The X-ray behaviour of Cygnus X-3

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Abstract. Cygnus X-3 is a peculiar X-ray source that despite its discovery already 40 years ago has eluded simple classification. This paper reviews results from recent studies of its X-ray behaviour in terms of its X-ray lightcurve, orbital modulation and spectral evolution. It seems likely that Cygnus X-3 indeed shows state transitions between a disc-dominated and a non disc-dominated state and that it may contain a massive black hole of $\sim 30\ M_{\odot}$.

Keywords: Accretion – accretion discs – black holes – stars: individual: Cyg X-3 – X-ray binaries
PACS: 97.10.Gz; 97.60.Lf; 97.80.Jp

INTRODUCTION TO CYG X-3

Cygnus X-3 is one of the brightest X-ray binaries, discovered already 40 years ago [1], extensively studied, but still poorly understood and usually referred to as a 'peculiar source'. The identification of the donor as a Wolf-Rayet star [2] classifies it as a high-mass X-ray binary (HMXB), despite its typical low mass binary period of 4.8 hours [3]. The system is located at a distance of 9 kpc ([4], assuming 8 kpc for the distance to the galactic centre; [5]), close to the Galactic plane. It shows signs of unusually strong and complex absorption, a consequence of the whole system being enshrouded in the wind of its companion Wolf-Rayet star. The problem in separating wind features from those arising in the photosphere of the companion makes determinations of radial velocity difficult, hence the masses of the components remain uncertain and the nature of the compact object unknown. Published results range from a neutron star of $1.4M_{\odot}$ [6] to a $17M_{\odot}$ black hole [7]. The mass of the companion is equally uncertain. Early claims of a detection of a 12.6 ms pulsar signal in γ-rays [8], which would serve as strong evidence for a neutron star in the system, were never confirmed. Numerous claims of the detection of Cyg X-3 at ultrahigh energies made the source famous in the 1980s. These detections also remain, however, unconfirmed (see review in [9]).

Cyg X-3 may represent a short-lived transitional phase of binary evolution that will be the fate of massive X-ray binaries in general [10, 11]. An understanding of its behaviour may therefore have broad implications for the study of HMXBs. Eventually, the Wolf-Rayet star will explode in a supernova, or possibly even in a gamma-ray burst. If the system is not disrupted in the explosion, a binary pulsar or a double black hole system may then be formed.

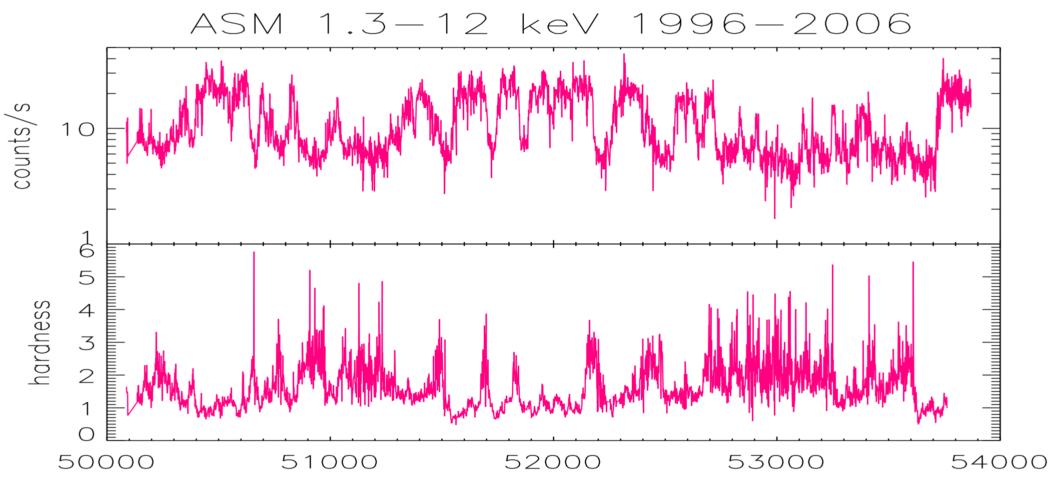

FIGURE 1. *Top panel*: The *RXTE*/ASM 1.3–12 keV daily count rate averages between 1996–2006. A count rate of 75 counts s^{-1} corresponds to 1 Crab. *Lower panel*: The (5–12)/(1.3–5) keV hardness. The X-axis shows date in MJD.

