CCO Pulsars as Anti-Magnetars:
Evidence of Neutron Stars Weakly Magnetized at Birth

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Abstract. Our new study of the two central compact object pulsars, PSR J1210–5226 (P = 424 ms) and PSR J1852+0040 (P = 105 ms), leads us to conclude that a weak natal magnetic field shaped their unique observational properties. In the dipole spin-down formalism, the 2-sigma upper limits on their period derivatives, < 2 × 10^{-10} for both pulsars, implies surface magnetic field strengths of \( B_s < 3 \times 10^{-11} \) G and spin periods at birth equal to their present periods to three significant digits. Their X-ray luminosities exceed their respective spin-down luminosities, implying that their thermal spectra are derived from residual cooling and perhaps partly from accretion of supernova debris. For sufficiently weak magnetic fields an accretion disk can penetrate the light cylinder and interact with the magnetosphere while resulting torques on the neutron star remain within the observed limits. We propose the following as the origin of radio-quiet CCOs: the magnetic field, derived from a turbulent dynamo, is weaker if the NS is formed spinning slowly, which enables it to accrete SN debris. Accretion excludes neutron stars born with both \( B_s < 10^{-11} \) G and \( P > 0.1 \) s from radio pulsar surveys, where such weak fields are not encountered except among very old (> 40 Myr) or recycled pulsars. We predict that these birth properties are common, and may be attributes of the youngest detected neutron star, the CCO in Cassiopeia A, as well as an undetected infant neutron star in the SN 1987A remnant. In view of the far-infrared light echo discovered around Cas A and attributed to an SGR-like outburst, it is especially important to determine via timing whether Cas A hosts a magnetar or not. If not a magnetar, the Cas A NS may instead have undergone a one-time phase transition (corequake) that powered the light echo.

Keywords: central compact objects, neutron stars, pulsars, supernova remnants

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INTRODUCTION TO CCO PULSARS

The discovery in recent years of many isolated neutron stars (NSs) at the centers of supernova remnants (SNRs) confirms the long-held notion that these ultradense stellar remnants are born in supernova explosions. Most NSs are identified as pulsars, whose emission derives either from rotational energy loss, as for the rapidly spinning pulsars in the Crab (\( P = 33 \) ms) and Vela (\( P = 89 \) ms) remnants, or from magnetic field decay, as posited for the highly magnetized (\( 10^{14} \lesssim B_s \lesssim 10^{15} \) G) anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). However, the nature of a significant fraction of the young (\( \lesssim 10^4 \) yrs) NSs in SNRs is uncertain. These so-called central compact objects (CCOs) are seemingly isolated NSs, distinguished by their steady flux, predominantly thermal X-ray emission, lack of optical or radio counterparts, and absence of a pulsar wind nebula (see review by Pavlov et al. [2]).

The properties of eight confirmed and proposed CCOs are summarized in Table 1. (We omit the unique source 1E 161348−5055 at the center of RCW 103 because its large-amplitude variability violates the adopted definition.) CCO luminosities are typically \( 10^{33} \) erg s\(^{-1}\), similar to the younger pulsars; however, their spectra are best characterized as hot blackbody emission of \( kT_{BB} \sim 0.4 \) keV, or two such components. This is significantly hotter than the surfaces of radio pulsars or other radio-quiet NSs and corresponds to only a small fraction of the NS surface area, with \( R_{BB} \sim 0.7 \) km.

Here we summarize new results on two unique pulsars that were initially identified as CCOs. Their properties, listed in Table 2, are strikingly different from both the traditional radio pulsars and the magnetars. The lack of a measurable period derivative requires that they have:

- small natal magnetic fields (\( \lesssim 10^{11} \) G),
- slow initial spin periods very near to their present values (\( > 0.1 \) s), and
- X-ray luminosities powered by internal cooling, and possibly by accretion of supernova (SN) debris.

We predict that these properties will come to characterize the CCO class of young neutron stars in general. This can be tested with more sensitive searches for pulsations from those objects listed in Table 1.

