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THE TRANSIENT X-RAY PULSAR 4U 0115+63 FROM QUIESCENCE TO OUTBURST THROUGH THE CENTRIFUGAL TRANSITION

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ABSTRACT

We report on a *BeppoSAX* observation of the transient X-ray pulsar 4U 0115+63, close to periastron. This led to the discovery of a dramatic luminosity variation from $\sim 2 \times 10^{34}$ to $\sim 5 \times 10^{36}$ ergs s^{-1} (a factor of $\gtrsim 250$) in less than 15 hr. The variation was accompanied by only minor (if any) changes in the emitted spectrum and pulse fraction. On the contrary, an observation near apastron detected the source in a nearly constant state at a level of $\sim 2 \times 10^{33}$ ergs s^{-1}. Direct accretion onto the neutron star surface encounters major difficulties in explaining the source variability properties. When the different regimes expected for a rotating magnetic neutron star subject to a variable inflow of matter from its companion are taken into consideration, the results of the *BeppoSAX* observations of 4U 0115+63 can be explained naturally. In particular, close to apastron, the regime of centrifugal inhibition of accretion applies, whereas the dramatic source flux variability observed close to periastron is readily interpreted as the transition regime between direct neutron star accretion and the propeller regime. In this centrifugal transition regime, small variations of the mass inflow rate give rise to very large luminosity variations. We present a simple model for this transition, which we successfully apply to the X-ray flux and pulse fraction variations measured by *BeppoSAX*.

Subject headings: stars: individual (4U 0115+63) — stars: neutron — X-rays: individual (4U 0115+63) — X-rays: stars

1. INTRODUCTION

Accreting collapsed stars in transient X-ray binaries are subject to very large variations of mass inflow rate and provide a laboratory for testing the physics of accretion over a range of different regimes that are inaccessible to persistent sources (see e.g., Parmar, White, & Stella 1989; Campana et al. 1998). The highly magnetic ($B \sim 10^{12}$ G) spinning neutron stars that are hosted in hard X-ray transients (HXRTs) have long been suspected to be in the so-called propeller regime when quiescent. In this regime, accretion onto the neutron star surface is inhibited by the centrifugal action of the rotating magnetosphere (Illarionov & Sunyaev 1975). On the other hand, there is little doubt that accretion onto the neutron star surface takes place in these systems while in outburst, since they display properties very similar to those of persistent X-ray pulsars.

Relatively little is known of the low-luminosity states of HXRTs. Observations of their quiescent state are still sparse (Campana 1996; Negueruela et al. 2000), and there are only hints that the transition from the lowest outburst luminosities to quiescence occurs in a sudden fashion (see, e.g., the case of V0332+53; Stella, White, & Rosner 1986). According to models of accretion onto rotating magnetic neutron stars (e.g., Illarionov & Sunyaev 1975), the transition from the accretion to the propeller regime (or vice versa) should take place over a very limited range of mass inflow rates and give rise to luminosity variation of the order of ~ 1000 for a neutron star spinning at a period of a few seconds. The observation of a paroxysmal luminosity variation when an HXRT emerges out of quiescence or fades away at the end of an outburst therefore holds great potential as a diagnostic of the different regimes experienced by a rotating magnetic neutron star.

In this paper we report on *BeppoSAX* observations of the transient X-ray pulsar 4U 0115+63 that reveal the quiescent state of the source and, more crucially, provide the first convincing evidence for the centrifugal transition regime of any X-ray transient.

2. 4U 0115+63

Like most HXRTs, 4U 0115+63 hosts a magnetic neutron star orbiting a Be star in a moderately eccentric orbit ($e \simeq 0.3$). The spin and orbital periods are $P_0 = 3.62$ s and $P_{\rm orb} \simeq 24.3$ days (Cominsky et al. 1978; Rappaport et al. 1978). The system has been extensively studied during its frequent outbursts (~ 20 have been detected so far), which occasionally reach a peak luminosity of $\sim 10^{38}$ ergs s^{-1} and usually last about a month (Bildsten et al. 1997; Campana 1996). The neutron star magnetic field is measured with good accuracy, $B_0 = 1.3 \times 10^{12}[(1+z)/1.2]$ G, through the cyclotron features detected in its X-ray spectrum (Santangelo et al. 1999, and references therein). Here, $(1+z) = 1 + GM/(c^2R) \simeq 1.2$ (we scale the neutron star mass and radius as $M = 1.4 M_{1.4}\ M_\odot$ and $R = 10 R_6$ km, respectively) is the gravitational redshift at the neutron star surface. The source distance was determined to be $(8 \pm 1) d_8$ kpc, such that the X-ray flux to luminosity conversion is correspondingly accurate (Negueruela & Okazaki 2001).