THE X-RAY LIGHTCURVE

Figure 1, top panel, shows the long-term lightcurve of Cyg X-3 as observed by the *RXTE*/ASM in the 1.3–12 keV soft X-ray band. The lightcurve is highly variable and shows periods of high and low flux levels. The lower panel shows the (5–12)/(1.3–5) keV hardness, indicating the slope of the spectrum in the 1.3–12 keV range. The flux and hardness are strongly anticorrelated [12]. The soft X-ray flux is also anticorrelated with the hard X-ray flux above 20 keV (e.g. [13, 14]). Periods of high, soft ASM flux correspond to the observed range of soft states and periods of low flux and high hardness correspond to the apparent hard state.

The distribution of ASM flux levels in Cyg X-3 was studied by Hjalmarsdotter et al. [14] and is shown in Fig. 2. The overall distribution is bimodal with the distribution inside each of the two peaks being well described by a lognormal function.

ORBITAL MODULATION

The X-ray emission of Cyg X-3 shows a stable 4.8 h modulation, generally interpreted as the orbital period of the binary system [3]. Despite its classification as a HMXB, the binary period in Cyg X-3 is thus extremely short, implying a very small orbital separation ($\sim 5R_{\odot}$). The period has been found to increase on a timescale of 850 000 yr [15], with mass loss from a massive companion as the most favoured explanation [16]. The 4.8 hour modulation was first observed in soft X-rays [3] where the pulse shape is quasi-sinusoidal [17] and asymmetric with a slow rise and a faster decline. In hard X-rays [18], the modulation is present with a comparable strength but with a more symmetric pulse shape.

Figure 3 shows the ASM (1.3–12 keV) and BATSE (20–230 keV) lightcurves folded

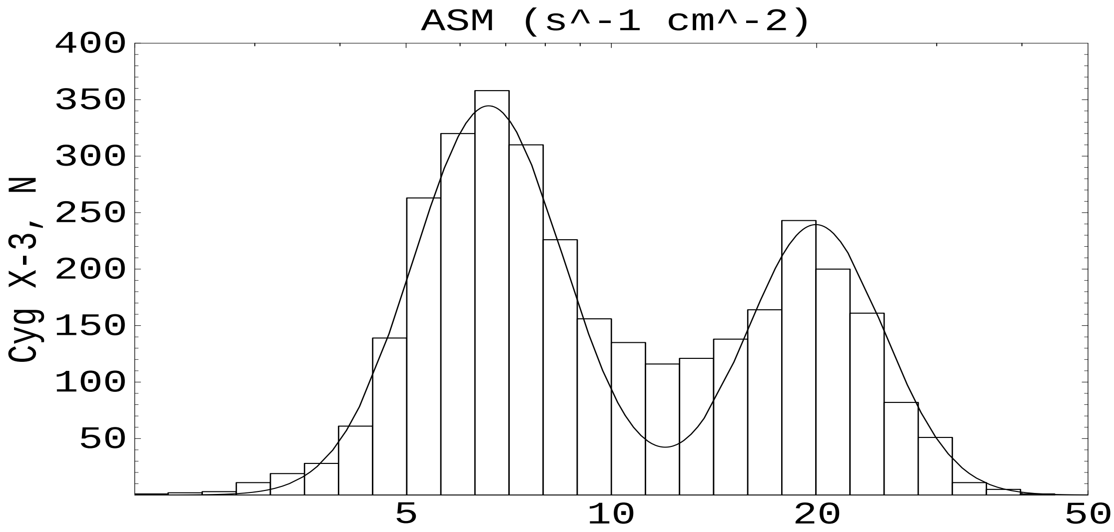

FIGURE 2. The distribution of soft X-ray flux (1.2–12 keV) in Cyg X-3 as measured by *RXTE*/ASM. The distribution is bimodal with each peak well described by a lognormal function.

over the orbital period using the quadratic ephemeris by Singh et al. [16]. The folded lightcurves show an energy dependence of the pulse shape with the rising phase becoming steeper with increasing energy. Similar plots were shown in [19], comparing *INTEGRAL* data of different energies with the folded ASM and BATSE lightcurves, and in [20] and [21] (both ASM and BATSE data $\leq$ 100 keV). The modulation has a strength of $\sim$ 60 per cent in the three ASM bands (1.3–12, 3–5 and 5–12 keV) and of $\sim$ 50 per cent in the 20–50, 50–100 and 100–320 keV bands. The presence of the modulation at energies $>$100 keV points to scattering in an ionized wind as the cause of the modulation rather than absorption. The shallower shape at phases 0.2–0.5 in soft X-rays is most likely an absorption effect [21], with the distribution of the column of less ionized matter as a function of the orbital angle being somewhat asymmetric.

