CHANDRA PULSAR SURVEY (ChaPS)

Oleg Kargaltsev1, Martin Durant1, George G. Pavlov2,3, and Gordon Garmire2

1 Department of Astronomy, University of Florida, Gainesville, FL 32611-2055, USA; okg1000@astro.ufl.edu
2 Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
3 St.-Petersburg State Polytechnical University, Polytekhnicheskaya ul. 29, St. Petersburg 195251, Russia

Received 2012 February 10; accepted 2012 July 8; published 2012 August 2

ABSTRACT

Taking advantage of the high sensitivity of the Chandra X-ray Observatory’s (CXO) Advanced CCD Imaging Spectrometer, we have conducted a snapshot survey of pulsars previously undetected in X-rays. We detected 12 pulsars and established deep flux limits for 11 pulsars. Using these new results, we revisit the relationship between the X-ray luminosity, $L_X^{psr}$, and spin-down power, $E$. We find that the obtained limits further increase the extremely large spread in the non-thermal X-ray efficiencies, $\eta_X^{psr} = L_X^{psr}/E$, with some of them being now below $10^{-5}$. Such a spread cannot be explained by poorly known distances or by beaming of pulsar radiation. We also find evidence of a break in the dependence of $L_X^{psr}$ on $E$, such that pulsars become more X-ray efficient at $E \lesssim 10^{34} - 10^{35}$ erg s$^{-1}$.

We examine the relationship between the $\gamma$-ray luminosity, $L^{psr}_\gamma$, and $E$, which exhibits a smaller scatter compared to that in X-rays. This confirms that the very large spread in the X-ray efficiencies cannot be explained just by the beaming because the $\gamma$-ray emission is generally expected to be beamed stronger than the X-ray emission. Intriguingly, there is also an indication of a break in the $L^{psr}_\gamma(E)$ dependence at $E \sim 10^{35}$ erg s$^{-1}$, with lower-$E$ pulsars becoming less $\gamma$-ray efficient. We also examine the distance-independent $L^{psr}_\gamma/L_X^{psr}$ ratio as a function of $E$ for a sample of $\gamma$-ray pulsars observed by CXO and find that it peaks at $E \sim 10^{35}$ erg s$^{-1}$, showing that the breaks cannot originate from poorly measured distances. We discuss the implications of our findings for existing models of magnetospheric emission and venues for further exploration.

Key words: pulsars: general – X-rays: general

Online-only material: color figures

1. INTRODUCTION

Along with observations in the radio band, X-rays have been the primary spectral window for studying rotation-powered pulsars. Thanks to their superb sensitivity and angular resolution, the latest-generation X-ray telescopes have detected emission from $\gtrsim 100$ rotation-powered isolated pulsars and about 60 pulsar-wind nebulae (PWNe; Kargaltsev & Pavlov 2008, 2010, hereafter KP08 and KP10). The growing sample allows one to look for dependences between the X-ray properties and other pulsar parameters, such as the pulsar rotational energy loss rate (spin-down power) $E$.

There have been multiple attempts to establish the relationship between the pulsar X-ray luminosity, $L_X^{psr}$, and $E$, including those based on Einstein data ($L_X^{psr} \propto E^{1.39}$; Seward & Wang 1988), ROSAT data ($L_X^{psr} \sim 10^{-3} E$; Becker & Trümper 1997), ASCA, RXTE, BeppoSAX, Chandra X-ray Observatory (CXO), and XMM-Newton data ($L_X^{psr} \propto E^{1.34}$; Possenti et al. 2002), CXO and XMM-Newton data ($L_X^{psr} \propto E^{0.92}$; Li et al. 2008), and CXO data (KP08).

