The First Glitch in a Central Compact Object Pulsar: 1E 1207.4–5209

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Abstract

Since its discovery as a pulsar in 2000, the central compact object (CCO) 1E 1207.4–5209 in the supernova remnant PKS 1209–51/52 had been a stable 0.424 s rotator with an extremely small spin-down rate and weak \( B \approx 9 \times 10^{10} \) G surface dipole magnetic field. In 2016 we observed a glitch from 1E 1207.4–5209 of at least \( \Delta f / f = (2.8 \pm 0.4) \times 10^{-9} \), which is typical in size for the general pulsar population. However, glitch activity is closely correlated with spin-down rate \( f \), and pulsars with \( f \) as small as that of 1E 1207.4–5209 are never seen to glitch. Unlike in glitches of ordinary pulsars, there may have been a large increase in \( f \) as well. The thermal X-ray spectrum of 1E 1207.4–5209, with its unique cyclotron absorption lines that measure the surface magnetic field strength, did not show any measurable change after the glitch, which rules out a major disruption in the dipole field as a cause or result of the glitch. A leading theory of the origin and evolution of CCOs, involving the prompt burial of the magnetic field by the fallback of supernova ejecta, might hold the explanation for the glitch.

Key words: pulsars: individual (1E 1207.4-5209) – stars: neutron

1. Introduction

The group of \( \approx 10 \) central compact objects (CCOs) in supernova remnants (SNRs) are defined by their steady surface thermal X-ray emission, lack of surrounding pulsar wind nebula, and nondetection at any other wavelength. Of the eight well-established CCOs, three were found to be pulsars (Zavlin et al. 2000; Gotthelf et al. 2005; Gotthelf & Halpern 2009). Their spin-down properties provide an estimate of surface dipole magnetic field strength via \( B = 3.2 \times 10^{8} \sqrt{-f / f_{3}} \) of \( (2.8, 3.1, 9.8) \times 10^{10} \) G (Halpern & Gotthelf 2010; Gotthelf et al. 2013a), two orders of magnitude less than those of canonical young pulsars. The homogeneous X-ray properties of the remaining CCOs that have not yet been seen to pulse suggest that they have similar or even weaker magnetic fields than the known CCO pulsars, or a more uniform surface temperature, or a more aligned geometry. The fact that CCOs are found in SNRs in comparable numbers to other classes of young neutron stars (NSs) implies that they must represent a significant fraction of NS births.

1E 1207.4–5209 in the SNR PKS 1209–51/52 is the first CCO pulsar discovered (Zavlin et al. 2000) and the most intensively studied. It is also the first isolated NS to display strong absorption lines in its X-ray spectrum (Mereghetti et al. 2002; Sanwal et al. 2002; Bignami et al. 2003; De Luca et al. 2004). The evenly spaced spectral features are widely accepted as the electron cyclotron fundamental at \( E_{0} = 0.7 \) keV and its harmonics in a magnetic field of \( B \approx 8 \times 10^{10} \) G. (More precisely, these features are due to quantum oscillations in the free–free opacity; Suleimanov et al. 2010). This is the first measurement of the surface magnetic field on a CCO by a direct technique that is independent of timing, and the result is fully consistent with the magnetic field inferred from its spin down, \( B_{y} = 9.8 \times 10^{10} \) G.

In a series of papers (Gotthelf & Halpern 2007; Halpern & Gotthelf 2011; Gotthelf et al. 2013a; Halpern & Gotthelf 2015) we have followed the long-term timing properties of 1E 1207.4–5209 which, until 2014, showed steady spin down with no evidence of timing noise or glitches. Glitches are sudden increases in spin frequency that are thought to result from either “starquakes,” stress relief of the NS crust (e.g., Link et al. 1998), or the sudden unpinning and repinning of neutron superfluid vortices in the inner crust (Alpar et al. 1984). Glitch activity among pulsars is correlated mainly with frequency derivative, such that pulsars with \( |f| \) as small as those of CCOs have never been seen to glitch (Espinoza et al. 2011; Fuentes et al. 2017). Nevertheless, interior properties of CCOs may be similar to those of canonical young pulsars, which may cause them to glitch (Ho 2015).

