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THE QUIESCENT X-RAY EMISSION OF THREE TRANSIENT X-RAY PULSARS

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ABSTRACT

We report on *BeppoSAX* and *Chandra* observations of three hard X-ray transients in quiescence containing fast-spinning ($P < 5$ s) neutron stars: A0538−66, 4U 0115+63, and V0332+53. These observations allowed us to study these transients at the faintest flux levels thus far. The spectra are remarkably different from the ones obtained at luminosities more than a factor of 10 higher, testifying that the quiescent emission mechanism is different. Pulsations were not detected in any of the sources, indicating that accretion of matter down to the neutron star surface has ceased. We conclude that the quiescent emission of the three X-ray transients likely originates from accretion onto the magnetospheric boundary in the propeller regime and/or from deep crustal heating resulting from pycnonuclear reactions during the outbursts.

Subject headings: accretion, accretion disks — pulsars: general — stars: individual (4U 0115+63, A0538−66, V0332+53) — X-rays: binaries

1. INTRODUCTION

Young magnetic neutron stars orbiting a Be star companion occasionally show transient X-ray emission. Their spectra are relatively hard up to energies of tens of keV (power laws with photon indices of ~1): hence, their name of hard X-ray transients (HXRTs; White, Kaluzienski, & Swank 1984). Be stars are characterized by equatorial mass-loss episodes likely originating from their high (nearly break up) rotational velocities. When the neutron star along its (eccentric) orbit enters this equatorial disk, an X-ray outburst episode is observed (Stella, White, & Rosner 1986; Bildsten et al. 1997). Part of the material outflowing from the Be star is captured by the gravitational field of the neutron star, and accretion onto its magnetic polar caps takes place, generating an intense pulsed X-ray flux. The spin periods of HXRTs range from 69 ms (A0538−66; Skinner et al. 1982) to 25 minutes (RX J0146.9+6121; Mereghetti, Stella, & De Nile 1993). Magnetic field strengths, when accurately inferred from cyclotron line features, lie in the range of $B \sim (1\text{–}10) \times 10^{12}$ G (Dal Fiume et al. 2000).

The powering mechanism and the accretion regime that pertain to the quiescent state of these sources are still uncertain. A change in the accretion regime should take place at lower luminosities in the case of fast-spinning neutron stars, since their magnetosphere expands beyond the corotation radius, therefore halting the infalling material at the magnetospheric boundary (i.e., the propeller regime). A contribution from matter leaking through the centrifugal barrier may still be present (Campana et al. 2001). A further emission mechanism is represented by the cooling of the neutron star surface (deep crustal heating) due to pycnonuclear reactions occurring during outbursts (Brown, Bildsten, & Rutledge 1998).

In this paper we present the first detailed investigation of the quiescent state of three of the fastest spinning (accreting) neutron stars in HXRTs. A0538−66 and 4U 0115+63 were detected in our *BeppoSAX* observations, while V0332+53 remained undetected. A *Chandra* pointing revealed the latter source as well (§ 2). We discuss these results in light of the regimes experienced by a neutron star subject to a range of matter inflow. By using the neutron star parameters deduced from observations in outburst, we infer that these sources are likely in the propeller regime (§ 3).

2. X-RAY OBSERVATIONS

We analyzed the data from the two imaging instruments on board the *BeppoSAX* satellite: the Low Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997) and the Medium Energy Concentrator Spectrometer (MECS; 1.6–10.5 keV; Boella et al. 1997). Nonimaging instruments (when active) provided only upper limits. Only two of the three MECS units were operating at the time of the observations. LECS data were collected only during satellite nighttime, resulting in shorter exposure times. For a summary of the observations, see Table 1.

