

DISCOVERY OF 424 MILLISECOND PULSATIONS FROM THE RADIO-QUIET NEUTRON STAR IN THE SUPERNOVA REMNANT PKS 1209–51/52

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ABSTRACT

The central source of the supernova remnant PKS 1209–51/52 was observed with the Advanced CCD Imaging Spectrometer aboard *Chandra X-Ray Observatory* on 2000 January 6–7. The use of the continuous clocking mode allowed us to perform the timing analysis of the data with a time resolution of 2.85 ms and to find a period $P = 0.42412924 \text{ s} \pm 0.23 \text{ } \mu\text{s}$. The detection of this short period proves that the source is a neutron star. It may be either an active pulsar with an unfavorably directed radio beam or a truly radio-silent neutron star whose X-ray pulsations are caused by a nonuniform distribution of surface temperature. To infer the actual properties of this neutron star, the period derivative should be measured.

Subject headings: pulsars: individual (1E 1207.4–5209) — stars: neutron —
 supernovae: individual (PKS 1209–51/52) — X-rays: stars

1. INTRODUCTION

Radio-quiet compact central objects (CCOs) of supernova remnants (SNRs) have emerged recently as a separate class of X-ray sources (see, e.g., Caraveo, Bignami, & Trümper 1996; Kaspi 2000). The nature of these sources, which are expected to be either neutron stars (NSs) or black holes formed in supernova explosions, remains enigmatic. They are characterized by soft, apparently thermal, X-ray spectra and a lack of visible pulsar activity and optical counterparts. Particularly important for elucidating the nature of these sources is measuring their periods. Some of these sources show periods in the range of 6–12 s, much longer than those of typical radio pulsars. These objects form a subclass of anomalous X-ray pulsars (e.g., Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995; Gotthelf & Vasisht 2000), which have been interpreted as either isolated magnetars (NSs with superstrong magnetic fields; see Thompson 2000) or accreting NSs with low magnetic fields. A putative period of 75 ms was proposed by Pavlov, Zavlin, & Trümper (1999) for the Puppis A CCO; however, a low significance of that detection requires it to be confirmed by other observations. An unusually long period of 6 hr has been reported for the RCW 103 CCO (Garmire et al. 2000); the origin of this periodicity is unclear. No periodicity has been found for the recently discovered CCO of the Cas A SNR (Pavlov et al. 2000; Chakrabarty et al. 2000).

In this Letter, we report detection of a period of 1E 1207.4–5209, the CCO of PKS 1209–51/52, a barrel-shaped radio, X-ray, and optical SNR (also known as G296.5+10.0). From the analysis of radio and optical observations of this SNR, Roger et al. (1988) estimated its age to be ~ 7000 yr, with an uncertainty of a factor of 3. A recent estimate of the distance to PKS 1209–51/52, $d = 2.1^{+1.8}_{-0.8}$ kpc, is given by Giacani et al. (2000). Estimates of the interstellar hydrogen column density from the radio, optical, and UV data yield $n_{\text{H},21} \equiv n_{\text{H}}/(10^{21} \text{ cm}^{-2}) \sim 1.0\text{--}1.8$ (see Kellet et al. 1987; Roger et al. 1988; Giacani et al. 2000), consistent with a distance $d_2 \equiv d/(2 \text{ kpc}) \sim 1$.

The point source 1E 1207.4–5209 was discovered with the *Einstein Observatory* (Helfand & Becker 1984), 6' off the center of the 81' diameter SNR. Mereghetti, Bignami, & Caraveo (1996) and Vasisht et al. (1997) showed that the *ROSAT* and *ASCA* spectra of 1E 1207.4–5209 can be interpreted as blackbody emission of $T \approx 3$ MK from an area with radius $R \approx 1.5 d_2$ km and suggested that this radiation comes from hot spots on the NS surface. The spots may be heated either by dissipative heating in the NS interior or by the bombardment of polar caps by relativistic particles from the NS magnetosphere if 1E 1207.4–5209 is an active pulsar. However, the former hypothesis can hardly explain the small sizes of the hot spots, even with allowance for large anisotropy of thermal conductivity of the magnetized NS crust. The latter heating mechanism is also in doubt because of the absence of radio and γ -ray emission from 1E 1207.4–5209.

