**ABSTRACT**

We report on an X-ray observation of the 166 Myr old radio pulsar J0108−1431 with *XMM-Newton*. The X-ray spectrum can be described by a power-law model with a relatively steep photon index $\Gamma \approx 3$ or by a combination of thermal and non-thermal components, e.g., a power-law component with fixed photon index $\Gamma = 2$ plus a blackbody component with a temperature of $kT = 0.11$ keV. The two-component model appears more reasonable considering different estimates for the hydrogen column density $N_H$. The non-thermal X-ray efficiency in the single power-law model is $\eta_{\text{PL}}^{1-10\text{keV}} = PL_{1-10\text{keV}} / E \sim 0.003$, higher than in most other X-ray-detected pulsars. In the case of the combined model, the non-thermal and thermal X-ray efficiencies are even higher, $\eta_{\text{PL}}^{1-10\text{keV}} \sim \eta_{\text{BB}} \sim 0.006$. We detected X-ray pulsations at the radio period of $P \approx 0.808$ s with significance of $\approx 7\sigma$. The pulse shape in the folded X-ray light curve (0.15–2 keV) is asymmetric, with statistically significant contributions from up to five leading harmonics. Pulse profiles at two different energy ranges differ slightly: the profile is asymmetric at low energies, 0.15–1 keV, while at higher energies, 1–2 keV, it has a nearly sinusoidal shape. The radio pulse peak leads the 0.15–2 keV X-ray pulse peak by $\Delta \phi = 0.06 \pm 0.03$.

**Key words:** pulsars: individual (PSR J0108−1431) – stars: neutron – X-rays: stars

**Online-only material:** color figures

1. INTRODUCTION

Radiation of rotation powered pulsars (RPPs) is powered by their rotational energy loss. Over 1700 RPPs have been detected in the radio and over 100 in X-rays. Their period and period derivative measurements are used to calculate the spin-down power, $\dot{E}$, the surface magnetic field, $B$, and the characteristic spin-down age, $\tau$. The X-ray spectra of RPPs exhibit some common features that evolve with spin-down age.

For very young pulsars ($\tau \lesssim 10$ kyr), the magnetospheric emission is observed to be dominant, burying the component of bulk surface thermal emission in most cases. Middle-aged pulsars, with spin-down ages $10^2 \lesssim \tau \lesssim 10^6$ years, tend to have a significant contribution from the surface thermal emission ($kT \sim 0.03–0.3$ keV) in the soft X-rays, eventually dominating the X-ray spectrum up to $\sim 1–2$ keV. The high-energy part of the X-ray spectrum contains a contribution from non-thermal, magnetospheric emission and may contain a component of thermal, polar-cap emission. The non-thermal component in the spectra of these young pulsars is usually fitted with a power law (PL) with photon index $\Gamma \lesssim 2$ (see, e.g., Figure 4 in Li et al. 2008). The fraction of the spin-down power emitted in the X-rays ($\gamma_{\text{X}} = L_{\text{X}} / \dot{E}$) has values in the range of $10^{-5} \lesssim \gamma_{\text{X}} \lesssim 10^{-3}$ (see, e.g., Figure 5 in Kargaltsev & Pavlov 2008). The X-ray pulse profiles of young pulsars show relatively sharp pulses for the non-thermal emission and smooth, broader pulses for the thermal emission. Asymmetric pulse shapes have been reported for middle-aged pulsars. For instance, Geminga, PSR B0656+14 and PSR B1055−52 ($\tau \sim$ a few 100 kyr), and PSR J0538+2817 ($\tau = 30$ kyr) show such asymmetric pulse profiles (e.g., De Luca et al. 2005; Zavlin & Pavlov 2004b; McGowan et al. 2003; Pavlov et al. 2002).

Old ($\tau \gtrsim 10^6$ years) RPPs have diminished spin-down powers ($\dot{E} \lesssim 10^{34}$ erg s$^{-1}$) and X-ray luminosities. This restricts the distance up to which such old pulsars can be detected and necessitates longer observations. There have been only a dozen of these old RPPs detected in the X-rays (see, e.g., Posselt et al. 2012, and references therein). Absorbed PL model fits for these pulsars yield $\Gamma \sim 2–4$. Hence, their spectra are softer than the non-thermal spectra of the younger pulsar population. The inferred absorbing hydrogen column density values, $N_H$, are usually larger than expected from the respective total Galactic hydrogen column densities and/or estimates from pulsar dispersion measures (DMs). The non-thermal X-ray efficiencies in the $1–10$ keV band show significant scatter, $\eta_{\text{PL}}^{1-10\text{keV}} \sim 10^{-4}–10^{-2}$, but are on average higher than the corresponding values calculated for younger pulsars (Kargaltsev et al. 2006; Zharikov et al. 2006).

Old neutron stars are too cold to have significant thermal X-ray emission from the bulk stellar surface (Yakovlev & Pethick 2004). However, a possible thermal X-ray contribution may come from polar caps heated by infalling accelerated particles (Harding & Muslimov 2001, 2002). An additional thermal component can explain the X-ray spectra of some of these old pulsars. If fitted with a simple blackbody (BB) model, these components have BB temperatures of $0.1–0.3$ keV and projected areas smaller than the conventional polar-cap area ($A_{\text{pc}} = 2\pi R_{\text{NS}}^2 / (cP) \sim 10^5$ m$^2$ for NS radius $R_{\text{NS}} \sim 10$ km and period $P \sim 1$ s). Thermal emission from the surface layers of a neutron star atmosphere (NSA) can differ substantially from BB emission (e.g., Pavlov et al. 1995). Assuming H or He atmosphere emission instead of the simple BB results in larger polar-cap area sizes and temperatures about a factor of two lower than the BB temperature (see, e.g., Zavlin & Pavlov 2004a for the atmosphere model analysis of the old PSR B0950+08).