Products were extracted using the FTOOLS package (Version 5.0.1). LECS and MECS events were extracted from a circle of 4′ radius. The background was subtracted using spectra from blank-sky files at the same detector coordinates (after checking that the background of the observation was comparable). For the spectral analysis, we used the XSPEC software (Version 11.1.0) and the public response matrices available in 2000 January. During the spectral fits, a variable normalization factor was included to account for the mismatch in the absolute flux calibration of the *BeppoSAX* instruments.[5]

2.1. *A0538−66*

The X-ray transient A0538−66 in the Large Magellanic Cloud contains a 69 ms accreting neutron star. Pulsations were detected only once during a strong outburst in the late

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[5] See the Cookbook for the *BeppoSAX* NFI Spectral Analysis (available at http://www.asdc.asi.it/bepposax/software/index.html).

TABLE 1
Summary of Observations

Source	Start–Stop Time	LECS Exposure Time (s)	MECS Exposure Time (s)
A0538−66......	1999 Sep 10–11	12706	38540
4U 0115+63...	2000 Aug 13–16	44295	85547
V0332+53......	1999 Aug 14–15	17748	39218
V0332+53[a]	2001 Jan 4	...	5146

[a] Taken with *Chandra*.

1970s with peak luminosities of $\sim 10^{39}$ ergs s^{-1} (2–17 keV; Skinner et al. 1982; Ponman, Skinner, & Bedford 1984). An upper limit on the magnetic field of $B \sim 10^{11}$ G was inferred through the presence of a pulsed signal as the source emitted a luminosity of $\sim 10^{39}$ ergs s^{-1}, under the (very likely) hypothesis that matter, unimpeded by the centrifugal barrier, accreted onto the neutron star surface at that time (Skinner et al. 1982). A 5 yr optical light curve obtained as a by-product of the MACHO project revealed a long-term modulation at ~421 days and confirmed the shorter term modulation at the orbital period of 16.651 days (Alcock et al. 2001). During the *ROSAT* All-Sky Survey, two weaker outbursts from A0538−66 were detected, with peak luminosities of ~4 and $\sim 2 \times 10^{37}$ ergs s^{-1} in the 0.1–2.4 keV range (Mavromatakis & Haberl 1993). This source was also observed a few times in its quiescent state. *ASCA* detected A0538−66 in a 40 ks observation close to periastron at a level of $\sim 2 \times 10^{36}$ ergs s^{-1} (Corbet et al. 1997). The spectrum could be described by the sum of a power law (with photon index $\Gamma \sim 2$) and a soft component (which could be fitted with a blackbody or a bremsstrahlung). An iron line also had to be included in order to obtain a good fit to the data. Campana (1997) analyzed *ROSAT* Position Sensitive Proportional Counter serendipitous pointings in which A0538−66 was (usually) detected at a level of (3–10) $\times 10^{34}$ ergs s^{-1} (0.1–2.4 keV).

The *BeppoSAX* observation of A0538−66 was carried out on 1999 September 10 and 11 and covered an orbital phase interval of 0.92–0.98 according to the ephemerides in Skinner et al. (1982) and Alcock et al. (2001). The phase of the 421 day periodicity discovered by Alcock et al. (2001) was approximately 0.77. Outbursts were observed in only a limited phase range of this cycle. This cycle is quasi-periodic, and our observation was carried out during the nonoutbursting part of the cycle.

The source was detected in the LECS and MECS data with a net count rate of 2×10^{-3} counts s^{-1} each. The source contributed 27% and 38% of the total counts in the LECS and MECS 4′ extraction circles. The LECS and MECS spectra had relatively poor statistics, with 97 and 456 source counts, respectively. We rebinned the LECS and MECS spectra in order to have 40 and 50 counts per bin, respectively. A spectral analysis was carried out in the 0.1–8 keV energy range for the LECS and 1.6–7 keV for the MECS. Single-component models provided a good description of the data. A power-law model with a photon index of $\Gamma = 2.1 \pm 0.6$ (errors are at a 90% confidence level for one parameter of interest; this is adopted throughout the text unless otherwise specified) and a column density of $N_H < 1.1 \times 10^{22}$ cm^{-2} provided a reduced $\chi^2_{red} = 1.3$ for 5 degrees of freedom (dof; see Fig. 1). A bremsstrahlung model could fit the data equally well with an equivalent temperature $T_{br} = 5.5^{+9.6}_{-2.9}$ keV and $N_H < 5.8 \times 10^{21}$ cm^{-2}, resulting in $\chi^2_{red} = 1.1$ (even if the nominal column density is consistent with zero). A blackbody model with an equivalent temperature of $T_{bb} = 0.8 \pm 0.2$ keV and a null column density ($N_H < 4.4 \times 10^{21}$ cm^{-2}) instead gave $\chi^2_{red} = 2.4$.