From observations at 4.8 GHz, Mereghetti et al. (1996) found an upper limit of ~ 0.1 mJy on the radio flux from 1E 1207.4–5209. They also set a deep limit of $V > 25$ for an optical counterpart in the *Einstein* HRI error circle, which supports the hypothesis that 1E 1207.4–5209 is indeed an isolated NS.

Zavlin, Pavlov, & Trümper (1998) reanalyzed the *ROSAT* and *ASCA* data, fitting the observed spectra with NS atmosphere models. They have shown that the hydrogen atmosphere fits yield more realistic parameters for the NS and the intervening hydrogen column than the traditional blackbody fit. In particular, for an NS of mass $1.4 M_{\odot}$ and radius 10 km, they obtained an NS surface temperature $T_{\text{eff}} = 1.4\text{--}1.9$ MK and distance $d = 1.6\text{--}3.3$ kpc, versus $T = 4.2\text{--}4.6$ MK and implausibly large $d = 11\text{--}13$ kpc for the blackbody fit, at a 90% confidence level. The hydrogen column density inferred from the atmosphere fits, $n_{\text{H},21} = 0.7\text{--}2.2$, agrees fairly well with independent estimates obtained from UV observations of nearby stars, radio data, and the X-ray spectrum of the SNR shell, whereas the blackbody and power-law fits give considerably lower and greater values, $n_{\text{H},21} = 0.2\text{--}0.4$ and $5.2\text{--}7.0$, respectively. The NS surface temperature inferred from the atmosphere fits is consistent with standard NS cooling models.

All the previous observations failed to detect pulsations of X-ray radiation from 1E 1207.4–5209. An upper limit of 18% (at a 95% confidence level) on flux modulation was set by Mereghetti et al. (1996) from the analysis of the *ROSAT* PSPC

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data. Due to its higher sensitivity and the possibility of continuous observations, the *Chandra X-Ray Observatory* is much more capable of searching for periodicity of X-ray sources. We have employed this capability to search for the period of 1E 1207.4–5209. The observation and data reduction are described in § 2, the timing analysis of the data is presented in § 3, and some implementations are briefly discussed in § 4.

2. OBSERVATION AND DATA REDUCTION

The object 1E 1207.4–5209 was observed with *Chandra* on 2000 January 6–7 with the spectroscopic array of the Advanced CCD Imaging Spectrometer (ACIS; see G. P. Garmire et al. 2000, in preparation) in the continuous clocking (CC) mode. This mode provides the highest time resolution of 2.85 ms available with ACIS by means of sacrificing spatial resolution in one dimension. The source was imaged on the back-illuminated chip S3. The total duration of the observation was 32.6 ks. Time history of detected events reveals that there were three relatively short time intervals with very strongly (by an order of magnitude) increased background (background “flares”) distributed over the whole detector. To mitigate the contamination of the source by the flares, we excluded these intervals from further analysis, which resulted in an effective exposure of 29,283 s.

The event arrival times were not properly corrected for the satellite wobbling (dither) and the Science Instrument Module (SIM) motion by the standard pipeline processing. The dither has a period of about 710 s and peak-to-peak variation of about 40 pixels. From our analysis (Sanwal et al. 2000) of *Chandra* data on PSR 1055–52, observed in the same mode, we have been aware that the lack of the dither correction results in false periodicities (side peaks) in the power spectrum of a pulsar. The SIM offset (shift of SIM in the Z-translation direction from the nominal aim point in the focal plane; see *Chandra* Proposer’s Observatory Guide, § 2.4) varied from 0.17 to 0.20 mm (from 7.1 to 8.3 pixels) during the time span of the observation. The lack of the SIM motion correction may result in a phase shift and broadening of a pulse. We corrected the event arrival times t in the event file making use of the data recorded in the aspect solution file and the formula (G. Allen 2000, private communication)