We present new observations of 1E 1207.4–5209 in 2016–2018 that detect a glitch for the first time in a CCO. In Section 2, we describe the new X-ray timing observations. Section 3 details the timing properties of the detected glitch, while Section 4 compares the pre- and post-glitch spectrum and flux to search for any changes. In Section 5, we compare the properties of this glitch to the ensemble of measured NS glitches, and discuss its implications for theories of the internal structure and evolution of CCOs. An alternative model of accretion-torque fluctuations is also briefly considered. Conclusions and suggestions for follow-up work are described in Section 6.

2. New X-Ray Observations

In the course of monitoring 1E 1207.4–5209 we found that the phase of the pulsar measured in 2016 July no longer followed the prediction of the prior ephemeris. We obtained a new set of XMM-Newton observations to confirm the glitch and to characterize its properties. Six observations in 2017 June–December were used to bootstrap a new timing solution. Then we began semi-annual XMM-Newton observations in 2017 and 2018 that supplement our annual Chandra monitoring. A log of the observations obtained since 2016 is presented in Table 1. Here we describe these data sets.

We concentrate on XMM-Newton data obtained with the European Photon Imaging Camera (EPIC) pn and MOS detectors. Data from the Reflection Grating Spectrometers are not used in this work. The EPIC pn (Strüder et al. 2001) sits at the focal plane of a coaligned, multinedest foil mirror with an on-axis point-spread function with FWHM of \( \approx 12^{7/5} \) at...
1.5 keV. The EPIC instruments are sensitive to X-rays in the 0.15−12 keV range with a moderate energy resolution of $E/\Delta E(\text{pn}) \sim 20$−50. In order to resolve the 0.424 s pulse of 1E 1207.4−5209, the EPIC pn data were obtained in PrimeSmallWindow mode ($4\times3 \times 4\times3$), which has high time resolution of 6 ms at the expense of 29% dead time. Data acquired with the two MOS detectors (Turner et al. 2001) were obtained in PrimePartialWindow mode on the central charged coupled device (CCD) with a 1/8 × 1/8 field of view. The time resolution in this mode is 0.3 s, insufficient to resolve the pulsations of 1E 1207.4−5209. The MOS cameras, less sensitive at the lower energy range of 1E 1207.4−5209, were used only to confirm the EPIC pn spectral results.

The XMM-Newton data were reduced and analyzed using the Standard Analysis Software (SAS) version 15.0.0 with the most up-to-date calibration files. After filtering out background flares we obtained the usable exposure times listed in Table 1. For the timing analysis all photon arrival times were converted to barycentric dynamical time (TDB) using the DE405 solar system ephemeris and the Chandra coordinates in Gotthelf et al. (2013a).

We also examined the Chandra observations that fell within the post-glitch time interval (see Table 1). The pulsar was placed on the S3 CCD of the Advanced Camera for Imaging and Spectroscopy that was run in continuous-clocking mode, which provides a time resolution of 2.85 ms. We processed this data set following the method outlined in Gotthelf & Halpern (2007) and Halpern & Gotthelf (2011).

### 3. Timing Analysis

Prior to 2015, a unique, quadratic ephemeris from XMM-Newton and Chandra observations of 1E 1207.4−5209 adequately described its rotation for 14 years (Halpern & Gotthelf 2015). Then, on 2016 July 28, we found a large ($\Delta \phi \approx -0.35$) and significant ($18\sigma$) deviation in phase between the observed pulse arrival time and that predicted from the pre-2015 ephemeris, consistent with the pulse arriving earlier than expected. Using the subsequent observations, we generated additional pulse times of arrival following the recipe given in our previous papers (Halpern & Gotthelf 2011; Gotthelf et al. 2013a) and continued to compare them to the pre-2015 ephemeris. The persistent deviation in phase over time is clearly evident in Figure 1 as a highly significant shift of up to $\sim -0.55$ cycles from the pre-2015 ephemeris. This is standard behavior for a glitch, namely, a speed-up in the spin frequency $f$ that causes the pulses to come successively earlier than the pre-glitch ephemeris predicts.