Pulsar J0108−1431 was discovered by Tauris et al. (1994). It has a period $P = 0.808$ s and a period derivative $\dot{P} = 7.7 \times 10^{-17}$ s$^{-1}$, which corresponds to $\tau = P / 2 \dot{P} \approx 166$ Myr, $\dot{E} \approx 5.8 \times 10^{30}$ erg s$^{-1}$, and $B = 2.5 \times 10^{11}$ G, as listed in the Australian Telescope National Facility (ATNF) Pulsar
of the collaborative program with the Fermi suggested by Mignani et al. (2008). The parallax distance of $d$ with an estimated very long baseline interferometry (VLBI) E-pulsars, PSR J0108–1431 is now regularly monitored as part of the collaborative program with the Fermi group (Weltevrede et al. 2010). An optical counterpart of PSR J0108–1431 was suggested by Mignani et al. (2008).

PSR J0108–1431 has the largest $\tau$ and lowest $\dot{E}$ among the X-ray-detected pulsars. Characterization of its spectrum is essential to understand the final stages of the spectral evolution of old pulsars. It is one of the nearest neutron stars to Earth, with an estimated very long baseline interferometry (VLBI) parallax distance of $d = 240^{+124}_{-61}$ pc (Deller et al. 2009), which was recently revised to $d = 210^{+50}_{-30}$ pc when accounting for the Lutz–Kelker bias (Verbiest et al. 2012). Deller et al. (2009) also measured the pulsar proper motion of $170.0 \pm 2.8$ mas yr$^{-1}$ in the south–southeast direction.

PSR J0108–1431 has been detected with the Chandra X-Ray Observatory (Pavllov et al. 2009). The spectral analysis, performed using the 51 counts detected in the 0.8–5 keV energy range, showed emission consistent with either a single-component, soft ($\Gamma \sim 2.2$–3.4) PL expected from the pulsar’s magnetosphere or a 3 MK thermal BB emission from an apparent emitting area of $\sim 50$ m$^2$. Pavlov et al. (2009) suggested the presence of both non-thermal (magnetospheric) and thermal (polar-cap) components in the spectrum, potentially distinguishable from each other by phase-resolved spectroscopy of the source.

The goal of our deeper XMM-Newton observation was to collect more photons for studying the pulsar spectrum. In addition, the high time resolution of the EPIC-pn detector could detect X-ray pulsations and potentially separate its non-thermal and thermal components through phase-resolved spectroscopy. The observation and data analysis are described in Section 2, the relation between the detected X-ray and radio pulse shapes is described in Section 3, followed by a discussion of the results in Section 4.

### 2. OBSERVATION AND DATA ANALYSIS

Pulsar J0108–1431 was observed on 2011 June 15 (MJD 55727) with XMM-Newton (ObsID 0670750101) using the European Photon Imaging Camera (EPIC) in full-frame mode with the thin filter. The EPIC-pn (Strüder et al. 2001) and EPIC-MOS1 and MOS2 cameras (Turner et al. 2001) observed the source for 126.7 ks and 127.8 ks, respectively. The EPIC data processing was done with the XMM-Newton Science Analysis System (SAS) 11.0, applying standard tasks. Our observation was contaminated by soft proton flaring events in the background. We considered different selections of good time intervals (GTIs) for optimal spectral and timing analysis, which are described in more detail below.

We detected the X-ray counterpart of PSR J0108–1431 at a position $\alpha = 01^{h}08^{m}08.25s$, $\delta = -14^{\circ}31^{\prime}53^{\prime\prime}4$ with EPIC-pn. This position is separated by 2.9 $^\circ$ from the earlier (MJD 54136) Chandra detection at $\alpha = 01^{h}08^{m}08.354s$, $\delta = -14^{\circ}31^{\prime}50^{\prime\prime}38$

| Table 1: Spectral Extraction Parameters for pn, MOS1/2 Events |
|----------------------|---------|------|------|
| **Extraction Parameters** | **pn** | **MOS 1** | **MOS 2** |
| Aperture radius | $12^\prime$ | $13^\prime$ | $13^\prime$ |
| Energy range (keV) | 0.2–2.5 | 0.3–2.5 | 0.3–2.5 |
| Total aperture counts | 682 | 155 | 152 |
| Source/total counts (%) | 69.9 | 74.0 | 74.4 |
| BO-cor. count rate (ks$^{-1}$) | 4.6±0.3 | 1.0±0.1 | 1.0±0.1 |

(Pavllov et al. 2009) after accounting for the proper motion by Deller et al. (2009). The X-ray position differs by 3 $^\prime$0 from the expected radio pulsar position using the proper motion and VLBI position: $\alpha = 01^{h}08^{m}08^{s}347$, $\delta = -14^{\circ}31^{\prime}50^{\prime\prime}187$ (MJD 54100) listed by Deller et al. (2009). The absolute astrometric 2$\sigma$ error of XMM-Newton is 2 $^\prime$7. Thus, the EPIC-pn X-ray position is consistent with the Chandra and VLBI radio position.

