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AN *XMM-NEWTON* STUDY OF THE 401 Hz ACCRETING PULSAR SAX J1808.4−3658 IN QUIESCENCE

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ABSTRACT

SAX J1808.4−3658 is a unique source, being the first low-mass X-ray binary showing coherent pulsations at a spin period comparable to that of millisecond radio pulsars. Here we present an *XMM-Newton* observation of SAX J1808.4−3658 in quiescence, the first that assessed its quiescent luminosity and spectrum with a good signal-to-noise ratio. *XMM-Newton* did not reveal other sources in the vicinity of SAX J1808.4−3658, likely indicating that the source was also detected by previous *BeppoSAX* and *ASCA* observations, even with large positional and flux uncertainties. We derive a 0.5–10 keV unabsorbed luminosity of $L_X = 5 \times 10^{31}$ ergs s^{-1}, a relatively low value compared with other neutron star soft X-ray transient sources. At variance with other soft X-ray transients, the quiescent spectrum of SAX J1808.4−3658 was dominated by a hard ($\Gamma \sim 1.5$) power law with only a minor contribution ($\lesssim 10\%$) from a soft blackbody component. If the power law originates in the shock between the wind of a turned-on radio pulsar and matter outflowing from the companion, then a spin-down to an X-ray luminosity conversion efficiency of $\eta \sim 10^{-3}$ is derived; this is in line with the value estimated from the eclipsing radio pulsar PSR J1740−5340. Within the deep crustal heating model, the faintness of the blackbody-like component indicates that SAX J1808.4−3658 likely hosts a massive neutron star ($M \gtrsim 1.7 \ M_\odot$).

Subject headings: accretion, accretion disks — binaries: close — stars: individual (SAX J1808−3658) —
stars: neutron

1. INTRODUCTION

Neutron star soft X-ray transients (SXRTs), when in outburst, closely resemble persistent low mass X-ray binaries (LMXRBs). In the last few years, it has become clear that SXRT sources form a rather inhomogeneous class (see Campana et al. 1998a for a review) comprising sources with well-defined outbursts as well as sources with long on/off activity periods. Moreover, sources displaying bright outbursts with peak X-ray luminosities $L_X \sim 10^{37}$–10^{38} ergs s^{-1} appear to be different from sources showing only faint outbursts reaching $L_X \sim 10^{36}$–10^{37} ergs s^{-1}, especially in the Galactic center region (Heise et al. 1998; King 2000; in 't Zand 2001).

A major leap forward came with the discovery of SAX J1808.4−3658, a bursting SXRT reaching a maximum luminosity of $\sim 2 \times 10^{36}$ ergs s^{-1} (for a distance of 2.5 kpc; in 't Zand et al. 2001). In 1998 April, the source resumed activity, and *Rossi X-Ray Timing Explorer* (*RXTE*) observations revealed coherent ∼401 Hz pulsations, the first detected in the persistent emission of a neutron star LMXRB. These testify to the presence of magnetic polar cap accretion onto a fast rotating magnetic neutron star (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). The inferred magnetic field strength of SAX J1808.4−3658 is in the 10^8–10^9 G range (see Psaltis & Chakrabarty 1999), providing convincing evidence for the long-suspected LMXRB–millisecond pulsar connection.

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SXRTs spend much of their time in quiescence. The origin of the quiescent X-ray emission is still uncertain. In the last few years, several sources have been studied in detail; the picture that emerged is that the quiescent spectrum consists of a soft component plus a high-energy excess. The former component is often fitted with a blackbody spectrum with an equivalent radius of 1–2 km and temperatures in the 0.1–0.3 keV range or with a neutron star atmosphere model with an equivalent radius consistent with the entire neutron star surface and slightly smaller temperatures (Brown, Bildsten, & Rutledge 1998; Rutledge et al. 2000). The high-energy component is well represented by a power law with a photon index $\Gamma \sim 1$–2 (Asai et al. 1996, 1998; Campana et al. 1998b, 2000). In all sources observed so far, the quiescent luminosity ranges between 10^{32} and 10^{33} ergs s^{-1}, indicating a clear difference with black hole transients in quiescence that have a lower X-ray luminosity (Garcia et al. 2001; Campana & Stella 2000). Flux and spectral variability have been reported in Aql X-1 and KS 1731−260 during quiescence (Campana et al. 1997; Rutledge et al. 2002; Wijnands et al. 2002a). This poses severe limitations on the emission mechanisms responsible for the quiescent luminosity.

