PRECISE TIMING OF THE X-RAY PULSAR 1E 1207.4–5209: 
a steady neutron star weakly magnetized at birth

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ABSTRACT

We analyze all X-ray timing data on 1E 1207.4–5209 in supernova remnant PKS 1209–51/52 gathered from 1993–2005 and find a highly stable rotation with $P = 424.130749(4)$ ms and $P = (6.6 \pm 9.0) \times 10^{-17}$ (1 $\sigma$ errors). This refutes previous claims of large timing irregularities in these data. In the dipole spin-down formalism, the 2 $\sigma$ upper limit on $P$ implies a spin-down luminosity $E < 1.3 \times 10^{32}$ ergs s$^{-1}$, surface magnetic field strength $B_s < 3.3 \times 10^{11}$ G, and characteristic age $\tau \equiv P/2P > 27$ Myr. This $\tau$ exceeds the remnant age by 3 orders of magnitude, requiring that the pulsar was born spinning at its present period. The X-ray luminosity of 1E 1207.4–5209, $L_{\text{rad}} \approx 2 \times 10^{30} \text{(d/2 kpc)}^2$ ergs s$^{-1}$, exceeds its $E$, implying that $L_{\text{rad}}$ derives from residual cooling and perhaps partly from accretion of supernova debris. The upper limit on $B_s$ is small enough to favor the electron-cyclotron model for at least one of the prominent absorption lines in its soft X-ray spectrum. This is the second demonstrable case of a pulsar born spinning slowly and with a weak $B$-field, after PSR J1852+0040 in Kesteven 79. We suggest that these properties define the class of central compact objects.

Subject headings: ISM: individual (PKS 1209–51/52) — pulsars: individual (1E 1207.4–5209, PSR J1852+0040) — stars: neutron — supernova remnants

1. INTRODUCTION

The neutron star 1E 1207.4–5209 in the center of supernova remnant PKS 1209–51/52 is the first discovered (Helfand & Becker 1984) and most intensively studied of the so-called central compact objects (CCOs). These seemingly isolated neutron stars (NSs) are defined by their steady flux, predominantly thermal X-ray emission, lack of optical or radio counterparts, and absence of a surrounding pulsar wind nebula (see Pavlov et al. 2004 for a review). 1E 1207.4–5209 acquired special importance when it became the first CCO in which pulsations were detected (Zavlin et al. 2000; Pavlov et al. 2002). It was distinguished again as the first isolated NS to display strong absorption lines in its X-ray spectrum (Sanwal et al. 2002; Mereghetti et al. 2002a; Bignami et al. 2003).

More recently, accumulated X-ray observations of 1E 1207.4–5209 were presented as showing large-amplitude changes in its spin period ($\Delta P \leq 0.9$ ms), with intervals of both spin-up and spin-down (Zavlin et al. 2004) that were unlike any other pulsar and difficult to explain. Consequently, the surface dipole magnetic field, which is a key parameter in all proposed mechanisms for the X-ray absorption lines, could not be estimated independently from the spin-down rate, which was indeterminate. Here we present a revised study of the spin history of 1E 1207.4–5209 that corrects previous errors in the data and their analysis. We discuss the implications for interpreting the X-ray spectrum of 1E 1207.4–5209 and, more generally, for the origin of the class of CCOs.

2. ARCHIVAL X-RAY OBSERVATIONS (1993–2005)

We reanalyzed all archival data on 1E 1207.4–5209 having sufficient time resolution and photons to detect the pulsations. These include ROSAT, Newton X-Ray Multi-Mirror Mission (XMM-Newton), and Chandra observations spanning 1993–2005; a log is given in Table 1.

