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This grant, titled "X-Ray Emission from Two Nearby Millisecond Pulsars," included ROSAT observations of the nearby pulsars PSR J2322+20 and PSR J2019+24. Neither was detected, although the observations were among the most sensitive ever made towards millisecond pulsars, reaching 1.5×10^{29} and 2.7×10^{29} erg s^{-1} (0.1–2.4 keV), respectively. This is about or slightly below the predicted level of emission from the Seward and Wang (1988, ApJ, 332, 199) empirical prediction, based on an extrapolation from slower pulsars. To understand the significance of this result, we have compared these limits with observations of four other millisecond pulsars, taken from the ROSAT archives (Danner, Kulkarni, and Thorsett, preprint attached). Except for the case of PSR B1821−21, where we identified a possible x-ray counterpart, only upper limits on x-ray flux were obtained. From these results, we conclude that x-ray emission beaming does not follow the same dependence on pulsar period as that of radio emission: while millisecond pulsars have beaming fractions near unity in the radio, x-ray emission is observed only for favorable viewing geometries.

Since the Danner *et al.* preprint was written, positions of a number of additional nearby millisecond pulsars have become available. The preprint will be updated before submission, in Aug 1994, to include the results of a search for these pulsars in archival ROSAT observations.

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ROSAT observations of six millisecond pulsars

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Abstract

We present ROSAT observations towards six known millisecond radio pulsars. These observations yielded upper limits to the X-ray flux in the ROSAT band (0.1–2.4 keV) for five pulsars and a possible association of an X-ray source with PSR B1821–24, in the globular cluster M28. At the 99.9% confidence level, the source is pulsed at the expected radio pulsar frequency. We compare our results with predicted X-ray luminosities by Seward and Wang (1988) and Ögelman (1994) and find disagreement between the predictions and observations for PSR B1257+12 and PSR B1821–24.

The X-ray luminosities of PSRs B1257+12 and J0437–4715, millisecond pulsars with similar periods and spin-down rates, are found to differ by more than a factor of 25. X-ray emission from radio pulsars has been ascribed to a thermal component arising from a surface hot-spot and a power law magnetospheric component (Halpern & Ruderman 1993). In the context of this model and these observations, we infer that the orientation of the magnetic and rotation axes with respect to the line of sight is very different for PSR J0437–4715 compared to PSR B1257+12. Finally, we argue that the beaming factor for X-ray emission is independent of the pulsar period, unlike that for radio emission; if so, most millisecond pulsars are visible in the radio but not at X-ray energies.

Subject headings: millisecond pulsars – ROSAT

High energy observations of millisecond pulsars are particularly important because it is quite clear that the bulk of the spin-down luminosities of pulsars is dissipated through high energy electromagnetic radiation and relativistic winds. Two millisecond pulsars, B1957+20 (Kulkarni et al. 1992; Fruchter et al. 1992) and J0437–4715 (Becker & Trümper 1993), have now been detected with ROSAT.

In this paper we present six intermediate-depth pointed ROSAT observations, setting upper-limits on X-ray flux in five cases and yielding one possible detection. All observations were obtained with the position sensitive proportional counter (PSPC) on ROSAT in the energy band 0.1–2.4 keV. Four of the six datasets, PSRs B1534+12, J2322+2057, J2019+2425 and B1257+12, were pointed observations where the pulsar was the primary target. We included two additional fields, PSRs B1620–26 and B1821–24 from the public ROSAT data archive. The former is associated with the globular cluster M4 (Lyne et al. 1988) and the latter with the cluster M28 (Johnston et al. 1994, Lyne et al. 1987). With the exception of PSR B1821–24, there are no X-ray sources closer than 0.5′ to the radio positions exceeding by far the positional uncertainties of the X-ray sources.