One of the reasons for such a variety of scaling relations is the different approaches used by different authors. For instance, they used different energy ranges, different contribution of extended PWN emission (because of the limited telescope resolution), and some of them did not isolate the non-thermal magnetospheric emission from a possible thermal component (generally seen below $\sim 2$ keV). Nevertheless, Possenti et al. (2002) already pointed out that the best-fit relation does not provide a statistically acceptable fit to the data due to the very large scatter in $L_X^{psr}$ for pulsars with similar $E$ values and noted that all $L_X^{psr}$ points appear to lie below the curve (upper bound) given by $L_X^{psr, crit} \propto E^{1.48}$. This conclusion was strengthened by KP08 who collected the results of CXO observations of $\sim 40$ pulsars and their PWNe and found $L_X^{psr, crit} \propto E^{1.3}$ and $L_X^{psr, crit} \propto E^{1.6}$ (generally consistent with Possenti et al. 2002, who did not separate the pulsar and PWN contributions).

After the launch of the Fermi $\gamma$-ray observatory, the number of $\gamma$-ray-detected pulsars has grown rapidly, and it has nearly matched the number of X-ray-detected pulsars after three years of Large Area Telescope (LAT) operation. The progress achieved makes it possible to carry out studies similar to those in X-rays. In particular, Marelli et al. (2011) studied both X-ray and $\gamma$-ray properties of 29 Fermi pulsars with well-characterized X-ray spectra. From analyzing the X-ray properties of these pulsars, Marelli et al. (2011) found the best-fit correlation $L_X^{psr} \propto E^{1.04}$, albeit again with a large scatter, which made this fit formally unacceptable. The best-fit correlation for the $\gamma$-ray luminosity, $L^{psr}_\gamma \propto E^{0.88}$, also resulted in a poor fit. However, in this case the poor quality of the fit could be caused by an apparent break at $E_{crit} \approx 3.7 \times 10^{35}$ erg s$^{-1}$ rather than just by the scatter. Above $E_{crit}$, the best-fit relation appears to be $L_x^{psr} \propto E^{0.2}$ while it is $L^{psr}_\gamma \propto E^{1.43}$ below $E_{crit}$. Marelli et al. (2011) also considered the dependence of the distance-independent $L^{psr}_\gamma/L_X^{psr}$ ratio on $E$ and found that the ratio shows a strong scatter (up to three orders of magnitude) and a very weak (or no) correlation with $E$ (see Figure 4 of Marelli et al. 2011). The scatter in $L^{psr}_\gamma/L_X^{psr}$ could simply be caused by the scatter in $L_X^{psr}$.

In this paper we present analysis based on the largest reported sample of isolated, rotation-powered pulsars observed by the Advanced CCD Imaging Spectrometer (ACIS) on board CXO. The advantage of CXO/ACIS is that even within a short
exposure it is possible to achieve deep detection limits, thanks to the very low ACIS background and sharp point-spread function (PSF) of the telescope (Garmire et al. 2003). Most of the pulsars reported here were observed in the course of our guaranteed time observation (GTO) program (PI: G. Garmire) with ∼10 ks ACIS exposures. The rest of the data were taken from the CXC archive. In the sample of 23 pulsars, 12 are detected by Fermi-LAT and listed in the 2FGL catalog (Nolan et al. 2012) or reported elsewhere. We also made use of KP08 and Pavlov et al. (2007) to include previously reported results.

In Section 2 we describe how we measure the fluxes and their upper limits. In Section 3 we provide the measured parameters for each pulsar, as well as derived quantities such as X-ray luminosities and efficiencies. These results are discussed in Section 4, where we combine our findings with the previous results in the X-ray range and compare these with the γ-ray properties. Finally, we present our conclusions in Section 5.