Among neutron star SXRTs, SAX J1808.4−3658 stands out for having, while in outburst, a magnetosphere and, of course, an accurately measured spin period. These characteristics make the source very well suited for testing the predictions of models for the quiescent emission in which the presence of a sizable magnetic field plays a crucial role (Stella et al. 1994). SAX J1808.4−3658 was detected in quiescence (Stella et al. 2000; Dotani, Asai, & Wijnands 2000; Wijnands et al. 2002b), although with large uncertainties. Here we report on an *XMM-Newton* observation of SAX J1808.4−3658 in quiescence, the first to detect the source with a good signal-to-noise ratio.

2. DATA ANALYSIS

SAX J1808.4−3658 was observed on 2001 March 24 with the *XMM-Newton* European Photon Imaging Camera (EPIC), consisting of two metal oxide semiconductor (MOS) cameras

Observation Date	Satellite	Exposure Time (ks)	Error Radius (arcmin)	Distance[a] (arcmin)	Reference
1999 Mar[b]	*BeppoSAX*	20	1.50 (90%)	1.43	1
1999 Sep	*ASCA*	61	0.24 (68%)	0.19	2
2000 Mar	*BeppoSAX*	89	0.55 (68%)	1.63	3
2001 Mar	*XMM-Newton*	33	0.10 (90%)	0.04	4

References.—(1) Stella et al. 2000; (2) Dotani et al. 2000; (3) Wijnands et al. 2002a, 2002b; (4) this Letter.

[a] Distance of the detected source from the radio position of SAX J1808.4−3658.

[b] The source position is affected by a large uncertainty that is due to the source faintness and an unfavorable roll angle, resulting in a systematic uncertainty of about 35″ on top of the intrinsic positional error (see the ASDC Technical Report by M. Perri & M. Capalbi 2002 at http://www.asdc.asi.it/bepposax/report/report.html).

(Watson et al. 2001) and one pn camera (Strüder et al. 2001). Medium filters were used for the MOS cameras, and the thin filter for the pn camera. The pn camera was operated in timing mode in order to search for pulsations in case the source was sufficiently bright. SAX J1808.4−3658 turned out to be faint (see below), preventing meaningful searches for pulsed emission. We do not discuss the pn camera data in the following but concentrate on data from MOS cameras that were operated in full frame mode with a readout time of 2.6 s.

We extracted the event file starting from the raw data using the Standard Analysis System (SAS) version 5.3.0. Data were manually screened to remove any remaining bright pixels or hot columns. Periods in which the background was high because of soft proton flares were excluded using an intensity filter; we rejected all events accumulated in the external CCDs (2–7) when the total count rate exceeded 15 counts in 100 s in the 10–12.4 keV band for the MOS1 and MOS2, independently. We obtained a net exposure time of 33.2 and 34.4 ks for MOS1 and MOS2, respectively (this is slightly different from what was reported in Campana et al. 2002 because of the use of standard processed files with SAS v5.0.3). Spectra were accumulated separately for MOS1 and MOS2. Event grades higher than 12 were filtered out. Photons were grouped within XMMSELECT to the nominal MOS resolution of 15 eV.

2.1. Source Position

Previous observations aimed at determining the position of SAX J1808.4−3658 were performed with *BeppoSAX* (Stella et al. 2000; Wijnands et al. 2002b) and *ASCA* (Dotani et al. 2000; see Table 1), but due to the limited angular resolution of these satellites, the resulting picture was quite confused. In particular, it was unclear whether the source revealed at a low flux of $\sim 10^{-13}$ ergs s^{-1} cm^{-2} and with large positional uncertainties was indeed SAX J1808.4−3658 (see Fig. 1 and Table 1). In fact, Wijnands et al. (2002b) claimed that SAX J1808.4−3658 was only detected in the *ASCA* data of 1999 September while neither of the *BeppoSAX* observations detected the millisecond pulsar but rather revealed a nearby source, SAX J1808.6−3658.

