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X-RAY OBSERVATIONS OF DISRUPTED RECYCLED PULSARS: NO REFUGE FOR ORPHANED CENTRAL COMPACT OBJECTS

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ABSTRACT

We present a *Chandra* X-ray survey of the disrupted recycled pulsars (DRPs), isolated radio pulsars with $P > 20$ ms and $B_s < 3 \times 10^{10}$ G. These observations were motivated as a search for the immediate descendants of the ≈10 central compact objects (CCOs) in supernova remnants (SNRs), 3 of which have similar timing and magnetic properties as the DRPs, but are bright, thermal X-ray sources consistent with minimal neutron star (NS) cooling curves. Since none of the DPRs were detected in this survey, there is no evidence that they are "orphaned" CCOs, NSs whose SNRs has dissipated. Upper limits on their thermal X-ray luminosities are in the range of $\log L_x[\mathrm{erg\ s^{-1}}] = 31.8$–$32.8$, which implies cooling ages $> 10^4$–10^5 yr, roughly 10 times the ages of the ≈10 known CCOs in a similar volume of the Galaxy. The order of a hundred CCO descendants that could be detected by this method are thus either intrinsically radio quiet or occupy a different region of (P, B_s) parameter space from the DRPs. This motivates a new X-ray search for orphaned CCOs among radio pulsars with larger *B*-fields, which could verify the theory that their fields are buried by the fall-back of supernova ejecta, but quickly regrow to join the normal pulsar population.

Key words: pulsars: individual (PSR J0609+2130, PSR J1038+0032, PSR J1320−3512, PSR J1333−4449, PSR J1339−4712, PSR J1355−6206, PSR J1548−4821, PSR J1611−5847, PSR J1753−1914, PSR 1821+0155, PSR B1952+29, PSR J2007+2722, PSR J1816−5643, PSR J2235+1506) – stars: neutron

Online-only material: color figure

1. INTRODUCTION

The group of about 10 so-called central compact objects (CCOs) in supernova remnants (SNRs) are distinguished by their steady surface thermal X-ray flux, lack of surrounding pulsar wind nebula, and non-detection at any other wavelength (Halpern & Gotthelf 2010a). Three CCOs are known pulsars with periods in the range 0.1–0.4 s and spin-down rates that provide an estimate of their surface dipole magnetic field strength, which falls in the range of $B_s = (3$–$10) \times 10^{10}$ G (Gotthelf et al. 2013), smaller than that of any other young neutron star (NS). This weak magnetic field is evidently the physical basis of the CCO class.

The homogeneous properties of the approximately seven remaining CCOs that have not yet been seen to pulse suggest that they have similar or even weaker *B*-fields than the known CCO pulsars and a more uniform surface temperature. That CCOs are found in SNRs (of ages 300–7000 yr) in numbers comparable to other classes of NSs implies that they must represent a significant fraction of NS births, probably greater than that of magnetars, for example, as only four to five Galactic SNRs are known to host magnetars (Halpern & Gotthelf 2010b).

The subsequent evolution of CCOs is a glaring unknown as their immediate descendants are not evident in any existing survey. CCOs should persist as cooling NSs, detectable in thermal X-rays, for 10^5–10^6 yr according to NS cooling curves (Page et al. 2009). If some are also radio pulsars, that phase could last for $\sim 10^9$–10^{10} yr. While there are not yet enough CCOs to know whether they are intrinsically radio-quiet, it is very unlikely that the huge expected population of CCO descendants are *all* hiding simply due to unfavorable radio beaming. Therefore, it is difficult to understand why the region of $(P, \dot{P})$ space in which CCOs are found, between the bulk of the ordinary radio pulsars and the recycled "millisecond" pulsars in binary systems, is relatively empty.

Most of the pulsars in this sparse region (see Figure 1) are thought to be "mildly recycled," having been spun up by accretion from a high-mass companion for a relatively short time before a second supernova (SN) occurred. Defined as having $P > 20$ ms and $B_s < 3 \times 10^{10}$ G, mildly recycled pulsars include double NS systems and single ones thought to be the disrupted recycled pulsars (DRPs; Lorimer et al. 2004) ejected when the binary is unbound after the second SN. (These are in contrast to the millisecond pulsars, which have low-mass companions.)