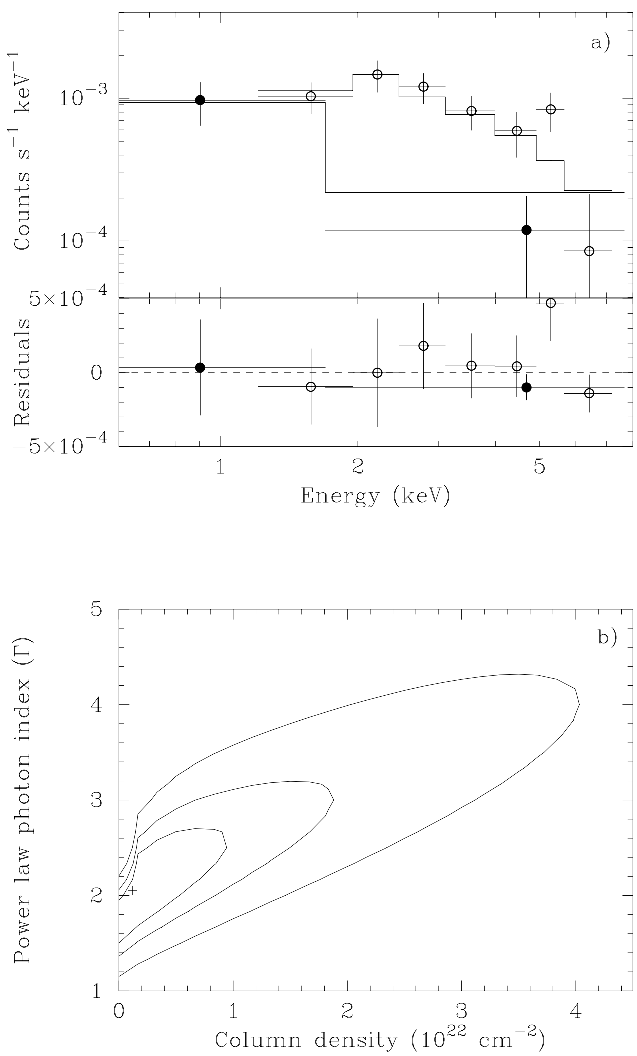

Fig. 1.—(*a*) X-ray spectrum of A0538−66 as observed by *BeppoSAX*. Filled and open circles refer to LECS and MECS data, respectively. The superposed model is a power law with interstellar absorption (see text). Residuals are shown in the bottom panel. (*b*) Contour plot of the power-law photon index vs. the column density. Contours are at a level of 1, 2, and 3 σ.

The equivalent blackbody radius is $R_{\rm bb} = 1.4^{+0.7}_{-0.5}$ km. For all the models, the 0.1–10 keV unabsorbed luminosity ranged between (1–3) $\times 10^{35}$ ergs s^{-1} for a distance of 50 kpc.

The 456 MECS photons were used for the timing analysis. Photon arrival times were first corrected to the barycenter of the solar system. We then searched for pulsations at the neutron star spin period (69 ms; Skinner et al. 1982). To decide the period range over which the search should be carried out, we estimated the variation of the period since the last observation in which pulsations were detected. The value of the period derivative measured during the 1979 outburst, $\dot{P} = 5 \times 10^{-10}$ s s^{-1} (Skinner et al. 1982), was too large to derive from accretion torques alone and was likely dominated by Doppler shifts. We adopt here as a scale value the $\dot{P}$ measured for 4U 0115+63 (see below). Due to the short spin period and long time elapsed since the last outburst (1982), the frequency range spanned by the assumed maximum $\dot{P}$ is fairly large, encompassing the range of 64–74 ms. No periodicities were found because of poor statistics.