We also checked for any change in pulse shape and pulsed fraction, in case what we think is a glitch might be due instead to a change in the location of a hot spot on the surface, or the emergence of a new emission process. There is no significant difference between the pre- and post-glitch pulse shape, pulsed fraction, or energy dependence of pulse phase, indicating that the surface thermal emission pattern has not changed. So a simple glitch is the most straightforward interpretation of Figure 1.

Because of the long, two-year gap in observations between 2014 and 2016, we cannot be certain of the exact residual cycle count after the glitch, nor determine the epoch of the glitch with any precision. Fitting possible linear slopes to a few points after the glitch in Figure 1 implies that the glitch magnitude is $\Delta f/f = (2.8 \pm 0.4) \times 10^{-9}$, which is the minimum possible magnitude corresponding to the minimum possible phase shift, as plotted. We also have independent evidence for an increase in frequency by fitting a new, phase-connected quadratic ephemeris to the 10 post-glitch points from 2016 July 28 to 2018 Aug 27. In this fit, $\Delta f/f_{\text{post-glitch}} = (5.22 \pm 0.80) \times 10^{-9}$ (at a glitch epoch of MJD 57295 = 2015 September 30), which is not precise enough to confirm the phase counting in Figure 1, but does suggests a larger glitch magnitude than the simple linear fit. Both pre- and post-glitch ephemerides are listed in Table 2.

Post-glitch behavior typically includes partial recovery toward the pre-glitch ephemeris, which can be fitted as a glitch also in $f$ that subsequently decays on one or more timescales (see examples in Espinoza et al. 2011). In this context, our post-glitch ephemeris only crudely estimates an average value for the post-glitch $f$ because the data points are not precise or numerous enough to track any change in $f$. Nevertheless, a post-glitch $f$ is significantly detected at $(-2.82 \pm 0.31) \times 10^{-16}$ s$^{-2}$, which is larger than the historical value of $(-1.2398 \pm 0.0083) \times 10^{-16}$ s$^{-2}$.

### Table 1

| Mission | Instrument /Mode | ObsID       | Date (UT) | Exposure (ks) |
|---------|-----------------|-------------|-----------|---------------|
| XMM     | EPIC pn/SW      | 07800000201 | 2016 Jul   | 34.0          |
| XMM     | EPIC pn/SW      | 0800960201  | 2017 Jun   | 34.8          |
| XMM     | EPIC pn/SW      | 0800960301  | 2017 Jun   | 22.2          |
| XMM     | EPIC pn/SW      | 0800960401  | 2017 Jun   | 24.1          |
| XMM     | EPIC pn/SW      | 0800960501  | 2017 Jul   | 25.0          |
| XMM     | EPIC pn/SW      | 0800960601  | 2017 Aug   | 21.3          |
| Chandra | ACIS-S3/CC      | 19612       | 2017 Oct   | 33.0          |
| XMM     | EPIC pn/SW      | 0800960701  | 2017 Dec   | 21.3          |
| XMM     | EPIC pn/SW      | 0821940201  | 2018 Jun   | 33.4          |
| Chandra | ACIS-S3/CC      | 19613       | 2018 Aug   | 66.6          |

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*Figure 1.* Pulse-phase residuals from the timing solution of Halpern & Gotthelf (2015), with the addition of the 10 post-2015 XMM-Newton data points. A glitch occurred some time during the interval denoted by the vertical dotted lines. By matching the phase of the pre- and post-glitch ephemerides, the estimated glitch time indicated by the diamond is 2015 September 30.
4. Spectral Analysis

We also examined the pre- and post-glitch XMM-Newton spectra of 1E 1207.4–5209 to look for any change by comparing six observations obtained in 2012 and six in 2017. For each EPIC pn observation we extracted spectra using an aperture of radius 0.5 and a nearby off-source circular region of radius 1.0. Response matrices and effective area files were generated for each observation using the SAS software suite. We combined the spectra extracted from the pre- and post-glitch observations, respectively, using the FTOOL addascaspec to produce a single source spectrum and associated files at each epoch. These spectra were grouped to include at least 200 counts per channel and were fitted using XSPEC v12.10.0c software (Arnaud 1996). The two spectra were fitted simultaneously to a two-blackbody model with interstellar absorption and cyclotron lines in the range of 0.3–2.5 keV. We characterize the column density using the TBabs absorption model, selecting the wilm Solar abundances (Wilms et al. 2000) and the vern photoionization cross-section (Verner et al. 1996).