Upper flux limits were calculated after background subtraction. All distances, with the exception of the distance to PSR B1821–24, were estimated using the revised dispersion measurement distance scale, which is thought to be accurate at the 30% level (Taylor & Cordes 1993). For PSR B1821–24 we used the distance to M28 of 5.1 ± 0.5 kpc, based on the color magnitude analysis of Rees & Cudworth (1991). The spectrum of PSR J0437–4715, the only millisecond pulsar with a well known spectrum, was used as a prototype to estimate the effect of absorption on the luminosities. Following Becker & Trümper (1993) we estimated the column density of neutral hydrogen, N_H, from the electron density, assuming 10 neutral hydrogen atoms per free electron. For PSR B1821–24, this N_H value is very close to that estimated from the known redenning to the cluster (Rees & Cudworth 1991). With the exception of the most distant pulsars in our sample, PSRs B1821–24 and B1620–26, these column densities will decrease the observed flux above 0.3 keV by less than 25 percent, less than the uncertainty in the dispersion measurement. Therefore, we are neglecting absorption for all pulsars that are closer than 1 kpc; for these, we use the rule of thumb of $1\,\mathrm{counts^{-1}} \approx 10^{-11}\mathrm{erg\,cm^{-2}s^{-1}}$ over the entire ROSAT band, 0.1–2.4 keV (ROSAT, Call for Proposals).

Seward and Wang (1988) found an empirical relationship between the spin-down luminosity of a pulsar

Pulsar	P	$\dot{P}$	d	$\log \dot{E}$	B	$L_{\text{Ögelman}}$	L_{SW}	R_{PSPC}	L_{PSPC}	$L_{\text{PSPC}}/\dot{E}$
B1534+12	37	24.17	0.7	33.28	9.7	1.28	4.6	≤ 1.0	≤ 5.8	≤ 0.00030
J2322+2057	4.8	0.04	0.8	33.15	0.13	0.86	3.0	≤ 0.2	≤ 1.5	≤ 0.00010
J2019+2425	3.9	0.02	0.9	33.12	0.09	0.78	2.7	≤ 0.28	≤ 2.7	≤ 0.00020
B1257+12	6.2	0.33	0.6	33.74	0.46	5.4	20	≤ 0.31	≤ 1.3	≤ 0.00002
B1620–26	11	*	3.7	32.38*	0.3*	0.08	0.26	≤ 1.0	≤ 160	≤ 0.0670
B1821–24	3.1	16	5.1	36.33	2.2	$1.7\,10^4$	$7.9\,10^4$	8.3	$3.5\,10^3$	0.00016
B1957+20	1.6	0.12	1.5	35.06	0.14	324	1360	2	180	0.00016
J0437–4715	5.7	0.24	0.14	33.51	0.38	2.6	9.5	200	33	0.00102

Table 1: Columns: 1) pulsar name, 2) radio period in ms, 3) intrinsic period derivative, corrected for proper motion, in 10^{-19} s s^{-1}, see text for discussion of PSR B1620–26, 4) distance in kpc, 5) logarithm of spin-down luminosity $I\Omega\dot{\Omega}$ in erg s^{-1}, 6) magnetic field in 10^9 Gauss, 7) predicted X-ray luminosity from magneto-rotation formula (Ögelman 1994) in 10^{29}erg s^{-1}, 8) predicted X-ray luminosity (Seward & Wang 1988) in 10^{29}erg s^{-1}, 9) PSPC event rate in 10^{-3}s^{-1}, 10) observed X-ray luminosity in 10^{29}erg s^{-1} (0.1–2.4 keV), 11) ratio of observed X-ray luminosity L_{PSPC} to spin-down luminosity $\dot{E}$, *) see text.