$$t_{\text{corr}} = t + c_1[(\alpha - \alpha_m) \sin \zeta \cos \delta_m - (\delta - \delta_m) \cos \zeta] \times \delta t - c_2 \Delta z \delta t, \quad (1)$$

where $c_1 = 3600''/0''.4919$ is the scaling coefficient transforming degrees to the detector pixels, $\delta t = 2.85$ ms is the integration time in the CC mode, ζ is the roll angle, $\alpha - \alpha_m$ and $\delta - \delta_m$ (in degrees) are the deviations of right ascension and declination from their median values, $c_2 = 1/0.024$ is the number of pixels per millimeter, and Δz is the SIM shift (in millimeters). We have checked that such a correction removes the artificial periodicities in the data on PSR 1055–52.

The one-dimensional image of 1E 1207.4–5209 in “sky pixels” (Fig. 1) can be fitted with a Gaussian profile with FWHM of 1.8 pixels ($0''.9$), consistent with the ACIS point-spread function. To obtain the source count rate, we extracted 23,337 source + background counts from a one-dimensional segment of 8 pixel length centered at the source position (10 pixels contain 23,602 counts). The background was taken from similar segments adjacent to the one-dimensional source aperture. Subtracting the background, we find the source count rate of 0.76 ± 0.01 s $^{-1}$. The observed source energy flux, $f_x = 2.2 \times 10^{-12}$

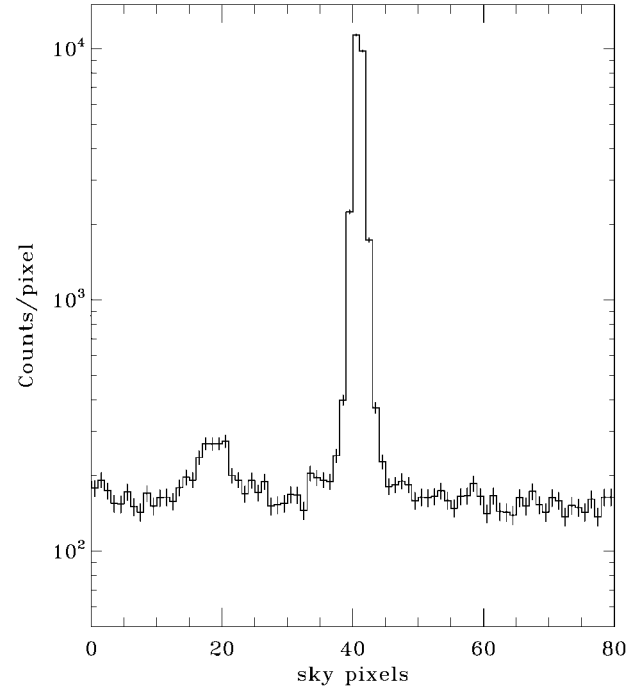


FIG. 1.—Distribution of detected counts over pixels in one-dimensional image in the vicinity of 1E 1207.4–5209. One sky pixel is equal to $0''.492$.

ergs cm $^{-2}$ s $^{-1}$ in the 0.2–5.0 keV range, corresponds to the (unabsorbed) luminosity $L_x \approx 3.5 \times 10^{33}$ ergs s $^{-1}$ compatible with that estimated by Zavlin et al. (1998) from the *ROSAT* and *ASCA* spectra. (This is the luminosity as measured at the surface of an NS with $M = 1.4 M_\odot$ and $R = 10$ km; it was obtained for $n_{\text{H},21} = 1$, assuming that the radiation originates from a magnetized hydrogen atmosphere with effective temperature of 1.5 MK.)

3. TIMING ANALYSIS

Previous *ROSAT* and *ASCA* observations of 1E 1207.4–5209 have not revealed pulsations of X-ray radiation from this object. This may be explained by the small number of counts collected in those observations. Moreover, those data were spread over very long time intervals, which always heavily complicates searching for weak pulsations.