2. OBSERVATIONS AND ANALYSIS

The fields of 23 pulsars were imaged with the ACIS I or S array, with typical exposure times of 10 ks, as part of our GTO program, between 2001 and 2011. The data for each observation were processed using the standard pipeline. We filtered the pipeline-produced event lists, keeping only photons with energies 0.5–8 keV, and searched for X-ray sources in the vicinity of the known pulsar coordinates (see Figure 1). The coordinates, taken from the most recent ATNF catalog (Manchester et al. 2005), typically have subarcsecond uncertainties (although there can be exceptions, see, e.g., Kargaltsev et al. 2007). The final positional uncertainty region in the image is the combination of the ATNF coordinate uncertainty with the typical CXO pointing error, 0′′.6 at 90% confidence. We then searched for significant X-ray detections within this area in each ACIS image.

We consider a target detected when, for N-detected counts, the probability of finding ≥N events by chance within a chosen aperture is less than 0.0001 (∼4σ). For Poisson statistics, this probability is given by

$$P(N, \lambda) = 1 - e^{-\lambda} \sum_{i=0}^{N} \frac{\lambda^i}{i!},$$

where \(\lambda\) is the average number of background counts in the source aperture. In observations where a source was seen within
the search area, we placed our measurement apertures at the centroid of the photon distribution; in the case of no detection, we placed our aperture at the center of the search region. In each case the background was measured in much larger regions free of sources, but located on the same chip.

For our short exposures, the numbers of detected photons are usually too small to perform a reliable spectral fitting. Therefore, we adopted a more straightforward approach to estimate the observed fluxes. We used the CIAO task psextract to calculate the effective area, \( A(E) \), at a given energy \( E \) of the detected photon, at the position of the source. The observed flux and its uncertainty were then estimated following Pavlov et al. (2009):

\[
f = T^{-1}\sum_i E_i A(E_i)^{-1}, \tag{2}
\]

\[
\delta f = T^{-1}\left[\sum_i E_i^2 A(E_i)^{-2}\right]^{1/2}, \tag{3}
\]

where \( E_i \) is the energy of the \( i \)th photon and \( T \) is the exposure time (the sum of good time intervals corrected for dead time). We measured the flux in both an \( r = 1'' \) aperture, appropriate for point sources (it contains \( \approx 93\% \) of the point-source flux for photons with \( E = 1 \) keV) and in a \( 1'' \leq r \leq 3'' \) annulus, to measure possible extended emission from a compact PWN. We subtracted 5\% of the point-source flux due to the wings of the PSF within the \( 1'' \leq r \leq 3'' \) annulus.

In the case of non-detection, there is not even a crude measure of the spectrum to use in Equations (2) and (3). Therefore, to calculate an upper limit, we calculate the number of counts corresponding to \( P(N, \lambda) = 0.1 \) (i.e., establishing a 90\% confidence limit) for the measured background rate, and use webPIMMS\(^6\) to calculate the equivalent flux in the 0.5–8 keV band for a typical pulsar spectrum (a power law (PL) with photon index \( \Gamma = 1.5 \) and an absorption column appropriate to a given source; see Section 3).

3. RESULTS

The immediate results of our analysis are summarized in Table 1 (detections) and Table 2 (non-detections). Although the detection significance is high for every source in Table 1, the flux measurements can be rather uncertain. For instance, it may be that several low- or mid-energy photons establish the detection, but the measured flux is dominated by a single high-energy photon (where the detector is much less sensitive). In such cases the flux uncertainty will be of the order of the measured flux.

The only dubious case is B1822–14, which has an excess of counts over the background in both data sets but no apparent point-like source. The excess counts could, in principle, be due to a PWN with an approximate flux of \( 3 \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\), close to the limit we derive. Although two significant X-ray sources happen to fall on the same S3 chip, their positions are inconsistent with that of B1822–14, and both sources have Two Micron All Sky Survey counterparts. Also, there is one additional ATNF pulsar in the field (J1837–0604), which does not have an X-ray counterpart. It is included as a non-detection in Table 2. Note that there are faint X-ray sources in the vicinity of PSRs J1105–6107 and J1730–3350, but in both cases they are too far away to be acceptable pulsar counterparts.