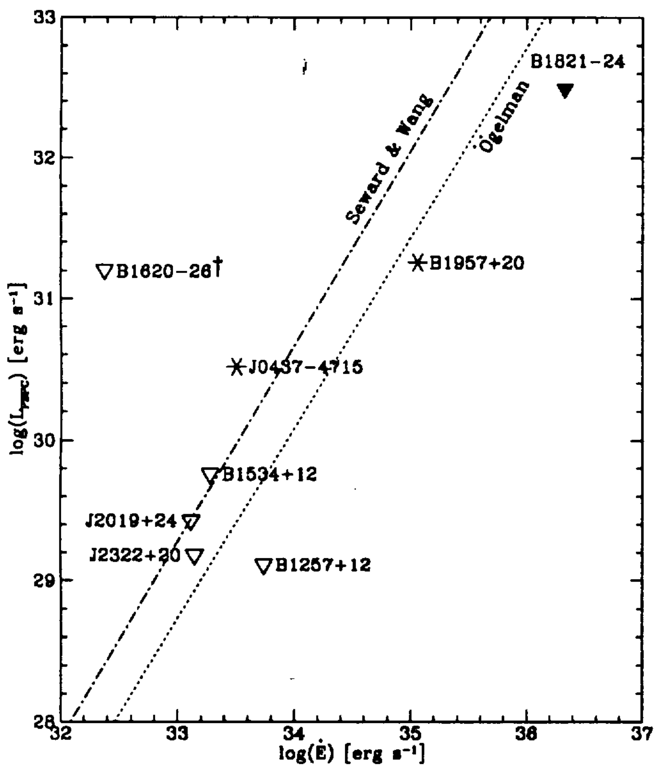

Fig. 1.— Plot of observed X-ray luminosities L_{PSPC} (0.1–2.4 keV) versus the spin-down luminosities. Lines indicate the values predicted by the two models (Seward & Wang, dashed dotted; Ögelman dotted). All pulsars from Table 1 are plotted. Triangles indicate upper limits, asterisks detections, a solid triangle the possible detection of PSR B1821–24. † See text.

$\dot{E}$ and the observed X-ray luminosity L_{SW},

$$\log L_{\text{SW}} = 1.39 \times \log \dot{E} - 16.6, \qquad (1)$$

based on observations of ordinary pulsars (i.e. slow pulsars) with the Einstein satellite. This estimator was calculated for each of our observations, including the two recently detected millisecond pulsars B1957+20 and J0437–4715, and included in Table 1.

Ögelman (1994) published an empirical magneto-rotation formula, based on a broader data sample, including ROSAT observations, for the *non-thermal* X-ray luminosities of pulsars:

$$L_{\text{Ögelman}} = 1.3 \times 10^{-10} (B\Omega^2)^{2.7} \text{erg s}^{-1}, \qquad (2)$$

where B is the surface magnetic field ($B^2 \simeq 10^{39} P\dot{P}$) and $\Omega = 2\pi/P$ the angular frequency. It can be brought into the same form as Equ.(1):

$$\log L_{\text{Ögelman}} = 1.35 \times \log \dot{E} - 15.82 \qquad (3)$$

Both relations use the intrinsic period and period derivative of the pulsar to estimate the X-ray flux. Recently, Camilo et al. (1994) pointed out that the measured period derivative can be significantly contaminated by an apparent acceleration due to the pulsar's transverse speed $v : \delta\dot{P}/P = v^2/cD$, where D is the the pulsar distance and c the speed of light. In this paper we use the corrected values for the intrinsic pulsar derivative, as published by Camilo et al. (1994). This is a fairly important correction in that the neglect of this effect will change significantly the location of the pulsars in Figure 1.

No intrinsic $\dot{P}$ can be measured for PSR B1620–26. The apparent $\dot{P}$ is changing on a timescale of a few years, probably due to the gravitational acceleration of the binary by a third body (Thorsett et al. 1993). In order to make some estimate of $\dot{E}$ for this pulsar, we have assumed a magnetic dipole moment typical for binary millisecond pulsars (Camilo et al. 1994) of 3×10^8 Gauss.

Considering the scatter of the data points used to generate the empirical fit, only two of the six upper limits in Fig. 1 deviate significantly from the prediction. The X-ray flux of PSR B1257+12 is lower by a factor of 15 and the flux of PSR B1821–24 by a factor of at least 27 than derived from the empirical formula by Seward & Wang; the corresponding factors for the Ögelman relation are 4 and 6.

The ROSAT observation on M28 (NGC 6626) was published by Johnston et al. (1994) in a survey of globular clusters. No counterparts for the X-rays sources in this field were identified by the authors. We analyzed this observation from the public ROSAT archive together with the reprocessed dataset made available to us by the principle investigator before it became public. Most important, the reprocessing fixed an error in the association of events and arrival times, which previously significantly increased the timing noise on the sub-second level. Additionally, a boresight correction was applied. For this reason, we focus here on the analysis of the reprocessed data.