Hjalmarsdotter et al. [14] studied the dependence of the shape and strength of the orbital modulation on X-ray spectral state. As discussed there, if a dense stellar wind serves as the cause of the modulation, any change in its optical depth and/or distribution would be reflected in a change in the depth and/or shape of the modulated light curve, since the wind distribution is centered on the companion Wolf-Rayet star and thus asymmetric to the X-ray source.

STATE TRANSITIONS IN CYG X-3

An important question regarding the spectral variability in Cyg X-3 is whether it actually displays a state transition from a soft disc-dominated state to a hard state with disc truncation in a way similar to e.g. Cyg X-1 [22], or whether the observed spectral variability at energies $<$ 10 keV is caused by variable local absorption in the strong wind of the companion Wolf-Rayet star. The unusually low cut-off energy of the hardest state of the source and the similar spectral shape above 20 keV to that of the most common

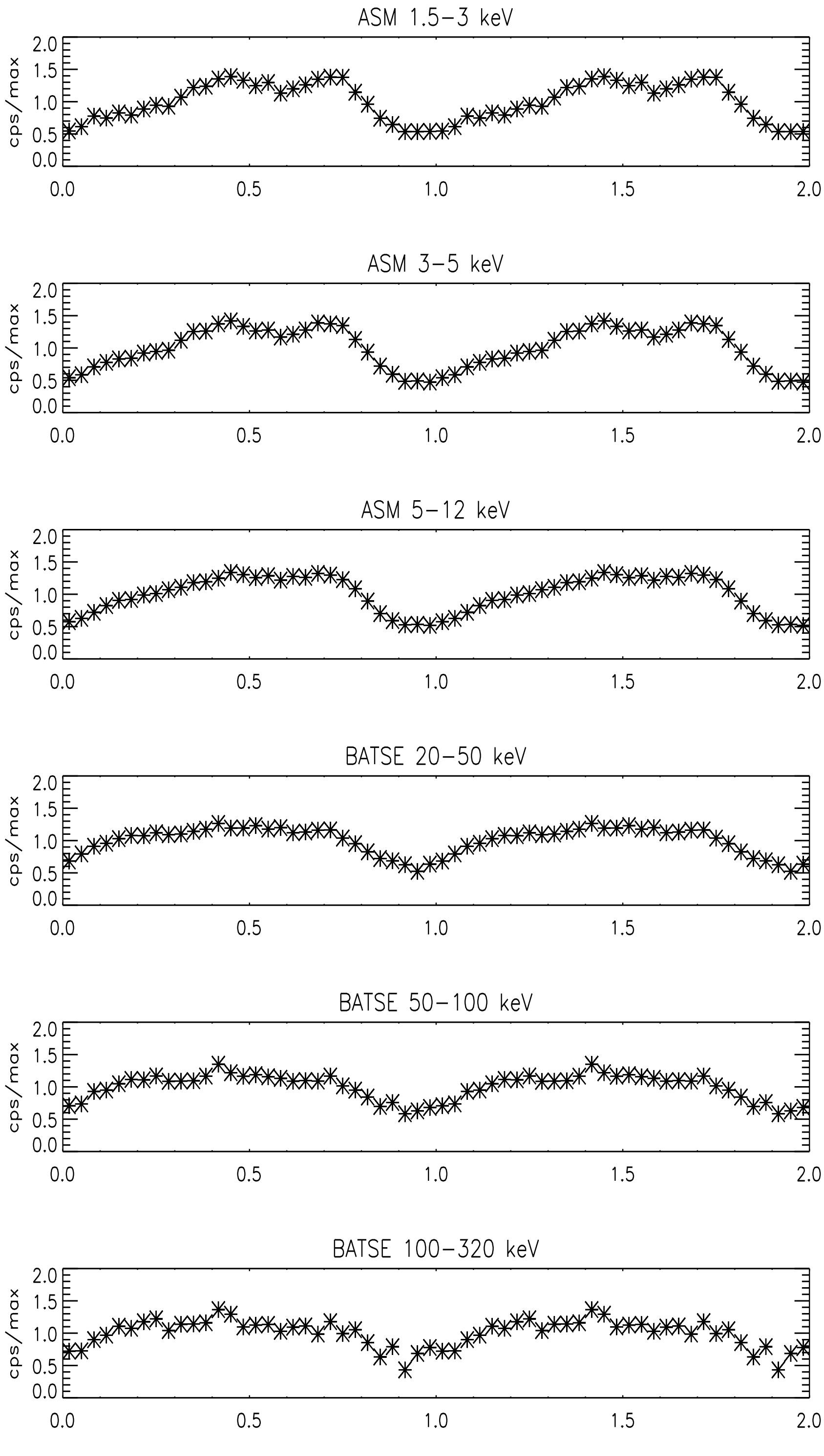

FIGURE 3. The *RXTE*/ASM and *CGRO*/BATSE lightcurves in different energy bands folded on the evolving orbital period.

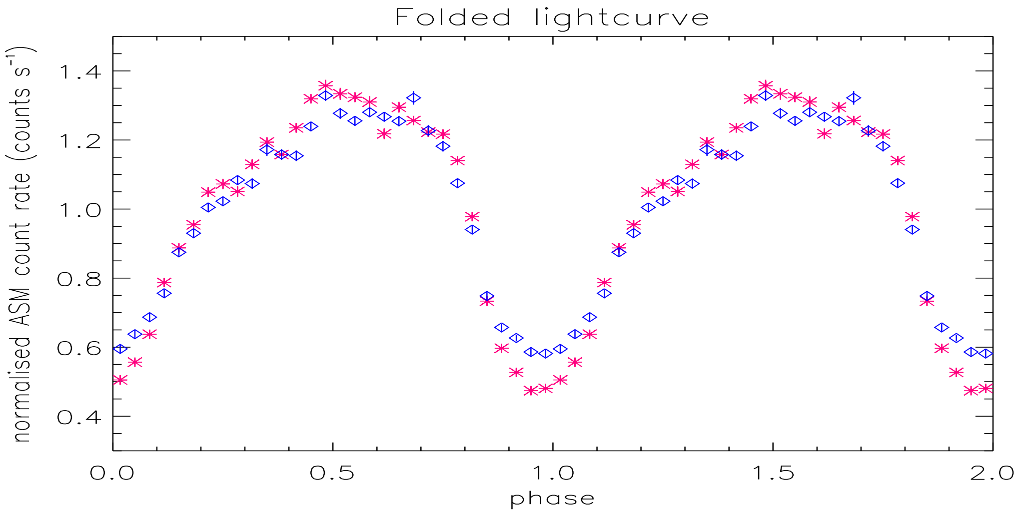

FIGURE 4. The ASM 1.3–12 keV light curve from Fig. 1 folded over the orbital period for the soft state(s) (ASM count rate $> 20s^{-1}$), crosses, and the hard state (ASM count rate $< 10s^{-1}$), diamonds, respectively.

of the soft states seem to suggest the latter. In Hjalmarsdotter et al. [14], this issue was thoroughly investigated and several arguments for a 'real' state transition as opposed to variable absorption were presented.

