CHANDRA AND XMM-NEWTON OBSERVATIONS OF THE EXCEPTIONAL PULSAR B0628–28

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Received 2005 May 21; accepted 2005 June 28; published 2005 August 15

ABSTRACT

PSR B0628–28 is a radio pulsar that was first detected in the X-ray band by ROSAT and then later observed with Chandra and XMM-Newton. The Chandra observation yielded an X-ray luminosity 2 orders of magnitude higher than what is expected for spin-powered pulsars; also, there were no pulsations detected. The XMM-Newton observation, however, reveals pulsations at the expected radio period, \( P = 1.244 \) s. The simultaneously analyzed spectra also give a luminosity (in cgs) of \( L_X = 30.34 \), which is \( \sim 350 \) times greater than what would be expected from the \( L_X/E \) correlation.

Subject headings: pulsars: individual (B0628–28) — stars: neutron — X-rays: stars

1. INTRODUCTION

PSR B0628–28 is an old pulsar that has a characteristic age \( \tau = P/2P \) of 2.8 Myr. Since older pulsars have radiated away their initial heat content and have relatively low rotational energy loss \( (\dot{E} = \dot{\mathcal{J}} t) \), one would expect to detect X-ray radiation coming either from the reheating of the surface (e.g., see Tsuruta 1998; Shibazaki & Lamb 1989) or from heated polar caps (Halpern & Ruderman 1993). In young pulsars, however, thermal radiation from the neutron star surface is dominated by the nonthermal component from the neutron star magnetosphere, whose spectrum can be described primarily by a power-law model. We also know from X-ray observations that the pulsar’s nonthermal luminosity \( (L_X) \) shows a correlation with the spin-down power \( \dot{E} \). For instance, Possenti et al. (2002) found a best fit based on 37 pulsars. Although the variance is large, pulsars follow a general trend that can be formulated as \( \log L_X^{10} = 1.34 \log \dot{E} - 15.34 \). This set included only three old \( (\tau > 10^6 \) yr) pulsars. The reason for having only three is twofold. The first reason is that older pulsars are less active and relatively cooler, and hence most of them were not detected until Chandra and XMM-Newton. The detected ones have low count rates and, consequently, statistically poor spectra. This makes it challenging to distinguish between spectral models. The other reason is that it is expected that surface emission from old neutron stars will be dominant, resulting in spectra being more like a blackbody. Hence, the X-ray radiation from these pulsars is not expected to be characterized by a power-law model. However, recent observations of PSR B0943+10 (Zhang et al. 2005), PSR B0823+26, PSR B0950+08, and PSR J2043+2740 with XMM-Newton (Becker et al. 2004) and of PSR B2224+65 with Chandra (Zavlin & Pavlov 2004) have unfolded a new perspective in understanding old neutron stars. Not only have many previously undetected sources been detected, but also it has been possible to distinguish between different spectral models for some of these old pulsars. These old pulsars have spectra harder than expected that are best described by a power-law and/or a polar cap (blackbody) model, as opposed to a blackbody model representing the thermal emission from the whole neutron star surface. The integrated model flux of these sources converts to unusually high X-ray efficiencies \( (L_X/E) \).

PSR B0628–28 is the longest period radio pulsar detected in X-rays. However, physical parameters inferred from radio observations are not by any means extreme. The Chandra data yielded a luminosity 2 orders of magnitude greater than what is expected for a spin-powered pulsar (Ögelman & Tepedelenlioğlu 2004). The varying efficiency of converting spin power into X-ray luminosity in pulsars can be explained by geometrical effects. But, none of these can amount to such a great excess flux in the X-ray band. In this paper we try to address the reasons for this extreme luminosity. We describe the XMM-Newton and Chandra data in § 2 and present the result of our timing and spectral analysis in § 3. We discuss the implications of the analysis results in § 4.