Before the present study, 4U 0115+63 was not detected in its quiescent state to a limit of $\sim 6 \times 10^{33}$ ergs s^{-1} (0.4–6 keV; Campana 1996). At the end of the 1990 outburst, a quick decrease of the luminosity was observed to below a

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level of $\sim 5 \times 10^{36}$ ergs s^{-1}, possibly indicating the transition to the onset of the centrifugal barrier (Tamura et al. 1992).

3. *BeppoSAX* OBSERVATIONS

A 35 ks observation of 4U 0115+63 was carried out with the Italian/Dutch satellite *BeppoSAX* (Boella et al. 1997) on 1999 August 3 06:37:04–August 4 01:41:32 UT, covering an orbital phase range (0.94–0.97) close to periastron. The source count rate varied by a very large amount (from $\gtrsim$ 0.02 to ~ 5 counts s^{-1}), showing a steep increase by a factor of $\gtrsim 250$ in ~ 15 hr (see Fig. 1; note that the y-axis is logarithmic). Superposed to this trend, variations of up to a factor of ~ 20 in less than 1 hr were clearly present.

Inspection of the *Rossi X-Ray Timing Explorer* (*RXTE*) all-sky monitor (ASM) light curve of 4U 0115+63 shows that the dramatic flux increase revealed by the *BeppoSAX* observation was not followed by a source outburst over the following days; the source remained instead below a daily average of $\sim 2 \times 10^{36}$ ergs s^{-1}.

In consideration of the extreme variability, we divided the entire observation into different time intervals (for spectral analysis), as well as intensity intervals (for temporal analysis),[6] in order to characterize the source properties at different luminosity levels. Energy spectra from the *BeppoSAX* Low-Energy Concentrator Spectrometer (LECS; 0.1–4 keV), Medium-Energy Concentrator Spectrometer (MECS; 1.8–10 keV), and Phoswich Detection System (PDS) (15–200 keV) were accumulated in each of these intervals. In all cases, the source spectrum from the three instruments was well fitted by a model consisting of an absorbed power law with a high-energy cutoff plus absorption, with photon index $\Gamma \sim 1.0$, cutoff energy $E_{\rm cut} \sim 12$ keV, and *e*-folding energy $E_{\rm fold} \sim 8$ keV. The column density amounts to $N_{\rm H} \sim 1.7 \times 10^{22}$ cm^{-2}, and it is consistent with the Galactic value. This model also nicely fits the spectrum of the entire observation and is compatible with the source spectrum measured during outburst (see, e.g., Nagase 1989). The best-fit parameters are reported in Table 1 for each interval (see also Gastaldello et al., in preparation). We note that all spectral parameters are nearly constant throughout the observation (see Table 1). Variations are observed only in the column density (4% probability of getting a higher χ^2 by chance from a constant distribution) and in the power-law index (probability of 1%). The main contribution to the variations of the power-law index comes from the first interval. If we exclude this value, we obtain a probability of 10%. Marginal evidence was found for the second cyclotron harmonic at a centroid

[6] Pulsations were also detected at the lowest intensity interval, even though the source spectrum could not be meaningfully characterized; this is why time intervals were used instead in the spectral analysis.

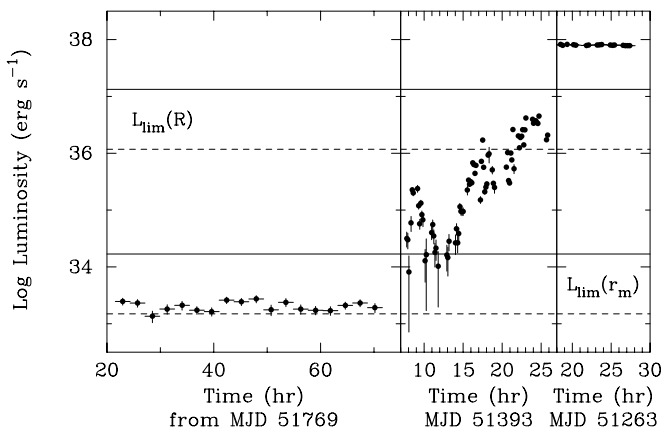

FIG. 1.—Light curve of the *BeppoSAX* MECS observations of 4U 0115+63, taken in quiescence (*left*), during the transition (*middle*), and in outburst (*right*). Background-subtracted light curves were converted into luminosities using the conversion factor derived from spectral fits (see text). Time bins are 10,000, 500, and 5000 s for the three observations, respectively. The time axis values (in hr) correspond to the start of the three observations discussed in the text (MJD 51769, 51393, and 51263, respectively). Solid lines represent the luminosity corresponding to the onset of the centrifugal barrier [$L_{\rm lim}(R)$], and the luminosity at which it closes completely [$L_{\rm lim}(r_m)$] for $\xi = 1$. Dashed lines give the same luminosities for $\xi = 0.5$.