Firstly, the above-mentioned anti-correlations between soft X-ray flux and hardness and between soft and hard X-ray fluxes show that the spectral variability cannot be due to simple variability of absorption with an underlying intrinsic spectrum of constant shape and strength. If the observed spectral variability were due to absorption effects only, the intrinsic spectrum and the accretion rate would have to be *higher* in the hard state at the same time as the low energy emission is more absorbed. Only such a combined effect could cause the simultaneous increase of hard X-rays and decrease of soft X-rays. While such a scenario is indeed possible, it was pointed out by [14] that the anti-correlations of soft and hard X-ray flux and of soft X-ray flux and hardness are very similar to those found in Cyg X-1 in its hard state [23, 24]. Zdziarski et al. [25] showed that in Cyg X-1 these anti-correlations are a natural result of a pivoting of the spectrum at ~ 50 keV as it responds to changes in the accretion rate. In the same way, an intrinsic spectral pivot somewhere between 12 and 20 keV would explain the observed anti-correlations in Cyg X-3 without any variable absorption.

Secondly, the bimodality in the distribution of soft X-ray flux shows that the appearance and disappearance of the soft X-ray component, associated with the accretion disc, between different spectral states is not gradual which would have been expected if the spectral variability was just an absorption effect. The two well defined intensity states are instead a likely sign of a bimodal behaviour of the accretion flow, with a switch between two different configurations, one where a high amount of soft X-rays from an accretion disc is present, and one where it is not.