#### 2.1. Spectral Analysis

For our spectral analysis of the X-ray counterpart of PSR J0108–1431, we aimed for the highest possible signal-to-noise ratio, $S/N = (N_s - a N_b)/(N_s + a^2 N_b)^{1/2}$, where $N_s$ and $N_b$ are the total numbers of counts extracted from the source and background regions of areas $A_s$ and $A_b$, respectively, and $a = A_s/A_b$. Given the strong background flaring in our observation, we tested different GTI filters derived from 100 s binned light curves of events with energies above 10 and 12 keV for pn and MOS detectors, respectively. For each GTI-filtered event file, we applied the regionsanalyse task to optimize the aperture size for high $S/N$ spectral extraction. Standard pattern filtering ($\leq 4$ for pn and $\leq 12$ for MOS) was enforced. We achieved the highest $S/N$ for a GTI count rate cutoff of 5.0 counts s$^{-1}$ and 0.5 counts s$^{-1}$ for the pn and MOS light curves, and for source aperture radii of 12 $^\prime$ and 13 $^\prime$ for pn and MOS, respectively. The net GTIs for pn, MOS1, and MOS2 are 104.8 ks, 112.5 ks, and 114.6 ks, respectively.

We used larger background regions for better statistics, with the radii of 42 $^\prime$, 75 $^\prime$, and 90 $^\prime$ for pn, MOS1, and MOS2, respectively. The extraction parameters are presented in Table 1. The source and background regions in the three processed EPIC images are shown in Figure 1. The background signal is comparable to the source signal at 1.2–2 keV and then exceeds the source signal for energies $>$3 keV. Considering the substantial count rate errors for the high energies, we restrict our spectral fitting to events in the 0.2–2.5 keV range in order to better constrain the spectral fit parameters.

Considering all three EPIC cameras together, we obtained around 990 total X-ray counts from the source apertures, or around 705 source counts (see Table 1). Redistribution matrices and effective area files were generated using the usual SAS tasks rafgen and arfgen. For the spectral fit, the SAS task specgroup was used to group the source counts of each spectrum with a minimal $S/N \geq 5$ bin$^{-1}$.

Using XSPEC 12.6.0, we tested different spectral models (PL: powerlaw; BB: bbodyrad, BB+PL, BB+BB) by applying the $\chi^2$ statistic. For the photoelectric absorption in the interstellar medium, we used tbabs with the solar abundance table from Anders & Grevesse (1989) and the photoelectric cross-section table from Balucinska-Church & McCammon (1992).
were obtained using XSPEC’s fitting parameters. The confidence levels for each parameter included both model and distance uncertainties. Therefore we had to freeze one parameter (see below).

An absorbed PL model with photon index $\Gamma = 3.1^{+0.5}_{-0.3}$ and hydrogen column density $N_H = (5.5^{+1.5}_{-2.2}) \times 10^{20} \text{ cm}^{-2}$ provides a good fit of the data with $\chi^2 = 1.1$: see Figure 2 for the X-ray spectral fit and Figure 3 for confidence contours for the three model parameters. Table 2 lists our best spectral parameters for each instrument agreed within the 90% confidence levels with the fit using the same normalization for all instruments. For simplicity, we give only the latter in the following. The spectral fit together with a new He cross-section based on Yan et al. (1998). We performed simultaneous fitting of the pn and MOS spectral data.

The values of the fits with separate normalizations for each instrument agreed within the 90% confidence levels with the fit using the same normalization for all instruments. For simplicity, we give only the latter in the following. The spectral fit parameters were allowed to vary freely for the single-component models, while for the combination of the PL with the BB there were not enough counts to constrain all the parameters sufficiently. Therefore we had to freeze a parameter (see below).

An absorbed PL model with photon index $\Gamma = 3.1^{+0.5}_{-0.3}$ and hydrogen column density $N_H = (5.5^{+1.5}_{-2.2}) \times 10^{20} \text{ cm}^{-2}$ provides a good fit of the data with $\chi^2 = 1.1$: see Figure 2 for the X-ray spectral fit and Figure 3 for confidence contours for the three model parameters. Table 2 lists our best spectral fitting parameters. The confidence levels for each parameter were obtained using XSPEC’s $\text{error}$ and $\text{steppar}$ commands. The non-thermal luminosity is estimated to be $L_{0.2-2.5\text{keV}} = 4\pi d^2 f_{\text{unabs}} = 1.2^{+1.3}_{-0.9} \times 10^{39} \text{ erg s}^{-1}$. The luminosity uncertainties include both model and distance uncertainties.

In contrast to the PL fit, a pure thermal model does not describe the data well. The best fit of the absorbed BB model has large residuals ($\chi^2 = 2.3$) that rule out the possibility of the emission being entirely BB-like. In principle, one could try to fit the spectrum with NSA models (Zavlin et al. 1996; Pavlov et al. 1995). However, the available atmosphere models in XSPEC were calculated either for $B = 0$ or strong magnetic fields ($B = 10^{12} \text{ G}$ and higher). For the magnetic field strength of PSR J0108–1431, $B = 2.5 \times 10^{11} \text{ G}$, the (redshifted) cyclotron energy is $\sim 2-3 \text{ keV}$. This is too close to the observed photon energy range and has a strong effect on the atmosphere spectrum, which is not considered in the weak or strong magnetic field models in XSPEC. Therefore, the NSA models are not applicable for PSR J0108–1431, and we have to stick to the simplistic BB models.

We also checked a two-component BB+BB model with photoelectric absorption. Such a model could describe the thermal emission from a nonuniformly heated neutron star surface. The best fit for this model also has residuals too large to be acceptable ($\chi^2 = 2.0$).