The DRPs have characteristic ages of $\tau_c \equiv P/2\dot{P}$ of 10^9–10^{10} yr. Historically, it was thought that hardly any pulsars are born with $B_s < 10^{11}$ G, so all such pulsars must be recycled, but the discovery of young CCOs in this region of parameter space invalidates that assumption. Just as the $\sim 10^8$ yr characteristic age of a CCO is meaningless, the possibility that *any* low *B*-field radio pulsar is much younger than its characteristic age may now be considered.

The majority of CCOs may have magnetic fields even weaker than those of the known CCO pulsars, and may fall among the DRPs in $(P, \dot{P})$ space. Once the SNR associated with a CCO has dissipated, it would be difficult to distinguish an "orphaned CCO" from a DRP by timing alone if some CCOs are radio pulsars. Thermal X-ray emission, however, would allow a recently orphaned CCO to be recognized as such up to $\sim 10^6$ yr. Thermal emission from the cooling NS is the diagnostic that would distinguish an evolving CCO from an old DRP whose negligible rotation-powered X-ray emission, thermal or non-thermal, would be orders of magnitude weaker.

Table 1
Properties of Disrupted Recycled Pulsars

PSR Name	R.A. (J2000) (h m s)	Decl. (J2000) (° ′ ″)	P (ms)	$\dot{P}$	DM (cm^{-3} pc)	$d_{\rm DM}$[a] (kpc)	$\|z\|$ (pc)	B_s (G)	$\dot{E}$ (erg s^{-1})	Reference
J0609+2130	06 09 58.89	+21 30 02.8	56	2.35×10^{-19}	38.73	1.2	22	3.66×10^9	5.4×10^{31}	1
J1038+0032	10 38 26.93	+00 32 43.6	29	6.70×10^{-20}	26.59	1.2	880	1.41×10^9	1.1×10^{32}	2
J1320−3512	13 20 12.68	−35 12 26.0	458	1.9×10^{-18}	16.42	0.68	310	2.99×10^{10}	7.8×10^{29}	3
J1333−4449	13 33 44.83	−44 49 26.2	346	5.4×10^{-19}	44.3	1.4	410	1.38×10^{10}	5.2×10^{29}	4
J1339−4712	13 39 56.59	−47 12 05.5	137	5.3×10^{-19}	39.9	1.2	310	8.62×10^9	8.1×10^{30}	4
J1355−6206	13 55 21.34	−62 06 20.1	277	3.1×10^{-18}	547	8.3	22	2.96×10^{10}	5.8×10^{30}	5
J1548−4821	15 48 23.26	−48 21 49.7	146	8×10^{-19}	126.0	4.4	360	1.09×10^{10}	1.0×10^{31}	5
J1611−5847	16 11 51.31	−58 47 42.3	355	2.0×10^{-18}	79.9	1.7	160	2.70×10^{10}	1.8×10^{30}	6
J1753−1914	17 53 35.17	−19 14 58	63	2.02×10^{-18}	105.3	2.2	130	1.14×10^{10}	3.2×10^{32}	6
J1816−5643	18 16 36.46	−56 43 42.1	218	1.93×10^{-18}	52.4	1.6	470	2.08×10^{10}	7.4×10^{30}	4
J1821+0155[b]	18 21 38.88	+01 55 22.0	34	2.94×10^{-20}	51.75	1.8	24	1.01×10^9	3.0×10^{31}	7
B1952+29	19 54 22.55	+29 23 17.3	427	1.71×10^{-18}	7.932	0.70	9	2.73×10^{10}	8.7×10^{29}	8
J2007+2722	20 07 15.83	+27 22 47.91	24	9.61×10^{-19}	127.0	5.4	250	4.91×10^9	2.6×10^{33}	9
J2235+1506	22 35 43.70	+15 06 49.1	60	1.58×10^{-19}	18.09	1.1	630	3.11×10^9	2.9×10^{31}	10

Notes.
[a] DM distance derived using the NE2001 Galactic free electron density model of Cordes & Lazio (2002).
[b] PSR J1821+0155 was discovered too recently to be included in this X-ray study.
References. (1) Lorimer et al. 2005; (2) Burgay et al. 2006; (3) D'Amico et al. 1998; (4) Jacoby et al. 2009; (5) Kramer et al. 2003; (6) Lorimer et al. 2006; (7) Rosen et al. 2013; (8) Hobbs et al. 2004; (9) Allen et al. 2013; (10) Camilo et al. 1996.