2. CHANDRA AND XMM-NEWTON OBSERVATIONS OF PSR B0628–28

2.1. Chandra

PSR B0628–28 was observed twice, first on 2001 November 4 and again on 2002 March 25 for 2000 and 17,000 s, respectively. For both observations photons were collected using the Advanced CCD Imaging Spectrometer (ACIS). Data were collected in the nominal timing mode, with 1.141 s exposures between CCD readouts. We reprocessed the level 1 event data to correct for the detrimental effects of charge transfer efficiency. The imaging, timing, and spectral analysis presented here were done only on the 17 ks observation; the 2.0 ks observation was disregarded due to an interruption by a large solar storm. The background count rate during this solar storm increased by a factor of \( \sim 20 \). The net source count rate during the first observation period was \( 0.111 \pm 0.001 \) counts s\(^{-1}\), where the error is in the 68% confidence range. Since by taking into account the 2.0 ks observation we gain only \( \sim 27 \) counts, which is not enough to improve our statistics significantly, we preferred to disregard these counts, which potentially can be misleading.

The measured point-spread function of PSR B0628–28 is consistent with the ACIS point-source response, and hence the ACIS image reveals a pointlike X-ray source at the pulsar position. The Chandra position of PSR B0628–28 is \( \alpha = 06^\circ 30'49.43, \delta = -28^\circ 34'43.60 \) (J2000.0), which, considering the 0.5 rms error and \( \sim 0.6 \) absolute astrometric accuracy of Chandra, is in good agreement with the radio position.
\[ \alpha = 06^h 30^m 49:53, \delta = -28^\circ 34' 43'' 60 \ (J2000.0), \text{ which was taken from the ATNF Pulsar Catalogue.}^3 \]

### Table 1

| Parameter                      | Value                        |
|--------------------------------|------------------------------|
| Frequency (Hz)                 | 0.80358811986                |
| Frequency derivative (Hz s^{-1}) | -4.59962 \times 10^{-15}     |
| Epoch (MJD)                    | 46,603.0                     |
| Spin-down age (10^3 yr)        | 27.7                         |
| Spin-down energy (10^{12} G)   | 1.3                          |
| Inferred magnetic field (10^{12} G) | 3.0                        |
| Dispersion measure (pc cm^{-3}) | 34.5                        |
| Distance (kpc)                 | 1.45                         |

**Note.** Distance is inferred from dispersion measure (Cordes & Lazio 2002).

2.2. XMM-Newton

PSR B0628–28 was observed with XMM-Newton on 2004 February 28 for a total on time of 48 ks. MOS1/2 were both operated in imaging (PrimeFullWindow) mode, and the medium filter was used. During the EPIC-pn exposure the thin filter was used and the detector was operated in imaging (PrimeLargeWindow) mode for 47 ks. The temporal resolutions achieved with this choice of science modes were 2.6 s and 43 ms for MOS1/2 and pn, respectively.

The background of the EPIC camera is known to be effected by soft proton flares. In order to screen for times of high background, we rejected bins with count rates greater than 0.4 counts s^{-1} with 100 s bins, and after inspection we rejected bins with count rates greater than 0.4 counts s^{-1}. The removal of high-background time intervals from the data leaves us with effective exposure times of 42.5 and 33.3 ks for MOS1/2 and pn, respectively. The pulsar is clearly detected in the EPIC image at \[ \alpha = 06^h 30^m 49:48, \ \delta = -28^\circ 34' 43'' 10 \ (J2000.0), \] which differs from the radio position by only 0\arcsec,8, well within the 2\arcsec–3\arcsec uncertainty of the EPIC absolute astrometry. The shape of the radial profile of the source is also consistent with that expected for a pointlike source.

3. Results

3.1. Timing

For searching pulsations from PSR B0628–28, Chandra ACIS and XMM-Newton EPIC-MOS data were not suitable due to their limited temporal resolution. The sampling frequency in both cases set by the detector readout rate give a Nyquist frequency greater than the pulsar frequency (see Table 1). Thus we used EPIC-pn data that has 43 ms timing resolution.