The *BeppoSAX* observation detected A0538−66 at its lowest flux level in the 0.1–10 keV range (a factor of ~50 less than in the *ASCA* observation; Corbet et al. 1997). The *BeppoSAX* spectrum was significantly different from that measured by *ASCA*. Assuming the *ASCA* spectral parameters and leaving the normalization free, $\chi^2_{\rm red} = 7.0$ was obtained. The main discrepancy was the absence of the soft component, which was clearly required by the *ASCA* data but unnecessary in the *BeppoSAX* spectrum. Setting the blackbody normalization to zero, $\chi^2_{\rm red}$ decreased to 1.4, i.e., the best fit derived above. The other feature found by Corbet et al. (1997), i.e., a highly ionized iron line (with equivalent width EW = 450 eV), was not detected in our spectrum, with an upper limit of EW $\lesssim$ 400 eV.

2.2. *4U 0115+63*

When in outburst, the X-ray flux of 4U 0115+63 is modulated at the spin period of 3.6 s (Cominsky et al. 1978). Pulse arrival-time analysis yielded an orbital solution with a period of 24.3 days and an eccentricity of 0.34 (Rappaport et al. 1978). Observations with *Ginga* confirmed earlier results (Wheaton et al. 1979; White, Swank, & Holt 1983) of cyclotron line features characteristic of a high magnetic field $B \sim 10^{12}$ G (Nagase 1989). *BeppoSAX* observations led to the detection of four cyclotron line harmonics, corresponding to a magnetic field of $B = 1.3 \times 10^{12}$ G at the neutron star surface (after correction for the gravitational redshift; Santangelo et al. 1999).

Tight upper limits on the quiescent emission of this source were derived from *Einstein*, *EXOSAT*, and *ROSAT* data (Campana 1996). The column density to the source is high (~10^{22} cm^{-2}) and limits the possibility of detecting and studying a possible soft X-ray component.

During a *BeppoSAX* observation close to periastron, we revealed a huge luminosity increase (a factor of $\gtrsim$250) in less than 15 hr. This was interpreted as the opening of the centrifugal barrier in the transition regime between propeller and accretion regimes, thus providing the best evidence to date for the onset of the propeller mechanism (Campana et al. 2001).

A further *BeppoSAX* observation was carried out on 2000 August 13–16 (a short account of the results was reported in Campana et al. 2001). The observation covered the orbital phase range 0.42–0.51 (adopting the ephemerides of Bildsten et al. 1997). The source was not detected in the LECS (likely due to high absorption) but was seen in the MECS data. The 3 σ upper limit on the LECS count rate was 2×10^{-3} counts s^{-1}. The net source count rate in the MECS was 10^{-3} counts s^{-1}, and it comprised only ~15% of the total flux in the 4′ extraction region and in the 1.4–9.5 keV energy band due to the large background. We rebinned the spectrum in order to have 150 counts per channel, resulting in six energy bins. The spectrum was very poor and could be fitted by a variety of single-component models. We fixed the column density to the best-fit value found during the observation at periastron, i.e., $N_{\rm H} = 1.74 \times 10^{22}$ cm^{-2} (Campana et al. 2001). In the case of a power-law model, we obtained a photon index $\Gamma = 2.6^{+2.1}_{-1.3}$ ($\chi^2_{\rm red} = 0.2$ for 1 dof; see Fig. 2). Bremsstrahlung and blackbody models both provided good fits. In particular, for the bremsstrahlung model we obtained $T_{\rm br} = 2.8^{+\infty}_{-2.0}$ keV ($\chi^2_{\rm red} = 0.2$ for 1 dof) and $T_{\rm bb} = 0.7^{+0.7}_{-0.3}$ keV ($\chi^2_{\rm red} = 0.5$ for 1 dof). All models provided an unabsorbed 0.5–10 keV luminosity of (0.8–2) $\times 10^{33}$ ergs s^{-1} for a distance of 8 kpc (Negueruela & Okazaki 2001).