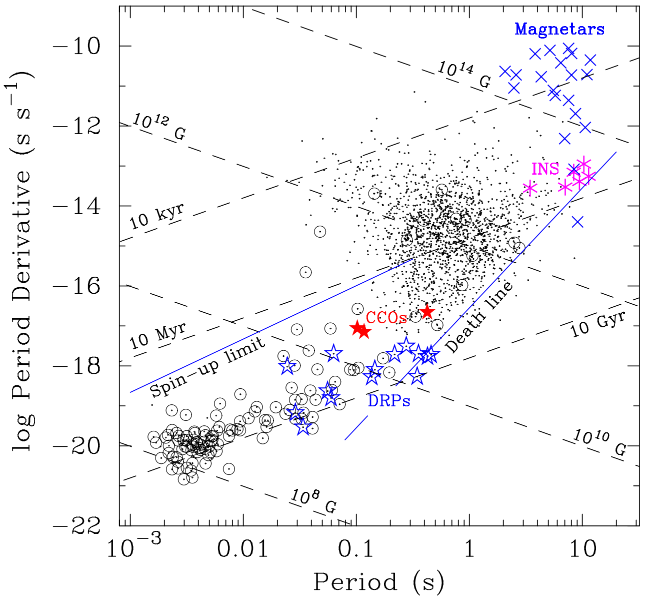

Figure 1. Pulsar populations on the P–$\dot{P}$ diagram, including magnetars (blue crosses), INSs (magenta asterisks), CCOs (filled red stars), and DRPs (open blue stars). Black dots are isolated pulsars and circled dots are pulsars in binaries. (Pulsars in globular clusters are excluded as their period derivatives are not entirely intrinsic.) Dashed lines of constant characteristic age and magnetic field are indicated.

(A color version of this figure is available in the online journal.)

In this paper, we report an X-ray search for orphaned CCOs from among the population of DRPs whose timing parameters are expected to be comparable. In Section 2, we describe the new and archival *Chandra* observations of the DRPs. Section 3 gives the resulting upper limits on their temperatures and luminosities. In Section 4, we discuss the implication of these results for the possible evolutionary tracks of CCOs.

2. OBSERVATIONS

Our targets selected for X-ray observations are the 12 radio pulsars classified as DRPs by Belczynski et al. (2010), plus the recently discovered PSR J2007+2722 (Knispel et al. 2010). These comprise all but one of the isolated pulsars in the Galactic disk with magnetic field strength $B_s < 3 \times 10^{10}$ G and spin period $P > 20$ ms listed in the Australia Telescope National Facility (ATNF) catalog[5] (Manchester et al. 2005, v1.46). Their properties are listed in Table 1. The latest DRP, PSR J1821+0155 (Rosen et al. 2013), the 14th member of the class, was discovered too recently to be included in our X-ray sample.

For 10 of these objects not already observed in X-rays, we obtained 3.5 ks *Chandra* observations to search for point-like emission at their known (sub-arcsecond) radio locations. We justified this short observing time based on its ability to detect thermal emission from a cooling NS younger than $\sim 10^5$ yr, while thermal or nonthermal emission from a $\sim 10^9$ yr old DRP would be many orders of magnitude less. Detailed calculations of the detection limits on temperature and luminosity from these observations are presented below. We also analyzed 5 ks archival exposures on PSR J0609+2130 and PSR B1952+29 and tabulate our prior results for PSR J2007+2722 (Allen et al. 2013).