All 10 XMM-Newton observations of 1E 1207.4–5209 used the pn detector of the European Photon Imaging Camera (EPIC-pn) in “small window” (SW) mode to achieve 5.7 ms time resolution. Several EPIC-pn data sets had photon timing errors uncorrected in their original processing (Kirsch et al. 2004). We reprocessed all EPIC data using the emchain and epchain scripts under Science Analysis System (SAS) version xmmmsas_20060628_1801-7.0.0, which evidently produces correct photon time assignments. The observations were affected by background to varying degrees. To maximize the signal-to-noise ratio in each, we adjusted the source extraction radii individually (21″ $\leq r < 60$″). An energy cut of 0.5–2.5 keV was found to maximize the pulsed power.

Simultaneous data were acquired with the EPIC MOS camera, operated in “full frame” mode. Although not useful for timing purposes (2.7 s readout), the location of the source at the center of the on-axis MOS CCD allows for a better background measurement to test for flux variability, an important indicator of accretion, than the EPIC-pn SW mode. The seven observations of 2005 exhibit rms source flux variability of less than 1% over the 40 day span. Comparing these count rates to the earlier XMM-Newton observation of 2001 December implies a marginally significant flux decrease of 5% ± 3% during the 5 yr interval. We also verified that the X-ray spectrum has not changed.

Four Chandra observations suitable for timing measurements of 1E 1207.4–5209 are available. They used the Advanced Camera for Imaging and Spectroscopy (ACIS) in continuous-clocking (CC) mode to provide time resolution of 2.85 ms. Two observations were taken with the Low Energy Transmission Grating (LETG) in place, the zeroth-order image being used for timing. This study uses data processed by the latest pipeline software (revision ver. 7.6.8.1 or ver. 7.6.6.10). Reduction and analysis used the standard software packages CIAO (ver. 3.4) and CALDB (ver. 3.3). The photon arrival times in CC mode are adjusted to account for the known position of the pulsar, spacecraft dither, and SIM offset using acis_process_events.

Five offset pointings were made by ROSAT in 1993 July 15–25 with the Position Sensitive Proportional Counter (PSPC). We extracted photons in the 0.4–2.5 keV range from
TABLE 1

Log of X-Ray Timing Observations of 1E 1207.4—5209 and Summary of Results

| Set | Mission | Instrum./Mode | ObsID/Sequence No. | Date (UT) | Span (ks) | Start Epoch (MJD) | Period* (ms) | Z* | Refs. |
|-----|---------|---------------|-------------------|-----------|----------|------------------|-------------|-----|-------|
| 1   | ROSAT  | PSPC          | 500239–500243     | 1993 Jul 15–25 | 836.7    | 49,183,452    | 424,130,710(10) | 15.9 |       |
| 2   | Chandra | ACIS-S/CC     | 0751/500047       | 2000 Jan 06   | 32.5     | 51,549,625    | 424,130,306(34) | 73.8 | 1', 2', 3' |
| 3   | XMM    | EPIC-pn/ACIS  | 0113050501        | 2001 Dec 23   | 26.8     | 52,266,799    | 424,130,766(36) | 115.1 | 4, 3' |
|     | Chandra | ACIS-S/CC     | 2799/500249       | 2002 Jan 05   | 30.4     | 52,285,975    | 424,130,626(38) | 62.2 | 2', 3' |
| 4   | XMM    | EPIC-pn/ACIS  | 0155960301        | 2002 Aug 04   | 116.5    | 52,266,999    | 424,130,794(10) | 169.6 |       |
|     | XMM    | EPIC-pn/ACIS  | 0155960501        | 2002 Aug 06   | 128.4    | 52,492,309    | 424,130,749(40) | 363.3 | 5, 6, 3' |
|     |        |               |                   |            |          |                  |              |      |       |
| 5   | Chandra | ACIS-S/CC     | 3915/500394       | 2003 Jan 10   | 155.7    | 52,800,443    | 424,130,646(13) | 26.9 | 3'   |
|     | Chandra | ACIS-S/CC     | 4398/500394       | 2003 Jun 18   | 115.1    | 52,808,369    | 424,130,858(16) | 29.3 | 3'   |
| 6   | XMM    | EPIC-pn/ACIS  | 0304531501        | 2005 Jun 22   | 14.9     | 53,543,515    | 424,129,999(10) | 41.7 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304531601        | 2005 Jul 05   | 18.0     | 53,556,038    | 424,130,789(92) | 47.5 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304531701        | 2005 Jul 10   | 20.4     | 53,561,280    | 424,131,265(9)  | 58.7 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304531801        | 2005 Jul 11   | 63.0     | 53,562,090    | 424,130,885(15) | 135.7 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304531901        | 2005 Jul 12   | 13.8     | 53,563,283    | 424,131,506(75) | 42.2 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304532001        | 2005 Jul 17   | 16.5     | 53,568,016    | 424,131,455(66) | 91.2 | 7*   |
|     | XMM    | EPIC-pn/ACIS  | 0304532101        | 2005 Jul 31   | 17.6     | 53,582,587    | 424,129,909(6)  | 32.3 | 7*   |
|     |        |               |                   |            |          |                  |              |      |       |