We find an X-ray source at $\alpha(2000) = 18\,\mathrm{h}\,24\,\mathrm{m}\,33.0\,\mathrm{s}$ and $\delta(2000) = -24°52'11.9''$. This source was associated by Johnston et al.(1994) at slightly different coordinates ($\alpha(2000) = 18\,\mathrm{h}\,24\,\mathrm{m}\,32.8\mathrm{s}$, $\delta(2000) = -24°51'58''$) with the core of M28. We noted that this source is now only 15″ distant from the radio position of PSR B1821–24 ($\alpha(2000) = 18\,\mathrm{h}\,24\,\mathrm{m}\,32.008\,\mathrm{s}$, $\delta(2000) = -24°52'10.75''$).

A total of 27.5±5.8 counts were attributed to this source by the standard processing routine (0.5–2.1 keV), resulting in a vignetting corrected event rate of $10.3 \pm 2.0 \times 10^{-3}\mathrm{s}^{-1}$. Assuming a spectrum similar to that of PSR J0437–4715 we derive a luminosity within the 2-σ uncertainty of the value given by Johnston. The 1σ-positional error due to photon statistics was 4.7″. The 1σ systematic bore-sight error, a deviation between the nominal pointing position and the actual center of the field of view, is on the order of 6″ (G. Hasinger, pers. comm.). Combining the photon error and the bore-sight error, we find a separation of the X-ray and the radio position close to the 2-σ-level.

In spite of this apparently large separation, we investigated the timing behavior of this source. To employ the full timing accuracy of the satellite, we folded all events within 45″ of the center of the source separately in two datasets. The first set contains data from the first two observation intervals of 963 s and 948 s duration, separated by only 4 s. The second set contains the last observation interval of 1422 seconds, about five days after the first two. As the total number of detected events at the source position (0.1–2.4 keV), including background, is only 13 and 29, standard χ^2-tests are not applicable. We performed a Z_2^2-test (Buccheri & De Jager 1989) after folding the data at the radio pulsar barycentric period, extrapolated to the time of the ROSAT observation (March 11 and 16, 1991), of 0.0030543146816475s. The folded light curves, split into 5 phase bins, for both sets are shown in Fig.2. The values found for Z_2^2 are 19.1 for the first and 8.9 for the second observing interval. The probability to get a value this large or larger by chance, in the absence of a signal, was estimated through a Monte-Carlo simulation to be 3×10^{-4} and 7×10^{-2} respectively. The uncertainty in the ROSAT clock calibration (≈0.5 ms per day, Predehl priv. comm.) precludes us from connecting the two datasets. If we

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1 : * *                      1 : * * * * * * * * *
2 : * * * * * * * *        2 : * *
3 : * *                      3 : * *
4 : *                        4 : * * * * * * * * *
5 :                          5 : * * * * * * *
1 : * *                      1 : * * * * * * * * *
2 : * * * * * * * *        2 : * *
3 : * *                      3 : * *
4 : *                        4 : * * * * * * * * *
5 :                          5 : * * * * * * *
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Fig. 2.— Folded light curves of the X-ray source close to PSR B1821–24 (0.1–2.4 keV) for the first interval (left) and the second (right), separated by about five days. All events within 45″ of the center of the source were folded at the radio pulsar period and split into 5 phase bins. The same data is plotted twice to guide the eye; each asterisk represents one event.

combine the close location of the X-ray source to the radio position and the result of the timing analysis, we find good evidence for the association of the X-ray source in M28 and the millisecond pulsar B1821–24. At the same time, we point out that the significance of this result is limited due to the small number of photons. We hope to overcome this through a much longer HRI observation with ROSAT.

Johnston et al. argued that millisecond pulsars in general are not likely counterparts of the faint globular cluster source population, because the two millisecond pulsars with known X-ray emission are at least an order of magnitude less luminous at X-rays. However, the total spin-down luminosity of PSR B1821–24 is a factor of 20 higher than for B1957+20 and even a factor of 630 higher than for PSR J0437-4715. Therefore, the possible detection of X-ray emission from this pulsar might not be too surprising. After all, this is the youngest in our sample (3×10^7 yr; Foster et al. 1988) with the highest spin-down luminosity, $\dot{E} = 2.3 \times 10^{36}$ erg s^{-1} (see Fig. 1).