The deep image that we obtained with EPIC allowed us to clarify this confused picture by revealing several faint sources
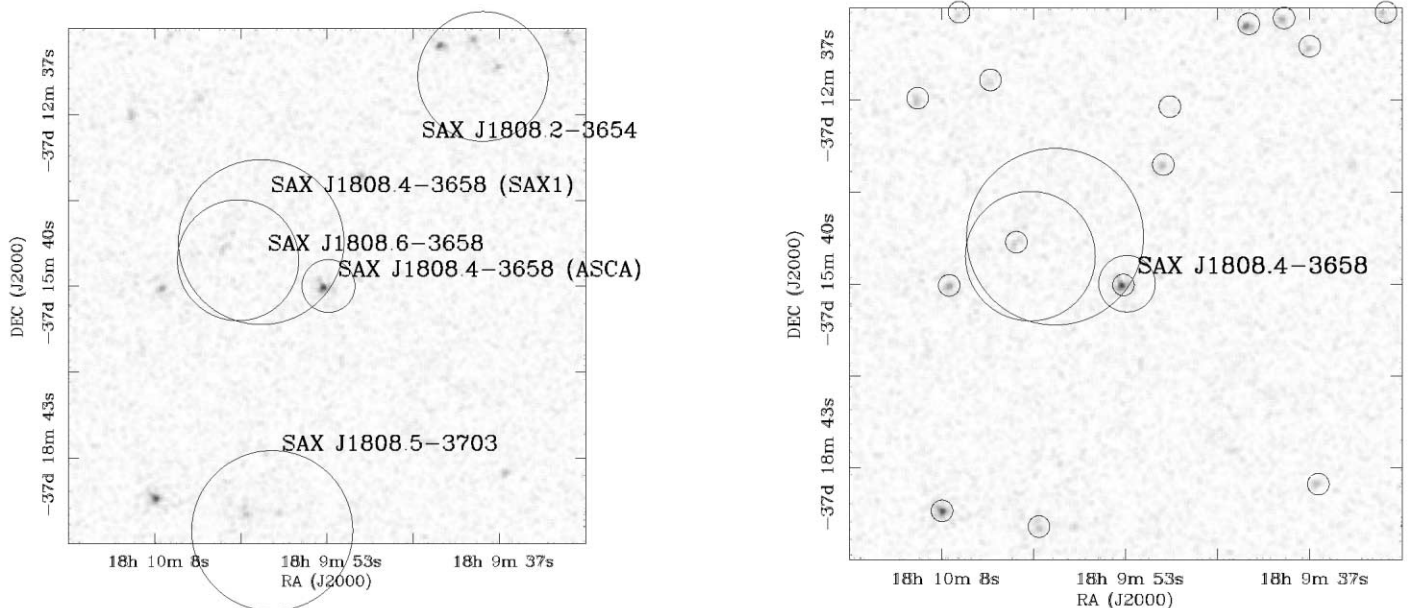

Fig. 1.—*Left panel*: *XMM-Newton* observation of the SAX J1808.4−3658 field with overlaid sources detected during previous observations with *BeppoSAX* and *ASCA* (see text for more details and Table 1). *Right panel*: Same field as left panel, but with *XMM-Newton* detections and previous detections of SAX J1808.4−3658. The error circles for the *XMM-Newton* sources have been enlarged to 15″ for display purposes.

TABLE 2
SPECTRAL MODELS AND RELATED LUMINOSITIES

Model	$N_{\rm H}$ ($\times 10^{21}$ cm^{-2})	Γ or kT	$\chi^2_{\rm red}$	Flux ($\times 10^{-14}$ cgs)	$L_{\rm X}$ ($\times 10^{31}$ ergs s^{-1})
Blackbody[a]	$0.0^{+0.3}$	$0.52^{+0.11}_{-0.08}$ keV	3.2	1.5	2.2
Power law	$0.3^{+0.7}$	$1.5^{+0.2}_{-0.3}$	1.1	2.9	4.6
Bremsstrahlung	$0.0^{+0.9}$	$15.5_{-10.4}$ keV	1.1	2.8	4.4
NS atmosphere[b]	$0.4^{+1.1}$	$0.27^{+0.0}_{-0.02}$ keV	4.4	1.1	1.8

NOTE.—Values without an explicit error indicate that the parameter is unconstrained. Fluxes and luminosities are in the 0.5–10 keV energy band. Fluxes are absorbed, and luminosities are unabsorbed.

[a] Even fixing the column density to 1.3×10^{21} cm^{-2}, we derive a temperature of 0.5 keV and a reduced $\chi^2 = 3.2$.

[b] The neutron star model for a hydrogen atmosphere is by Gänsicke et al. 2002. The temperature collapses to the maximum allowed value of 0.275 keV.

in the region. Source detection was obtained following the prescriptions of Baldi et al. (2002). This revealed 20 sources in the central part ($12' \times 9'$) of the field of view. The brightest one was clearly coincident with the radio position of SAX J1808.6−3658. A few other sources were contained in the error regions of sources previously seen with *ASCA* and in the longer *BeppoSAX* observation (see Fig. 1).

