down rates (Halpern & Gotthelf2010; Gotthelf et al.2013a), while the solid squares show X-ray dim isolated neutron stars. The solid line shows the theoretical death line, beyond which pulsars cease to generate radio emission, and the spin-up limit, while the dashed lines show tracks of constant age and magnetic fields.

Notes. a Distance derived from the pulsar dispersion measure and the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002).


Table 1
Parameters of the Eight Pulsars Targeted in This Study

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>α (J2000) (h m s)</th>
<th>δ (J2000) (° ′ ″)</th>
<th>P (s)</th>
<th>D90 (kpc)</th>
<th>DM (pc cm−3)</th>
<th>τ (Myr)</th>
<th>E (1033 erg s−1)</th>
<th>B (1012 G)</th>
<th>References</th>
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<tr>
<td>B0905−51</td>
<td>09 07 15.90</td>
<td>−51 57 59.2</td>
<td>0.25</td>
<td>2.7</td>
<td>104</td>
<td>2.2</td>
<td>4.4</td>
<td>0.69</td>
<td>1, 2</td>
</tr>
<tr>
<td>B1703−40</td>
<td>17 07 21.72</td>
<td>−40 53 56.1</td>
<td>0.58</td>
<td>5.1</td>
<td>360</td>
<td>4.8</td>
<td>0.39</td>
<td>1.1</td>
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<tr>
<td>B1736−29</td>
<td>17 39 34.27</td>
<td>−29 03 03.5</td>
<td>0.32</td>
<td>3.2</td>
<td>139</td>
<td>0.65</td>
<td>9.2</td>
<td>1.6</td>
<td>5, 6</td>
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<tr>
<td>B1742−30</td>
<td>17 45 56.30</td>
<td>−30 40 23.5</td>
<td>0.37</td>
<td>2.1</td>
<td>88</td>
<td>0.55</td>
<td>8.5</td>
<td>2.0</td>
<td>7, 8</td>
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<tr>
<td>J1808−2701</td>
<td>18 08 13.23</td>
<td>−27 01 21</td>
<td>2.46</td>
<td>2.4</td>
<td>95</td>
<td>0.59</td>
<td>0.17</td>
<td>12.9</td>
<td>9</td>
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<tr>
<td>B1822−14</td>
<td>18 25 09.29</td>
<td>−14 46 52.6</td>
<td>0.28</td>
<td>5.0</td>
<td>357</td>
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<tr>
<td>J1901+0254</td>
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<td>+02 54.41</td>
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<td>3.5</td>
<td>185</td>
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<tr>
<td>B1919+21</td>
<td>19 21 44.81</td>
<td>+21 53 02.2</td>
<td>1.33</td>
<td>1.0</td>
<td>12</td>
<td>16</td>
<td>0.022</td>
<td>1.4</td>
<td>11, 8</td>
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Table 2
Summary of X-Ray Observations

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<th>Epoch</th>
<th>Exp. (ks)</th>
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<tr>
<td>B0905−51</td>
<td>XMM/EPIC 011293101</td>
<td>2001 Dec 10</td>
<td>37.4</td>
</tr>
<tr>
<td>B1703−40</td>
<td>XMM/EPIC 0144080101</td>
<td>2002 Sep 27</td>
<td>16.8</td>
</tr>
<tr>
<td>B1736−29</td>
<td>XMM/EPIC 0406580101</td>
<td>2006 Aug 25</td>
<td>26.4</td>
</tr>
<tr>
<td>B1742−30</td>
<td>XMM/EPIC 0103261301</td>
<td>2001 Mar 21</td>
<td>7.6</td>
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<tr>
<td>B1822−14</td>
<td>XMM/EPIC 0406580101</td>
<td>2006 Aug 25</td>
<td>26.4</td>
</tr>
<tr>
<td>J1808−2701</td>
<td>XMM/EPIC 0692210101</td>
<td>2012 Sep 15</td>
<td>21.9</td>
</tr>
<tr>
<td>J1901+0254</td>
<td>XMM/EPIC 0692210301</td>
<td>2013 Mar 29</td>
<td>16.9</td>
</tr>
<tr>
<td>B1919+21</td>
<td>XMM/EPIC 0670940101</td>
<td>2012 Mar 20</td>
<td>16.9</td>
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</table>

3. DATA REDUCTION AND ANALYSIS

Table 2 lists the X-ray data used in this analysis. We performed the re-processing, reduction, and analysis of the Chandra data with CIAO6. 4.6 and the corresponding calibration products CALDB version 4.5.9 (Fruscione et al. 2006). For the XMM-Newton data, we used the Science Analysis Software (SAS)7 version xmsas_20130501_1901−13.0.0. The XMM-Newton event lists were cleaned by applying the recommended flag, pattern, and pulse invariant filters, and screening for instances of severe background flares.