PSR J1210−5226 in SNR PKS 1209−51/52

The central source 1E 1207.4−5209 in the SNR PKS 1209−51/52 (Fig. 1) is the most intensively studied of the CCOs. It acquired special importance as the first CCO detected as a pulsar [8, 28]. It was distinguished again as the first isolated NS to display strong...
absorption lines in its X-ray spectrum [27, 8, 10]. We have made a comprehensive study of all X-ray timing data on 1E 1207.4–5209 (PSR J1210–5226) [25], showing that its rotation is highly stable (Fig. 2), with \( P = 424.130749(4) \text{ ms} \) and \( P = (6.6 \pm 9.0) \times 10^{-17} \) (1σ errors), superseding previous claims of large period changes in the same data [28, 29]. In the dipole spin-down formalism, the 2σ upper limit on \( P \) implies a spin-down luminosity \( \dot{E} = -I Q \Omega < 1.3 \times 10^{33} \text{ erg s}^{-1} \), surface magnetic field strength \( B_s < 3.3 \times 10^{11} \text{ G} \), and characteristic age \( \tau_c = P/2P > 27 \text{ Myr} \). This lower limit on \( \tau_c \) exceeds the SNR age by at least 3 orders of magnitude, requiring that the pulsar was born spinning at its present period to three significant digits. The X-ray luminosity of 1E 1207.4–5209, \( L_{\text{bol}} \approx 2.1 \times 10^{33} (d/2 \text{ kpc})^2 \text{ erg s}^{-1} \), exceeds its \( \dot{E} \), implying that \( L_{\text{bol}} \) derives from residual cooling, and perhaps partly from accreting SN debris.

**TABLE 1. Central Compact Objects in Supernova Remnants**

| CCO                 | SNR    | Age   | \( d \) | \( P \)  | \( \dot{P} \)  | \( \dot{E} \)  | References |
|---------------------|--------|-------|---------|---------|-------------|-------------|------------|
| RX J0822.0–4300     | Puppis A | 3.7   | 2       | ...     | < 5         | 5 \times 10^{33} | [3]        |
| CXOU J085201.4–61753| G266.1–1.2 | 1     | 1       | ...     | < 13        | 2.5 \times 10^{32} | [4, 5, 6, 7] |
| 1E 1207.4–5209      | PKS 1209–51/52 | 7     | 2       | 424     | 9           | 2.1 \times 10^{33} | [8, 9, 10, 11] |
| CXOU J16103.1–51353 | G330.2–1.0 | \( \geq 3 \) | 5       | ...     | 1.0 \times 10^{33} | \( \leq 12 \) |
| IWGA J1713.4–3949   | G347.3–0.5 | 1.6   | 1.3     | ...     | < 25        | 1 \times 10^{33} | [13, 14] |
| CXOU J181852.0–150213| G15.9+0.2 | 1–3   | 8.5     | ...     | ...         | 1 \times 10^{33} | [15] |
| CXOU J185238.6+04020 | Kes 79 | 7     | 7       | 105     | 80          | 3.3 \times 10^{33} | [16, 17, 18] |
| CXOU J23237.9+584824 | Cas A  | 0.33  | 3.4     | ...     | < 27        | 2.6 \times 10^{33} | [19, 20, 21, 22] |

* Upper limits on pulse fraction are for a search down to \( P = 12 \text{ ms} \) or smaller.

**TABLE 2. Spin Parameters of CCO Pulsars**

| Parameter | PSR J1209–5226 | PSR J1852+0040 |
|-----------|----------------|----------------|
| \( P \)  | 424.1307       | 104.9126       |
| \( P (10^{-17} \text{ s}^{-1}) \) | 6.6 \pm 9.0 | -34 \pm 27 |
| \( \dot{E} (10^{32} \text{ erg s}^{-1}) \) | < 1.3 | < 70 |
| \( L_{\text{bol}}/\dot{E} \) | > 15 | > 0.5 |
| \( B_1 (10^{11} \text{ G}) \) | < 3.3 | < 1.5 |
| \( \tau_c \) (Myr) | > 27 | > 8 |
| SNR age (kyr) | \sim 7 | \sim 7 |
| Reference | [26] | [18] |

* 2σ limit assuming magnetic dipole spin-down.