A faint source is visible about $2'$ east of SAX J1808.4−3658 [R.A. (J2000) = 18$^{\rm h}$08$^{\rm m}$36$^{\rm s}$6; decl. (J2000) = −36°58′01″]. This is within the error region of the source detected by Wijnands et al. (2002b) in the 2000 March *BeppoSAX* observation. If it had the same luminosity that we measure with EPIC (a count rate a factor ∼5 lower than that of SAX J1808.4−3658), it was probably too faint to be detected by *BeppoSAX*, but a small contamination from this source could perhaps explain why all the error regions for SAX J1808.4−3658 derived with low angular resolution instruments are systematically centered to the east of the radio position. A further bias is provided by another source $2'.9$ to the east [R.A. (J2000) = 18$^{\rm h}$08$^{\rm m}$42$^{\rm s}$2; decl. (J2000) = −36°58′44″], which has a comparable flux to SAX J1808.4−3658 and went undetected in previous observations (Wijnands et al. 2002b). Furthermore, given the source density revealed in this field by *XMM-Newton*, the probability of finding by chance at least one source within the *BeppoSAX* 90% error circle of SAX J1808.6−3658 is ∼70%. It appears to be unlikely that this faint source was much brighter and, at the same time, SAX J1808.4−3658 was much fainter just during the *BeppoSAX* observations, and therefore we conclude that

SAX J1808.4−3658 was the source detected in both 1999 March and 2000 March.

2.2. *X-Ray Spectrum and Luminosity*

In total, we collected 91 and 77 counts with the MOS1 and MOS2 detectors, respectively, within a $10''$ radius circle centered on the position of SAX J1808.4−3658. This corresponds to about 55%–60% of the source flux for energies between 1 and 5 keV (extending the extraction region would just decrease the signal-to-noise ratio because of the background and source faintness). The background was extracted from an annular region with inner and outer radii of $0'.5$ and $2'.5$ (excluding contaminating sources), respectively. Within the SAX J1808.4−3658 extraction region, about 15%–20% of the counts are to be attributed to the local background.

The MOS1 and MOS2 spectra were rebinned to contain at least 15 photons per channel. The spectral analysis was carried out with XSPEC v11.1.0. We adopted the latest on-axis standard response matrices ("m1_medv9q20t5r6_all_15.rsp" and "m2_medv9q20t5r6_all_15.rsp") and correct the fluxes for the fraction of photons collected within the extraction radius. The spectral analysis was carried out in the 0.3–7 keV energy range (M. Kirsch 2002, private communication). Given that the cross calibration between MOS1 and MOS2 agrees within 5% (M. Kirsch 2002, in preparation)[7] we did not include a constant for the two MOS instruments. The statistics was relatively poor, and the spectrum could be well fitted by an absorbed power-law (or a bremsstrahlung) model (see Table 2 and Fig. 2). A power-law model gave a better fit ($\chi^2_{\rm red} = 1.1$) with $\Gamma = 1.5^{+0.2}_{-0.3}$ (90% confidence level) and a column density of $N_{\rm H} = 0.3 \times 10^{21}$ cm^{-2} ($<1.1 \times 10^{21}$ cm^{-2}, 90% confidence level; here we used the Wisconsin cross sections in the WABS model). We note that a model with the column density fixed at the value derived from the source data in outburst (e.g., Gilfanov et al. 1998) and consistent with the Galactic value of 1.3×10^{21} cm^{-2} provides also a good fit with $\Gamma = 1.8 \pm 0.3$ and $\chi^2_{\rm red} = 1.2$ (with a null hypothesis probability of 20%). The unabsorbed 0.5–10 keV luminosity of SAX J1808.4−3658 was 5×10^{31} ergs s^{-1} for the power-law model and for a (revised) distance of 2.5 kpc (in 't Zand et al. 2001). Single-component blackbody or neutron star atmosphere models (Gänsicke, Braje, & Romani 2002) did not provide an adequate fit to the data with $\chi^2_{\rm red} > 3$.