From the same extraction region, we selected 690 events for the timing analysis. The photon arrival times were corrected to the barycenter of the solar system. Pulsations at the neutron star spin period were searched for. We consider a period interval of 3.616–3.617 s derived from the spin period detected in 1999 August (Campana et al. 2001) and a maximum spin-up or spin-down rate of 8×10^{-12} s s^{-1} (Bildsten et al. 1997). The search over 13 independent Fourier frequencies provided an upper limit on the pulsed fraction of 30% (3 σ).

2.3. *V0332+53: BeppoSAX Observation*

EXOSAT observed three outbursts from V0332+53 between 1983 November and 1984 January, leading to the discovery of the 4.4 s spin period and a sudden decrease of luminosity at the end of ~1 month long recurrent outbursts.

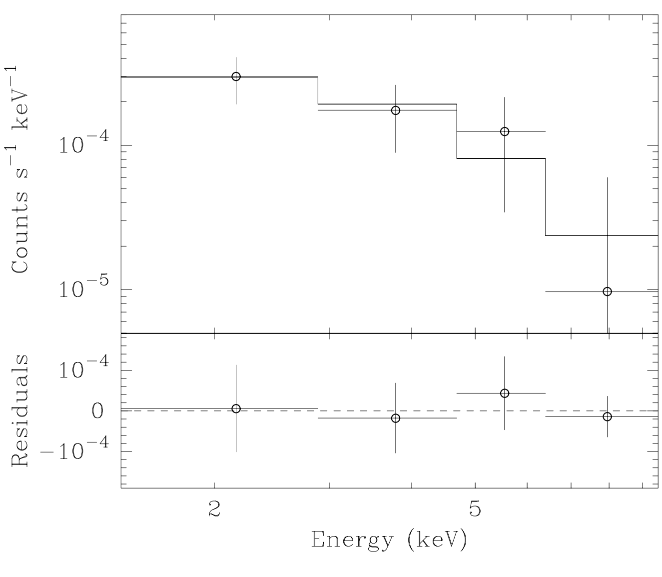

FIG. 2.—X-ray spectrum of 4U 0115+63 as observed by the *BeppoSAX* MECS. The superposed model is a power law with interstellar absorption (see text). Residuals are shown in the bottom panel.

TABLE 2

Relevant Luminosities of HXRTs of Our Sample

Source	Spin Period (s)	B[a] (10^{12} G)	$\log L_{\rm min}(R)$ (ergs s^{-1})	Centrifugal Gap (Δ)	$\log L_{\rm min}(r_{\rm cor})$ (ergs s^{-1})	$\log L_{\rm obs}$ (ergs s^{-1})
A0538−66........	0.07	∼0.1	<37.9–38.9	28	<36.4–37.5	35.3
4U 0115+63.....	3.62	1.3	35.5–36.5	400	32.9–33.9	33.0
V0332+53........	4.37	3.5	36.1–37.2	450	33.5–34.5	32.7

Note.—Luminosity ranges have been computed for the limiting cases $\xi = 0.5$ and 1.

[a] The magnetic field was estimated from cyclotron line features. In the case of A0538−66, it was estimated indirectly from the detection of pulsations during a very luminous outburst (see text), and therefore we adopt a magnetic field value consistent with the estimate of Skinner et al. 1982 and our definition of B, i.e., a factor of 2 higher.

The latter result was interpreted as the onset of the centrifugal barrier (Stella et al. 1985, 1986). An upper limit of $\sim 5 \times 10^{33}$ ergs s^{-1} to the source quiescent emission (1–15 keV) was derived on that occasion with the *EXOSAT* Medium Energy Detector. Doppler shifts in pulse arrival times indicate that the pulsar is in orbit around a Be star with period of 34.3 days and eccentricity 0.3 (Stella et al. 1985). Observations during a subsequent outburst with *Ginga* led to the discovery of a cyclotron line feature corresponding to a $\sim 3 \times 10^{12}$ G magnetic field (Makishima et al. 1984).