We extracted source plus background photons from a 30\arcsec radius circle centered at the pulsar position, which encircles about 85\% of all detected source counts. The extraction region contained 1047 counts, of which 16\% is background. The photon arrival times were solar system barycenter corrected. The pulsar’s spin parameters (Table 1) are well known from radio observations and can be extrapolated to the mean epoch of the XMM-Newton observation: MJD = 53,063.339. Around this predicted pulsar frequency, we then generated a periodogram using the \[ Z^2 \]-statistic. The X-ray periodogram is shown in Fig. 1. We found a peak at \[ f = 0.80358444 \pm 0.00000112 \ Hz, \] which is consistent with the extrapolated pulsar frequency \[ f = 0.80358551 \ Hz. \] The \[ Z^2 \] for this peak is 40.4, which has a probability of chance occurrence of \( 1.69 \times 10^{-5} \). The pulse profile of PSR B0628–28 over the whole energy band (Fig. 2, bottom panel) is broad and single-peaked, with a pulse fraction of \[ f_p = 35\% \pm 12\%. \] Here we define the pulse fraction as \[ \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} \], where \[ C_{\text{max}} \] and \[ C_{\text{min}} \] are the maximum and minimum counts per bin, respectively.

We also looked at the pulse profile of the pulsar at different energy bands (Fig. 2, top three panels). Most of the counts are in the soft band: 67\% and 87\% of all counts are in the 0.2–1 and 0.2–2 keV energy bands, respectively. The pulse fraction in each selected energy band seems to be consistent with the others within the associated 1\sigma errors. The pulse shape does not seem to be energy-dependent, which would suggest that all pulsed X-rays are coming from the same region.

3.2. Spectral

The pulsar’s energy spectrum was extracted from the MOS1/2 data by selecting all events detected in a circle of radius 50\arcsec centered on the pulsar position. This region includes 90\% of

\[ f_p = 64 \pm 29\% \]

\[ f_p = 67 \pm 58\% \]

\[ f_p = 85 \pm 12\% \]

3 See http://www.atnf.csiro.au/research/pulsar/psrcat.
all events from the pulsar. Due to a source located close to the pulsar, we extracted the background spectrum from a nearby circular region with radius 87″. For the EPIC-pn data we extracted the spectrum from a circle centered on the pulsar with radius 30″ (includes 80% of source counts). The fact that PSR B0628−28 was located very close to the chip boundary precluded the extraction of the background spectrum from an annular region around the pulsar. Hence, we used an off-source circular region with radius 66″.

To extract the spectrum from the Chandra data we used a circular region centered on the pulsar position with a 2″ radius. This region contains 95% of all source counts. The background spectrum was extracted from an annulus of radii 3″ < r < 50″.

In total, the extracted spectra include 780 EPIC-pn source counts and 754 EPIC-MOS1/2 source counts. Both spectra were binned so that each bin contained a minimum of 25 counts per bin. Chandra data had a total of 184 source counts. The extracted photons were binned and regrouped such that each fitted spectral bin contained a minimum of 20 counts. All three extracted spectra were then simultaneously fitted with model spectra.

Among the single-component spectral models, an absorbed power-law model gave the statistically best representation ($\chi^2 = 56.2$ for 62 degrees of freedom [dof]) of the observed spectrum. A single blackbody ($\chi^2 = 93$ for 62 dof) did not give a statistically acceptable fit. This fit when the absorbing column is left to vary also yields a very low $N_H$. The best-fit power-law spectrum and residuals are shown in Figure 3.

The power-law model yields a column density of $N_H = 1.38^{+0.37}_{-0.23} \times 10^{21}$ cm$^{-2}$, a photon index $\Gamma = 3.20^{+0.26}_{-0.23}$, and a normalization of $1.73^{+0.26}_{-0.22} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at $E = 1$ keV. The errors are the upper and lower bounds of the 1σ confidence range. The normalization converts to an unabsorbed energy flux of $f_{\nu}^{2-10} = 8.61^{+2.15}_{-1.31} \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the 2−10 keV band. Given the distance of $d = 1.45$ kpc, this yields an X-ray luminosity of $L_{x}^{2-10} = 2.17^{+0.55}_{-0.48} \times 10^{30}$ ergs s$^{-1}$. This luminosity implies a rotational energy to X-ray energy conversion factor of $L_x/E = 0.015$ within the 2−10 keV band.