One of the main advantages of the *Chandra* observation is that a large number of source counts (about 10 times the number of counts previously detected) has been acquired in a short time span. The spectral analysis shows that the background exceeds the source radiation at energies above 5 keV. Therefore, for the timing analysis we chose 22,535 counts with energies below 5 keV from a 6 pixel segment centered at the 1E 1207.4–5209 position. Of these counts, about 98% were estimated to belong to the source. To search for pulsations, we used the well-known Z_1^2 (Rayleigh) test (Buccheri et al. 1983), which is expected to be optimal to search for smooth pulsations. We ran the test in the 0.01–100 Hz frequency range with a step $\delta f = 3$ μ Hz. The oversampling by a factor of 10 (compared to the expected widths of $\sim 1/T$ of the Z_1^2 peaks, where $T = 32.6$ ks is the observational span) was chosen to resolve separate Z_1^2 peaks; it guarantees that the peak corresponding to a periodic signal would not be missed. The number of statistically independent trials in the chosen frequency range can be estimated as $N = (100 \text{ Hz})T = 3.26 \times 10^6$. The test yields only one high

peak of $Z_{1,\max}^2 = 65.0$ at the frequency $f_* = 2.357769$ Hz (see Fig. 2). Since the variable Z_1^2 has a probability density function equal to that of a χ^2 with 2 degrees of freedom, the probability of obtaining a noise peak of a given height in one trial is $\exp(-Z_1^2/2)$. This means that the probability of obtaining by chance a peak of $Z_1^2 = 65.0$ in N independent trials is $\rho = N \exp(-Z_{1,\max}^2/2) = 2.5 \times 10^{-8}$, which corresponds to a detection of pulsations at a confidence level of $C = (1 - \rho) \times 100\% = 99.9999975\%$, or 5.5σ . The next highest peak is $Z_1^2 = 32.0$. The probability of obtaining such a peak by chance in N trials is 35%.

To be sure that the pulsations found at the frequency f_* are not associated with instrumental effects, we ran the Z_1^2 test at $f = f_*$ on the same amounts of counts extracted from a few background regions and obtained a maximum Z_1^2 equal to 5. We also varied the size of the segment for source counts extraction and found that the initial choice of a 6 pixel extraction region was optimal to produce the maximum Z_1^2 value. We found that contributions from higher harmonics to the value of Z^2 are insignificant: $Z_2^2 = 65.1$ and $Z_3^2 = 65.2$.

To evaluate the pulsation frequency more precisely and find its uncertainty, we employed the method suggested by Gregory & Loredo (1996, hereafter GL), based on the Bayesian formalism. The method uses the phase-averaged epoch-folding algorithm to calculate a frequency-dependent odds ratio $O_m(f)$, which specifies how the data favor a periodic model of a given frequency f with m phase bins over the unpulsed model (see Gregory & Loredo 1992 for details of odds ratio computations). To weaken the dependence on number of bins, GL suggested using the odds ratio $O_{\text{per}}(f) = \sum_{m=2}^{m_{\max}} O_m(f)$, with a characteristic number of $m_{\max} = 10$ –15. The distribution of probability for a signal to be periodic, with frequency f in a chosen frequency range (f_1, f_2) , can be written as

$$p(f) = \frac{O_{\text{per}}(f)}{f} \left[(1 + O_{\text{per}}^*) \ln \frac{f_2}{f_1} \right]^{-1}, \quad (2)$$

where

$$O_{\text{per}}^* = \left(\ln \frac{f_2}{f_1} \right)^{-1} \int_{f_1}^{f_2} \frac{df}{f} O_{\text{per}}(f) \quad (3)$$

and the probability for the signal to be periodic in (f_1, f_2) is $O_{\text{per}}^*/(1 + O_{\text{per}}^*)$. Using PSR 0540–69 as an example, GL have demonstrated that this method allows one to determine the pulsation frequency with much higher accuracy than can be determined with more traditional methods. The most probable frequency f_0 is given by the maximum of $O_{\text{per}}(f)$ in (f_1, f_2) . The uncertainty δf at a given confidence level $C = \tilde{\rho} \times 100\%$ can be calculated from the following equation:

