CONSTRAINTS ON THERMAL X-RAY RADIATION FROM SAX J1808.4–3658 AND IMPLICATIONS FOR NEUTRON STAR NEUTRINO EMISSION¹

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ABSTRACT

Thermal X-ray radiation from neutron star soft X-ray transients in quiescence provides the strongest constraints on the cooling rates of neutron stars and thus on the interior composition and properties of matter in the cores of neutron stars. We analyze new (2006) and archival (2001) *XMM-Newton* observations of the accreting millisecond pulsar SAX J1808.4–3658 in quiescence, which provide the most stringent constraints to date. The X-ray spectrum of SAX J1808.4–3658 in the 2006 observation is consistent with a power law of photon index 1.83 ± 0.17, without requiring the presence of a blackbody-like component from a neutron star atmosphere. Our 2006 observation shows a slightly lower 0.5–10 keV X-ray luminosity, at a level of 68^{+15}_{-13} % of that inferred from the 2001 observation. Simultaneous fitting of all available *XMM-Newton* data allows a constraint on the quiescent neutron star (0.01–10 keV) luminosity of $L_{\rm NS} < 1.1 \times 10^{31}$ ergs s⁻¹. This limit excludes some current models of neutrino emission mediated by pion condensates and provides further evidence of additional cooling processes, such as neutrino emission via direct Urca processes involving nucleons and/or hyperons, in the cores of massive neutron stars.

Subject headings: dense matter — neutrinos — stars: neutron — X-rays: binaries

1. INTRODUCTION

The X-ray transient SAX J1808.4-3658 (hereafter 1808) has provided many fundamental breakthroughs in the study of accreting neutron stars (NSs). It was discovered in 1996 by BeppoSAX's Wide Field Cameras, and type I X-ray bursts were seen, identifying it as an accreting NS and constraining the distance (in 't Zand et al. 1998; Galloway & Cumming 2006). Coherent millisecond X-ray pulsations, the first discovered in accreting systems, were identified during an outburst using the Rossi X-ray Timing Explorer (RXTE; Wijnands & van der Klis 1998). Burst oscillations have also been seen at 1808's 401 Hz spin frequency, confirming that thermonuclear burst oscillations in low-mass X-ray binaries (LMXBs) represent the spin period of the NS (in't Zand et al. 2001; Chakrabarty et al. 2003). A pair of kilohertz quasiperiodic oscillations (QPOs) were seen from 1808, with a frequency difference equal to one-half of the spin period, forcing a revision of the most popular models for QPOs (Wijnands et al. 2003). Optical observations of the brown dwarf companion while 1808 was in quiescence showed a sinusoidal optical modulation attributed to heating of the companion (Homer et al. 2001). However, the required irradiating luminosity is larger than the available X-ray luminosity, giving rise to speculation that a radio pulsar mechanism is active during quiescence (Burderi et al. 2003; Campana et al. 2004).

In addition to these discoveries, 1808 has provided one of the lowest quiescent thermal luminosities yet measured from any accreting NS (Campana et al. 2002; Wijnands et al. 2002), along

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with 1H 1905+000 (Jonker et al. 2006). Transiently accreting NSs in quiescence are usually seen to have soft, blackbody-like X-ray spectra, often accompanied by a harder X-ray component generally fit by a power law of photon index 1-2 (Campana et al. 1998). The harder component is of unknown origin; an effect of continued accretion or a shock from a pulsar wind have been suggested (Campana et al. 1998). The blackbody-like component is generally understood as the radiation of heat from the NS surface. This heat is produced by deep crustal heating during accretion and is radiated by the crust on a timescale of 10^4 yr, producing a steady quiescent thermal NS luminosity (Brown et al. 1998; Campana et al. 1998; Haensel & Zdunik 1990). Measurement of the blackbody-like component is particularly important because it indirectly constrains the interior structure of NSs.

What fraction of this heat escapes the NS as neutrinos rather than photons depends on the physical conditions (i.e., composition, density, and pressure) of the NS interior. If the outburst history (fluence, recurrence time) and distance of a NS are reasonably well known, then the determination of the quiescent thermal NS luminosity constrains the neutrino versus photon emission and thus models for the NS interior (Yakovlev & Pethick 2004; Levenfish & Haensel 2006). For example, the transient Cen X-4 has been identified as having a rather low quiescent X-ray luminosity compared to deep crustal heating predictions. This suggests that Cen X-4 has enhanced neutrino emission, produced in the high-density core of a relatively high mass NS (Colpi et al. 2001). Many other LMXBs have also shown low quiescent thermal X-ray luminosities, indicating either enhanced neutrino emission or extremely long quiescent intervals (e.g., Wijnands et al. 2001; Jonker et al. 2004b, 2006; Tomsick et al. 2004). The coolest of these provide the strongest constraints to date on neutrino cooling from NS cores, as a range of cooling rates broader than that for young cooling pulsars is necessary to explain the data (Page et al. 2004; Yakovlev & Pethick 2004).