All observations were taken with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003), operating in timed/faint exposure mode with the targets placed on the back-illuminated ACIS-S3 CCD. ACIS has $0\farcs5$ pixels, comparable to the on-axis point-spread function. The nominal ACIS pointing uncertainty is a radius of $0\farcs6$. All data reduction and analysis was performed with the Chandra Interactive Analysis of Observation software (Fruscione et al. 2006) version 4.5, using the calibration database version 4.1.3. The background rates for these observations showed no evidence of flaring behavior and the full exposure time was retained for analysis in each case.

3. RESULTS

Figure 2 presents *Chandra* thumbnail images in the 0.3–10 keV band centered around the radio coordinates of each DRP, excluding PSR J2007+2722 reported elsewhere (Allen et al. 2013). In these $45'' \times 45''$ sub-images, no pixel that is not definitely associated with a significant source contains more

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[5] http://www.atnf.csiro.au/research/pulsar/psrcat/expert.html

Figure 2. *Chandra* ACIS-S 0.3–10 keV X-ray images of targeted radio pulsars listed in Table 1. Each gray square is a detected count and black squares contain two counts. A nearby source to PSR J1816−5643 is evident by a cluster of counts. No X-ray sources are found within the adopted $1\farcs2$ radius *Chandra* error circle centered on the radio coordinates (crosses). The plots are $45''$ on a side; the inner dimensions of the crosses are $2''$.

than two counts in the 0.3–10 keV energy band. Examination of each image shows no evidence for a source at the radio location within twice the nominal $r = 0\farcs6$ pointing uncertainty. In fact, no counts are detected in an adopted aperture of radius $1\farcs2$ at the position of any target. This is not unexpected given the mean background rate of $\approx 1.1 \times 10^{-6}$ counts s^{-1} pixel^{-1}, uniform across the 12 observations. For this rate, the mean number of counts in a 3.5 ks observation is 0.073 in a $1\farcs2$ radius circle. There is a 93% probability of detecting no counts in that aperture for a single observation, and only a 58% chance of getting one or more counts in any of the 12 observations. In no case are the coordinates of the nearest detected X-ray source consistent with the radio location, the closest being $\approx 16''$ from PSR J1816−5643.

With no evidence of any photon at the location of each DRP, we calculate an upper limit on the thermal flux from an assumed cooling NS of radius $R_\infty = 14.5$ km, to match the radius used to derive the theoretical cooling curves discussed in Section 4. As photon counts follow the Poisson distribution, the probability of having gotten zero photons is 0.0023 when the

Table 2
Upper Limits on X-Ray Emission from DRPs

PSR Name	*Chandra* ObsID	Livetime (ks)	$N_{\mathrm{H}}^{\mathrm{DM}}$ [a] (cm^{-2})	kT_{max} [b] (eV)	$L_{\mathrm{max}}^{\mathrm{bol}}$ [b] (erg s^{-1})
J0609+2130	12687	4.99	1.2×10^{21}	49	1.6×10^{32}
J1038+0032	13801	3.50	8.2×10^{20}	50	1.6×10^{32}
J1320−3512	13797	3.42	5.1×10^{20}	43	9.4×10^{31}
J1333−4449	13800	3.42	1.4×10^{21}	54	2.4×10^{32}
J1339−4712	13799	3.42	1.2×10^{21}	52	2.0×10^{32}
J1355−6206	13806	3.42	1.7×10^{22}	135	9.0×10^{33}
J1548−4821	13805	3.42	3.9×10^{21}	84	1.3×10^{33}
J1611−5847	13802	3.41	2.5×10^{21}	62	4.1×10^{32}
J1753−1914	13803	3.42	3.3×10^{21}	69	6.2×10^{32}
J1816−5643	13804	3.42	1.6×10^{21}	57	2.9×10^{32}
B1952+29	12684	4.99	2.5×10^{20}	40	6.9×10^{31}
J2007+2722	6438, 7254, 8492	94.04	3.9×10^{21}	68	5.8×10^{32}
J2235+1506	13798	3.42	5.6×10^{20}	47	1.4×10^{32}

Notes.
[a] $N_{\mathrm{H}}^{\mathrm{DM}}$ approximated as 10×DM.
[b] Upper limit on blackbody temperature and bolometric luminosity at 99.73% confidence for a cooling NS of radius $R_\infty = 14.5$ km at the DM distance given in Table 1.