We extracted events within 2″ of the radio pulsar position for the Chandra data and 40″ for the XMM-Newton MOS1/2 data. Data from XMM-Newton EPIC PN was not used as we found it to be more severely affected by strong background flares, resulting in much shorter exposures relative to the MOS data. The analysis was restricted to the 0.3−3 keV band, where most of the thermal radiation from pulsars is typically detected with these telescopes. The background was taken from a source-free region in the image near the pulsar position on the same detector chip.

Notes. a Distance derived from the pulsar dispersion measure and the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002).

4. RESULTS

The characteristic ages of the pulsars considered here range from 0.2 to 45 Myr. If these pulsars were, in fact, born in the centers of the SNRs, their characteristic ages do not correspond to their true age, as is the case for CCOs. In this scenario, we can estimate their kinematic ages by calculating the travel time from the remnant center to the current position. For PSR B1919+21, a proper motion measurement is available and implies a velocity of 190 km s$^{-1}$ at the DM-derived distance of 1 kpc (Zou et al. 2005). It is interesting to note that the proper motion vector of the pulsar points in the direction away from the center of the remnant. For PSR B1822–14 (aka PSR J1825–1446), Moldón et al. (2012) report a proper motion-derived transverse velocity of 690 km s$^{-1}$ at a distance of 5 kpc. Although the direction of the pulsars’ proper motion is generally consistent with the pulsar moving away from the inner regions of the remnant, due to the irregular morphology of G16.8–1.1 and contamination in the radio from the bright source RCW 164, the exact center of the remnant is difficult to determine. As a result, we can only crudely estimate an angular separation of $\sim 4'$ between the pulsar and the inner region of the SNR.

For the remaining pulsars, we assume the mean velocity of pulsars in the Galaxy of 380 km s$^{-1}$ derived by Faucher-Giguère & Kaspi (2006) and the DM distances. Based on this, the putative pulsar-remnant associations in Table 2 imply ages in the range 4–28 kyr, orders of magnitude smaller than their $\tau_c$.

If the pulsars are indeed that young, their surfaces should be at substantially higher temperatures (and thus luminosity) compared to $10^5$–$10^6$ yr old pulsars. Assuming this emission is powered by residual cooling, if we scale the luminosity of the CCO in Kesteven 79, PSR J1852+0040, based on the neutron star cooling curves given in Viganó et al. (2013, see, in particular, their Figure 11), we estimate that for ages $\gtrsim 10^3$ yr, they would have a blackbody temperature of $kT \lesssim 0.37$ keV with a bolometric luminosity $\gtrsim 10^{31}$ erg s$^{-1}$. On the other hand, typical old pulsars have $L_X \sim 10^{-5}$–$10^{-3}$ $L_{\odot}$, suggesting that the eight pulsars in Table 2 would have $L_X \lesssim 10^{32}$ erg s$^{-1}$ if they are solely rotation-powered (see, e.g., Kaspi et al. 2006). Hence, an observed $L_X$ much greater than this would be strong evidence for a young neutron star.

The results of the analysis for the eight pulsars are summarized in Table 3. Six pulsars are not detected in X-rays: PSRs B1703–40, B1742–30, B1736–29, J1808–2701, J1901+0254, and B1919+21 implying bolometric luminosities $L_X \lesssim 10^{32}$ erg s$^{-1}$. Although we detect PSRs B1822–14 and B0905–51 at high significance, their bolometric luminosities are not anomalously high ($L_X \sim 10^{31}$–$10^{32}$ erg s$^{-1}$) since they account for $\sim 10^{-3}$ of the pulsar spin-down luminosity, consistent with the values observed for many ordinary pulsars (see, e.g., Kargaltsev et al. 2012, and references therein). Middle-aged and old pulsars show thermal emission with $kT \approx 0.1$–0.3 keV and small emission radii, indicative of heating of the polar cap regions by a return current from the pulsar magnetosphere. Based on this, to compute upper limits on the bolometric luminosity for the non-detections, we consider a thermal spectrum with $kT = 0.2$ keV and the expected $N_H$ computed using the empirical relation between the pulsar DM and $N_H$ found by He et al. (2013). The low implied luminosities indicate that all eight pulsars are genuinely middle-aged/old and are simply superposed on the SNRs by chance.