1808 is a particularly interesting system due to its known distance and constrained mass transfer rate (Bildsten & Chakrabarty 2001). Campana et al. (2002) observed 1808 in quiescence with *XMM-Newton* in 2001, finding a low-luminosity [$L_X(0.5-10 \text{ keV}) = 5 \times 10^{31} \text{ ergs s}^{-1}$ for d = 2.5 kpc] and a relatively

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FIG. 1.— *Top panel: XMM-Newton* X-ray spectra (data and best-fit power-law model) of SAX J1808.4–3658. The solid line with crosses shows the 2006 pn data and model. The dashed line with triangles shows the 2006 MOS data and model. The solid line with circles shows the 2001 MOS data and model. *Bottom panel:* Residuals to the fit in units of χ^2 .

hard spectrum, with less than 10% of the X-ray flux attributable to a possible blackbody-like component. We obtained a deeper *XMM-Newton* observation of 1808 in quiescence in 2006 to place more stringent constraints on neutron star cooling processes.

2. DATA REDUCTION

We observed 1808 on 2006 September 14 (ObsID 0400230401) for 54 ks with XMM-Newton's EPIC camera, using two MOS CCD detectors (Turner et al. 2001) with medium filters and one pn CCD detector (Strüder et al. 2001) with a thin filter. We also downloaded the 2001 March 24 XMM-Newton observation (ObsID 0064940101, reported by Campana et al. 2002) from the HEASARC archive. All data were reduced using FTOOLS and SAS version 7.0.0. We used only the MOS data from 2001, since the pn data were taken in timing mode, and the target was too faint to be detected in this mode. Intervals of flaring background were excluded by excluding times when the total MOS count rate exceeded 50.2-12 keV counts s⁻¹ and times when the total pn count rate exceeded 50 0.2–12 keV counts s^{-1} . This left 36.6, 47.0, 48.1, and 39.3 ks in the 2001 MOS data, the 2006 MOS1 data, the 2006 MOS2 data, and the 2006 pn data, respectively. Event grades higher than 12 were also excluded. We extracted spectra from a 10'' circle around the position of 1808, correcting the fluxes for the fraction of photons collected within the extraction radius and combining the pairs of simultaneous MOS spectra and responses using FTOOLS. We generated response and effective area files using the SAS tasks rmfgen and arfgen and produced background spectra from 90" circular source-free regions on the same CCD. The spectra were grouped to >15 counts per bin for the MOS data, and >30 counts per bin for the pn data (other choices gave similar results). To assess variability within the 2006 and 2001 observations, background-subtracted light curves were produced within SAS and analyzed using HEASARC's XRONOS software. KS and χ^2 tests on the last 15 ks of 0.2–12 keV pn data (unaffected by background flaring) revealed no evidence of variability.

3. SPECTRAL ANALYSIS

Our fitting includes photoelectric absorption (XSPEC model phabs), with a hydrogen column density, $N_{\rm H}$, fixed at the value derived from observations in outburst (1.3×10^{21} cm⁻²; note that this is equal to the value derived from Dickey & Lockman 1990). We also tested models with photoelectric absorption as a free parameter, in all cases finding $N_{\rm H}$ consistent with the outburst value. Quoted errors are at 90% confidence.

We fit the combined 2001 MOS spectrum to a power-law model, finding $\Gamma = 1.72 \pm 0.28$ (see Fig. 1 and Table 1). Fits using only a hydrogen-atmosphere model, the NSATMOS model of Heinke et al. (2006a; similar to the NSA model of Zavlin et al. 1996), gave poor fits ($\chi^2_{\nu} > 4.8$). We then performed fits with NSAT-MOS plus a power law, fixing the true NS radius to 10 km, the gravitational mass to 1.4 M_{\odot} , and the distance to 3.5 kpc (Galloway & Cumming 2006). No thermal component is required, but a thermal component with kT < 42 eV (90% confidence)⁸ is permitted, thus placing a limit on the NS's thermal 0.01–10 keV (essentially bolometric) luminosity of $L_{\rm NS} < 2.4 \times 10^{31}$ ergs s⁻¹. The inclination of this system is known to be low (Bildsten & Chakrabarty 2001), and it is rare for LMXBs to show higher $N_{\rm H}$ in quiescence than outburst (e.g., Jonker & Nelemans 2004), so we regard a higher $N_{\rm H}$ as very unlikely. The total 0.5–10 keV unabsorbed luminosity is $L_{\rm X} = 7.6^{+1.7}_{-1.5} \times 10^{31}$ ergs s⁻¹.