expected number of photons from a source is six. Therefore the 99.77% confidence (3σ) upper limit on the source flux is that which would predict six counts. We determine the blackbody temperature required for a fiducial source to produce six counts plus background in the detector by convolving an absorbed blackbody spectrum through the ACIS spectral response and computing the total counts in the 0.3–10 keV bandpass generated for each observation. The blackbody flux normalization is fixed by the ratio $(R_\infty/d_{\mathrm{DM}})^2$ for each target, where d_{DM} is the distance derived using the NE2001 Galactic free electron density model of Cordes & Lazio (2002). An absorbing column density $N_{\mathrm{H}}^{\mathrm{DM}}$ is estimated from the dispersion measure (DM) assuming a rule-of-thumb $N_{\mathrm{H}}^{\mathrm{DM}}/N_e \approx 10$, i.e., $N_{\mathrm{H}}^{\mathrm{DM}} = 10\times\mathrm{DM}$ (He et al. 2013). Table 2 presents the upper limits computed in this way on the blackbody temperature and bolometric luminosity of each pulsar, quantities measured at infinity. These generally correspond to T_{max} in the range of $(5–8) \times 10^5$ K and $\log L_{\mathrm{max}}^{\mathrm{bol}}[\mathrm{erg\ s^{-1}}] = 31.8–32.8$. The two outliers are PSR J1355−6206 and PSR J1548−4821, which are less constrained because of their large distances and $N_{\mathrm{H}}^{\mathrm{DM}}$.

The uncertainties on these upper limits are dominated by systematic errors involving the DM-derived distances and column densities. DM distance can have fractional uncertainty of 25% or larger (e.g., Camilo et al. 2009). The neutral column density estimated using a typical ionized fraction involves another uncertain assumption. Furthermore, an error on N_{H} amplifies the error on the temperature measurement, which comes from the low-energy end of the ACIS-S instrument response, around 0.3 keV, where the detector sensitivity falls off rapidly and is poorly calibrated. Unfortunately, these effects are difficult to quantify.

We repeat, for completeness, that we would not expect to detect any of the DRPs if they are old, rotation-powered NSs with spin-down power $\dot{E}$. For comparison, we can use the dozen old pulsars whose X-ray detections were compiled by Posselt et al. (2012a). These typically have $L_x(1–10\,\mathrm{keV}) \sim 10^{-3}\,\dot{E}$ with a scatter of a factor of 10. The same X-ray efficiency for the DRPs would produce $L_x \sim 10^{27}–10^{30}$ erg s^{-1}, which is orders of magnitude below our upper limits.

4. DISCUSSION

The upper limits on the temperature and luminosity of each DRP can be compared with standard (minimal) NS cooling curves (e.g., Page et al. 2009) to place a lower limit on the DRPs age. These limits depend strongly on uncertain variables such as the critical temperature for superfluid neutron pairing and the composition of the NS envelope, which is why there cannot be a unique age limit for each entry in Table 2. Roughly speaking, a luminosity limit of $\log L_{\mathrm{max}}[\mathrm{erg\ s^{-1}}] = 32.8$ requires an age of $\tau > 10^4$ yr for heavy element envelopes and $\tau > 3 \times 10^4$ yr for light elements, while $\log L_{\mathrm{max}}[\mathrm{erg\ s^{-1}}] = 31.8$ implies that $\tau > 5 \times 10^4$ yr (light) or $\tau > 2 \times 10^5$ yr (heavy). The cooling curves for light and heavy element envelopes cross over in this range of luminosities. The upper limits on temperatures and luminosities for the DRPs (with the possible exception of PSR J1355−6206) are smaller than those of all CCOs but one. In no case does a DRP overlap in possible age with the SNR ages of the known CCOs, which are 300–7000 yr. The dozen DRPs fail to qualify as evolved CCOs in the age range that is, roughly speaking, 10 times the ages of the known CCOs, where we expect their descendants to be 10 times as numerous.