Table 3 lists the dispersion measurement (DM), spin-down luminosity \( \dot{E} \), pulsar period, and galactic coordinates, taken from the ATNF catalog (Manchester et al. 2005). Using these values, we estimated the absorption column, \( N_H = 3.1 \times 10^{19} \) DM cm\(^{-2}\) (assuming an average 10\% degree of ionization along the line of sight), unabsorbed flux, luminosity, and efficiency.\(^7\) For 20 pulsars with known DMs we also adopted the distances based on the Galactic electron density distribution given in the ATNF catalog (Manchester et al. 2005). For three pulsars (J1958+2846, J1413–6205, and J1023–5746), which were detected in \( \gamma \)-rays but not in the radio, the DM is not known. In these cases we assumed a distance based on the position of the most prominent spiral arms in the direction to the pulsar. The absorption column

\(^6\) http://heasarc.nasa.gov/Tools/w3pimms.html

\(^7\) This conversion does not account for the Local Bubble or for other structures in the ISM, which can produce significant variations in the ionization fraction, abundances, or molecular gas fraction.
was estimated from the total Galactic H I absorption (Kalberla et al. 2005) scaled by the distance to the arm. The calculated luminosity and efficiency values must therefore be taken with particular caution for these three pulsars. For the detected pulsars whose fluxes where estimated using Equations (2) and (3), we also estimated the fluxes in the same way as we estimated the upper limits for the non-detections (i.e., assuming a PL with \( \Gamma = 1.5 \) and using PIMMS). The differences between the two methods did not exceed 50\% of the unabsorbed flux value given in Table 1. We also note that most of the pulsars (and PWNe)
Figure 2. Top panel shows non-thermal X-ray luminosity vs. spin-down power $\dot{E}$. The dashed and dash-dotted lines correspond to $\log(L_{psr}^X, \text{crit}) = 1.51 \log(\dot{E}) - 21.4$ and $\log(L_{psr}^X, \text{crit}) = 0.38 \log(\dot{E}) - 17.7$, respectively (see the text). The constant efficiency ($\eta = L/\dot{E}$) lines are shown by the dotted lines. The downward arrows show 90% confidence upper limits. The blue stars mark $\gamma$-ray pulsars. The red error bars and limits are from this paper, the rest are taken from KP08. In most cases, the uncertainties of the luminosities are dominated by the distance uncertainty, which we assumed to be 40%. The bottom panel shows $\gamma$-ray luminosity (in 0.1–100 GeV) vs. the pulsar’s $\dot{E}$. X-ray-detected pulsars are shown in blue.

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

presented in KP08 are significantly brighter so that their spectra could be fitted in a standard way with the unabsorbed fluxes calculated from best-fit model parameters (which in some cases included $N_H$). Obviously, when the number of counts is small, the flux estimated according to Equation (2) is less certain because the statistical uncertainty (given by Equation (3)) is large and also because the $N_H$, needed to calculated the unabsorbed flux, is assumed (based on DM or pulsar position in the Galaxy) rather than fitted. The latter uncertainty is hard to calculate but for the typical photon index of 1.5 it is unlikely to be more than 30% of the flux (luminosity) value, in the 0.5–8 keV band. Therefore, in most cases the uncertainties of the luminosities shown in Figure 2 are dominated by the distance uncertainty, which we assumed to be 40% (similar to Marelli et al. 2011 and Li et al. 2008).

