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CONSTRAINING THE EVOLUTIONARY FATE OF CENTRAL COMPACT OBJECTS: "OLD" RADIO PULSARS IN SUPERNOVA REMNANTS

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ABSTRACT

Central compact objects (CCOs) constitute a population of radio-quiet, slowly spinning ($\geqslant$100 ms) young neutron stars with anomalously high thermal X-ray luminosities. Their spin-down properties imply weak dipole magnetic fields ($\sim 10^{10-11}$ G) and characteristic ages much greater than the ages of their host supernova remnants (SNRs). However, CCOs may posses strong "hidden" internal magnetic fields that may re-emerge on timescales of $\gtrsim$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 orders of magnitude greater than the host SNR ages. 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 ($\tau_c \geqslant 10^5$ 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+0040 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 τ_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 ($L_X \geqslant 10^{33}$ 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 SNRs[4] (Green 2009) and the ATNF pulsar catalog[5] (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. Five

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

Table 1
Parameters of the Eight Pulsars Targeted in This Study

Pulsar	α (J2000) (h m s)	δ (J2000) (° ′ ″)	P (s)	D^{a} (kpc)	DM (pc cm^{-3})	τ_c (Myr)	$\dot{E}$ (10^{33} erg s^{-1})	B_s (10^{12} G)	References
B0905−51	09 07 15.90	−51 57 59.2	0.25	2.7	104	2.2	4.4	0.69	1, 2
B1703−40	17 07 21.72	−40 53 56.1	0.58	5.1	360	4.8	0.39	1.1	3, 4
B1736−29	17 39 34.27	−29 03 03.5	0.32	3.2	139	0.65	9.2	1.6	5, 6
B1742−30	17 45 56.30	−30 40 23.5	0.37	2.1	88	0.55	8.5	2.0	7, 8
J1808−2701	18 08 13.23	−27 01 21	2.46	2.4	95	0.59	0.17	12.9	9
B1822−14	18 25 02.92	−14 46 52.6	0.28	5.0	357	0.20	41	2.6	5, 6
J1901+0254	19 01 15.67	+02 54 41	1.30	3.5	185	45	0.0082	0.78	10
B1919+21	19 21 44.81	+21 53 02.2	1.33	1.0	12	16	0.022	1.4	11, 8

Notes. [a] Distance derived from the pulsar dispersion measure and the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002).
References. (1) Manchester et al. 1978; (2) Siegman et al. 1993; (3) Johnston et al. 1992; (4) Wang et al. 2001; (5) Clifton & Lyne 1986; (6) Hobbs et al. 2004b; (7) Komesaroff et al. 1973; (8) Zou et al. 2005; (9) Lorimer et al. 2006; (10) Hobbs et al. 2004a; (11) Hewish et al. 1968.

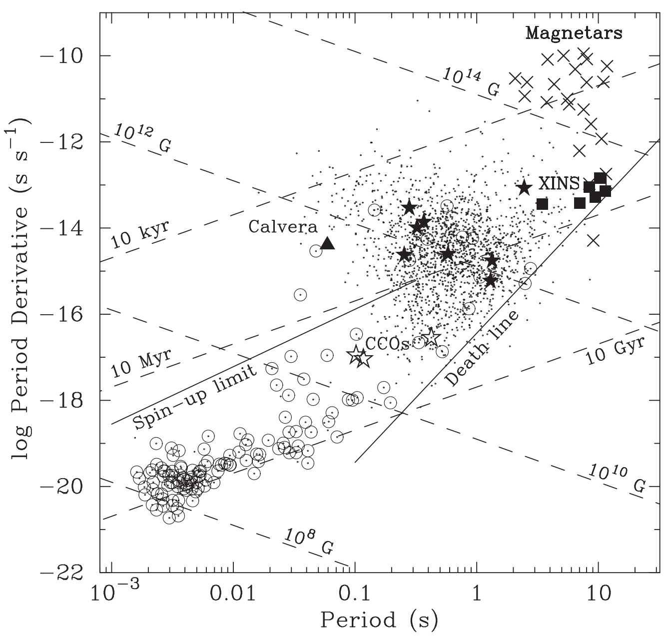

Figure 1. $P - \dot{P}$ diagram of neutron stars. The open stars mark the three CCOs with measured spin-down rates (Halpern & Gotthelf 2010; Gotthelf et al. 2013a), while the solid stars show the eight pulsars considered in this Letter. The radio- and γ-ray quiet X-ray pulsar Calvera is shown with the solid triangle. The dots show all radio pulsars from the ATNF pulsar catalog with the binary pulsars marked with a circle. The crosses show the population of magnetars and 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.

pulsar positions fall within existing *Chandra* and/or *XMM-Newton* images. In order to obtain a volume-complete sample within 6 kpc, we have targeted the remaining three objects, PSR J1808−2701, J1901+0254, and B1919+21 with *XMM-Newton*. The basic parameters of all eight objects are summarized in Table 1 and their locations in the $P - \dot{P}$ diagram are shown in Figure 1. All eight objects have spin periods $P > 0.25$ s and are representative of the population of ordinary radio pulsars. Their distances were estimated based on the dispersion measure (DM) combined with the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002). Among the eight SNRs, only G272.2−3.2, coincident with PSR B0905−51, has a published distance estimate of $1.8^{+1.4}_{0.8}$ kpc (Harrus et al. 2001), which is consistent with the DM-derived pulsar distance of 2.7 kpc.