We note that it is not possible to uniquely fit for the column density, softer blackbody \(kT_1\), and the absorption features simultaneously. Furthermore, the detailed shape of the absorption features is not known. We used a Gaussian line whose overall value for this fixed Gaussian width. We consider this a constant post-glitch \(f\).

### Table 2

| Parameter                  | Valuea |
|----------------------------|--------|
| R.A. (J2000)               | 12h10m00s91 |
| Decl. (J2000)              | -52°26′28.7" |
| Surface dipole dipole field, \(B_s\) | 9.8 × 1010 G |
| Spin-down luminosity, \(E\) | 1.2 × 1031 erg s⁻¹ |
| Characteristic age, \(\tau_c = P/2\) | 301 Myr |

### Pre-glitch Timing Solution (2000–2014)

| Epoch of ephemeris (MJD TDB) | 53562.00000052 |
| Span of ephemeris (MJD)       | 51549–56829 |
| Frequency, \(f\)              | 2.3577635028666(65) s⁻¹ |
| Frequency derivative, \(\dot{f}\) | -1.2398(13) × 10⁻¹⁶ s⁻² |
| Period, \(P\)                | 0.4241307488(12) s |
| Period derivative, \(\dot{P}\) | 2.230(14) × 10⁻¹⁷ |
| \(\chi^2_{\text{DoF}}\)       | 2.68(25) |

| Epoch of ephemeris (MJD TDB) | 57977.0000040 |
| Span of ephemeris (MJD)       | 57597–58358 |
| Frequency, \(f\)              | 2.35776345859(38) s⁻¹ |
| Frequency derivative, \(\dot{f}\) | -2.82(31) × 10⁻¹⁶ s⁻² |
| Period, \(P\)                | 0.42413075678(68) s |
| Period derivative, \(\dot{P}\) | 5.06(56) × 10⁻¹⁷ |
| \(\chi^2_{\text{DoF}}\)       | 0.86(7) |

### Post-glitch Timing Solution (2016–2018)

### Table 3

| Parameter                  | Pre-glitchb | Post-glitchb |
|----------------------------|-------------|--------------|
| Epoch                      | 2012        | 2017         |
| \(N_H (\text{cm}^{-2})\) (fixed) | 1.66 × 10²¹ | 1.66 × 10²¹ |
| \(kT_1 (\text{keV})\)      | 0.0801 ±0.0046 | 0.0742 ±0.0037 |
| \(kT_2 (\text{keV})\)      | 0.2513 ±0.0021 | 0.2509 ±0.0021 |
| \(E_0 (\text{keV})\)       | 0.710 ±0.017 | 0.710 ±0.015 |
| \(\sigma_0 (\text{keV})\) (fixed) | 0.08     | 0.08         |
| \(\tau_0\)                 | 0.26        | 0.22         |
| \(E_1 (\text{keV})\)       | 1.429 ±0.0088 | 1.4216 ±0.0089 |
| \(\sigma_1 (\text{keV})\) (fixed) | 0.08     | 0.08         |
| \(T_1\)                    | 0.098       | 0.10         |
| \(F_p (\text{ph})\)        | 2.084 ±0.011 | 2.078 ±0.012 |
| \(\chi^2_{\text{DoF}}\)    | 1.39(283)   | 1.32(276)    |

Notes. EPIC pn spectral fit in the 0.3–2.5 keV range, with the column density and Gaussian line widths held fixed (see the text). Uncertainties on \(kT\) and \(E\) are given at the 68% confidence level for four interesting parameters. Uncertainty on the flux is given at the 90% confidence level.

b Pre-glitch live time 107 ks from ObsIDs 0679590101/201/301/401/501/601.

Post-glitch live time 98 ks from ObsIDs 0800960201/301/401/501/601/701.

c Absorbed 0.3–2.5 keV flux in units of 10⁻¹² erg cm⁻² s⁻¹.
and its harmonics in magnetic field of $B \approx 8 \times 10^{10}$ G, according to the relation $E_0 = 1.16(B/10^{11})/(1 + z)$ keV, where $z \approx 0.3$ is the gravitational redshift. Within the statistics of the spectra, we find no change in the spectrum from 2012 to 2017, specifically, no definite shift in $E_0$ that would indicate a change in surface magnetic field strength after the glitch. Instead, the field strength is seen to be constant to $\approx 2\%$. The two temperatures and total flux are also unchanged, the latter at the 0.5\% level.