**REFERENCES.**—These references are to period measurements in the literature. Some have errors originating from applied analysis, designated with a dagger, or from the supplied data, designated with an asterisk. (1) Zavlin et al. 2000; (2) Pavlov et al. 2002; (3) Zavlin et al. 2004; (4) Mereghetti et al. 2002a; (5) Bignami et al. 2003; (6) De Luca et al. 2004; (7) Woods et al. 2007.

* Combined data sets are added coherently (phase-linked), accounting for every rotation of the NS between observing epochs.

For each observation in Table 1, we transformed the photon arrival times to Barycentric Dynamical Time using the coordinates given in Table 2. The value of the period in each observation was derived from a Z* test. In contrast to the large period changes claimed by Zavlin et al. (2004), a linear (incoherent) ephemeris is an excellent fit to our set of period measurements (see Fig. 1), with χ2 = 0.73 for 13 degrees of freedom and a 2 σ upper limit of 0.1 cycles the actual phase derived from the adjacent observations. After completing this procedure for all the 2005 observations, a coherent fit was obtained for this set. The best-fit

3. TIMING ANALYSIS

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![Fig. 1.—Period residuals after fitting a linear solution to individual observations](top panel) and phase-linked data sets (bottom panel) from Table 1.
The two XMM-Newton observations of 2002 August 4 and 6 were easily joined, resulting in the period listed in Table 1. Now knowing the precise and consistent values of $P$ in 2002 and 2005, we were able to make a phase-connected combination of the 2001 December XMM-Newton observation and the 2002 January Chandra one, which are 13 days apart, by finding an unambiguous period match for the correct peak from among nearby aliases. Finally, we combined the set of two Chandra observations spanning 2003 June 10–19, which again yielded a consistent period at the highest peak in the $Z_\text{p}$ periodogram. After making these coherent combinations, it was not possible to achieve a further phase-connected solution over a longer time span, as the intervening cycle counts could not be determined uniquely. Therefore, we made a final linear least-squares fit to the six coherently determined periods listed in Table 1, yielding the ephemeris presented in Table 2. This piecewise coherent analysis yields a 2σ upper limit of $\dot{P} < 2.5 \times 10^{-16}$, more precise than the fully incoherent result described earlier in this section (see Fig. 1).

4. Interpretation

Contrary to previous claims, the timing behavior of 1E 1207.4–5209 does not require glitches or a binary companion, and perhaps not even accretion of fallback material, although the latter may still be needed to contribute to its X-ray spectrum and luminosity. In the dipole spin-down formalism, the 2σ upper limit $P < 2.5 \times 10^{-16}$ implies, for an isolated pulsar, a spin-down luminosity $E = -\dot{P}^2 \Omega = 4\pi^2 I P^3 < 1.3 \times 10^{42}$ erg s$^{-1}$, surface magnetic field strength $B_p = 3.2 \times 10^{19}(P\dot{P})^{1/2} < 3.3 \times 10^{11}$ G, and characteristic age $\tau = P/2P < 27$ Myr. In its spin properties, 1E 1207.4–5209 resembles another CCO, PSR J1852+0040 (Gotthelf et al. 2005; Halpern et al. 2007). The next section includes a summary of the discussion in Halpern et al. (2007) that anticipated the present result.