TABLE 1

EXPONENTIAL CUTOFF POWER-LAW FITS TO SPECTRA FROM DIFFERENT INTERVALS FROM THE 1999 AUGUST 3–4 OBSERVATION.

Interval	Time (hr)	N_H (10^{22} cm^{-2})	Power Law Γ	$E_{\rm cutoff}$ (keV)	$E_{\rm fold}$ (keV)	0.1–200 keV Flux[a] (ergs s^{-1} cm^{-2})	$\chi^2_{\rm red}$ (dof)
1[b]	7.5–14.9	$2.30^{+1.08}_{-0.97}$	$1.58^{+0.40}_{-0.40}$	12.0 (fixed)	8.2 (fixed)	1.1×10^{-11}	1.52 (24)
2	15.4–17.2	$1.83^{+0.72}_{-0.57}$	$0.82^{+0.18}_{-0.16}$	$14.3^{+2.5}_{-4.8}$	$6.3^{+5.2}_{-2.2}$	1.5×10^{-10}	1.13 (28)
3	17.5–19.4	$1.80^{+0.80}_{-0.64}$	$1.00^{+0.23}_{-0.20}$	$11.7^{+12.0}_{-3.9}$	$13.2^{+10.5}_{-8.3}$	1.5×10^{-10}	1.07 (33)
4	20.5–21.5	$1.72^{+0.40}_{-0.37}$	$0.90^{+0.13}_{-0.13}$	$9.7^{+3.7}_{-1.6}$	$8.5^{+2.3}_{-3.3}$	2.8×10^{-10}	1.04 (43)
5	22.0–22.5	$1.41^{+0.35}_{-0.30}$	$0.89^{+0.12}_{-0.11}$	$10.3^{+4.0}_{-2.0}$	$8.0^{+2.8}_{-3.6}$	5.0×10^{-10}	0.97 (40)
6[c]	22.5–22.7	1.74 (fixed)	$1.10^{+0.13}_{-0.13}$	$12.5^{+4.9}_{-6.3}$	$6.0^{+6.6}_{-2.9}$	5.7×10^{-10}	0.78 (41)
7[c]	22.7–23.3	1.74 (fixed)	$0.95^{+0.13}_{-0.13}$	$13.2^{+4.4}_{-2.2}$	$5.5^{+3.7}_{-2.1}$	7.3×10^{-10}	1.48 (36)
8	23.3–23.9	$1.83^{+0.46}_{-0.36}$	$0.94^{+0.17}_{-0.14}$	$9.4^{+4.2}_{-1.8}$	$11.2^{+5.1}_{-4.4}$	1.1×10^{-9}	1.02 (33)
9	23.9–24.2	$1.48^{+0.45}_{-0.39}$	$0.85^{+0.15}_{-0.15}$	$11.7^{+2.7}_{-4.2}$	$7.8^{+2.4}_{-1.8}$	8.9×10^{-10}	0.98 (44)
10[c]	24.2–24.4	1.74 (fixed)	$0.93^{+0.11}_{-0.11}$	$9.1^{+3.4}_{-2.3}$	$9.7^{+2.4}_{-2.8}$	9.0×10^{-10}	0.88 (44)
11	24.5–25.7	$3.45^{+1.00}_{-0.84}$	$1.30^{+0.21}_{-0.21}$	$15.0^{+4.0}_{-7.0}$	$9.4^{+4.2}_{-3.1}$	7.3×10^{-10}	1.13 (36)
Mean value		1.74 ± 0.18	0.95 ± 0.05	12.0 ± 1.3	8.2 ± 1.1		
$\chi^2_{\rm red}$(cons)		1.7	2.1	0.8	0.6		

NOTE.—Time is measured in hours from the start of MJD 51393.

[a] Fluxes are unabsorbed. Errors are at 90% confidence level for one parameter of interest (i.e., $\Delta\chi^2 = 2.71$).

[b] Because of poor statistics, we fixed the cutoff and folding energies to the mean value of the entire observation. In the case of a simple power-law fit, a column density of $(2.2^{+1.1}_{-0.9}) \times 10^{22}$ cm^{-2} and a photon index of $\Gamma = 1.54^{+0.42}_{-0.33}$ ($\chi^2_{\rm red} = 1.44$) were obtained.

[c] Only MECS and PDS data available. The column density has been fixed to the mean value, since without the LECS data it is difficult to constrain its value.

energy of 22.5 ± 2.5 keV in the spectrum from the entire observation (95% significance; Santangelo et al. 1999 measured 24.16 ± 0.07 keV during outburst). Note that the first harmonic falls just in the gap between the MECS and the PDS spectra.