CCO pulsars then highlights the difficulty of existing theories to explain the high luminosities and temperatures of CCO thermal X-ray spectra. Their X-ray luminosities are a large fraction of their \( \dot{E} \), challenging the rotation-powered assumption, and greater than their reservoirs of B-field energy, refuting the magnetar hypothesis.

**ACCRETING AND/OR COOLING**

Instead, the high blackbody temperatures (\( kT_{\text{BB}} \sim 0.4 \text{ keV} \)) and small blackbody radii (\( R_{\text{BB}} \sim 0.7 \text{ km} \)) of CCOs may be evidence of accretion onto a polar cap, possibly from a fallback disk of SN debris. Interior cooling models, even with anisotropic conduction, do not make such a concentrated hot spot. We [18] proposed this as the origin of CCOs: Magnetic field is generated by a turbulent dynamo whose strength depends on the rotation rate of the proto-neutron star [31, 32], so the magnetic field strength would be inversely correlated with the initial period. If \( P \) is large and \( B_1 \) is small, accretion of SN debris is possible. Accretion excludes neutron stars born with both \( B_1 < 10^{11} \text{ G} \) and \( P > 0.1 \text{ s} \) from radio pulsar surveys, where \( B_1 < 10^{11} \text{ G} \) is not found except in very old (\( \tau_c > 40 \text{ Myr} \)) or recycled pulsars.

PSR J1852+0040 in SNR Kes 79

We also discovered pulsations from a second CCO, in the SNR Kes 79 [17] (Fig. 3). Our follow-up program to time PSR J1852+0040 produced a remarkable result: no change in its 105 ms period over 2.4 yr [18]. From the data shown in Figure 4, we derived a 2σ upper limit of \( P < 2.0 \times 10^{-16} \), which leads to a spin-down luminosity \( \dot{E} < 7 \times 10^{33} \text{ erg s}^{-1} \), surface magnetic field strength \( B_s < 1.5 \times 10^{11} \text{ G} \), and characteristic age \( \tau_c > 8 \text{ Myr} \). Again, this implies that the pulsar was born spinning at its current period, with a weaker B-field than that of any other young pulsar.

These are the only two NSs whose initial rotation periods are so precisely inferred. They are longer than what was once thought typical, but in fact are consistent with recent statistical analyses of the radio pulsar population, e.g., Faucher-Giguère & Kaspi [30] who favor a wide distribution of birth periods (Gaussian mean \( P \sim 300 \text{ ms} \) and \( \sigma_P \sim 150 \text{ ms} \)). The absence of spin-down for both
Another clue to the nature of CCOs is the soft X-ray spectrum of 1E 1207.4−5209. It has broad absorption lines centered at 0.7 keV and 1.4 keV \[27, 28, 10, 11\]. Our upper limit, \(B_s < 3.3 \times 10^{11} \) G, favors the electron cyclotron model \[10, 11\], for at least one of the lines, over all others that require stronger fields. The basic cyclotron prediction, \(B_s = 8 \times 10^{10} \) G, assumes that 0.7 keV is the fundamental energy \(E_c = 1.16(B_s/10^{11} \text{G})/(1+z) \) keV, where \(z\) is the gravitational redshift. Another solution postulates hydrogenic oxygen for the 0.7 keV line, while the 1.4 keV line is the cyclotron fundamental \[33, 34\]. As the authors of the latter hypothesis pointed out, abundant oxygen may be accreted from SN debris.

Accretion from a fallback disk of SN debris in the propeller regime has been considered for CCOs by several authors \[35, 36, 28, 37, 38\]. We propose that this may be the first phase in the life of those neutron stars born rotating slowly with weak magnetic fields. The X-ray luminosity of CCOs, or possibly just their hot spots, can be powered by accretion of \(\dot{m} \approx 3 \times 10^{13} \text{ g s}^{-1}\), or only \(\approx 0.1\) lunar masses of supernova debris over their \(\sim 7 \text{ kyr}\) lifetimes. The main barrier to disk accretion is the speed-of-light cylinder, of radius \(r_\ell = cP/2\pi\). If an accretion disk cannot penetrate the light cylinder, the NS cannot interact with the disk, and it behaves as an isolated pulsar. But if \(B_s\) is as small as \(10^{10} \) G, accretion at a rate \(\dot{M} \geq 10^{13} \text{ g s}^{-1}\) can penetrate the light cylinder to the magnetospheric radius \(r_m\), since \(r_m < r_\ell\) in this case.
so, the system is in the propeller regime, in which matter flung out from $r_m$ at a rate $\dot{M}$ takes angular momentum from the NS, causing it to spin down. In the case of PSR J1852$+0040$, we estimated the propeller spin-down rate as