Thirdly, if the apparent state transitions are merely an effect of variable absorption, the implied strong variations in the absorbing medium are likely to affect the orbital modulation in the soft X-ray band. Contrary to what would have been expected if the hard state is just a strongly absorbed version of the softer states, the modulation was found to be stronger in the soft states than in the hard state (see Fig. 4). The observed change in the depth of the modulation from 55 per cent in the hard state to 65 per cent in the soft states points to an increase of the effective wind optical depth τ by ~ 0.2 in the soft states. This argues against an interpretation of the hard state in Cyg X-3 being an artefact of increased absorption, at least not by increased stellar wind, which would require the wind to be Compton thick in the hard state.

The perhaps strongest argument for a real state transition in Cyg X-3 is the existence of a similar type of radio/X-ray correlation in its hard state to that seen in other sources. Hjalmarsdotter et al. [14] showed that the turnover of the radio/X-ray correlation from a steady branch of positive correlation into a totally different behaviour with radio flux density levels ranging from quenching to huge flares, depending on hardness rather than X-ray flux level (see further discussion in [26]) corresponds exactly to the ASM flux level for the apparent transition between the hard state and the range of soft X-ray states. This again suggests that the apparent transition marks a real change in the configuration of the accretion flow.

SPECTRAL STATES AND ACCRETION GEOMETRIES

While the range of soft states displayed by Cyg X-3 resembles those seen in many other black hole binary systems, the hard state is much more difficult to interpret. Uncertainties about the effects of absorption make a wide range of models for the hard state possible [14]. Szostek & Zdziarski [27] studied the effect of the stellar wind on the spectra of Cyg X-3 using medium resolution *BeppoSax* data and modelled the wind using the photoionization code `cloudy` [28]. They found that the emission and absorption structure at low energies required a two-phase wind made up by a hot tenous plasma together with cool dense clumps filling ~ 1 per cent of the wind volume. The average wind optical depth along the line of sight in their models was 0.31 in the hard state and 0.43 in the soft - again speaking against an interpretation of the hard state as a strongly absorbed version of a softer intrinsic state.

In Hjalmarsdotter et al. [14] it was noted that the shape of the spectrum in the hard state resembles very much the spectrum resulting from Compton reflection. A Compton reflection model, with most of the direct emission obscured from our view, was shown to give the best fit to the *INTEGRAL* data presented in [14] and to the *BeppoSAX* data in [27]. Both these models assumed very high reflection fractions, which not only predicts a very strong neutral fluorescent iron line, that was not observed, but also a very strong incident i.e. emitted continuum spectrum from the source, the latter not consistent with the assumption of a transition to a lower accretion rate hard state. In Hjalmarsdotter et al. [29], a model of an intrinsic moderately hard state with strong but not dominant reflection was shown to give the best fit to the hard state as observed by *RXTE*. This model has proven to give a good fit to the data used in both [14] and [27], and thus represents the best model for the hard state presented so far. A possible geometry for the reflector in Cyg X-3 is a thickened or perhaps warped disc. Such a geometry has to be symmetrical with respect to the compact object, not to cause any significant spectral