The *BeppoSAX* observation took place on 1999 August 14 and 15. The current orbital ephemerides are not accurate enough to assess the orbital phase interval of this observation. V0332+53 was not detected in the LECS and MECS instruments (see below). A source unrelated to V0332+53 was revealed in the MECS data $\sim 6'$ off axis. The LECS and MECS exposures provided a 3 σ upper limit on the V0332+53 count rate of 2×10^{-3} counts s^{-1}. This translates into an unabsorbed luminosity limit of $\lesssim 3 \times 10^{33}$ ergs s^{-1} (0.1–10 keV), assuming a power-law spectrum ($\Gamma = 2$), a column density of $N_{\rm H} = 1 \times 10^{22}$ cm^{-2} (consistent with the value observed in outburst; Makishima et al. 1984), and a distance of 7 kpc (Negueruela et al. 1999). A harder power law with $\Gamma = 1$ results in a factor of 4 higher upper limit.

2.3.1. *V0332+53: Chandra Observation*

V0332+53 was observed by *Chandra* on 2001 January 4 with the ACIS-S instrument for 5 ks. Despite the short exposure time, the superb angular resolution of the *Chandra* telescope afforded a much fainter limiting flux. Our Brera Multiscale Wavelet detection algorithm tailored for *Chandra* (Moretti et al. 2002) was used to detect the source. V0332+53 was detected at the very low level of 4.4×10^{-3} counts s^{-1} (22 counts). Assuming a power-law spectrum with $\Gamma = 2$ and a column density of 10^{22} cm $^{-2}$, this rate converts to a 0.5–10 keV unabsorbed flux of $\sim 9 \times 10^{-14}$ ergs s^{-1} cm^{-2}. The corresponding luminosity was $\sim 5 \times 10^{32}$ ergs s^{-1}. A harder power law with $\Gamma = 1$ resulted in a factor of 3 larger luminosity. This is the faintest luminosity yet observed from an HXRT in quiescence. Its value is comparable to the level observed in low-mass transients containing an old, weakly magnetic, fast-spinning neutron star (e.g., Campana et al. 1998). The softness ratio (0.5–2 keV)/(2–6 keV) was 2.6 ± 1.4. Assuming the same column density as in outburst, we constrain the power-law photon index within the 2–3.5 range (68%).

3. DISCUSSION

We observed a sample of fast-spinning neutron stars in HXRTs during quiescence with *BeppoSAX* and *Chandra*. The quiescent luminosities observed in the fast HXRTs of our sample are very low (especially in the case of V0332+53; see Table 2), and one can ask if the inflowing matter can reach the neutron star surface. If accretion onto the neutron star surface takes place in quiescence, then the mass inflow rate has to decrease by a large factor (up to 10^6 in the case of V0332+53) from outburst to quiescence, posing severe limitations to the Be wind and disk characteristics. A different way out is represented by the limited efficiency of the accretion process, because matter is halted at the neutron star magnetosphere (r_m) when the magnetic field lines rotate locally at super-Keplerian speed. This process is often referred to as the centrifugal barrier or propeller mechanism (Illarionov & Sunyaev 1975; Stella et al. 1986). These systems have well-known spin periods and magnetic field strengths, thus allowing us to estimate the luminosity at which the centrifugal barrier starts operating. Using simple spherical accretion theory (which also provides a good approximation in the case of disk accretion, e.g., Wang 1995, 1996), one can work out the limiting mass inflow rate $\dot{M}_{\rm lim}$ and in turn the limiting accretion luminosity for the onset of the propeller:

$$L_{\rm lim}(R) = \frac{GM\dot{M}_{\rm lim}}{R} \simeq 3.9 \times 10^{37} \xi^{7/2} B_{12}^2 P_0^{-7/3} M_{1.4}^{-2/3} R_6^5 \ {\rm ergs\ s^{-1}} \quad (1)$$