$$P' \approx 2.2 \times 10^{-16} P_{28}^{8/7} M_{13}^{-1/7} \left( \frac{M}{M_\odot} \right)^{-2/7} \times I_{45}^{-1} \left( \frac{P}{0.105 \text{s}} \right) \left( 1 - \frac{P}{P_{\text{eq}}} \right)$$

(1)

using the prescription of Menou et al. \[53\]. Here $I \approx 10^{45}$ g cm$^2$ is the NS moment of inertia, $\mu = B_r R^3 \approx 10^{28}$ G cm$^3$, and $P_{\text{eq}}$ is the equilibrium, or minimum period for disk accretion. Appropriate scaling for the 0.424 s period of 1E 1207.4$-5209$ can be substituted in equation (1). These predictions for accretion are close to the observed upper limits on $\dot{P}$ (Table 2).

We distinguish here between $\dot{M}$, the matter expelled that is responsible for the torque on the NS, and $\dot{m} \approx 3 \times 10^{13}$ g s$^{-1}$, the matter accreted, which is responsible for the X-ray emission from the surface, presumably at a magnetic pole of the NS. For the propeller model to be self-consistent, $\dot{M}$ must be $> \dot{m}$, which is possible according to equation (1) as long as $B_r < 10^{10}$ G. In X-ray binaries, the propeller effect does not necessarily preclude accretion onto the NS surface. The disposition of material leaving the inner edge of the accretion disk is not well understood, and many authors, e.g., Rappaport et al. \[40\], consider that accretion onto the NS can proceed even in the propeller (fast pulsar) regime. We adopt that point of view here. Accreting X-ray binary pulsars are often found in near equilibrium states where $P$ changes sign without changing luminosity. Equation (1) may then represent the typical magnitude of $P'$, independent of sign, albeit at an accretion rate 4–5 orders of magnitude less than in binaries.

Whether CCO pulsars are accreting or not, the conclusion that they have weak magnetic fields is unavoidable. The hypothesis of dipole spin-down can be quantified by measuring $P$ using phase-coherent timing, the only method that is effective in a reasonable time span for detecting such small $B$-fields. A steady, positive $P'$ will yield $B_r$ via the dipole spin-down formula, $B_r = 3.2 \times 10^{19} (P' P)^{1/2}$. But if the pulsars show episodes of fluctuating or negative $P'$, that will be evidence of accretion, i.e., torque noise.

Existing data cannot (yet) be used to accomplish these tests because they were not densely spaced enough to span gaps of several months with a coherent timing solution free of cycle count uncertainties. But a carefully planned sequence of new observations can be used to fit a coherent ephemeris that will bootstrap the historical data into a phase-linked timing solution spanning 4.5 years for PSR J1852$+0040$, and 10 years for PSR J1210$-5226$, which will improve the sensitivity to $P$ by 3 orders of magnitude over the limits in Table 2, reaching limits of $B_r \sim 10^{10}$ G.

**ARE THERE YOUNGER CCOs?**

CCOs represent a significant fraction of young NSs. Here, we propose that their birth properties are common enough to be a likely explanation for the inconspicuous nature of the two youngest NSs, the CCO in Cas A, and an undetected pulsar in the SN 1987A remnant.

**Cas A: Magnetar or Anti-Magnetar?**

The Cas A CCO is the youngest known NS (327 yr); the SN was probably seen by Flamsteed in 1680, which agrees with the measured convergent date of the SNR ejecta \[41\]. The simple argument that CCOs are born spinning at their current periods, and with their current magnetic field strengths, implies that their luminosities need not decrease substantially since birth. Only their interior cooling would reduce their soft X-ray emission. The Cas A CCO is characterized, like the others, by its steady X-ray luminosity of $\approx 2.6 \times 10^{33}$ erg s$^{-1}$, compared to $\sim 10^{35}$ erg s$^{-1}$ for magnetars.