A combination of non-thermal magnetospheric emission and thermal emission from polar caps can be modeled by a PL+BB model. Because of the noise in the data, we had to freeze one fitting parameter. We froze the photon index to $\Gamma = 2$, motivated by the typical photon indices of younger pulsars, $\Gamma \sim 1-2$ (Li et al. 2008). The fit is acceptable ($\chi^2 = 1.1$) and its BB temperature is $kT = 0.11^{+0.03}_{-0.01} \text{ keV}$. We use the $\text{bbbodyrad}$ model in XSPEC, whose normalization factor gives the projected area $A_{\perp} = 5700^{+1300}_{-2400} d_{210}^2 \text{ m}^2$ and the corresponding radius of an

![Figure 1. X-ray images (0.2–2.5 keV) of the field in the direction of the PSR J0108–1431. The pn image ($\sim 4\times 2$), and the MOS1 and MOS2 images (each $\sim 2.6\times 2.6$) are shown on the top, bottom left, and bottom right, respectively. North is up, east is to the left. The source extraction regions (radii of 12″ for pn, 13″ for MOS) are marked with blue circles and the background regions are marked with red circles. (A color version of this figure is available in the online journal.)](image1)

![Figure 2. Absorbed PL fit and its residuals in units of sigmas for the pn (black), MOS1 (red), and MOS2 (green) data. (A color version of this figure is available in the online journal.)](image2)

![Figure 3. 68%, 90%, and 99% confidence contours in the $\Gamma - N_H$ plane (top) and in the $\Gamma$-PL normalization plane. $N_H$ is in units of $10^{21} \text{ cm}^{-2}$ and the PL normalization $N_{\text{PL}}$ is in units of $10^{-6} \text{ photons cm}^{-2} \text{s}^{-1} \text{ keV}^{-1}$ measured at 1 keV. Also plotted are the contours of constant unabsorbed flux $F_{\text{unabs}}$ in units of $10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}$ for the 0.2–2.5 keV band (bottom). (A color version of this figure is available in the online journal.)](image3)
only the propagated normalization error); see Table 2 for PL norm (10^{-3}). The radius of the blackbody emission was obtained from the normalization using a distance of \(d = 210 \text{ pc}\) (Verbist et al., 2012). Its error is the propagated normalization error only. If one also considers the distance error the corresponding value is \(R_{\text{bb}} = 43^{+24}_{-14} \text{ m}\).

![Figure 4](image_url)  
**Figure 4.** Top: absorbed PL+BB fit and the residuals in units of sigma deviations for the pn (black), MOS1 (red), and MOS2 (green) data. Bottom: underlying individual PL and BB spectral model components. (A color version of this figure is available in the online journal.)

![Figure 5](image_url)  
**Figure 5.** 68%, 90%, and 99% confidence contours in the \(kT-N_{\text{H}}\) plane (top) and \(kT-A_1\) plane (bottom) for the absorbed PL+BB model. \(N_{\text{H}}\) is in units of \(10^{22} \text{ cm}^{-2}\). Lines of constant bolometric luminosities in units of \(10^{28} \text{ erg s}^{-1}\) are overplotted in the \(kT-A_1\) plane.

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

This table shows the best-fit values with 90% confidence limits for the parameters of the absorbed PL+BB fit.

| Parameters | Best-fit Values |
|------------|-----------------|
| \(N_{\text{H}}\) (10^{20} \text{ cm}^{-2}) | 5.5^{+1.6}_{-1.2} |
| \(\Gamma\) | 3.1^{+0.5}_{-0.2} |
| PL norm (10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} at 1 \text{ keV}) | 2.8^{+0.4}_{-0.4} |
| \(\chi^2_{\text{red}}\) | 1.1/27 |
| \(F_{\text{unabs}}\) (0.2–2.3 keV) (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}) | 9.4^{+1.0}_{-1.0} |
| \(F_{\text{unabs}}\) (0.2–2.3 keV) (10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}) | 2.3^{+1.2}_{-0.8} |

**Table 2**  
Best-fit Parametric Values with 90% Confidence Limits

Additional fit results. Since \(R_{\text{NS}} \gg R_{\text{bb}}\), the emission likely comes from part of the surface like from hot polar caps. Figure 4 shows the spectral fit and its residuals, while the 68%, 90%, and 99% confidence contours in the \(kT-N_{\text{H}}\) and \(kT-A_1\) planes are plotted in Figure 5. As mentioned above, there are no available atmospheric models for the magnetic field strength of PSR J0108–1431. Therefore, we do not fit a two-component PL+NSA model to the data.

The luminosity for both components together is estimated to be \(L_{\text{BB+PL}} = L_{\text{unabs}} + L_{\text{NS}}\). The luminosity of the non-thermal component is \(L_{\text{PL}} = 3.7^{+5.2}_{-2.1} \times 10^{28} \text{ erg s}^{-1}\). The derived values of the temperature and area correspond to the bolometric thermal luminosity of an equivalent sphere \(L_{\text{bol}}^{\text{bb}} = 4A_1 \sigma T^4 = 3.7^{+5.8}_{-2.2} \times 10^{28} \text{ erg s}^{-1}\). The luminosity errors include the propagated distance error and the corresponding propagated fit errors in flux, temperature, and emission area. Lines of constant bolometric luminosities are overplotted in the \(kT-A_1\) plane (Figure 5, bottom). The above-listed errors of \(L_{\text{bol}}\) encompass nearly the whole 3\(\sigma\) contours in the \(kT-A_1\) plane because we additionally considered the distance error in our conservative error estimate.

2.2. Timing Analysis

Hobbs et al. (2004) reported the radio ephemerides of PSR J0108–1431 to be \(\nu = 1.23829100810(3) \text{ Hz}\) and \(\dot{\nu} = 0.11813(18) \times 10^{-15} \text{ Hz s}^{-1}\) at MJD 50889.0. At the start of our X-ray observations, MJD 55727.2, the expected frequency change, \(-0.049 \mu\text{Hz}\), is negligible for X-ray timing. The EPIC-pn detector with a nominal frame time of 73.4 ms in the full-frame mode is well suited for the timing analysis of PSR J0108–1431, while the time resolution of the MOS...
detectors in full-frame mode, 2.6 s, does not allow such an analysis.