5. Discussion

5.1. Glitch Magnitude

The distribution of glitch magnitudes in pulsars is bimodal, with a broad peak centered at $\Delta \dot{f}/f \approx 3 \times 10^{-9}$ and a narrow peak at $\Delta \dot{f}/f \approx 1 \times 10^{-10}$ (Espinoza et al. 2011). The glitch in 1E 1207.4–5209 is thus typical of the lower-amplitude group, and also of glitch sizes found for the Crab pulsar. However, it is unprecedented for a pulsar with the timing properties of 1E 1207.4–5209 to even have a glitch. Glitch activity correlates best with the spin-down rate of pulsars in a linear manner such that the average amount of spin down reversed in a glitch, $\dot{f}_{\text{rev}}$, is $\approx 0.01f$, i.e., 1\% of the long-term spin down is reversed (Espinoza et al. 2011; Fuentes et al. 2017). This has been interpreted in terms of the vortex creep theory (Alpar et al. 1984) to imply that 1\% or more of the moment of inertia of the NS is contained in a crustal superfluid whose vortices are repeatedly pinned and unpinned.

In this picture, it is natural that pulsars with small $\dot{f}$ would not glitch frequently. Among pulsars with $|\dot{f}| < 1 \times 10^{-15}$ s$^{-2}$, only three glitches have been observed in $\approx 4260$ pulsar-years of monitoring, and no pulsar with $|\dot{f}| < 3 \times 10^{-16}$ s$^{-2}$ has glitched in 1780 years (Fuentes et al. 2017). For 1E 1207.4–5209 with its $\dot{f} = -1.24 \times 10^{-16}$ s$^{-2}$ to have glitched once in 15 years of monitoring makes it, therefore, a significant outlier with 99\% confidence.

In addition, typical glitches have a $\Delta \dot{f}/f$ of only $\approx 10^{-3}$ to $10^{-2}$, much smaller than the order unity change in 1E 1207.4–5209 if we take its post-glitch ephemeral literally. In magnetars, however, it is common to see glitches in reversed manner such that the average amount of spin down reversed in a glitch, $\dot{f}_{\text{rev}}$, is $\approx 0.01f$, i.e., 1\% of the long-term spin down is reversed (Espinoza et al. 2011; Fuentes et al. 2017). This has been interpreted in terms of the vortex creep theory (Alpar et al. 1984) to imply that 1\% or more of the moment of inertia of the NS is contained in a crustal superfluid whose vortices are repeatedly pinned and unpinned.

There is a class of intermittent radio pulsars, whose $|\dot{f}|$ is larger by a factor of order unity when they are turned on as radio pulsars in comparison with their off states (e.g., Lyne et al. 2017). States can persist for days up to years, with the most extreme example being that of PSR J1841–0500 (Camilo et al. 2012), which was off for 540 days. Its $|\dot{f}|$ was higher by a factor of 2.5 while the radio pulsations were turned on. The implication is that a magnetospheric plasma is present and contributing to the spin-down torque only during the radio-on state. If the glitch triggered a transition to a magnetospherically active state in 1E 1207.4–5209, then its higher $|\dot{f}|$ could be an indicator that it has turned on as a radio pulsar. We reserve judgment on this unexpected result until future observations can measure a new, long-term value of $\dot{f}$ with a precision comparable to the pre-glitch ephemeris.