Given that the best studied quiescent SXRTs display a soft blackbody component plus a hard power-law tail, we also con-
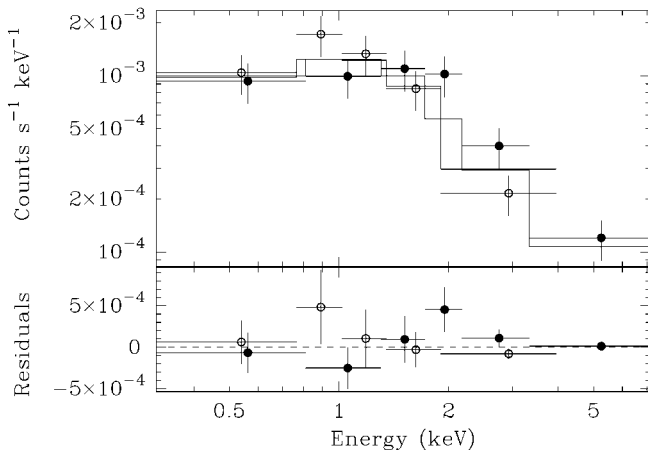
FIG. 2.—MOS1 (*open circles*) and MOS2 (*filled circles*) spectra of SAX J1808.4−3658. Overlaid is the fit with an absorbed power-law model described in the text. In the lower panel are reported the residuals of the fit.

[7] The EPIC status of calibration and data analysis (XMM-SOC-CAL-TN-0018) is in preparation.

sider this model (even though it is not strictly required by the data). In this case, we again fixed the column density to 1.3×10^{21} cm^{-2}. The power-law fit alone could adequately describe the data, and so we first fixed the best-fit power law and derived constraints on the blackbody component. SXRTs in quiescence display blackbody temperatures ranging between 0.1 and 0.3 keV (e.g., Rutledge et al. 2000). By using this range, we derived a 90% upper limit to the normalization of the blackbody component and, in turn, a (unabsorbed, bolo-metric) soft blackbody flux of ∼2 × 10^{-15} ergs s^{-1} cm^{-2}. This corresponds to a factor of 15 less than the power-law luminosity in the 0.5–10 keV band. If we repeat the same exercise with a neutron star atmosphere model (Gänsicke et al. 2002), we derive a factor of 30 less luminosity in the soft component. Alternatively, by fixing the normalization ratio of the blackbody and power-law components as observed in the best studied quiescent SXRTs (e.g., Campana et al. 1998b; even if recent observations on Aql X-1 challenge this picture; Rutledge et al. 2002), we obtained a very low blackbody temperature. By also fixing the column density to 1.3×10^{21} cm^{-2}, we succeeded in obtaining a good fit ($\chi^2_{\rm red} = 1.2$), with a blackbody tem-perature of $kT = 0.16^{+0.04}_{-0.05}$ keV and a power law $\Gamma = 1.5 \pm 0.5$. The source flux is in any case low, 2.5×10^{31} ergs s^{-1}. With a neutron star atmosphere model, we obtain an equally good fit ($\chi^2_{\rm red} = 1.2$), with a temperature $kT = 0.09^{+0.03}_{-0.03}$ keV and an emitting radius $R < 1.1$ km.

3. DISCUSSION

The high throughput and good angular resolution of *XMM-Newton* provided the first firm determination of the quiescent luminosity of SAX J1808.4−3658. This is lower by a factor of ∼2 than previous best-fit estimates. However, once the large uncertainties in the spectral parameters are taken into account, a fairly constant luminosity is inferred since 1999 March at a level of 5×10^{31} ergs s^{-1} (at a distance of 2.5 kpc; note that the reduced χ^2 of a fit with a constant is 1.8, a 15% null hypothesis variability; see Fig. 3). We conclude that the source variability issue raised by Dotani et al. (2000) is questionable. The source luminosity is a factor of 2 lower than that usually measured in SXRTs in quiescence; this ranges between 10^{32} and 10^{33} ergs s^{-1} (e.g., Campana et al. 1998a; Campana & Stella 2000; Garcia et al. 2001). For a distance of 4 kpc, how-ever, it would be fully consistent with what is usually observed in other SXRTs.