The implication of these X-ray non-detections of DRPs for the evolution of CCOs depends on the volume sampled by the surveys that discovered both populations and their relative completeness. Both are difficult to evaluate; however, the volumes appear to be at least comparable. The ≈10 CCOs are found in SNRs up to a maximum distance of $\lesssim 8$ kpc, and the DRPs appear to have a similar distribution of distance and Galactic coordinates. Therefore, the absence of radio pulsar counterparts of orphaned CCOs appears to be real, at least in the range of magnetic field strengths that define the DRPs. Belczynski et al. (2010) noted that roughly four of the DRPs so defined could actually be interlopers from the population of normal pulsars, as extrapolated from the statistics of studies such as Faucher-Giguère & Kaspi (2006). However, as we argued previously, it may not be possible to make such a distinction. In any case, it would not change our conclusion regarding the fate of CCOs, which is that there are no known radio pulsars with $B_s < 3 \times 10^{10}$ G that are their immediate, $\tau < 10^5$ yr old descendants where we would expect to find $\sim 10^2$ orphans.

Another clue to the age of DRPs should be their distribution of heights z above the Galactic plane as listed in Table 1. However, as discussed by Belczynski et al. (2010), these heights are smaller than one would expect for the average NS kick velocity of 265 km s^{-1} (Hobbs et al. 2005), which makes it difficult to use z as an indicator of age for DRPs. At this velocity, an NS would travel only 270 pc in 10^6 yr, implying that X-ray-detected orphaned CCOs could have a similar z height as the DRPs, which are thought to be much older. Since they are old, the small scale height of the DRPs still requires an explanation. Belczynski et al. (2010) propose that the first SN in the parent binary was of a different type that would give little or no kick to the system, perhaps an electron-capture SN.

A priori, one might not have expected DPRs to be orphaned CCOs. As it is, there are not enough DRPs compared to double NS systems according to standard evolutionary models that link them (Belczynski et al. 2010). Any DRP that is reassigned to a different population would only exacerbate this shortage. Still, the evolutionary fate of CCOs remains unknown after this survey.

One possible solution is that radio luminosity is a declining function of spin-down power. If so, radio surveys could be grossly incomplete in detecting such low $\dot{E}$ pulsars, even though they are on the active side of the radio pulsar death line. There is good evidence that ordinary radio pulsars behave this way, with $L_r \propto \dot{E}^{1/2}$ (Faucher-Giguère & Kaspi 2006), because there is no pileup in the number of pulsars near the death line. However, it is not clear that this effect alone could explain the absence of orphaned CCOs because there are, in fact, many radio pulsars with lower $\dot{E}$ than the CCO pulsars. Such an effect may also apply to the seven *ROSAT*-discovered, radio-quiet isolated neutron stars (INSs; Haberl 2007) that have strong magnetic fields (Kaplan & van Kerkwijk 2009) but are close to the radio pulsar death line. The INSs (Figure 1) are a good analogy to our problem in that they *are* plausibly the descendants of the magnetars, following a fast epoch of magnetic field decay around $\sim 10^4$ yr (Colpi et al. 2000). It is likely that the INSs are kept hot for longer than CCOs by their continuing magnetic field decay for up to $\sim 10^6$ yr (Pons et al. 2007), which could account for their abundance relative to the elusive orphaned CCOs.

It may be difficult to detect and/or recognize orphaned CCOs if they cool faster than ordinary NSs. One effect that can accelerate cooling is an accreted light-element envelope, which has higher heat conductivity than an iron surface (Kaminker et al. 2006). However, this effect actually makes CCOs hotter than bare NSs for their first 10^5 yr, after which their temperatures plummet. Therefore, the prediction that CCO descendants should be detectable in soft X-rays remains robust.

Another plausible home for orphaned CCOs would be among the radio pulsars with magnetic fields comparable to or higher than those of the CCO pulsars. One theory for CCOs postulates that they are born with a canonical NS magnetic field of $\sim 10^{12}$ G that was largely buried by fall-back of a small amount of SN ejecta, $\sim 10^{-5}$–10^{-4} $M_\odot$, during the hours and days after the explosion. The buried field will diffuse back to the surface on a time scale that is highly dependent on the amount of mass accreted (Muslimov & Page 1995; Ho 2011; Viganò & Pons 2012; Bernal et al. 2013), after which the CCOs will join the bulk of the population of ordinary pulsars. For an accretion of $\sim 10^{-5}$ $M_\odot$, the regrowth of the surface field is largely complete after $\sim 10^3$ yr, but if >0.01 $M_\odot$ is accreted, then the diffusion time could be millions of years.