5.2. CCO Structure and Evolution

Although the glitch activity of 1E 1207.4–5209 would not have been predicted from its small $\dot{f}$ and weak surface dipole field $B_\text{s}$, its internal magnetic field may be as strong as those of canonical young pulsars that do glitch, according to two arguments. First, the thermal X-ray pulsations by which CCO pulsars are discovered are difficult to explain in the context of weak magnetic fields, since the only mechanism thought to be capable of creating a nonuniform surface temperature is anisotropic heat conduction in a strong magnetic field. The effects of different magnetic field configurations on heat transport in the crust and envelope of NSs were modeled by Geppert et al. (2004, 2006), Pérez-Azorín et al. (2006), and Pons et al. (2009). A toroidal field is expected to be the initial configuration generated by differential rotation in the proto-NS dynamo (Thompson & Duncan 1993). One of the effects of crustal toroidal field is to insulate the magnetic equator from heat conduction, resulting in warm spots at the poles. To have a significant effect on heat transport, the crustal toroidal field strength required in all models is $>10^{14}$ G, many orders of magnitude greater than the polaroid field if the latter is measured by the spin down. Shabaltas & Lai (2012) tried to model the pulse profile of the CCO PSR J1852+0040 in Kes 79 with anisotropic conduction in such a model, and concluded that they needed a toroidal crustal field of $B_\text{s} > 2 \times 10^{14}$ G to achieve the large observed pulsed fraction of 64\% ± 2\%, although they could not actually match the broad pulse shape (see also Bogdanov 2014).

Second, a theory of CCOs posits that they are born with a canonical NS magnetic field that was buried by the fallback of a small amount of supernova ejecta, $\sim 10^{-4} M_\odot$, during the hours and days after the explosion. The buried field will diffuse back to the surface on a timescale of $\sim 10^5$ years (Geppert et al. 1999; Bernal et al. 2010, 2013; Ho 2011, 2015; Viganò & Pons 2012). During this time the CCO will move vertically up in the $P$–$P$ diagram due to its rapidly increased braking as the dipole field grows (see Figure 1 of Liao et al. 2015). Eventually it will join the bulk of the population of ordinary radio pulsars. Such a scenario addresses the absence of CCO descendants that should remain in the same region of $P$–$P$ space long after their natal SNRs fade, if their weak magnetic fields are intrinsic. Searches for a thermal X-ray signature from such CCO descendants have yet to find a single example (Gotthelf et al. 2013b; Bogdanov et al. 2014; Loo et al. 2015), except possibly for the unusual X-ray pulsar Calvera (Halpern et al. 2013; Halpern & Gotthelf 2015). The field growth hypothesis also has the feature 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 supernova rate (Keane & Kramer 2008).

More generally, magnetic field growth (Blandford et al. 1983) or dipole axis counteralignment (Macy 1974) have long been considered as possible reasons as to why most measured pulsar braking indices, defined as $n \equiv \dot{f} / f^2$, are less than the static dipole value of 3. If the dipole magnetic field strength $B_\text{s}$
is increasing at the rate $\dot{B}_s$, the braking index is reduced to

$$n = 3 - 2 \frac{\dot{B}_s f}{B_0 |f|}.$$  

Ho (2015) calculated that the upward vectors in the $P$-$\dot{P}$ diagram of three pulsars with $n < 1.7$, namely, PSR B0833−45 (Vela), PSR J0537−6910 in the LMC, and PSR J1734−3333, could be explained by the same processes of field burial and diffusion as in CCOs, but with a smaller amount of accreted mass, $\sim 10^{-5} M_{\odot}$. These three pulsars also happen to have large glitches, in the upper peak of the bimodal distribution of glitch magnitudes. The possible connection of low braking index to regular, large glitches, led Ho (2015) to propose that this type of glitch activity could be triggered by the motion of magnetic fields through the NS crust, interacting with the neutron superfluid there. Although only a small glitch has been seen from 1E 1207.4−5209, it is interesting to consider that, even though there is no evidence that glitch activity is correlated with dipolar magnetic field strength (Fuentes et al. 2017), a glitch may be triggered by the motion of the internal magnetic field.