4.1. Cooling and/or Accreting

The X-ray spectrum of 1E 1207.4–5209 is of thermal origin, with $L_{\text{bol}} \approx 2 \times 10^{33}(d/2 \text{kpc})^2$ ergs s$^{-1}$ (De Luca et al. 2004). This is more luminous than the upper limit on its spin-down power, $E$, and argues that it is mostly residual cooling. However, it fits to the spectrum require two blackbody components; the hotter one, of temperature $kT_{\text{bol}} = 0.32$ keV, has an area of only 0.87 km$^2$ (De Luca et al. 2004), which may indicate heating by accretion onto the polar cap. The canonical area of the open-field-line polar cap is $A_p = 2\pi R^2 P c \approx 0.27$ km$^2$. This is $\sim 30\%$ of the fitted blackbody component, but accretion may cover a wider area.

The characteristic age $\tau > 27$ Myr, compared to the remnant age, estimated as 7 kyr with an uncertainty of a factor of 3 (Rogier et al. 1988), requires that the pulsar was born spinning at its current period. A recent population analysis of radio pulsars by Faucher-Giguère & Kaspi (2006) favors a wide distribution of birth periods (Gaussian-centered on $\sim 300$ ms, $\sigma \sim 150$ ms).

Furthermore, as the magnetic field is generated by a turbulent dynamo whose strength depends on the rotation rate of the proto–neutron star (Thompson & Duncan 1993), it is natural that pulsars born spinning slowly would have the weaker $B$-fields; the model of Bonanno et al. (2006) supports this.

The region of parameter space with $B_p < 10^{13}$ G and $\tau < 47$ Myr is devoid of radio pulsars (Manchester et al. 2005), even though it is not beyond the death line of Faucher-Giguère & Kaspi (2006) or Chen & Ruderman (1993). One possible explanation is that low-level accretion of supernova debris prevents CCOs from becoming radio pulsars for thousands or even millions of years. Accretion from a fallback disk (Alpar 2001; Shi & Xu 2003; Eksi et al. 2005; Liu et al. 2006) was one of the theories considered by Zavlin et al. (2004) to explain the now repudiated timing irregularities of 1E 1207.4–5209. But accretion may still be needed to account for its radio-quiet and X-ray-hot properties.

If the magnetic field is weak enough that an accretion disk can penetrate the light cylinder, the hotter portion of the NS surface in 1E 1207.4–5209 can be powered by a mass accretion rate of only $\dot{m} \approx 10^{15}$ g s$^{-1}$. For 1E 1207.4–5209 to accrete in the propeller regime would require $B_p < 5 \times 10^{11}$ G. But in this limit, the pulsar would tend to spin down at a rate that is excluded by observations,

$$\dot{P} \approx 1.2 \times 10^{-14} \mu^{1/2} M_i^{9/2} I_{45}^{1/2} \left( \frac{P}{0.424 \text{s}} \right)^{-2/7},$$

where the magnetic moment $\mu = B_p R^2/2 \approx 10^{22} B_p \text{G cm}^3$. Also, $M_i$, the disk accretion rate, would have to be $> m_\odot$, as most matter is flung out from the magnetospheric radius rather than accreted onto the NS. However, if $B_p < 2 \times 10^9$ G, then 1E 1207.4–5209 may accrete as a “slow rotator” and spin up at a small rate,

$$\dot{P} \approx -2.1 \times 10^{-17} \mu^{1/2} M_i^{6/7} I_{45}^{1/2} \left( \frac{P}{0.424 \text{s}} \right)^{-2/7}.$$

In this regime, the secular spin-up and the torque noise, which may be of the same magnitude, are below the sensitivity of the existing measurements.