$$\int_{f_0 - \delta f}^{f_0 + \delta f} p(f) df = \tilde{\rho}. \quad (4)$$

We implemented the GL method, taking $m_{\max} = 12$ and $f_2 - f_* = f_* - f_1 = 200 \mu\text{Hz}$. The frequency dependence of the odds ratio is shown in Figure 2. The maximum value, $O_{\text{per}}^{\max} = 8.6 \times 10^8$, is at $f = f_0 = 2.3577717$ Hz ($f_0 - f_* \approx 3 \mu\text{Hz} \approx 0.1/T$). The uncertainty of f_0 at 68%, 90%, and 95% confidence levels is $\delta f = 1.3, 2.5$, and $3.5 \mu\text{Hz}$, respectively. This estimate is practically independent of choice of frequency range if $\Gamma \ll f_2 - f_1 \ll f_*$, where $\Gamma \approx 3 \mu\text{Hz}$ is a

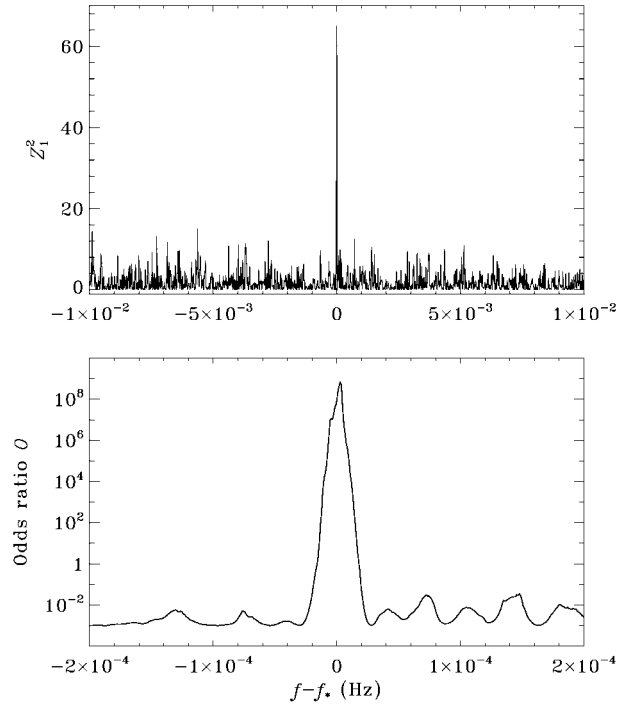


FIG. 2.—Power spectrum (top panel) and frequency dependence of odds ratio (bottom panel) around $f_* = 2.357769$ Hz.

characteristic width of the peak of the odds ratio (see Fig. 2). Thus, we finally derive the frequency and the period of the detected pulsations,

$$f_0 = 2.3577719 \text{ Hz} \pm 1.3 \mu\text{Hz}, \quad (5)$$

$$P_0 = 0.42412924 \text{ s} \pm 0.23 \mu\text{s}, \quad (6)$$

at the barycentric epoch of 51,549.630051303 MJD.

The light curve extracted at $f = f_0$ (Fig. 3) reveals one broad pulse per period with an intrinsic source pulsed fraction of $f_p = 9\% \pm 2\%$. Assuming that the detected signal is sinusoidal, we obtain an estimate on the pulsed fraction $f_p = (2Z_{1,\max}^2/N)^{1/2} = 7.6\%$ (where N is the number of counts), in fair agreement with the value calculated from the extracted light curve. Figure 3 indicates that the shape of the light curve may vary slightly with photon energy.

4. DISCUSSION

The detection of the period $P \approx 424$ ms proves that 1E 1207.4–5209, the central compact object of the PKS 1209–51/52 SNR, is the neutron star.