4. DISCUSSION

By adding the flux measurements or upper limits for 23 pulsars observed with Chandra/ACIS, we have significantly expanded the sample of pulsars analyzed by KP08. In Figure 2 (top panel) we plot the pulsar luminosity, $L_{psr}^X$, versus spin-down power $\dot{E}$. One can see that, in general, $L_{psr}^X$ increases with $\dot{E}$, in agreement with the previously noticed trends (e.g., Seward & Wang 1988; Becker & Trümper 1997; Possenti et al. 2002; Cheng et al. 2004; Li et al. 2008; KP08). However,
the correlation is rather weak, and, because of the very large dispersion, it cannot be meaningfully described by a simple dependence $L_{\gamma}^{\text{psr}}(E)$. The large scatter is also manifest in X-ray efficiencies, $n_X^{\text{psr}} = L_X^{\text{psr}}/E$, which range from $\sim 10^{-5.5}$ to $\sim 10^{-1.8}$ in Figure 2 (top). For instance, such well-known pulsars as the Crab and B0540–69 are very efficient, while the very young, high-$E$ pulsar J2022 + 3842, recently discovered by Arzoumanian et al. (2011), has $n_X^{\text{psr}} = 10^{-5}$ (for a plausible $d = 8$ kpc). Similarly large variations in $n_X^{\text{psr}}$ are seen at lower $E$ down to $E \sim 10^{36}$ erg s$^{-1}$.

An obvious cause of the scatter could be incorrectly determined distances for some of the pulsars. However, for the majority of them (including J2022+3842), the distances cannot be wrong by more than a factor of a few, too little to explain the scatter. One can allude to the beaming of the magnetospheric radiation as another possible factor contributing to the spread in $n_X^{\text{psr}}$. However, the X-ray efficiencies of the PWNe accompanying many of these pulsars show a similarly large scatter (see Figure 1 in KP10), even though the PWN emission is not expected to be substantially beamed. In several cases neither pulsar nor PWN were detected, including the most X-ray underluminous PSR J1913+1011, for which $n_X^{\text{psr}} + n_X^{\text{pwn}} < 6 \times 10^{-6}$. (Note that the limit also includes any thermal pulsar emission and compact PWN contribution, which means that the actual limit on the non-thermal magnetospheric emission must be even lower.) Therefore, the lack of tight correlation between the $L_X^{\text{psr}}$ and $E$ can hardly be explained just by the beaming and poorly known distances.

Despite the huge scatter, the maximum upper bound on $L_X^{\text{psr}}$ at given $E$ appears to be well defined. Using the method described by Cardiel (2009), we find that for $E \gtrsim 10^{35}$ erg s$^{-1}$ it follows $\log(L_{X,\text{crit}}^{\text{psr}}) = 1.51 \log(E) - 21.4$ (dashed line in Figure 2, top panel); however, for $E \lesssim 10^{35}$ erg s$^{-1}$ the dependence on $E$ flattens to $\log(L_{X,\text{crit}}^{\text{psr}}) = 0.38 \log(E) - 17.7$. These upper bounds are shown by the dashed and dash-dotted lines in Figure 2 (top panel; cf. also Figure 5 in Posselt et al. 2012). Note that the dash-dotted line also appears to represent well the lower bound to the current sample of data points (in the entire $E$ range shown) which, however, may simply be due to the limited sensitivity of the existing pulsar observations.

Both the extreme scatter and the existence of the upper bound suggest that additional parameters must enter in the $L_X^{\text{psr}}(E, \ldots)$ dependence. One possibility is that there may be two qualitatively different emission regimes, which correspond to two distinct $L_X^{\text{psr}}(E)$. Given all the uncertainties mentioned above, the current data could be consistent with such a dichotomy, although other alternatives, such as a continuous dependence of $n_X^{\text{psr}}$ on some parameter, are also possible. This parameter, however, is unlikely to be just the angle between the magnetic dipole and pulsar spin axis because the orthogonal rotator B0906–49 (Kramer & Johnston 2008) has an unremarkable X-ray efficiency compared to other pulsars with similar $E$. One can also speculate that for low-$E$ pulsars the PWN becomes so compact that it cannot be resolved even with CXO. A larger sample of pulsars with well-known distances and good quality spectra is required to discriminate between the various alternatives. Also, the measurements of pulsed non-thermal emission can be used to constrain the very compact PWN contribution.