For the 2006 data, we find a similar spectral shape and therefore fit similar models to the pn and MOS data simultaneously. A simple power law fits the data adequately, with a photon index of $\Gamma = 1.83 \pm 0.17$ and an unabsorbed $L_X(0.5-10 \text{ keV}) = 5.2 \pm 0.7 \times 10^{31}$ ergs s⁻¹. The 2006 flux appears less than the 2001 flux. We test this by fitting the spectra simultaneously and tying their power-law slopes together, finding that the 2001 0.5–10 keV unabsorbed flux is higher at 97% confidence; the 2001 flux is $1.28^{+0.24}_{-0.21}$ (90% confidence) that of the 2006 observation. If the power-law slopes are allowed to vary (1.61 ± 0.3 for 2001, 1.83 ± 0.17 for 2006), then the best-fit flux ratio is $1.47^{+0.35}_{-0.27}$.

Fitting the 2006 and 2001 data allows a tighter constraint on the presence of a NS atmosphere component than the 2001 data alone, requiring a NS kT < 34 eV and a thermal 0.01–10 keV

⁸ kT is the redshifted temperature, or kT_{∞} .

TABLE 1Spectral Fits to SAX J1808.4–3658

Epoch	$(10^{22} \text{ cm}^{-2})$	Г	$\chi^2_{ u}/{ m dof}$	$L_{\rm X}$ (ergs s ⁻¹)	kT (eV)	$L_{\rm NS}$ (ergs s ⁻¹)
2001	(0.13)	1.61 ± 0.3	0.51/9	$7.6^{+1.7}_{-1.5} \times 10^{31}$	<42	$< 2.4 \times 10^{31}$
2006	(0.13)	1.83 ± 0.17	0.86/45	$5.2 \pm 0.7 \times 10^{31}$	<35	$< 1.2 \times 10^{31}$
2001 and 2006	(0.13)	1.83 ± 0.16	0.79/55	$5.2 \pm 0.7 imes 10^{31}$	<34	$< 1.1 \times 10^{31}$
2001 and 2006	$0.15\!\pm\!0.04$	$1.93\substack{+0.37 \\ -0.29}$	0.78/54	$5.2 \pm 1.0 \!\times\! 10^{31}$	<61	$< 1.0 \times 10^{32}$

NOTES.—Spectral fits with power law plus NSATMOS model to SAX J1808.4–3658. Errors are 90% confidence for a single parameter. $N_{\rm H}$ is held fixed in the first three rows. $L_{\rm X}$ for 0.5–10 keV range, $L_{\rm NS}$ for 0.01–10 keV.