Table 2
Summary of X-Ray Observations

Pulsar	Telescope/ Instrument	Observation ID	Epoch	Exp. (ks)
B0905−51	*XMM*/EPIC	011293101	2001 Dec 10	37.4
	CXO/ACIS	10572	2008 Aug 27	22.8
	CXO/ACIS	9147	2008 Aug 26	41.6
B1703−40	*XMM*/EPIC	0144080101	2002 Sep 27	16.8
	XMM/EPIC	0406580101	2006 Aug 25	26.4
B1736−29	*CXO*/ACIS	8678	2008 May 18	2.2
	CXO/ACIS	8679	2008 May 18	2.2
B1742−30	*XMM*/EPIC	0103261301	2001 Mar 21	7.6
	CXO/ACIS	8747	2008 May 15	2.2
B1822−14	*CXO*/ACIS	4600	2004 Jul 9	11.0
	CXO/ACIS	5341	2004 Jul 11	18.0
J1808−2701	*XMM*/EPIC	0692210101	2012 Sep 15	21.9
J1901+0254	*XMM*/EPIC	0692210301	2013 Mar 29	16.9
B1919+21	*XMM*/EPIC	0670940101	2012 Mar 20	16.9

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 CIAO[6] 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 `xmmsas_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 regions in the image near the pulsar position on the same detector chip.

6 *Chandra* Interactive Analysis of Observations, available at http://cxc.harvard.edu/ciao/.
7 The *XMM-Newton* SAS is developed and maintained by the Science Operations Centre at the European Space Astronomy Centre and the Survey Science Centre at the University of Leicester.

Table 3
Parameters of the Eight Supernova Remnants: Pulsar Superpositions

Pulsar	Supernova Remnant	Remnant Diameter	Angular Offset[a]	τ_c (Myr)	Kin. Age[b] (kyr)	N_H[c] (10^{21} cm^{-2})	L_X[d] (10^{31} erg s^{-1})	References
B0905−51	G272.2−3.2	∼15′	11.′1	2.2	22	3.1	2.3	1, 2, 3
B1703−40	G345.7−0.2	6′	1.′03	4.8	4	11	<22	4, 5
B1736−29	G359.1+0.9	12′ × 11′	8.′0	0.65	19	4.2	<4.6	6, 7, 8
B1742−30	G358.5−0.9	∼17′	3.′4	0.55	28	2.6	<2.6	9, 7
B1822−14	G16.8−1.1	30′ × 24′	4.′4	0.20	10	11	6.9	10
J1808−2701	G4.2−3.5	28′	10.′5	0.59	19	2.9	<2.1	11, 12
J1901+0254	G36.6−0.7	25′	11.′0	45	27	5.6	<13	13, 14
B1919+21	G55.7+3.4	23′	11.′1	16	11	0.36	<0.14	15

Notes.
[a] Angular separation between the pulsar and the estimated center of the SNR.
[b] Estimated kinematic age (i.e., the time required for the pulsar to traverse the distance from the SNR center to its current position) based on the pulsar distance and transverse velocity, where available. Where no proper motion information is available, a velocity of 380 km s^{-1} is assumed.
[c] Hydrogen column density along the line of sight computed based on the empirical relation $N_H\,(10^{20}\ \mathrm{cm}^{-2}) \simeq 0.30\,\mathrm{DM}\,(\mathrm{pc\ cm}^{-3})$ found by He et al. (2013).
[d] Estimated bolometric luminosity or 2σ upper limit assuming thermal emission with $kT = 0.2$ keV.
References. (1) Greiner et al. 1994; (2) Duncan et al. 1997; (3) Harrus et al. 2001; (4) Whiteoak & Green 1996; (5) Green et al. 1997; (6) Gray 1994; (7) Roy & Bhatnagar 2006; (8) Law et al. 2008; (9) Gray 1994; (10) Reich et al. 1986; (11) Reich et al. 1988; (12) Reich et al. 1990; (13) Fürst et al. 1987; (14) Kassim 1992; (15) Goss et al. 1977.

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's 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 ∼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 τ_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 Viganò et al. (2013, see, in particular, their Figure 11), we estimate that for ages $\lesssim 10^5$ yr, it would have a blackbody temperature of $kT \gtrsim 0.37$ keV with a bolometric luminosity $\gtrsim 10^{33}$ erg s^{-1}. On the other hand, typical old pulsars have $L_X \sim 10^{-5}$–$10^{-3}\dot{E}$, 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 ($L_X \sim 10^{31-32}$ 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 $B_{\mathrm{surf}} < 3 \times 10^{10}$ 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 ($\leqslant 10^{11}$ G, as inferred from P and $\dot{P}$), may be the result of a submerged field, which may eventually diffuse outward on timescales of $\gtrsim$kyr (Halpern & Gotthelf 2010). Therefore, CCOs may, in principle, evolve into normal radio pulsars (with $B \gtrsim 10^{12}$ G) after $\gtrsim$1 kyr. The buried field will diffuse back to the surface on a timescale that is determined in large part by the amount of mass accreted (Ho 2011; Viganò & Pons 2012). Here, we have investigated this possible evolutionary path of CCOs, assuming that the neutron stars activate as radio pulsars in the process. For the first $\sim 10^5$ yr, rapid field growth would move a CCO upward in 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 $\lesssim 10^4$ yr and $\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 latent 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 γ-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 (Diehl 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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