Following up on SAS warnings during the data processing, we checked the EPIC-pn CCD with the target on it for time jumps in the data. We set the SAS environment parameter SAS_JUMP_TOLERANCE\(^9\) to a value of 33 to account for the known temperature effect on the actual frame time of the EPIC-pn detector (Freyberg et al. 2005; M. Freyberg et al., in preparation\(^10\)). In addition, we excluded the end of the observation (>119.28 ks after the start). At that time, a bright X-ray background flare caused the instrument to switch to the counting mode\(^11\) which resulted in finding of false time jumps by the SAS. Our final data for the timing analysis were free of apparent time jumps. All times of arrival (TOAs) of the X-ray photons were corrected to the solar barycentric system using the standard task barycen.

We used the \(Z^2\) test, the sum of powers of the first \(n\) harmonics (e.g., Buccheri et al. 1983), to search for pulsations in these data. For our timing analysis, we checked 7 different GTI screenings, 11 different energy regions, and 5 different extraction regions in order to maximize the \(Z^2\). The GTI screening with pn count rate <4 counts s\(^{-1}\) for a 100 s binned background light curve (10–12 keV), the extraction radius of 8\(^\prime\)±\(^\prime\)0, the energy range of 0.15–2 keV were found to be the optimal choices among the variants tested. At the chosen GTI filter, there is only one small (200 s) time gap in the last fifth of the exposure. This filtering provided 507 events during a time span of \(T_{\text{span}} = 119.1\) ks.

PSR J0108–1431 has been monitored for 16 years, and no glitches have been detected (Espinoza et al. 2011). Investigating possible timing irregularities for 366 pulsars, Hobbs et al. (2010) found PSR J0108–1431 to be a very stable pulsar with low timing noise like other pulsars with similarly low \(v\). Therefore, we could search for X-ray pulsations at the radio pulsation frequency. However, to check whether the above-mentioned time jump correction worked properly, we searched a frequency range of 1.2382–1.2384 Hz with a sampling of 0.1 \(\mu\)Hz, thus oversampling the expected \(Z^2\) peak width, \(\sim T_{\text{span}}^{-1} = 8.4 \mu\)Hz, by a factor of 80. A peak \(Z^2_{\text{max}} = 48.0\) is found at \(v_0 = 1.2382908 \pm 0.7 \mu\)Hz, corresponding to a period of 0.8075647 ± 0.5 \(\mu\)s. The frequency uncertainty was derived similarly to Chang et al. (2012) as \(\delta v = 0.557 T_{\text{span}}^{-1} (Z^2_{\text{max}}) \cdot 1/2\).

Within errors the X-ray pulse frequency agrees with the radio pulse frequency very well. The probability to find \(Z^2_{\text{max}} = 48.0\) by chance is \(p = \exp(-Z^2_{\text{max}}/2) = 4 \times 10^{-11}\), which corresponds to the 6.6\(\sigma\) confidence level.

To explore the harmonic content of the X-ray pulsations and refine the significance estimate, we performed the \(Z^2\) test accounting for up to \(n = 7\) harmonics. The peak \(Z^2\) values (and the respective significances) are \(Z^2_1 = 57.9\) (6.8\(\sigma\)), \(Z^2_2 = 61.5\) (6.7\(\sigma\)), \(Z^2_3 = 66.4\) (6.7\(\sigma\)), \(Z^2_4 = 75.3\) (6.9\(\sigma\)), \(Z^2_5 = 75.5\) (6.6\(\sigma\)), and \(Z^2_6 = 80.0\) (6.4\(\sigma\)) at frequencies consistent within errors with the one found from the \(Z^2_1\) test. For the application of the \(H\)-test (de Jager et al. 1989), \(H = \max[H_m]\), we found \(H_m = Z^2_m - 4m + 4\) to be 48.0, 53.9, 53.5, 54.4, 59.3, 55.5, and 56.0 for the first to seventh harmonic, respectively, i.e., the pulsations have statistically significant contributions from five leading harmonics of the principal frequency.\(^12\) Thus, the pulsations of PSR J0108–1431 are unambiguously detected in X-rays with a significance of 6.9\(\sigma\).

In order to visualize the pulse shape, we obtained a folded light curve in the form of a histogram for the energy range 0.15–2 keV (507 counts), as well as for the split energy ranges 0.15–1 keV (416 counts) and 1–2 keV (92 counts). The frequency \(v_0 = 1.2382908\) Hz was used for the folding. We applied the so-called Scott’s rule of Terrell & Scott (1985) for setting the upper bound for the histogram bin width. These authors concluded that their rule to avoid oversmoothing gives nearly optimal results for a variety of smooth probability densities. However, choosing the optimal histogram bin size remains a matter of debate in statistical data analysis (for a review, see, e.g., Scott 1992). According to Scott’s rule the number of bins must be \(\geq (2N)^{1/3}\), where \(N\) is the number of events. We selected \(N_{\text{hist}} = 11\) bins for the energy ranges 0.15–2 keV and 0.15–1 keV, and \(N_{\text{hist}} = 6\) for the energy range 1–2 keV.