In this paper we estimate the source bolometric luminosities by using the 0.1–200 keV unabsorbed luminosities as derived from the best-fit parameters of the spectrum from the entire observation and the MECS count rates in the 1.8–10 keV band. The corresponding conversion factor is 1 count $s^{-1} = 8.5 \times 10^{35}$ ergs s^{-1}. The luminosity inferred in this way varies between 2×10^{34} and $(5 \times 10^{36}) d_8^2$ ergs s^{-1} (see Fig. 2).

Pulsations at the ~3.62 s neutron star spin period are detected in all intensity intervals. The pulsed fraction (semiamplitude of modulation divided by the mean source count rate) in the 1.8–10 keV energy band is determined for each interval after folding the data at the best period. Values range between ~29% and ~54%, with the lowest value corresponding to the lowest intensity interval (see Fig. 2).

A further 86 ks *BeppoSAX* observation was carried out on 2000 August 13 21:33:06–August 16 00:22:36 UT around apastron (orbital phase of 0.42–0.51). The source was very weak and remained at a virtually constant level of $\sim 2 \times 10^{-3}$ counts s^{-1} in the MECS; it was not detected in the LECS (less than 2×10^{-3} counts s^{-1}). The spectrum was softer than in the 1999 August observation. Fitting a power-law model to the MECS data and fixing the column density to the best-fit value of the periastron observation yielded a photon index of $\Gamma = 2.6^{+1.0}_{-0.8}$ (at 68% confidence level [c.l.], $\chi^2_{\rm red} = 0.2$ for two degrees of freedom [dof]). The uncertainties in the spectral parameters also translate into a fairly large uncertainty in the inferred 0.1–200 keV unabsorbed luminosity, which is (0.6–3) $\times 10^{33}$ ergs s^{-1}. A pure blackbody model also gives a reasonable fit for a temperature of $kT = 0.7^{+0.3}_{-0.2}$ keV (68% c.l., $\chi^2_{\rm red} = 0.5$).

The ~3.62 s pulsations were not detected; a 3 σ upper limit of ~30% on the pulsed fraction was derived (see also Campana et al., in preparation).

In order to facilitate the comparison with the source properties while in outburst, we also analyzed the data from the 48 ks *BeppoSAX* observation that took place on 1999 March 26, during the outburst decay. This observation covered an orbital phase interval of 0.61–0.65. The source light curve is also shown in Figure 1 for comparison; the average 0.1–200 keV luminosity was $\sim 8 \times 10^{37}$ ergs s^{-1}. The source spectrum could be described by a power law with a high-energy cutoff, with $\Gamma \sim 0.8 \pm 0.1$, $E_{\rm cut} \sim 9.4 \pm 0.5$ keV, $E_{\rm fold} \sim 16 \pm 2$ keV, and $N_{\rm H} \sim (1.5 \pm 0.1) \times 10^{22}$ cm^{-2}. To obtain an acceptable fit, an iron line and a cyclotron line feature also had to be included.

4. EVIDENCE FOR THE TRANSITION FROM THE PROPELLER TO THE ACCRETION REGIME

The factor of $\gtrsim 250$ luminosity variation of 4U 0115+63 during the 1999 August (close to periastron) observation, when the source luminosity ranged between 2×10^{34} and 5×10^{36} ergs s^{-1} in ~15 hr, was the most extreme ever seen in an HXRT. Previously, the steepest flux increases detected from this source (and other HXRTs) were those associated with the rise to an outburst peak, involving variations of up to a factor of ~3–4 on a comparable timescale. On the contrary, during the 2000 August observation (close to apastron), the source luminosity was low and nearly constant, around a level of 2×10^{33} ergs s^{-1}.

One possibility to explain the extreme variability in the 1999 August observation is that the source was subject to a factor of $\gtrsim 250$ variations in the mass inflow rate, which in turn gave rise to a comparable variation in the accretion luminosity (under the hypothesis that accretion onto the neutron star surface took place unimpeded also for luminosities as low as $\sim 10^{34}$ ergs s^{-1}). This possibility faces serious problems. First, models of Be star disks/winds predict a neutron star mass-capture rate variation of a factor of ~5 at the most for a binary system such as 4U 0115+63 over an orbital phase interval of 0.94–0.97 (Raguzova & Lipunov 1998).