TABLE 2							
LUMINOSITIES	AND MASS TRANSFER	RATES					

Source	$N_{\rm H}$ (10 ²² cm ⁻²)	kT (eV)	D (kpc)	Outbursts	Years	$\dot{M} \ (M_{\odot} { m yr}^{-1})$	$L_{\rm NS}$ (ergs s ⁻¹)	References
Aql X-1	$4.2 imes 10^{21}$	~94	5	8	10.7	4×10^{-10}	5.3×10^{33}	1, 2, 3, 4
Cen X-4	5.5×10^{20}	76	1.2			$< 3.3 \times 10^{-11}$	4.8×10^{32}	5, 3
4U 1608-522	8×10^{21}	170	3.6	4	10.7	$3.6 imes10^{-10}$	5.3×10^{33}	6, 3, 4
KS 1731–260	$1.3 imes 10^{22}$	70	7	1	30	$< 1.5 \times 10^{-9}$	5×10^{32}	7, 4
MXB 1659-29	2.0×10^{21}	55	$\sim 10?$	2	10.7	$1.7 imes 10^{-10}$	2.0×10^{32}	7,4
EXO 1747-214	4×10^{21}	<63	<11			$< 3 \times 10^{-11}$	$< 7 \times 10^{31}$	8
Terzan 5	1.2×10^{22}	<131	8.7	2	10.7	$3 imes 10^{-10}$	$<2.1 \times 10^{33}$	9, 10, 4
NGC 6440	7×10^{21}	87	8.5	3	35	$1.8 imes 10^{-10}$	3.4×10^{32}	11, 4
Terzan 1	1.4×10^{22}	74	5.2			$< 1.5 \times 10^{-10}$	$< 1.1 \times 10^{33}$	12
XTE 2123-058	6×10^{20}	<66	8.5	1	10.7	$< 2.3 \times 10^{-11}$	$< 1.4 \times 10^{32}$	3, 4
SAX J1810.8-2609	$3.3 imes 10^{21}$	<72	4.9	1	10.7	$< 1.5 \times 10^{-11}$	$< 2.0 \times 10^{32}$	13, 3, 4
RX J1709-2639	4.4×10^{21}	122	8.8	2	10.7	$1.8 imes 10^{-10}$	2.2×10^{33}	14, 15, 4
1H 1905+000	1.9×10^{21}	<50	10			$< 1.1 \times 10^{-10}$	$< 4.8 \times 10^{31}$	16, 15
SAX J1808.4-3658	1.3×10^{21}	<34	3.5	5	10.7	1.0×10^{-11}	$< 1.1 \times 10^{31}$	17, 4, 15

Notes.—Estimates of quiescent thermal luminosities from neutron star transients, and mass transfer rates (inferred from *RXTE* ASM observations for systems with *RXTE*-era outbursts). Quiescent thermal luminosities are computed for the unabsorbed NS component in the 0.01-10 keV range. Outbursts and years columns give the number of outbursts and the time baseline used to compute \dot{M} , if this calculation was performed in this work (indicated by referring to reference 4).

REFERENCES.—(1) Rutledge et al. 2001b; (2) Campana & Stella 2003; (3) Tomsick et al. 2004; (4) Mass transfer rate computed in this work; (5) Rutledge et al. 2001a; (6) Rutledge et al. 1999; (7) Cackett et al. 2006a; (8) Tomsick et al. 2005; (9) Wijnands et al. 2005; (10) Heinke et al. 2006b; (11) Cackett et al. 2005; (12) Cackett et al. 2006b; (13) Jonker et al. 2004b; (14) Jonker et al. 2004a; (15) Quiescent bolometric luminosity computed in this work; (16) Jonker et al. 2006; (17) Galloway & Cumming 2006.

NS luminosity $L_{\rm NS} < 1.1 \times 10^{31}$ ergs s⁻¹. Choosing a NS radius of 12 km, or a mass of 2.0 M_{\odot} , varies this constraint by only 3%. The rather tight distance limits of Galloway & Cumming (2006; 3.5 ± 0.1 kpc) produce only a 6% uncertainty. Allowing the $N_{\rm H}$ to float freely permits a thermal 0.01–10 keV NS luminosity $L_{\rm NS} < 1.0 \times 10^{32}$ ergs s⁻¹ (for $N_{\rm H} = 1.7 \times 10^{21}$ cm⁻²).

4. RAMIFICATIONS

We have estimated the time-averaged mass transfer rates for 1808 and several other transient LMXBs (Agl X-1, Cen X-4, 4U 1608-52, KS 1731-260, RX 1709-2639, MXB 1659-29, XTE 2123-058, SAX 1810.8-2609, and those in Terzan 5 and NGC 6440) from the RXTE All-Sky Monitor (ASM) record (1996 to November 2006), under the assumption that the timeaveraged mass accretion rate over the last 10 yr reflects the timeaveraged mass transfer rate (Table 2). We use PIMMS and a power law of photon index 2 to convert the ASM count rates during outbursts into 0.1–20 keV fluxes.⁹ This is, of course, a rough approximation, as the spectral shapes of LMXBs in outburst vary substantially. Additional sources of potential error include poor ASM time coverage of some outbursts, uncertainty in the NS mass and radius (affecting the energy released per accreted gram and thus the conversion from L_X to mass accretion rate), variability in the mass transfer rate, and uncertain distances (which will equally affect the quiescent luminosity). We plot an arbitrary uncertainty of 50% in both mass transfer rate and quiescent luminosity for each point in Figure 2. For Cen X-4 we use the lowest measured quiescent luminosity and the mass transfer rate limit inferred if Cen X-4 undergoes outbursts every 40 yr with a fluence similar to its 1969 outburst (Chen et al. 1997). The NS component flux for Aquila X-1 is somewhat uncertain and possibly variable (Rutledge et al. 2002; Campana & Stella 2003). We assume that all outbursts from NGC 6440 since 1971 have been detected. For KS 1731–260, we assume that the average flux seen with RXTE/ASM during outburst was the average flux during the

entire 12.5 yr outburst. For KS 1731-260 and the transient in Terzan 1 (for which we take a 12 yr outburst), we take a minimum recurrence time of 30 yr.