It is interesting to compare the $L_X^{\text{psr}}-E$ trends with those seen in $\gamma$-rays. Abdo et al. (2010) presented the first analysis of the properties of 46 pulsars detected by Fermi-LAT. Shortly afterward, more Fermi pulsars were discovered (Saz Parkinson et al. 2010; Pletsch et al. 2012). We calculated the $>0.1$ GeV luminosities of the 54 $\gamma$-ray pulsars using the published$^8$ pulsar fluxes and the best published estimates of the distances. Figure 2 (bottom panel) shows the correlation between the $\gamma$-ray luminosity, $L_{\gamma}^{\text{psr}}$, and $E$ (cf. Figure 2 in Marelli et al. 2011). The correlation between $L_{\gamma}^{\text{psr}}$ and $E$ appears to be tighter than that between $L_X^{\text{psr}}$ and $E$ (despite the presumably stronger beaming in $\gamma$-rays as follows from higher pulsar fractions; Abdo et al. 2010), and it also differs in shape from the $L_X^{\text{psr}}-E$ correlation$^9$ (cf. top and bottom panels in Figure 2). For the energetic pulsars ($E \gtrsim 10^{35}$ erg s$^{-1}$) the $L_{\gamma}^{\text{psr}}-E$ correlation appears to be consistent with the expected $E^{1/2}$ law (e.g., Harding 1981), or with an even flatter one (see the $L_{\gamma}^{\text{psr}} \propto E^{\eta/3}$ line in Figure 2, bottom). However, at lower $E$ the observed correlation is more consistent with an $L_{\gamma}^{\text{psr}} \propto E$ scaling (see $\eta = 0.5$ line in Figure 2, bottom panel), implying a break around $E \sim 10^{35}$ erg s$^{-1}$ in the $L_{\gamma}^{\text{psr}}(E)$ dependence. The possible break hints at a qualitative change either in the emission mechanism or in the spectral energy distribution (SED) of the primary particles (see below). Such a break was expected to occur at somewhat lower $E \sim 10^{33}$ erg s$^{-1}$ in the polar cap model (Harding et al. 2002). However, recent simulations based on the slot-gap model seem to predict a break in the $L_{\gamma}^{\text{psr}}-E$ relationship at $E \sim 10^{35}$ erg s$^{-1}$ (see Figure 1 in Pierbattista et al. 2011). It is more difficult to determine how the break in the SED of primary particles would affect the properties of the secondary particles and their synchrotron emission (see below), but some impact is likely, and it could be seen in the $L_{\gamma}^{\text{psr}}-E$ relationship (Figure 2, top panel) and in the multiwavelength (MW) spectra. Indeed, there is an intriguing coincidence between the values of $E$ at which the $L_{X,\text{crit}}^{\text{psr}}-E$ and $L_{\gamma}^{\text{psr}}-E$ appear to exhibit a break, although the slopes change in the opposite ways. Also, the $L_{\gamma}^{\text{psr}}-E$ correlation is significantly stronger (i.e., the scatter is weaker) than the $L_X^{\text{psr}}-E$ correlation.

The comparison of the top and bottom panels in Figure 2 makes it obvious that while the X-ray and $\gamma$-ray efficiencies can be similar for some very young pulsars, older pulsars are generally more efficient $\gamma$-ray emitters. This can also be seen in Figure 3, where we plot the distance-independent X-ray to $\gamma$-ray luminosity ratio for $\gamma$-ray pulsars observed in X-rays (cf. Figure 4 in Marelli et al. 2011). Although the scatter is large (mainly due to that in $L_{\gamma}^{\text{psr}}$), the ratio increases with decreasing $E$ down to $E \sim 10^{35}$ erg s$^{-1}$, at which point the trend appears to reverse. These results suggest $E$-dependent changes in the shapes of the MW spectra of pulsars. Perhaps it could be a change in the slope of a broadband PL spectrum (if one attempts to describe most MW emission as a curved or broken PL) or more complex changes. To better understand the implications of our findings for the magnetospheric models, a larger number of $\gamma$-ray pulsars with $E = 10^{33}-10^{35}$ erg s$^{-1}$ should be observed in X-rays with exposures long enough to either detect their X-ray emission or set restrictive upper limits.