Moreover, within the direct-accretion scenario (required by the interpretation above), the question of why extreme

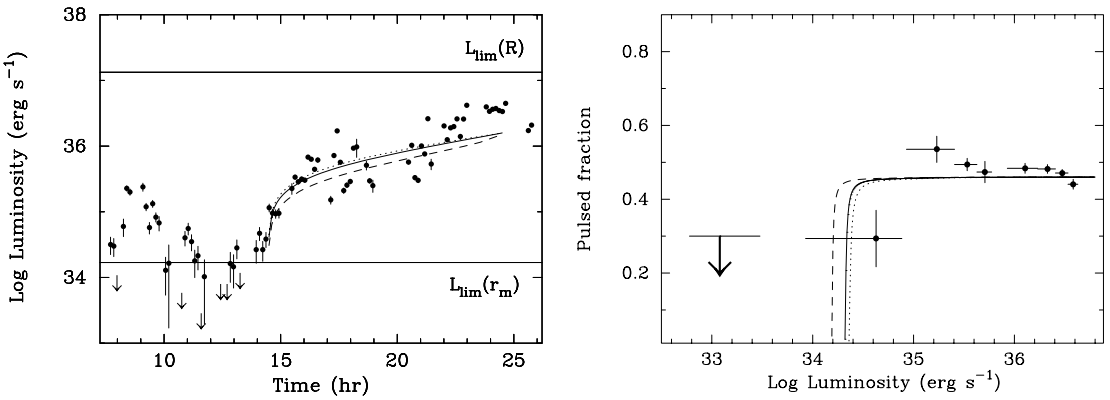

FIG. 2.—*Left panel*: Light curve of the 0.1–200 keV unabsorbed luminosity of 4U 0115+63 vs. time during the 1999 August 3–4 *BeppoSAX* observation. Arrows indicate 500 s intervals for which only upper limits (3 σ) can be set. The solid lines are the same as in Fig. 1. The other curves show different applications of the stellar-wind and centrifugal-transition model presented in § 4. The dashed, solid, and dotted lines refer to angles $\chi = 28°$, 35°, and 80°, respectively. These are the minimum angles compatible with the assumed mass inflow rate variation (28°), the maximum value (we take 80°, since 90° provides the same result but more computational problems), and an angle providing a curve in between (35°). In the fit, $\xi = 1$ and the Be star equatorial-disk model described in § 4 have been assumed. *Right panel*: Pulsed fraction vs. 0.1–200 keV unabsorbed luminosity during the *BeppoSAX* observations. Pulsed fractions were obtained by fitting the folded light curve with a sinusoidal signal. Error bars are a 1 σ. The curves represent the pulsed fraction k from the model presented in § 4. No free parameter is involved except for the normalization $k_{\rm mag}$ (=0.5). The dashed, solid, and dotted lines refer to angles $\chi = 28°$, 35°, and 80°, respectively. The upper limit (90%) refers to the *BeppoSAX* observation of 2000 August 13–16.

variability manifests itself over a range of intermediate luminosities (between 2×10^{34} and 5×10^{36} ergs s^{-1}), while the source variability is much less pronounced for both higher and lower luminosities, remains unaddressed.

The behavior of 4U 0115+63 has a much more natural explanation in terms of the different regimes that are expected for a rotating magnetic neutron star subject to a variable mass capture rate. The inflow of matter toward an accreting magnetic star is dominated by gravitational forces and possibly mediated by an accretion disk down to the magnetospheric boundary at r_m. From this radius, matter can proceed inward to the star surface *only if* the centrifugal force due to magnetospheric drag is weaker than gravity. This translates into the condition that the radius at which a test particle in a Keplerian circular orbit corotates with the central object [the so-called corotation radius, $r_{\rm cor} = (GMP^2/4\pi^2)^{1/3}$, where P is the neutron star spin period and G the gravitational constant] is larger than r_m (Illarionov & Sunyaev 1975). In this direct-accretion regime, the matter-to-radiation conversion efficiency is high, $L(R) = GM\dot{M}/R$, and gives rise to luminous X-ray sources (here $\dot{M}$ is the mass inflow rate). If $r_m > r_{\rm cor}$, the drag by the rotating magnetosphere is super-Keplerian, such that the centrifugal force exceeds gravity and accretion is inhibited. However, as the inflowing matter reaches r_m, an accretion luminosity of $L(r_m) \simeq GM\dot{M}/(2r_m)$ must be released (the factor of $\frac{1}{2}$ comes from the assumption that the flow down to r_m is mediated by a disk). The $L(r_m)$ is expected to scale approximately as $\sim \dot{M}^{9/7}$. Therefore, above and below the transition to the propeller regime, a smooth, close-to-linear relationship between the accretion luminosity and $\dot{M}$ is expected.