(where the neutron star magnetic field, spin period, mass, and radius are scaled as $B = B_{12} 10^{12}$ G,[6] $P = P_0$ s, $M = M_{1.4} 1.4\ M_\odot$, and $R = R_6 10^6$ cm, respectively; e.g., Stella et al. 1986). The quantity $\dot{M}$ indicates the mass accretion rate, and G is the gravitational constant. The factor ξ accounts for the deviations of r_m as computed in spherical symmetry from the case of an accretion disk. In general, ξ is in the range 0.5–1.5 (here we use $\xi = 1$). Values in the range of $\sim 10^{34}$–10^{37} ergs s^{-1} are derived for the onset of the centrifugal inhibition in the fast HXRTs of our sample (see below and Table 2).

For lower mass inflow rates than those in equation (1), the great majority of accreting matter can no longer reach the neutron star surface, and a sharp drop-off of the accre-

[6] The magnetic field is obtained from the magnetic dipole moment $\mu = BR^3/2$.

tion luminosity is expected. The corresponding luminosity jump mainly depends on the spin period of the neutron star,

$$\Delta = \left(\frac{GMP^2}{4\pi^2 R^3}\right)^{1/3} = 170 M_{1.4}^{1/3} R_6^{-1} P_0^{2/3} \qquad (2)$$

(e.g., Corbet 1996; Campana & Stella 2000) and is a factor of 30–500 for the HXRTs in our sample (see Table 2). Therefore, the maximum accretion luminosity that can be emitted in the propeller regime is

$$L_{\rm min}(r_{\rm cor}) = \frac{L_{\rm min}(R)}{\Delta} = \frac{GM\dot{M}_{\rm lim}}{r_{\rm cor}} = 2.4 \times 10^{35} \xi^{7/2} B_{12}^2 P_0^{-3} M_{1.4}^{-1} R_6^6 \ {\rm ergs\ s^{-1}} \ . \qquad (3)$$

Clearly, these luminosities are all bolometric. While in the case of accretion onto the neutron star surface most of the emission goes into X-rays, in the propeller regime this is not clear, and these numbers should be referred to as upper limits. Moreover, the physics of the propeller regime are poorly understood, and a fraction of matter may still leak through the barrier.

As can be noted from Table 2, the observed X-ray luminosities are all below the threshold for the onset of the centrifugal barrier and below the maximum expected luminosity in the propeller regime (this is true even for $\xi = 0.5$). This testifies that the HXRTs in our sample are all likely detected in the propeller regime, and the observed luminosity derives from the mass inflow releasing its gravitational energy down to the magnetospheric radius.

The luminosity level pertaining to quiescence in the propeller regime clearly depends on the unknown quiescent mass inflow. An additional and independent luminosity can derive from the cooling of the neutron star made hot during the events of intense accretion: the inner crust compressed by the loaded material becomes the site of pycnonuclear reactions that may deposit enough heat into the core (Brown et al. 1998; Colpi et al. 2001; see also Campana et al. 1998). In the last few years, V0332+53 and A0538−66 did not show any outburst activity, and therefore it is difficult to estimate a mean accretion rate. This is instead possible for 4U 0115+63, which showed two strong outbursts and a number of small outbursts during the *Rossi X-Ray Timing Explorer* lifetime. Based on the observed outbursts, one can derive a time-averaged rate of $\sim 4 \times 10^{15}$ g s^{-1}, resulting in a deep crustal heating luminosity of 4×10^{33} ergs s^{-1}. This value has to be compared with the inferred blackbody luminosity of $\sim 10^{33}$ ergs s^{-1}, which is a factor of ~ 4 lower; this luminosity, however, could be hidden in the lower energy part of the spectrum. Similar luminosity levels (if not lower) apply to V0332+53 and A0538−66. A quiescent luminosity for A0538−66 of $\sim 5 \times 10^{35}$ ergs s^{-1} cannot be supported by this emission mechanism alone.

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