Such a scenario addresses the absence of CCOs descendants; they turn into ordinary pulsars. It also has the advantage of not requiring yet another class of NS to exist that would only exacerbate the apparent excess of pulsars with respect to the Galactic core-collapse SN rate, a problem emphasized by Keane & Kramer (2008). Furthermore, magnetic field growth has long been considered a reason why measured pulsar braking indices are all less than the dipole value of 3. In this picture, CCOs represent one extreme in the evolution of surface magnetic field and almost any radio pulsar *might* be a former CCO. Finally, an intrinsically strong crustal magnetic field appears to be necessary to explain the existence of the thermal hot spots that enable us to detect pulsations from CCOs in the first place (see discussion in Gotthelf et al. 2013).

For the first $\sim 10^5$ yr, rapid field growth can only move a CCO vertically upward in the $P - \dot{P}$ diagram. Such movement is difficult to detect directly using CCOs because it would require measuring the braking index or observing the change of the dipole magnetic field spectroscopically, neither of which is likely to be possible if the relevant time scale is $\geqslant 10^3$ yr. However, during their first 10^5 yr, orphaned CCOs in this scenario should still have periods of ~ 0.1–0.5 s and could have magnetic fields in the range of 3×10^{10}–3×10^{11} G. A search of all 159 isolated radio pulsars in this range for thermal X-ray emission from such "old" pulsars would provide a promising avenue for finding orphaned CCOs. Of these, two are known X-ray sources, the faint ($\sim 10^{29}$ erg s^{-1}) nearby radio pulsars PSR B1451−68 and PSR B0950+08. X-rays from these sources are attributed to a combination of heated polar caps and non-thermal (magnetospheric) emission (Posselt et al. 2012b; Zavlin & Pavlov 2004). If further X-ray surveys of radio pulsars fail to find any orphaned CCOs, then it will be difficult to escape the conclusion that they are intrinsically radio quiet.

5. CONCLUSIONS

Following the discovery that CCOs have weaker magnetic fields than any other young pulsar, it became apparent that their descendants were not obviously present in radio or X-ray surveys. If their magnetic fields at birth are intrinsic and do not change with time, then the region around the CCOs in the $(P, \dot{P})$ diagram of radio pulsars should be densely populated with all of their descendants unless they are radio quiet. The fact that this area is quite sparsely populated led us to survey a large fraction of the available radio candidates in X-rays, those which were previously understood to be mildly recycled pulsars. The "smoking pulsar" evidence of an orphaned CCO should be an X-ray hot NS that could be detected, in a short observation, at an age of up to 10^5 yr, which is much younger than the characteristic ages of the targeted DRPs but much older than the known CCOs. Only upper limits on their thermal X-ray luminosities were found, in the range of $\log L_x[\mathrm{erg\ s^{-1}}] = 31.8$–$32.8$, which implies cooling ages $> 10^4$–10^5 yr.

Up to the age limits implied by the X-ray non-detections, there should be ~ 100 CCO descendants in the volume sampled by radio pulsar surveys. Since none have been found among radio pulsars with $B_s < 3 \times 10^{10}$ G, the next step should be to search for young, cooling NSs among the radio pulsars with larger B-fields, comparable to or even larger than that of the CCO 1E 1207.4−5209, with $B_s = 1 \times 10^{11}$ G. An especially interesting possibility is that CCOs have intrinsically strong B-fields that were promptly buried by a small amount of SN debris, but will grow back to "normal" strength in $\sim 10^4$ yr. If such descendants of CCOs are found in thermal X-rays among the ordinary radio pulsar population, it would help solve problems about their surface thermal patterns in addition to their evolution. Otherwise, if the orphaned CCOs are truly radio silent for some unknown reason, they could still be found in more sensitive all-sky surveys in soft X-rays, analogous to the (evidently more luminous) INSs that were discovered this way.

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