Let us assume that 1E 1207.4–5209 is an active pulsar of age τ within a range of 2–20 kyr (estimated limits of the SNR age). Then, for a braking index of 2.5, we should expect $f \sim f/(1.5\tau) \sim (2.5\text{--}25) \times 10^{-12} \text{ Hz s}^{-1}$, $\dot{P} = (4.5\text{--}45) \times 10^{-13} \text{ s s}^{-1}$. A crude estimate for the pulsar magnetic field (at the magnetic pole) would be $B \sim 6.4 \times 10^{19} (PP)^{1/2} \sim (3\text{--}9) \times 10^{13} \text{ G}$, close to the critical value $B_{\text{cr}} = 4.4 \times 10^{13} \text{ G}$, above which nonlinear QED effects can affect the processes in the pulsar magnetosphere. The pulsar spin-down luminosity (rotation energy loss) would be $\dot{E} = (2.3\text{--}23) \times 10^{35} I_{45} \text{ ergs s}^{-1}$. This \dot{E} may be high enough to power a compact synchrotron neb-

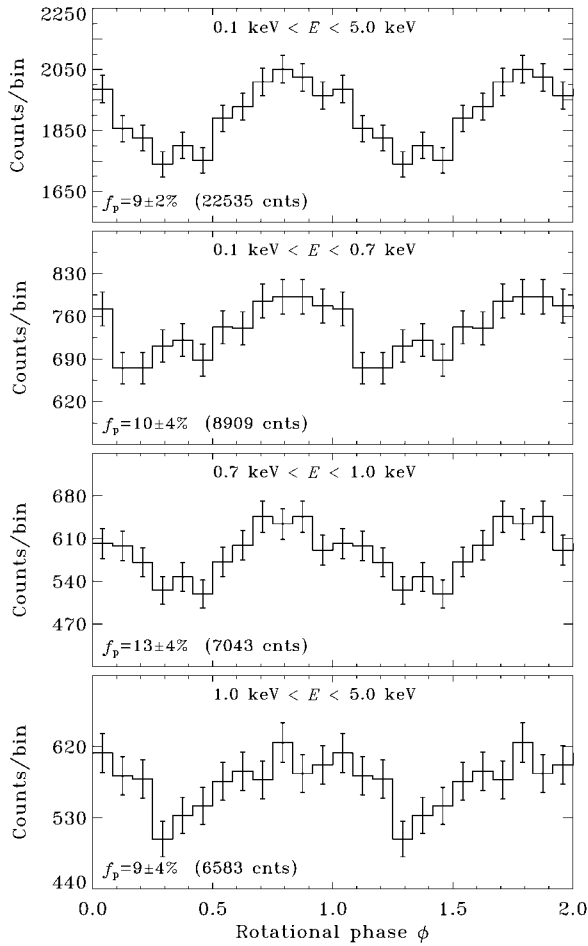


FIG. 3.—Light curves extracted in different energy ranges, at the period P_0

ula—for instance, Gaensler et al. (1998) found a radio nebula with a radius of $0.3(d/7 \text{ kpc}) \text{ pc}$ around a 100 kyr old PSR B0906–49, whose spin-down luminosity is $4.9 \times 10^{35} \text{ ergs s}^{-1}$. A nebula of similar size would have an angular radius of $\sim 30''$ at a distance of 2 kpc. The one-dimensional image of 1E 1207.4–5209 puts an upper limit of $3''\text{--}4''$ on the radius of a compact X-ray nebula around the pulsar.

If 1E 1207.4–5209 is an ordinary radio pulsar whose radio-quiet nature is due to an unfavorable orientation of the pulsar beam, the pulsar could be detected in deep radio observations at low frequencies, where radio beams are broader. On the other hand, the lack of manifestations of pulsar activity may indicate that 1E 1207.4–5209 is *not* an active pulsar, e.g., because a very high magnetic field can inhibit the cascade processes in the pulsar's acceleration zone (Baring & Harding 1997). In this case, the most natural explanation of the observed pulsations would be anisotropy of temperature distribution caused by anisotropic heat conduction in a superstrong magnetic field (Greenstein & Hartke 1983). This hypothesis can be verified by a phase-dependent spectral analysis which will be done on the same data when the ACIS response is known with better precision. Particularly useful for elucidating the nature of the NS would be measuring the period derivative, which requires at least one more observation. For instance, a similar ACIS observation in CC mode, taken a year later, would allow us to determine the frequency with an accuracy of $\sim 2 \mu\text{Hz}$ and detect a frequency derivative if it exceeds $\sim 2 \times 10^{-13} \text{ Hz s}^{-1}$, which is substantially smaller than the above estimates.

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