An important prediction is that the accretion luminosity across the transition from direct accretion to the propeller regime (corresponding to $r_m \simeq r_{\rm cor}$) or vice versa should be characterized by a sudden luminosity jump:

$$\frac{L_{\rm lim}(R)}{L_{\rm lim}(r_m)} \simeq \frac{2r_{\rm cor}}{R} \simeq 2\left(\frac{GMP^2}{4\pi^2R^3}\right)^{1/3} . \quad (1)$$

This is a factor of ~ 800 in the case of 4U 0115+63 (Corbet 1996; Campana & Stella 2000). In practice, the transition separating the two regimes is expected to take place over a finite, although small, range of mass inflow rates around $\dot{M}_{\rm lim}$, such that a very steep dependence of the accretion luminosity on $\dot{M}$ ensues temporarily.

Since the magnetospheric radius changes in response to variations of the mass inflow rate, the absolute luminosity at which the centrifugal barrier is expected to close can be determined based on models of the interaction between the inflowing matter and the rotating magnetosphere. In a simple spherical accretion approximation, r_m is expected to scale as $\dot{M}^{-2/7}$ (Davidson & Ostriker 1973). A similar dependence is obtained in the detailed models of the disk/magnetosphere that were developed by, e.g., Ghosh & Lamb (1979) and Wang (1996) in the regime in which the disk is dominated by gas pressure (the one relevant to the case of 4U 0115+63). In order to account for the predictions of different models, we adopt the scaling above and introduce a correction factor ξ, the ratio of the magnetospheric radius determined on the basis of a given model to that of simple spherical accretion. We obtain

$$L_{\rm lim}(R) \simeq (1 \times 10^{37})\xi^{7/2}B_0^2\,P_0^{-7/3}\,M_{1.4}^{-2/3}\,R_6^5 \text{ ergs s}^{-1} , \quad (2)$$

where $\xi = 1$ for spherical accretion (by definition), $\xi = 0.5$ in the model by Ghosh & Lamb (1979), and $\xi \sim 1$ in the model by Wang (1996). We take this range as representative of the accuracy with which r_m can be predicted by current models ($M_{1.4}$ and R_6 are the neutron star mass and radius in units of 1.4 $M_\odot$ and 10^6 cm, respectively; see, e.g., Campana et al. 1998). Since the source distance (and therefore luminosity) and neutron star magnetic field are fairly accurately measured in the case of 4U 0115+63, we obtain $L_{\rm lim}(R) \simeq \xi^{7/2}10^{37}$ ergs s^{-1}; correspondingly $L_{\rm lim}(r_m) \simeq \xi^{7/2}2 \times 10^{34}$ ergs s^{-1}.

The corresponding lines for $\xi = 1$ (*solid line*) and $\xi = 0.5$ (*dashed line*) are shown in Figure 1. It is immediately apparent that the variations of the 1999 August observation fall just in the luminosity range of the transition between the propeller and the direct-accretion regime, where very large luminosity variations are expected in response to modest changes of the mass inflow rate. On the contrary, the quiescent-state luminosity of the 2000 August observation, during which the source flux was approximately constant, lies in the propeller regime, while the luminosity during the outburst observation in 1999 March is well in the range of the direct-accretion regime.

5. A SIMPLE MODEL FOR THE CENTRIFUGAL TRANSITION REGIME

In this section we develop a simple model for the centrifugal transition regime and compare its predictions with the results from the 1999 August observation of 4U 0115+63. In general, we express the source accretion luminosity in the transition regime as the sum of two contributions: (1) the luminosity of the disk extending down to the magnetospheric boundary, $L_{\rm disk}$; we assume that mass flows through the disk at rate $\dot{M}$, which is equal to the rate at which mass is captured at the neutron star accretion radius; and (2) the luminosity released within the magnetosphere $L_{\rm mag}$ by the fraction f of the mass inflow rate that effectively accretes onto the neutron star surface. We have

$$\begin{aligned} L &= L_{\rm disk} + L_{\rm mag} = L(r_m) + f[L(R) - L(r_m)] \\ &= GM\dot{M}[1/2r_m + f(1/R - 1/2r_m)] . \end{aligned} \quad (3)$$

In this approximation, the direct-accretion regime corresponds to $f = 1$, and the propeller regime to $f = 0$.