The number of counts in the histogram bins depends on the reference phase, which was chosen arbitrarily. The histogram can look quite different for another choice of reference phase, especially if there are few bins. To obtain the folded light curve independent of the reference phase choice, we averaged the histogram over the reference phase,\(^13\) varying the latter within one histogram bin; see the Appendix for a short description of the algorithm used. In the following, we call the new histogram obtained the reference phase averaged (RPA) pulse profile. The histograms of the folded light curve together with the respective RPA pulse profiles are shown in Figure 6. The pulse shape for the full energy band, 0.15–2 keV, and the soft energy band appear to be asymmetric, with a slower rise and steeper decay. The two RPA pulse profiles have their maxima at similar phases. The 1–2 keV RPA pulse profile appears more sinusoidal and slightly shifted to smaller phases compared to the low-energy and broad bands. However, the pulse shape in the energy range 1–2 keV has poorer statistics, and direct comparisons must be regarded with caution. Using the RPA pulse profiles as probability distribution templates and the respective number of events as sample sizes, we carried out Monte Carlo simulations of the profiles to estimate the uncertainties of the phase positions of the respective RPA pulse profile maxima. The maxima of the RPA pulse profiles in Figure 6 are at \(\phi = 0.96 \pm 0.03, 0.97 \pm 0.03,\) and 0.86 ± 0.06 for the energy ranges 0.15–2 keV, 0.15–1 keV, and 1–2 keV, respectively (see Figure 6).

For the full energy band, 0.15–2 keV, for which we have the best statistics, we also use another visualization method. We apply Fourier decomposition \(F_m(\phi)\) up to a harmonic \(m\) to describe the pulse shape:

\[
F_m(\phi) = \frac{N}{N_{\text{hist}}} \left[1 + 2 \sum_{k=1}^{m} a_k \cos(2\pi k\phi) + b_k \sin(2\pi k\phi)\right],
\]

where

\[
a_k = \frac{1}{N} \sum_{i=1}^{N} \cos(2\pi k v_i), \quad b_k = \frac{1}{N} \sum_{i=1}^{N} \sin(2\pi k v_i)
\]

\(^9\) SAS_JUMP_TOLERANCE is given in units of 20.48 \(\mu\)s. Only deviations of the measured actual frame time from the nominal frame time larger than the SAS_JUMP_TOLERANCE are identified as time jumps by the SAS.

\(^10\) See also: http://www2.le.ac.uk/departments/physics/research/src/Missions/xmm-newton/technical/leicester-2012-03/freyberg-cal-2012.pdf

\(^11\) XMM-Newton Users Handbook, Section 3.3.2. Science modes of the EPIC cameras.

\(^12\) We checked \(H_m\) up to 20 harmonics as recommended by de Jager et al. (1989) with the same result.

\(^13\) A similar phase averaging was applied by Zavlin et al. (2002, their Figure 5).
Figure 6. Folded light curves as histograms and reference phase averaged (RPA) pulse profiles (see the text). For a better overview, two full phase cycles are shown. Upper panel: the upper 11-bin histogram represents the full energy range considered, 0.15–2 keV, the corresponding RPA pulse profile is shown in blue, and its average background level is indicated with a blue dashed line. Similarly, for the energy range 0.15–1 keV, the red RPA pulse profile corresponds to the lower histogram and the average background level for this energy range is indicated with a red dashed line. Lower panel: the 6-bin histogram and the RPA pulse profile represent the folded light curve in the energy range 1–2 keV.

Figure 7. Folded light curve histogram for the full energy range considered, 0.15–2 keV, together with the Fourier series including up to three harmonics (dark blue), four harmonics (cyan), and five harmonics (yellow). For comparison, the RPA pulse profile from Figure 6 is also plotted as the red dashed curve.

3. COMPLEMENTARY RADIO DATA

It is interesting to compare the radio pulse with the X-ray pulse, in particular the phase difference between them. We use the monitoring radio data described by Weltevrede et al. (2010) for our comparison of the radio and the X-ray profiles. Observations at 1.4 GHz were obtained from 2009 December...
Figure 8. Folded X-ray light curve histogram (energy range 0.15–2 keV) is plotted together with the corresponding RPA pulse profile (both in black). The red curve shows the total intensity of the 1.4 GHz radio pulse in mJy; the blue curve shows the linearly polarized part of the radio pulse. The reference phases of the X-ray and radio profiles were aligned as described in the text. (A color version of this figure is available in the online journal.)

to 2012 July using the 64 m radio telescope at Parkes, NSW, Australia. The data were calibrated and TOAs produced using prearchive routines (Hotan et al. 2004) and the tempo2 package (Hobbs et al. 2006). An accurate value of the radio DM is necessary to correct for the dispersion delay when comparing the relative phases of the 1.4 GHz radio and high-energy pulse profiles. The measured DM for PSR J0108–1431 is 2.38 ± 0.19 cm−3 pc (Hobbs et al. 2004). This translates into a DM-induced uncertainty of ∼402 µs or 5 × 10−4 in the phase of the radio pulse.

For the comparison with the radio pulse shape, we converted the TOAs of the X-ray photons to the solar system barycenter using the standard SAS task barycen with the same coordinates as in the radio tempo2 analysis and the same DE405 solar system ephemeris (Standish 1998). We used the barycentric TOAs of five X-ray events in tempo2 to derive their phases relative to the radio profile. Knowing the X-ray phases of these events as well, we determined the offset between the radio and X-ray phase reference points to be 0.898 ± 0.003. Correcting for this shift between the reference systems, Figure 8 shows the X-ray and radio profiles together in the same phase range. We confirm the unusual high linear polarization of the radio pulse reported by Weltevrede et al. (2010), obtaining a value of 77% for the fractional linear polarization at the pulse peak. Using the peak positions of the RPA pulse profiles from Section 2.2, the radio pulse leads the X-ray pulse peak by 0.06 ± 0.03 and 0.08 ± 0.03 in the energy ranges 0.15–2 keV and 0.15–1 keV, respectively. In contrast, the X-ray pulse at 1–2 keV leads the radio pulse by 0.03 ± 0.06. The quoted errors take into account the uncertainties in the reference phase shift, the DM-induced phase uncertainty, the absolute XMM-Newton EPIC-pn timing accuracy of 48 µs (Martin-Carrillo et al. 2012), and the dominating error of the maximum position in the RPA pulse profile (Section 2.2).