It is natural to assume that in addition to the magnetospheric emission, thermal emission from polar caps or from the surface due to reheating of the superfluid interior contributes to the observed X-ray flux. In order to explore this possibility and how it represents the data, we used a two-component model, thermal and magnetospheric, to fit the spectra. As a first approach we let every parameter vary. The fit gives a blackbody temperature of $T = 3.28^{+1.31}_{-0.62} \times 10^6$ K and an effective radius of $R = 59^{+65}_{-46}$ m. The power-law photon index does not change significantly and has a value of $\Gamma = 2.98^{+0.91}_{-0.65}$. The bolometric luminosity of the thermal component is $L_{bol} = 2.87 \times 10^{30}$ ergs s$^{-1}$, whereas the total luminosity in the 2−10 keV band is $L_x^{2-10} = 1.67^{+0.62}_{-0.62} \times 10^{30}$ ergs s$^{-1}$. The nonthermal X-ray luminosity in the 2−10 keV band converts to an X-ray efficiency of $L_x/E = 0.01$. The hydrogen column density is not well bound, $N_H = 0.62^{+0.09}_{-0.08} \times 10^{23}$ cm$^{-2}$, but still is consistent with the estimate obtained from the single power-law fit. The quality of the composite model ($\chi^2 = 54.5$ for 62 dof) is slightly better than that obtained from single power-law model. However, both fits are statistically acceptable, and the addition of a new model will always tend to decrease the $\chi^2$.

4. DISCUSSION

With the observations of new sensitive X-ray telescopes such as XMM-Newton and Chandra, we are uncovering a class of new sources: X-ray–luminous old radio pulsars. Up to now there are only seven such sources that have been detected, namely, PSRs B2224+65, J2043+2740, B1929+10, B0823+26, B0950+08, B0943+10, and B0628−28 (see Zavlin & Pavlov 2004; Becker et al. 2004; Zhang et al. 2005; Ogelman & Tepedelenlioğlu 2004). Of these six sources, only two (PSRs B0950+08 and B0628−28) have spectra of high enough quality that one can distinguish between spectral models (e.g., thermal vs. nonthermal). Becker et al. (2004) suggested that the three pulsars observed with XMM-Newton (PSRs B0950+08, 0823+26, and J2043+2740) all have spectra described better by a single power-law model, indicating that nonthermal emission is dominant. For these pulsars, however, there are alternate representations that do give statistically and physically acceptable results (Zavlin & Pavlov 2004). For example, Zavlin & Pavlov (2004) argue that the soft part of the spectrum of PSR B0950+08 can be interpreted as radiation from heated polar caps on the neutron star surface covered with a hydrogen atmosphere. For PSR B2224+65, Zavlin & Pavlov (2004) arrive at the conclusion, from the analysis of the Chandra ACIS observation, that the pulsar definitely shows nonthermal emission. All these pulsars have X-ray luminosities greater than what is predicted from the $L_x^{2-10}$−$E$ correlation (Possenti et al. 2002). For example, in the case of PSR B0628−28 and PSR B2224+65 the luminosities inferred from spectral fits are greater then the so-called maximum efficiency line derived by Possenti et al. (2002) such that all pulsars lie below this line in the log $L_x$−log $E$ plane. PSR B0628−28 has been known to be an exceptional emitter and, with the detection of pulsations from this source at the radio frequency, has left no doubt that it is the X-ray counterpart of the pulsar. These luminous old pulsars (in particular PSR B0628−28) seem not to follow the trend their possible progenitors do, which suggests that pulsars become more X-ray efficient as they grow older, given that $\tau$ is inversely proportional to $E$. From multiwavelength observations, Zharikov et al. (2005) have arrived at the same conclusion. However, Zavlin & Pavlov (2004) suggest that the most plausible reason for the observed high nonthermal X-ray efficiencies associated with the old pulsars is the geometrical effects. We discuss these below.