5. DISCUSSION AND CONCLUSIONS

To date, targeted deep radio searches have found no radio emission associated with the three CCOs with measured periodicities (Gaensler et al. 2000; Camilo 2004; Halpern et al. 2007). It is possible that (for as-yet-unknown reasons) the particle acceleration mechanism in these objects never activates, rendering them permanently radio-quiet. As a result, as they age and cool, these objects may eventually fade away, becoming undetectable in X-rays as well. However, the sample of CCOs is not yet large enough to know if they are intrinsically radio-quiet as unfavorable viewing geometries may cause the radio beams to not sweep toward us.

Previously, Gotthelf et al. (2013b) explored the possibility that isolated radio pulsars with $P > 20$ ms and $B_{surf} < 3 \times 10^{12}$ G are actually “orphan” CCOs, namely, neutron stars whose SNRs have dissipated. In this scenario, CCOs maintain their weak magnetic fields but at some stage become radio-loud. None of the 13 objects considered were detected in X-rays, suggesting that CCOs and radio-loud pulsars with $\sim 10^{10}$ G...
are disjoint classes of objects. The dearth of low-field, non-recycled radio pulsars in the portion of the $P - \dot{P}$ diagram occupied by CCOs (Figure 1), despite no observational selection effects against them, provides an additional argument against this evolutionary outcome.

There is growing evidence that the apparently low magnetic fields of CCOs ($\lesssim 10^{11}$ G, as inferred from $P$ and $\dot{P}$), may be the result of a submerged field, which may eventually diffuse outward on timescales of $\gtrsim$1 kyr (Halpern & Gotthelf 2010). Therefore, CCOs may, in principle, evolve into normal fields of CCOs (this evolutionary outcome.

effects against them, provides an additional argument against occupied by CCOs (Figure 1), despite no observational selection

$P_{\text{recycled}}$ radio pulsars in the portion of the $P - \dot{P}$ diagram. The location of several pulsars from Table 1 in the $P - \dot{P}$ diagram directly above the CCO 1E 1207.4-5209 is consistent with this scenario.

Since there are 9 CCOs (Halpern & Gotthelf 2010) with ages $\lesssim 10^5$ yr and $\dot{P} = \sim 15$ radio pulsars in SNRs with comparable ages (see, e.g., Popov & Turolla 2012, and references therein), if the CCO formation channel supplies a portion of the radio pulsar population, we estimate that approximately three of the eight objects we have targeted should be CCO descendants. However, none of the pulsars from the volume-complete sample within 6 kpc exhibit unusually high X-ray luminosity, implying that they are all genuinely middle-aged/old rotation-powered pulsars. This suggests that CCOs may not be transient radio pulsars but may instead be permanently radio silent. Alternatively, this could mean that the buried strong magnetic fields in CCOs re-emerge long after they leave their birth site and/or the SNR dissipates. If in the process they activate as radio pulsars, CCOs may be hidden among the population of ordinary radio pulsars. In this case, a systematic sensitive X-ray survey of isolated radio pulsars is required to identify the “orphan” CCOs among them, using the unusually high thermal X-ray luminosity as a discriminant. If, however, orphan CCOs remain radio-quiet, they would be difficult to identify as X-ray pulsars unless they are relatively nearby. As suggested in Halpern et al. (2013), a possible candidate for a CCO descendant is the nearby radio-quiet X-ray pulsar Calvera (1RXS J141256.0+792204), although further investigation is necessary to establish whether the apparent lack of radio and $\gamma$-ray emission is simply due to an unfavorable viewing geometry.

Given that CCOs may account for up to approximately one-third of neutron star births (Popov & Turolla 2012), if they represent a truly distinct population the discrepancy between the Galactic core–collapse supernova rate (Diel et al. 2006) and the neutron star formation rate is exacerbated even further.

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Facilities: CXO (ACIS), XMM (EPIC)

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