For 1808 we derive a time-averaged mass transfer rate of $1.0 \times 10^{-11} M_{\odot}$ yr⁻¹, an excellent match to the prediction of general relativity of $0.95 \times 10^{-11} (M_2/0.05 M_{\odot}) M_{\odot}$ yr⁻¹ (Bildsten & Chakrabarty 2001). We note that the true mass transfer rate cannot



Fig. 2.—Cooling curves for various NS interior neutrino emission scenarios, compared with measurements (or 95% confidence upper limits) of the quiescent 0.01–10 keV NS luminosity and time-averaged mass transfer rate for several NS transients (see Table 2). The cooling curves are taken from Yakovlev & Pethick (2004); the dotted curve represents a low-mass NS, while the lower curves represent high-mass NSs with kaon or pion condensates or direct Urca (Durca) processes mediated by nucleons or hyperons. Limits on the quiescent NS luminosity of SAX J1808.4–3658 are given for the 2001 and 2006 observations. The effect of a distance error as large as a factor of 1.5 is also indicated (*upper left*).

⁹ We have verified that this conversion is correct to within 50% for outbursts of the transients EXO 1745–245 and Aquila X-1.

be less than $7 \times 10^{-12} M_{\odot}$ yr⁻¹ for a NS mass $\ge 1.4 M_{\odot}$, under the assumption of an index n = -1/3 for the donor's mass-radius relation, or less than $3.5 \times 10^{-12} M_{\odot}$ yr⁻¹ for an index n = 1 mass-radius relation. It is unclear whether the entropy of the donor can be maintained by the low quiescent luminosity of the neutron star (Homer et al. 2001; Burderi et al. 2003); we plan future observations and modeling to address this issue.

We have plotted the cooling curves calculated by Yakovlev & Pethick (2004) for a variety of models in Figure 2. Low-mass NSs will cool slowly (Fig. 2, dotted line) in the model of Yakovlev & Pethick (2004) only through photon emission and neutronneutron neutrino bremsstrahlung processes, while modified Urca neutrino emission is suppressed by proton superfluidity. Other slow cooling models (invoking, e.g., neutrino emission through Cooper pair formation) give similar results (e.g., Page et al. 2004). Higher mass NSs should have higher central densities, sufficient to promote more rapid direct Urca neutrino cooling processes involving nucleons and/or hyperons, or direct Urca-like processes mediated by pions, kaons, or quark matter, in their cores. Mediummass models can produce intermediate cooling rates if proton superconductivity is important at low densities, as its decay at moderate densities can allow a smooth transition between fast and slow cooling rates (Yakovlev et al. 2003; Levenfish & Haensel 2006). Thus, NSs of different masses should lie between the top curve and one of the lower curves in Figure 2, where the lower curve is the maximum neutrino cooling curve. We note a possible trend that NSs with low mass transfer rates seem to have particularly low quiescent luminosities, well below the "standard cooling" predictions. This might be explained through binary evolution; NSs with low mass transfer rates may be very old systems, which may have accreted significant mass. In enhanced neutrino emission scenarios, these massive NSs would then have higher neutrino and lower photon luminosities than younger systems.

Our constraint on the quiescent thermal 0.01-10 keV NS luminosity of 1808 from the 2006 observations thus seems to rule out some models of direct Urca neutrino emission via pion condensates, favoring direct Urca processes involving nucleons and/or hyperons. An extremely large distance uncertainty of 50% (see Fig. 2; cf. Galloway & Cumming 2006) would be required to bring 1808's thermal luminosity up to the pion condensate predictions. The 2001 observation by itself rules out some models of direct Urca neutrino emission from kaon condensates. Other modelers of NS cooling have suggested that medium effects (Blaschke et al. 2004) or diquark condensates (Grigorian et al. 2005) could provide a wide range of NS cooling rates. These models may also be sufficient to explain the data on 1808 presented here. Our results agree with the principal conclusions of, e.g., Yakovlev & Pethick (2004), Levenfish & Haensel (2006), and Page et al. (2006), and provide a firmer observational basis for future studies.

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