More interestingly, if we consider the spectral fit with a power-law component plus a blackbody, the soft X-ray com-ponent comprises only a small part ($\lesssim 10\%$) of the total lu-minosity, whereas in the great majority of SXRTs, it accounts for about half of the luminosity in the 0.5–10 keV energy band (e.g., Campana et al. 1998b, 2000; see, however, Rutledge et al. 2002). The soft component is usually ascribed to the cooling of the neutron star surface powered by the deep nuclear heating that the neutron star receives during each outburst (Brown et al. 1998; Rutledge et al. 2000; Colpi et al. 2001; see also Campana et al. 1998a). The *RXTE* All-Sky Monitor provides us with a continuous monitoring of the high-level activity of SAX J1808.4−3658. From these data, we can extrapolate a mean mass transfer rate of ∼5 × 10^{-12} $M_\odot$ yr^{-1}, in line with previous estimates (Bildsten & Chakrabarty 2001). This mean mass inflow rate translates into a soft quiescent luminosity of 10^{32} ergs s^{-1} within the 0.5–10 keV energy band from deep crustal heating (Brown et al. 1998; Colpi et al. 2001). This is
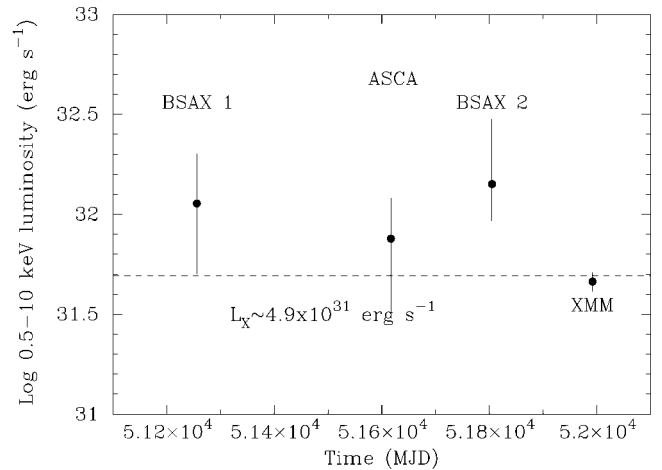

Fig. 3.—Quiescent 0.5–10 keV unabsorbed luminosities of SAX J1808.4−3658 observed with *BeppoSAX*, *ASCA*, and *XMM-Newton* with relative errors (1 σ). The dashed line represents the fit with a constant value. In the case of the BSAX 2 observation, a smaller uncertainty was reported by Wijnands et al. (2002b). The small number of counts, the high *BeppoSAX* background within the extraction radius (comparable to the source flux), the a posteriori discovery of a weak source within this radius make the flux uncertainty quoted by Wijnands et al. (2002b) too small. We adopt here this larger value.

a factor of ∼10 higher than observed. Given the fact that pre-dictions from deep nuclear heating are quite robust, one is led to conclude that an additional source of cooling is present. A simple and well-known solution is when the direct Urca process is allowed in the neutron star core; then, in turn, the neutrino cooling does affect the neutron star thermal evolution (Colpi et al. 2001). This can occur only for massive neutron stars with masses higher than 1.7–1.8 $M_\odot$. If this interpretation were correct, the neutron star of SAX J1808.4−3658 would have to be fairly massive, in agreement with accretion spin-up sce-narios.

The main contribution to the quiescent luminosity of SAX J1808.4−3658 appears to derive from the power-law component. A pure propeller contribution is ruled out since this mechanism should stop operating at a luminosity of about 10^{33} ergs s^{-1}, with the turning on of a radio pulsar (e.g., Campana et al. 1998a, 1998b). One interpretation for this power law relies on the emis-sion at the shock front between the relativistic wind of a radio pulsar and matter outflowing from the companion star (see the discussion in Stella et al. 2000). Being the first SXRT for which the presence of a sizable magnetic field is unambiguously es-tablished, SAX J1808.4−3658 can be used to infer the efficiency η with which spin-down power is converted into 0.5–10 keV luminosity. We derive $\eta \sim 5 \times 10^{-3} B_8^2$, where $B_8 = B/10^8$ G is the neutron star magnetic field (as derived from the accretion luminosity at the propeller onset; Gilfanov et al. 1998; see also Psaltis & Chakrabarty 1999).

Recently, an ideal laboratory for studying the shock emission has been discovered: PSR J1740−5340, a 3.7 ms radio pulsar in a 32.5 hr orbit around a Roche lobe–filling main-sequence companion, which displays a partial and total eclipse over a wide range of orbital phases (D'Amico et al. 2001; Ferraro et al. 2001; Burderi, D'Antona, & Burgay 2002). The X-ray lu-minosity of PSR J1740−5340 measured by *Chandra* (8 × 10^{30} ergs s^{-1}, 0.5–2.5 keV range, unabsorbed; Grindlay et al. 2001) implies $\eta \sim 10^{-4}$. Taking this system as a prototype for modeling the shock emission power (which is likely less ef-

ficient since the radio pulsar is not completely engulfed) and scaling the efficiency as the square of the orbital separation, one infers $\eta \sim 3 \times 10^{-3}$, well consistent with the value above, given the uncertainties involved.

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