It is generally believed that the pulsar GeV emission is produced by the curvature radiation of primary electrons pulled from the neutron star (NS) surface and accelerated by the electric field component parallel to the magnetic field. The curvature photons initiate pair cascades leading to the production of secondary or higher-generation electrons that emit synchrotron

---

$^8$ If no published flux values were found, we took them from the 2FGL catalog (Nolan et al. 2012).

$^9$ Note that the vertical axis range is the same in both panels of Figure 2.
radiation at lower frequencies (optical to X-rays; e.g., Cheng et al. 1998; Harding 2008, 2009, and reference therein). In the high-altitude slot-gap and outer-gap models the primary particles keep accelerating up to 10–100 NS radii, gain momentum transverse to the magnetic field via resonant cyclotron absorption (Lyubarskii & Petrova 1998), and emit significant synchrotron radiation up to MeV (and possibly even GeV) energies in young pulsars (e.g., Baring 2011). Within this framework, it is still possible to have an MW (from optical to GeV) spectrum whose shape would resemble a single broadband PL with a cutoff at the highest energies (Takata et al. 2008), which seems to be in qualitative agreement with MW spectra of some pulsars (Durant et al. 2011). However, additional processes, such as the modification of the spectrum by inverse Compton scattering (Harding 2008) or by synchrotron self-Compton process (Zhang & Cheng 2002), can play an important role under certain conditions. Our findings imply that the relative contributions of these processes may vary, depending on the geometry of the magnetosphere or the $E$ magnitude.

5. SUMMARY

By analyzing the population of rotation-powered pulsars detected by CXO, we found that the $L_X - \dot{E}$ relationship cannot be meaningfully described as a simple $L_{\text{MW}}^\text{psr} (\dot{E})$ dependence. There is some degree of correlation between $L_X^\text{psr}$ and $\dot{E}$, but the extreme scatter (by $\geq 4$ orders of magnitude) in the X-ray radiative efficiencies is present for pulsars with $\dot{E} \gtrsim 10^{36}$ erg s$^{-1}$. Although existing data hint that the scatter may decrease with decreasing $\dot{E}$, perhaps becoming substantially smaller at $\dot{E} \lesssim 10^{35}$ erg s$^{-1}$, this could simply be the result of small-number statistics (few pulsars with low $\dot{E}$ have been detected) and of the limited sensitivity of existing observations. The reasons for the scatter are unclear. The deepest X-ray limits reported in this paper strongly support the idea that $L_X^\text{psr}$ depends not only on $\dot{E}$ but also strongly depends on other parameters. At the same time, it seems that the upper bound on the $L_X - \dot{E}$ relationship is fairly well defined ($L_X^\text{crit} \propto E^{1.5}$), corresponding to such values of the “hidden” parameters that deliver maximum radiative efficiency at a given $\dot{E}$.

The comparison with a sample of $\gamma$-ray pulsars detected by Fermi-LAT shows that the correlation between $L_X^\text{psr}$ and $\dot{E}$ is much tighter, but again it can hardly be described by a simple PL dependence. The break between $\dot{E} \sim 10^{34}$ and $10^{35}$ erg s$^{-1}$ is suggested by the existing data. Intriguingly, a break in $L_X^\text{crit} - \dot{E}$ is at similar $\dot{E}$ values.

We thank Brian Newman who participated in the initial stages of this work. We are also grateful to the anonymous referee for the useful comments. The work on this project was partly supported through NASA grants NNX06AG36G, NNX09AC81G, and NNX09AC84G, and National Science Foundation grant Nos. AST0908733 and AST0908611. The work by G.G.P. was partly supported by the Ministry of Education and Science of the Russian Federation (contract 11.634.31.0001).