In the case of 4U 0115+63, where $2r_{\rm cor} \sim 800R$, $fL(R) > (1-f)L(r_m)$ for $f \gtrsim 10^{-3}$, i.e., the luminosity produced by matter accreting onto the neutron star surface is dominant over most of the centrifugal transition. This has two important implications. First, being dominated by the release of energy within the magnetosphere, the emitted X-ray spectrum should be similar to that observed in the direct-accretion regime (i.e., source outbursts) for luminosities $\leq 10^{37}$ ergs s^{-1} and remain nearly unchanged across most of the centrifugal transition. We also note that according to models of accretion columns onto magnetic neutron stars, the spectrum is virtually insensitive to accretion rate variations as long as the optical depth remains less than 1 (Nagel 1981). Only for luminosities of $\lesssim 10^{34}$ ergs s^{-1} (corresponding to $f \lesssim 10^{-3}$), when $L_{\rm disk}$ becomes non-negligible, are substantial spectral changes to be expected. The apparent (relative) stability of the *BeppoSAX* spectra during the 1999 August observation are consistent with this expectation. Second, since the transition regime involves only a relatively small variation of r_m, the geometry of accretion close to the polar caps should show only minor changes (Wang & Welter 1981; Parmar et al. 1989). There-

fore, the pulse fraction is expected to remain essentially unaltered as long as $L_{\rm mag}$ dominates. On the other hand, $L_{\rm disk}$ is expected to be unpulsed, and the source pulsed fraction should decrease close to the bottom of the transition regime. This is also consistent with the results from the 1999 August observation of 4U 0115+63 (see Table 1 and Fig. 2).

We explore a simple model to determine f and the source behavior across the centrifugal transition: we consider a magnetic dipole field, the axis of which is tilted relative to the neutron star rotation axis by an angle χ. We determine the azimuthal (ϕ) dependence of the magnetospheric boundary in the disk plane by equating the ram pressure of radially free-falling matter with the local magnetic pressure. The magnetospheric boundary takes an elongated shape given by

$$r_m(\dot{M}, \phi) = \xi B^{4/7} R^{12/7} \times (1 + 3\sin^2 \chi \sin^2 \phi)^{2/7} (2GM\dot{M}^2)^{-1/7} \quad (4)$$

(Jetzer, Strässle, & Straumann 1998). The minimum radius $r_m(\dot{M}, 0)$ also corresponds to $\chi = 0$, the approximation usually adopted in models of the disk-magnetosphere interaction. The maximum radius $r_m(\dot{M}, \pi/2)$ is only a factor of $(1 + 3\sin^2 \chi)^{2/7} \leq 1.49$ larger. If $r_{\rm cor} < r_m(\dot{M}, 0)$, the magnetospheric boundary is larger than the corotation radius for any ϕ, and the propeller regime applies (i.e., $f = 0$). If, on the contrary, $r_{\rm cor} > r_m(\dot{M}, \pi/2)$, every point on the boundary is within the corotation radius and the standard accretion regime applies ($f = 1$). In the intermediate regime, $r_m(\dot{M}, 0) < r_{\rm cor} < r_m(\dot{M}, \pi/2)$, only the fraction $f = \Delta\phi/2\pi$ of the magnetospheric boundary for which $r_{\rm cor} > r_m(\dot{M}, \phi)$ leads to accretion onto the neutron star surface, and the transition regime applies. The accretion luminosity versus mass inflow rate curves have been calculated by using this model, with $\xi = 1$. Different curves correspond to different values of the angle χ, with the sharpest transitions occurring for the lowest values of χ, as expected (see Fig. 3).

We also adopt the model above to describe the evolution of the source pulse fraction versus luminosity (see Fig. 2). If $L_{\rm disk}$ is unpulsed, the observed pulsed fraction k can be expressed as $k \simeq k_{\rm mag}\, f/(R/2r_m + f)$, where $k_{\rm mag}$, the pulsed fraction of $L_{\rm mag}$ alone, can effectively be regarded as a free parameter. The term k depends on ξ (which sets the onset luminosity of the transition regime) and χ (which determines the range of the mass inflow rates over which the transition regime applies). Here too, the dependence on χ is such that for low values, the transition is sharp, whereas for large values, the transition occurs over a mass inflow rate variation of ~ 4 (see Fig. 3).

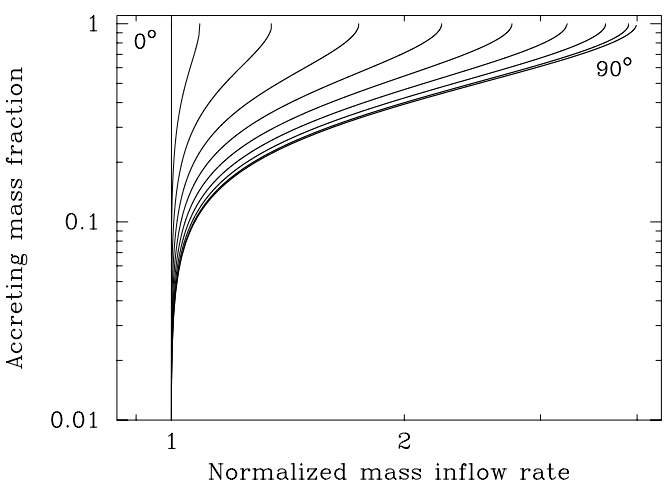

FIG. 3.—Fraction of accreting mass f as a function of the mass inflow rate $\dot{M}$, normalized to the maximum mass inflow rate in the propeller regime, on the basis of the model discussed in § 5. The different curves refer to angles χ between 0° (*left*) and 90° (*right*) in steps of 10°.