5.3. Accretion-torque Noise?

Here we consider an alternative interpretation of the apparent glitch: torque noise during low-level accretion, possibly from a fallback debris disk, following the arguments in Halpern et al. (2007). While the $B$-field of 1E 1207.4−5209 derived from timing only assumes dipole braking, its spin parameters fall in a regime where both dipole braking and accretion-disk torques are conceivably significant. Accretion at a rate of $M = 10^{11} \text{g s}^{-1}$ (or less if the NS magnetic field is weaker) can penetrate the light cylinder to the magnetospheric radius. If so, the system is in the propeller regime, in which matter flung out takes angular momentum from the NS, causing it to spin down. The propeller spin-down rate is

$$\dot{f} \approx -9.5 \times 10^{-15} \mu_{29}^{8/7} M_{14}^{-2/7} \left( \frac{M_{\text{NS}}}{M_{\odot}} \right)^{-2/7} \left( \frac{f_{\text{eq}}}{f} \right) \left( \frac{I_{45}}{2.357 \text{Hz s}^{-2}} \right) \left( 1 - \frac{f_{\text{eq}}}{f} \right) \text{ s}^{-2},$$

(Menou et al. 1999). Here $I_{45}$ is the NS moment of inertia in units of $10^{45} \text{g cm}^2$, $\mu_{29} = B_s R_{15}^3$ is the magnetic dipole moment in units of $10^{29} \text{G cm}^3$, $M_{14}$ is the mass transfer rate in units of $10^{14} \text{g s}^{-1}$, and $f_{\text{eq}}$ is the equilibrium spin frequency, presumed to be $< f$ because of the small age and young $M$. In this model $M$ is the rate of mass expelled, which must be $> \dot{m}$, the accretion rate onto the NS. While $\dot{m}$ must be $< 3 \times 10^{12} \text{g s}^{-1}$ so as not to exceed the bolometric luminosity of $1E \, 1207.4$−$5209$, $\approx 2.5 \times 10^{38} \text{erg s}^{-1}$, even such a small accretion rate is ruled out by upper limits on the accretion-disk luminosity from the nondetection of an optical counterpart by the Hubble Space Telescope (HST; De Luca et al. 2011). The latter observation requires an even smaller $M < 10^{12} \text{g s}^{-1}$.

Assuming that $M \approx 10^{11} \text{g s}^{-1}$, accretion contributes negligibly to the luminosity, thus not violating the upper limits on X-ray variability, while still allowing $\dot{f} \approx -1.3 \times 10^{-15} \text{ s}^{-2}$ from the propeller effect. This is a factor of $\approx 4$ greater than the $\dot{f}$ of the post-glitch ephemeris. Therefore, fluctuations in the propeller $\dot{f}$ cannot be immediately ruled out as an explanation for the observed timing irregularity. Evolutionary models of fallback disks predict that an initial disk mass of $< 10^{-4} M_{\odot}$ can easily supply, at the estimated 7000 years present age of PKS 1209−51/52, accretion at the above assumed rate (De Luca et al. 2011).

Whether the NS can acquire such a disk from the homologously expanding ejecta moving with it, or from reverse-shocked supernova (SN) ejecta, depends on the details of the explosion. However, if $\sim 10^{-4} M_{\odot}$ of debris can fall directly onto the NS to bury its magnetic field, it is likely that $10^{-5} M_{\odot}$ can end up in a disk because of its angular momentum. Not so obvious is the spectrum of timing noise produced at such a low accretion rate, a regime which has thus far not been observed. For now, the overall resemblance of the timing residuals to a classic glitch profile in an isolated pulsar leads us to prefer the glitch model over accretion-torque noise.

6. Conclusions and Future Work

We have detected the first glitch in a CCO pulsar, 1E 1207.4−5209. Its frequency jump is at least $\Delta f / f = (2.8 \pm 0.4) \times 10^{-9}$, and possibly larger if a fitted change in $\dot{f}$ by a factor of 2.3 is real. It is crucial to continue timing the pulsar to establish the post-glitch $\dot{f}$ more accurately. A radio pulsation search should be made to test for new magnetospheric activity. There is no evidence for a change in the weak surface magnetic field from the X-ray cyclotron features, and no change in luminosity. Old pulsars with $\dot{f}$ as small as that of 1E 1207.4−5209 have not been seen to glitch, which implies that the glitch mechanism is contingent upon an internal property of this young pulsar, such as high magnetic field strength or temperature. Ho (2015) suggested that diffusion of a previously buried $B$-field could be the trigger for a glitch. Ho (2015) further suggested that glitches could identify the missing descendants of CCOs. Finding descendants among the ordinary radio pulsar population would solve a major observational problem in CCO evolution, and provide strong support to the field-burial theory of their origin.

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