Assuming that the X-ray source is not associated with PSR B1821–24 and replacing the number of detected photons at this position with the background limit, we derive an upper limit about a factor of two lower than in the suggested detection. Regardless of the association between the detected X-ray source and PSR B1821–24, the observed X-ray luminosity from this pulsar is less than sixteen percent of the amount predicted by the empirical models. This result depends on the assumption that the observed spin-down rate of the pulsar is actually the rest-frame spin-down rate. Phinney (1991) has argued that the observed $\dot{P}$ of this pulsar is intrinsic and not corrupted by gravitational field of the cluster.

Interestingly enough, the eclipsing binary PSR B1957+20 (Fruchter et al. 1988) lies close to the Ögelman line. However, the X-ray emission from this pulsar could arise from either the magnetosphere or from the shock of the pulsar wind at the companion or from the shock at the nebular boundary (Kulkarni et al. 1992; Tavani & Arons 1993). Thus, the magnetospheric emission from PSR B1957+20 could be significantly below the empirical prediction. On the other hand, if one attributes the observed X-ray emission to be of magnetospheric origin then we have to conclude that very little X-ray emission arises at these two shocks. This would indicate that even less than 20% of the pulsar's spin-down luminosity, as estimated by Kulkarni et al. (1992), is carried away by electrons and positrons with Lorentz factor $\gamma \approx 10^5$. This would reinforce the distinctly different nature of this pulsar from the more highly magnetized Crab pulsar.

The most striking result from our analysis is the difference in X-ray luminosity between PSRs J0437–4715 and B1257+12. The period and period derivative of these two pulsars are nearly identical, but their X-ray luminosities differ by at least a factor of 25. For PSR J0437–4715, both a black body and a power-law component were detected in the spectrum. Each of the two components, if PSR J0437–4715 were at the distance of PSR B1257+12, would have exceeded the detection threshold of the observation towards PSR B1257+12 by more than a factor of nine.

From these findings we can draw conclusions for two different mechanisms of X-ray emission:

(1) *Thermal Component.* In the model of Halpern and Ruderman (1993), the thermal component seen in the spectrum of PSR J0437–4715 and other pulsars arises from a hot spot on the surface, heated by particles returning from the magnetosphere. If the hot spot occupies only a small fraction of the neutron star surface, the signal strength depends on the orientation of the magnetic field axis and the rotational axis to the line of sight. The X-ray peak flux can be attenuated through this effect significantly. In the contrary situation, the X-ray signal is maximal if the magnetic axis and the line of sight are aligned. Radio polarization studies have been used to infer the orientation of the magnetic axis relative to the spin axis. We predict, in the frame of the hot-spot model, that the orientation of the axes for PSRs B1257+12 and J0437–4715 are very different. If, however, the orientation of these two pulsars, with respect to the line of sight, proves similar, the model of Halpern and Ruderman would need to be reexamined.

(2) *Power law component.* This is usually associated with emission from the magnetosphere. Like radio emission (see below), we expect magnetospheric X-ray emission to be beamed. Then, the lack of detection of the power law component in either PSRs B1257+12 or B1821–24 can be most conveniently attributed to unfavorable beaming. To first order the beaming factor — the solid angle swept by the pulsar beam over 4π — for X-ray emission from millisecond pulsars is ≈ 0.25 with significant uncertainty due to small number statistics.

It is well known that radio emission (usually ascribed to magnetospheric emission) is beamed (Narayan 1987; Lyne & Manchester 1988). The beaming factor is found to be a function of the pulsar period and is expected to be close to unity for millisecond pulsars. Millisecond pulsars should be therefore visible at radio wavelengths independent of the orientation of the spin axis.

The fact that we detect X-rays only from one (or two) out of four millisecond pulsars, suggests that the beaming factor for X-ray emission does not show the same dependence on the period of the pulsar as in radio. Thus we suggest that a good fraction of millisecond pulsars may not be visible at X-ray wavelengths. When the geometry is favorable, as appears to be the case in J0437–4715, we note that the X-ray emission is similar to that of slower pulsars with the same $\dot{E}$. Taken together, these arguments suggest that most of the X-ray emission from PSR B1957+20 is of magnetospheric origin. If so, as explained earlier, the relativistic winds of millisecond pulsars are qualitatively different from slower pulsars.

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