4. DISCUSSION

4.1. The X-Ray Spectrum and Luminosity

PSR J0108–1431 is the oldest among the non-recycled ordinary pulsars detected in X-rays, with the spin-down age a factor of four larger than that of PSR B1451–68, the previous record holder. It also has the lowest $\dot{E}$ among the same sample of X-ray-detected non-recycled pulsars. Our new XMM-Newton observation provided a factor of 20 more source counts enabling better characterization of the pulsar’s spectrum compared to the previous Chandra observation. However, the strong flaring and high background at energies above ∼2 keV have undermined energy-resolved timing and phase-resolved spectral analysis of the pulsar emission.

Formally, a simple absorbed PL model and an absorbed PL+BB model describe the data equally well. The photon index $\Gamma$ = 3.1 ± 0.5 (see also Figure 3) of the PL fit is larger (i.e., the spectrum is steeper) than $\Gamma \sim 1–2$, typical for young pulsars (Li et al. 2008). As mentioned above, for the BB+PL fit we had to freeze one parameter because of the small number of counts and strong noise. We chose to fix the photon index at $\Gamma = 2$, assuming similar magnetospheric emission characteristics for young and old pulsars.

The PL fit falls in line with the trend observed in other old pulsars, for which the PL fits suggest too large $N_H$ values in conjunction with larger photon indices $\Gamma$. For the line of sight of PSR J0108–1431, the Leiden–Argentina–Bonn (LAB) Survey of Galactic H I reports $N_{HI} = 2.1 \times 10^{20}$ cm$^{-2}$ in this direction (Kalberla et al. 2005), the Dickey & Lockman (1990) neutral hydrogen survey reports $N_{HI} = 1.8 \times 10^{20}$ cm$^{-2}$. The $N_H = 5.5^{+1.8}_{−1.2} \times 10^{20}$ cm$^{-2}$ from our PL fit is above those total Galactic values. We use the Lutz–Kelker-corrected, parallactic distance $d = 210^{+90}_{−50}$ pc by Verbiest et al. (2012) to estimate the expected $N_H$ value applying the “analytical” three-dimensional (3D) extinction model described by Posselt et al. (2007). For the close (<250 pc) solar neighborhood, this model is based on the 3D Na D absorption line mapping by Lallement et al. (2003) and has a resolution of ∼25 pc; at larger distances an analytical model is used for the extinction (see Posselt et al. 2007, 2008 for more details). Considering the errors of the distance, we derived an expected $N_H$ in the range (0.3–0.8) × 10$^{20}$ cm$^{-2}$. Assuming 10 H atoms per electron, we derive a similarly low expected $N_H$ of $0.7 \times 10^{20}$ cm$^{-2}$ from the pulsar DM = 2.38 pc cm$^{-3}$ (Hobbs et al. 2004). Thus, the absorption is overestimated in the simple PL fit (see Figure 5) while the 90% confidence range of the $N_H$ parameter in the BB+PL fit includes the expected $N_H$ value.
The temperature obtained in the BB+PL fit, $T = 1.3$ MK, is a reasonable estimate for the expected heated polar-cap region. The effective projected emitting area is $A_{\perp} = 5700$ m$^2$. This is a factor of $\sim 14$ smaller than the conventional polar-cap area $A_{\text{pc}} = 2\pi R^2 \frac{\text{NS}}{(cP)} \approx 82,000$ m$^2$, using $R_{\text{NS}} = 10$ km. PSR J0108–1431 is very similar to other old pulsars in this respect (Posselt et al. 2012; Pavlov et al. 2009; Misanovic et al. 2008; Kargaltsev et al. 2006; Zhang et al. 2005). We should note, however, that the values of the temperature and, particularly, the projected area are rather uncertain because of their strong correlation (Figure 5).

As mentioned in the Introduction, one has to take into account that thermal emission from the surface layers of a neutron star can differ substantially from the BB emission (e.g., Pavlov et al. 1995). In particular, if the emission emerges from a light-element (H or He) atmosphere, fitting with NSA models may yield the effective temperature a factor of two lower than $T_{\text{BS}}$, and the projected emitting area a factor of 10–100 larger than $A_{\perp}$, while the bolometric luminosity does not change substantially. The magnetic field can have a strong impact on the observed emission of an NSA. The current NSA models available in XSPEC are not applicable to PSR J0108–1431 because the electron cyclotron line, caused by its magnetic field, $B = 2.5 \times 10^{11}$ G, is in the observable energy range, but it is not included in the XSPEC models. Therefore, we do not discuss atmosphere models for PSR J0108–1431.

Overall, there are now several old pulsars whose spectra could be described by the PL model, but the properties of these fits—in particular, the large $\Gamma$ and the much higher than expected $N_{\text{H}}$—suggest a more complicated model. Adding a thermal (e.g., BB) component to the spectral model allows lower $N_{\text{H}}$ values and, correspondingly, smaller $\Gamma$, similar to those of younger pulsars.