As mentioned in § 1, Possenti et al. (2002) used data from 39 X-ray–emitting pulsars to find a best fit that describes the log $L_x$−log $E$ correlation. These 39 sources were divided into the following subcategories: millisecond pulsars ($P \lesssim 10$ ms), Crab-like ($\tau \sim 10^4$ yr), Vela-like ($\tau \sim 10^3$−$10^5$ yr), Geminga-like ($\tau \sim 10^5$ yr, where substantial amount of the X-ray flux...
comes from the internal cooling), and finally old pulsars ($\tau \approx 10^8$ yr). In Figure 4 we show a similar plot. In this plot we only include Crab-, Vela-, and Geminga-like pulsars. We did not include millisecond pulsars because they are recycled and do not represent the naturally aging pulsars with the same $E$. Also, when converting count rates to luminosities, Possenti et al. (2002) adopted a power-law spectrum with $\Gamma = 2$ for all millisecond pulsars. Hence, the luminosities do not come from spectral analysis, but rather from assumptions based on other pulsars. We also excluded the three old pulsars because their fluxes were obtained by scaling their ROSAT count rates to that of PSR B1929+10.

This newly formed set of pulsars represent the evolution of pulsars on the log $L_X$– log $E$ plane, where older pulsars are on the bottom left (low $E$) and young Crab-like pulsars are on the top right (high $E$). Using only these three subclasses (26 sources), we performed a linear fit of the form log $L_X = a \log E + b$ (see Fig. 4). Due to exclusion of the stated pulsars, our fit yields a line with a steeper slope ($a \sim 1.5$). We also identified the line of maximum efficiency as the line for which every pulsar lies underneath. We then overlaid only two of the seven old pulsars, with well-known spectra. We should note, however, that with their luminosities derived from the power-law fits, PSR B0943+10 (Zhang et al. 2005) and PSR B2224+65 (Zavlin & Pavlov 2004) have efficiencies exceeding the maximum efficiency.

From Figure 4 it is apparent that old pulsars have very high nonthermal X-ray efficiencies. This is contrary to what Possenti et al. (2002) have found and to what has been found when millisecond pulsars were excluded. The observed luminosities for younger pulsars also show large deviations from this dependence. But in their case the deviation is symmetric around the trend line. The scatter that young pulsars exhibit could be due to uncertainties in pulsar distances and spread in the orientations of magnetic and rotational axes versus the line of sight. For example, seeing a certain fraction of the beam would result in lower inferred X-ray efficiency and vice versa.

Although there should be a thermal contribution to the overall luminosity, this effect will not change the nonthermal luminosity significantly. For instance, when we subtract the thermal luminosity obtained for PSR B0628+28 (see § 3.2) from the total, the nonthermal luminosity only changes by a factor of 0.5. The resulting luminosity is still too big and gives a

nonthermal X-ray efficiency 2–3 orders of magnitude greater than the maximum efficiency.

The quality of the observed spectrum for these old pulsars is in general not high enough to distinguish between a thermal and a nonthermal model, or a combination of both. The current set of old pulsars all either show a nonthermal emission or do not have statistics high enough to rule it out. For example, Becker et al. (2004) suggest that the X-ray emission from old, nonrecycled, rotation-powered pulsars is dominated by nonthermal radiation. When the data are fit by a power-law model, which in all cases is statistically acceptable, the obtained power-law indices are on average larger than the younger rotation-powered pulsars. The mean of the photon indices of the 26 pulsars (Fig. 4) is $\sim 1.9$, as opposed to $\sim 2.5$ for the old pulsars. The power-law fits suggest that the spectra of these old pulsars being steeper should result in lower luminosities in the 2–10 keV band. However, we observe an inverse effect where not only are the spectra steeper but also they have higher luminosities. Further X-ray observations of old radio pulsars should help us understand these puzzling features.

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