While flickering is also an indicator of accretion, we do not have strong evidence of the variability of 1E 1207.4–5209 (<1% on month timescales). Also, upper limits on optical/IR emission from 1E 1207.4–5209 are comparable to that expected from a geometrically thin, optically thick disk accreting at the rate re-
quired to account for its X-ray luminosity (Zavlin et al. 2004; Wang et al. 2007). Therefore, it may be necessary to invoke a radiatively inefficient flow in order to consider accretion.

4.2. X-Ray Absorption Lines

Broad absorption lines in the soft X-ray spectrum of 1E 1207.4—5209 are centered at 0.7 and 1.4 keV (Sanwal et al. 2002; Mereghetti et al. 2002a), and possibly at 2.1 and 2.8 keV (Bignami et al. 2003; De Luca et al. 2004), although the reality of the two higher energy features has been disputed (Mori et al. 2005). Proposed absorption mechanisms include an electron cyclotron in a weak (8 × 10^{10} G) magnetic field (Bignami et al. 2003; De Luca et al. 2004), atomic features from singly ionized helium in a strong (2 × 10^{14} G) field (Sanwal et al. 2002; Pavlov & Bezchastnov 2005), and iron (Mereghetti et al. 2002a) or oxygen/neon in a normal (10^{13} G) field (Hailey & Mori 2002; Mori & Hailey 2006).

One caveat of any model is that the magnetic field strength at the NS surface can be larger in places than the global dipole that controls the spin-down. Our upper limit, B_p < 3.3 × 10^{13} G, favors the electron-cyclotron model, for at least one of the lines, over all others that require stronger fields. The cyclotron prediction, G ∼ 10^{10} G/(1 + z), 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 (Hailey & Mori 2002; Mori & Hailey 2006). As these authors pointed out, abundant oxygen may be accreted from supernova debris.

4.3. Are CCOs a Class?

The half-dozen radio-quiet CCOs are similar in their X-ray luminosities, high temperatures, and absence of pulsar wind nebulae. Therefore, they may comprise a fairly uniform class defined by a weak magnetic field, which in turn results from slow natal rotation. If accreting, a slow initial spin is still unavoidable, since even at high accretion rates, the spin-up and spin-down timescales in § 4.1 and in Halpern et al. (2007) are much longer than the ages of the remnants. While we do not assume that 0.7 keV is the fundamental energy parameter is causally related and, projecting from the near twins 1E 1207.4—5209 and PSR J1852+0947, initially is as small as 10^{9} G and if some of the X-ray luminosity of 1E 1207.4—5209 is due to accretion from a debris disk, spin-up could be detected.

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5. CONCLUSIONS

A comprehensive analysis of all timing data on the X-ray pulsar 1E 1207.4—5209 shows that it is simply a low magnetic field NS that has had no discernible change of period in 12 years. The upper limit on its spin-down power is much less than its bolometric X-ray luminosity, which leaves only internal cooling and accretion as possible energy sources. In either case, 1E 1207.4—5209 must have been born with a weak magnetic field and its long rotation period. We speculate that these two parameters are causally related and, projecting from the near twins 1E 1207.4—5209 and PSR J1852+0947, possibly the physical basis of the CCO class.

This result is a new constraint on proposed absorption-line models for 1E 1207.4—5209, which depend on the magnetic field strength. Our upper limit on the dipole field is close to the prediction of the electron-cyclotron model for both lines and perhaps oxygen for one of the lines. To actually make a significant measurement of B_p as small as 8 × 10^{10} G from dipole spin-down would require a fully phase-coherent timing solution spanning ≥6 yr, assuming that there is no glitch or other timing noise. Such a program would also be sensitive to accretion torques at the lowest rates predicted here for spin-up. If B_p is as small as 10^{10} G and if some of the X-ray luminosity of 1E 1207.4—5209 is due to accretion from a debris disk, spin-up could be detected.