For comparison with other pulsars, we calculated the non-thermal (PL) luminosity in the 1–10 keV energy range: $L_{\text{PL}}^{1-10\text{keV}} = 2.0^{+1.8}_{-1.1} \times 10^{25}$ erg s$^{-1}$ for the PL fit, and $L_{\text{PL}}^{1-10\text{keV}} = 3.3^{+3.0}_{-1.6} \times 10^{28}$ erg s$^{-1}$ for the PL component in the BB+PL fit.\(^{15}\) The higher photon index of the PL fit, obtained from the fitting at a lower energy range, is the reason why the $L_{\text{PL}}$ is smaller in the case of the PL fit than in the case of the PL+BB fit. The errors were calculated from the 90% confidence errors of the unabsorbed flux and the distance uncertainty of the Lutz–Kelker-corrected distance as listed by Verbist et al. (2012). These luminosities translate into non-thermal X-ray efficiencies of $\eta_{\text{PL}}^{1-10\text{keV}} = 0.003 d_{\odot}^2$ and $\sim 0.006 d_{\odot}^2$ for the PL fit and the PL+BB fit, respectively. Using the bolometric luminosity $L_{\text{bol}}^{\text{bb}} = 3.7^{+5.8}_{-2.7} \times 10^{28}$ erg s$^{-1}$ (Section 2.1), one can also estimate the thermal polar-cap heating efficiency from the PL+BB fit, $\eta_{\text{bb}}^{\text{bb}} = 0.006 d_{\odot}^2$, which gives the fraction of spin-down power heating the polar caps. Harding & Muslimov (2001) predicted that the expected polar-cap heating efficiency for ordinary pulsars for ages $\tau \lesssim 10^7$ years grows with age and period (e.g., $\eta_{\text{PC}} \sim 0.1$ for $\tau = 1.5 \times 10^7$ years, $P = 0.2$ s; see their Figure 7). For pulsars with $\tau > 10^7$ years they cautioned that the pulsar cannot produce enough electron–positron pairs to fully screen the electric field. Thus, the fraction of the returning positrons that heat the polar cap decreases, and the heating efficiency will drop. Comparing the estimated polar-cap heating efficiency with the predictions by Harding & Muslimov (2001), PSR J0108–1431 has a lower efficiency than one would expect for a pulsar having the same period (0.8 s) at an age of $\tau = 10^7$ years. This could indicate that the returning positron fraction is indeed smaller for PSR J0108–1431 than for younger pulsars.

In Figure 9, we updated the X-ray luminosities versus spin-down power plot by Posselt et al. (2012) (their Figure 4\(^{16}\)). The pulsar again shows properties comparable to those of other old pulsars. In particular, its non-thermal X-ray efficiency is higher than those of young pulsars, most of which have $\eta_{\text{PL}}^{1-10\text{keV}} < 10^{-4}$. Thus, the observation that older pulsars seem to radiate in X-rays more efficiently than younger ones (Zharikov et al. 2006; Kargaltsev et al. 2006) is reinforced.

4.2. The X-Ray Pulsations of PSR J0108–1431

The timing analysis of PSR J0108–1431 establishes, for the first time, unambiguous X-ray pulsations from this pulsar. More than two harmonics are required to explain the asymmetric pulse profile. Such asymmetric pulse profiles can have several explanations, different for non-thermal and thermal emission.

Asymmetric pulse profiles can be easily produced by non-thermal emission in the outer gap model (Romani & Yadigaroglu 1995), especially if special relativity effects, such as aberration and retardation, are taken into account (e.g., Dyks & Rudak 2003, and references therein). A comparison of the detected pulse shapes with those predicted by the models of magnetospheric high-energy emission could be useful in establishing the geometry of the emitting region, especially if additional information about directions of the pulsar’s magnetic and spin axes is available from, e.g., radio polarimetry. For PSR J0108–1431, we do not know if the bulk of the observed X-ray emission is produced in the pulsar’s magnetosphere (as is implied by the PL

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\(^{15}\) The 1–10 keV PL component luminosity and its errors were estimated for the fixed $\Gamma = 2$.

\(^{16}\) Note that Posselt et al. (2012) used distances derived from the Lutz–Kelker-corrected parallaxes (Verbist et al. 2010), which differ from the Lutz–Kelker-corrected distances. See Verbist et al. (2012) for details about the differences.
up to five harmonics to describe it. The peaks of the radio and the X-ray pulses are close to each other in phase. The X-ray spectrum and the high non-thermal X-ray efficiency of PSR J0108−1431 are comparable to other old pulsars. In particular, while the spectrum can formally be well described by a PL fit, the expected smaller photon index and lower \( N_{\text{H}} \) are better accounted for in a PL+BB model. We were not able to investigate phase-resolved spectra because of the high background in the strongly flare-impaired observation.

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**APPENDIX**

**OBTAINING THE REFERENCE PHASE AVERAGED PULSE PROFILE**

In the following, we briefly describe the sliding average bin algorithm used to average over reference phases within one histogram bin, producing the RPA pulse profile. First, we create \( k = 0, 1, \ldots, (N_{\text{sub}} − 1) \) folded light curve histograms with \( N_{\text{hist}} \) bins by shifting the reference time in the time series by \( \Delta t_k = k P / (N_{\text{hist}} \times N_{\text{sub}}) \), where \( P \) is the period of the pulsations and \( N_{\text{sub}} \) is an integer, which is equivalent to shifting the reference phase by \( \Delta \phi = \Delta t_k / P \). As usual, the bin heights of the histograms are the number of photon counts in the respective bins. Second, we divide the whole phase interval into \( n = 1, 2, \ldots, N_{\text{sub}} \times N_{\text{hist}} \) sub-intervals with bin heights \( h_n^k \), i.e., there are \( N_{\text{sub}} \) sub-intervals in each original bin all having the same bin heights. Finally, we average the bin heights of the \( N_{\text{sub}} \) histograms in each of the sub-intervals:

\[
h_n^{\text{RPA}} = \frac{1}{N_{\text{sub}}} \sum_{k=0}^{N_{\text{hist}}-1} h_n^k.
\]

For our histograms and RPA pulse profiles in Figure 6, we used \( N_{\text{sub}} = 100 \), and, as mentioned in Section 2.2, we used \( N_{\text{hist}} = 11 \) bins for the energy ranges 0.15−2 keV and 0.15−1 keV, and \( N_{\text{hist}} = 6 \) for the energy range 1−2 keV.

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