Nevertheless, despite the strong evidence that CCO pulsars have weak magnetic fields, there is circumstantial evidence that Cas A may host a magnetar. Rapidly moving IR features detected by the Spitzer Space Telescope outside Cas A were interpreted as a light echo from a beamed, high-energy flare some 55 years ago that is heating the surrounding interstellar dust \[42\]. An SGR-like outburst of $\sim 2 \times 10^{46}$ erg (isotropic equivalent) would have been required to explain the reprocessed IR luminosity. Until recently, a quiescent magnetar was a favored hypothesis for the nature of the Cas A point source.

However, the magnetar hypothesis implies that the present rotation period of the 327 old pulsar is $P \approx 0.45(B_r/10^{14} \text{ G})$ s, assuming that its initial period $P_0 \ll P$, which also requires that $E \approx 9.5 \times 10^{36}(B_r/10^{14} \text{ G})^{-2}$ erg s$^{-1}$. Cas A could therefore have a spin-down luminosity that exceeds the typical $10^{35}$ erg s$^{-1}$ X-ray luminosity of all other magnetars. Such a large spin-down luminosity is almost always accompanied by substantial non-thermal X-ray luminosity, of order $10^{-3} E$, including a resolvable pulsar wind nebula. The absence of any X-ray evidence of such energetic spin-down argues against the presence of a typical magnetar $B$-field in the Cas A point source.

Thus, Cas A is the focus of sharply contradictory evidence about the birth properties of CCOs: their natal magnetic field strengths and initial spin periods. Apart
from waiting for an SGR or AXP-like outburst (which may never occur), the only way to resolve whether Cas A hosts a transient magnetar or an “anti-magnetar” is by direct measurement of its spin properties. A pulsar in Cas A will reveal the spin period and dipole B-field of a NS at an age that is only a few percent of the known AXPs’ and CCOs’ ages, providing a correspondingly more secure representation of their initial values. If the magnetar hypothesis is not confirmed, it may imply that the high-energy flare was powered by a one-time event in Cas A, a first-order phase transition (corequake) [43], e.g., to a pion or kaon condensate or deconfined quarks. That would be a remarkable outcome.

Is there a CCO in SN 1987A?

It has long been known that the non-detection of a pulsar in SN 1987A can be explained if the NS was born with a weak B-field or a long rotation period [44, 45]. Now, we have established that a CCO can have both, which gives it essentially the same spin-down luminosity at birth that it has at an age of 10^4 yr. This means that a CCO can emit less than the observed limits from SN 1987A even if 100% of its spin-down power is reprocessed into IR emission by dust in the surrounding SN ejecta. The observed luminosity limits for a point source inside the ring of SN 1987A are – in X-rays: $L_x(2-10\text{ keV}) < 1.5 \times 10^{34} \text{ erg s}^{-1}$ corrected for extinction [46], in the visible range: $L(2900-9650 \ \mu \text{m}) < 8 \times 10^{33} \text{ erg s}^{-1}$ corrected for dust absorption [47], and at mid-IR wavelengths: $L(10 \ \mu \text{m}) < 1.5 \times 10^{36} \text{ erg s}^{-1}$ for dust emitting at $T \approx 90-100 \ \text{K}$ [48]. This mid-IR luminosity can be accounted for by radioactive decay of $^{44}$Ti, and therefore represents a very conservative upper limit on the spin-down power of an embedded pulsar. At an age of 10 – 20 yr, a cooling NS need emit only $\approx 3 \times 10^{34} \text{ erg s}^{-1}$ of soft X-rays at a temperature of 2.5 $\times 10^6 \text{ K}$ [49], some of which is absorbed by SN ejecta or ISM in the LMC. So we conclude that a CCO is a promising model for an unseen NS in SN 1987A. Given the lack of any other NS signatures from CCOs, a continuing search for surface thermal X-ray emission as the ejecta thin out is perhaps the best hope of detecting the NS in SN 1987A, even though it is becoming more difficult as the SNR brightens dramatically.

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