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJS, 187, 460
Arzoumanian, Z., Gotthelf, E. V., Ransom, S. M., et al. 2011, ApJ, 739, 39
Baring, M. G. 2011, in AIP Conf. Ser. 1379, Astrophysics of Neutron Stars 2010, ed. E. Göğüş, T. Belloni, & U. Ertan (Melville, NY: AIP), 184
Becker, W., & Trümper, J. 1997, A&A, 326, 682
Cardiel, N. 2009, MNras, 396, 680
Cheng, K. S., Gil, J., & Zhang, L. 1998, ApJ, 493, L35
Cheng, K. S., Taam, R. E., & Wang, W. 2004, ApJ, 617, 480
Durant, M., Kargaltsev, O., & Pavlov, G. G. 2011, ApJ, 743, 38
Garmire, G. P., Bautz, M. W., Ford, P. G., Nousek, J. A., & Ricker, G. R., Jr. 2003, Proc. SPIE, 4851, 28
Harding, A. K. 1981, ApJ, 245, 267
Harding, A. K. 2008, in AIP Conf. Ser. 968, Astrophysics of Compact Objects, ed. Y.-F. Yuan, X.-D. Li, & D. Lai (Melville, NY: AIP), 104
Harding, A. K. 2009, in Neutron Stars and Pulsars, ed. W. Becker (Astrophysics and Space Science Library, Vol. 357; Berlin: Springer), 521
Harding, A. K., Muslimov, A. G., & Zhang, B. 2002, ApJ, 576, 366
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kargaltsev, O., & Pavlov, G. G. 2008, in AIP Conf. Ser. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi (Melville, NY: AIP), 171 (KP08)
Kargaltsev, O., & Pavlov, G. G. 2010, in AIP Conf. Ser. 1248, X-Ray Astronomy 2009: Present Status, Multi-wavelength Approach and Future Perspectives, ed. A. Comastri, L. Angelini, & M. Cappi (Melville, NY: AIP), 25 (KP10)
Kargaltsev, O., Pavlov, G. G., & Garmire, G. P. 2007, ApJ, 660, 1413
Kramer, M., & Johnston, S. 2008, MNras, 390, 87
Li, X.-H., Lu, F.-J., & Li, Z. 2008, ApJ, 682, 1166
Lyubarskii, Y. E., & Petrova, S. A. 1998, A&A, 337, 433
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Marelli, M., De Luca, A., & Caraveo, P. A. 2011, ApJ, 733, 82
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Pavlov, G. G., Kargaltsev, O., Garmire, G. P., & Wolszczan, A. 2007, ApJ, 664, 1072
Pavlov, G. G., Kargaltsev, O., & Garmire, G. P. 2009, ApJ, 691, 458
Pierbattista, M., Grenier, I., Harding, A., & Gonthier, P. 2011, in AIP Conf. Ser. 1357, Radio Pulsars: An Astrophysical Key to Unlock the Secrets of the Universe, ed. M. Burgay, N. D’Amico, P. Esposito, A. Pellizzoni, & A. Possenti (Melville, NY: AIP), 249
Pletsch, H. J., Guillotet, L., Allen, B., et al. 2012, ApJ, 744, 105
Posselt, B., Pavlov, G. G., Manchester, R. N., Kargaltsev, O., & Garmire, G. P. 2012, ApJ, 749, 146
Possenti, A., Cerutti, R., Colpi, M., & Moregghetti, S. 2002, A&A, 387, 993
Saz Parkinson, P. M., Dormody, M., Ziegler, M., et al. 2010, ApJ, 725, 571
Seward, F. D., & Wang, Z.-R. 1988, ApJ, 332, 199
Takata, J., Chang, H.-K., & Shibata, S. 2008, MNRAS, 386, 748
Zhang, L., & Cheng, K. S. 2002, ApJ, 569, 872