Modeling the time evolution of the source luminosity during the 1999 August observation would require knowing the time evolution of $\dot{M}$. We approximate $\dot{M}(t)$ with the mass capture rate of the neutron star in its orbital motion within the equatorial disk of the Be star companion over the phase interval 0.94–0.97. We assume a 10 km s^{-1} nearly Keplerian disk-outflow velocity and a density profile $\propto r^{-3}$ (as in Raguzova & Lipunov 1998). This model predicts an $\dot{M}$ variation of $\lesssim 3$ over the phase interval covered by the 1999 August observation. We remark that this is among the largest mass capture rate variations that wind models predict. The centrifugal-transition model described above, with $\chi = 35°$ and $\xi = 1$, is also used to calculate the line shown in Figure 2; this reproduces reasonably well the overall behavior of the light curve. Accordingly, a luminosity variation of a factor of $\gtrsim 250$ is produced in response to a factor of ~ 2 variation in $\dot{M}$: clearly, the centrifugal transition works like a very efficient amplifier. Moreover, these values of χ and ξ are among those that nicely match the pulsed fraction versus luminosity variation (see Fig. 2). By adopting the same model for the equatorial wind of the Be star over the phase interval of the 2000 August observation (0.42–0.51), the predicted $\dot{M}$ is a factor of ~ 10 smaller (a value for which the neutron star is well in the propeller regime), giving rise to a luminosity in good agreement with the observed value.

6. CONCLUSIONS

The *BeppoSAX* observations of the transient X-ray pulsar 4U 0115+63 revealed for the first time the presence of extreme variations as the source approached periastron. The luminosities encompassed by these variations are within the range predicted by modeling of the centrifugal transition, which separates the propeller from the direct-accretion regime over a small interval of mass inflow rates. On the contrary, during a quiescent state observation, the source was most probably in the propeller regime, since its luminosity was lower still and nearly constant (however, see below).

Before the present work, the evidence for the onset of the centrifugal barrier was based on the sudden steepening of the outburst decay below a luminosity of $\sim 10^{36}$ ergs s^{-1} in V0332+53 (Stella et al. 1986) and 4U 0115+63 (Tamura et al. 1992). In both cases, the source quickly became undetectable in the relevant (collimator) instruments, such that the transition toward the propeller regime could not be seen. It was also proposed that several other sources in their quiescent (or low) state host a neutron star in the propeller regime: among these are the HXRTs A0538−66 (Campana 1997; Corbet et al. 1997) and A0535+26 (Negueruela et al. 2000). The evidence reported here is far more convincing in that dramatic source-flux variations of the kind expected in the centrifugal transition regime were observed for the first time. These variations occur within the luminosity interval predicted by models of disk-magnetospheric interaction for the case of 4U 0115+63, in which the neutron star spin and magnetic field, as well as distance, are fairly accurately measured. The source flux level and absence of sizeable variabil-

ity in the faint state away from periastron is also in agreement with basic expectations for the regime in which the centrifugal barrier is fully closed. Yet, owing to poor statistics, a thermal-like spectrum cannot be ruled out. The analogy with neutron star soft X-ray transients suggests that such a spectral component, if present, might be due to reemission of heat in the inner crust caused by pycnonuclear reactions (Brown, Bildsten, & Rutledge 1998; Campana et al. 1998; Colpi et al. 2001). The inferred blackbody luminosity[7] is $\sim 10^{33}$ ergs s^{-1}, to be compared with an expected deep crustal heating luminosity of $\sim 5 \times 10^{33}$ ergs s^{-1}, under the hypothesis that 4U 0115+63 has accreted at a time-average rate of $\sim 5 \times 10^{15}$ g s^{-1} (as suggested by the *RXTE* ASM light curves)[8] for some $\sim 10^4$ yr. Independent of the origin of the quiescent emission from 4U 0115+63, the data presented in this paper provide substantial new evidence in favor of the centrifugal transition regime.

This research has made use of SAXDAS linearized and cleaned event files (Revision 2.0) produced at the *BeppoSAX* Science Data Center. This work was partially supported by ASI, Co-fin, and CNAA grants.

[7] Note that the spectrum emerging from a hydrogen atmosphere would be different from that of a pure blackbody, yet bolometric corrections are relatively small (factor of 2–3 depending on the spectrum) and are ignored here.

[8] The light curves are available at http://xte.mit.edu/lcextrct/.

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