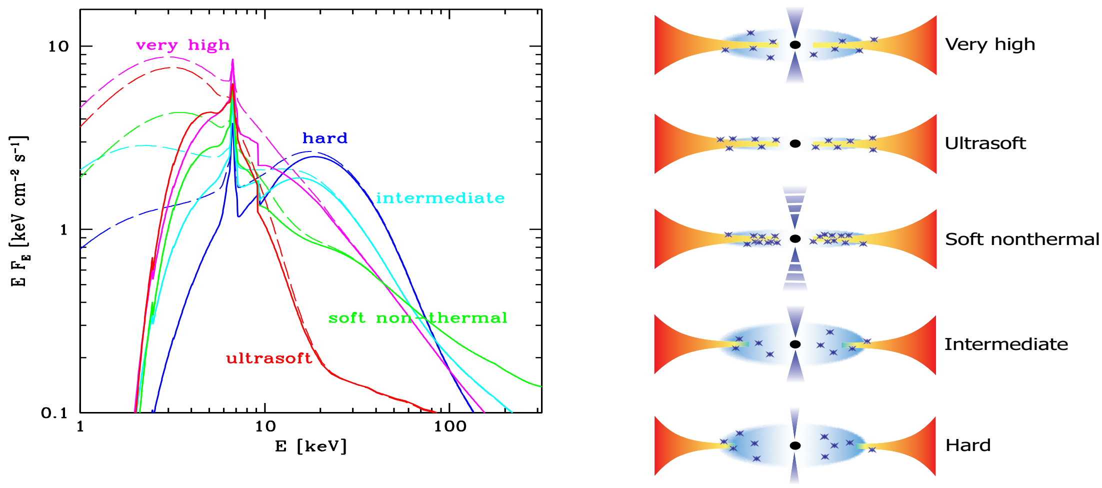

FIGURE 5. Spectral states and accretion geometries of Cygnus X-3. *a:* Spectral energy distribution showing unabsorbed (solid lines) and absorbed (dashed lines). *b:* Proposed accretion geometries for the range of spectral states including radio behaviour. The non-thermal electron contribution is shown as stars.

changes related to the orbital phase, which are not observed. Figure 5 shows the range of spectra in Cyg X-3 as modelled by [29] and envisaged accretion geometries for the different states. The spectra were modelled using the Comptonization code `eqpair` [30].

Figure 6a shows the colour-colour (CC) diagram of Cyg X-3 (data from [29] with the soft colour defined as the ratio of the intrinsic fluxes in the 4–6.4 keV and 3–4 keV bands, and the hard colour as the ratio of the intrinsic fluxes in the 9.7–16 keV and 6.4–9.7 keV bands) overplotted on the data from [31–34] to enable comparison with other classes of X-ray binaries, black holes as well as neutron stars. It is obvious that the track in the CC-diagram traced out by Cyg X-3 does not resemble that of the atoll sources but is more similar to that of the black hole binaries, except that the high value of the soft colour of Cyg X-3 in its soft states keeps it from entering the lower left corner of the diagram, the area occupied *only* by black holes and inaccessible to neutron stars as defined by [31]. Overall, the track of Cyg X-3 in the colour-colour diagram is rather similar to that of GRO J1655–40 ([31], fig. 2), a black hole transient harbouring a $7 M_\odot$ black hole [35] and a strong radio source, just like Cyg X-3.

THE MASS AND NATURE OF THE COMPACT OBJECT

Since the mass of the compact object in Cyg X-3 is unknown, to study the spectral evolution as a function of Eddington luminosity, L_E, we have to assume a probable mass for the compact object. It was shown by Hjalmarsdotter et al. [29] that the high X-ray luminosity in Eddington units for a neutron star accretor ($L \simeq 1.5 \times 10^{38}$ corresponding to $\simeq 0.5\, L_E$ for $M = 1.4 M_\odot$ helium star) in the hard and intermediate states of the source is incompatible with its compact object being a neutron star since state transitions to

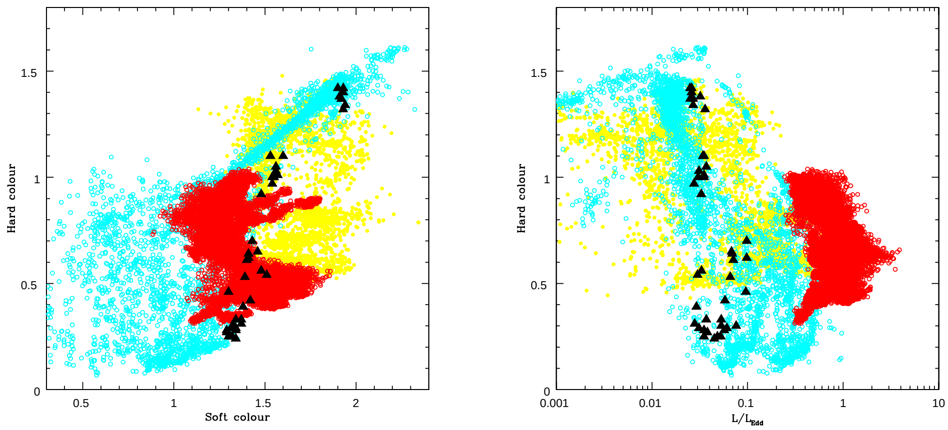

FIGURE 6. *a:* Colour-colour diagram of Cyg X-3 shown as black triangles overplotted on the data from the Galactic black holes (cyan circles) and atolls (yellow filled circles) from [31, 33, 34] and GRS 1915+105 (red circles) from [32]. *b:* Colour-luminosity diagram of Cyg X-3 assuming a mass of its compact object of $30M_\odot$ (black triangles) overplotted on the same data. About a factor of two in the spread in luminosity is due to orbital modulation.

the hard state are not in agreement with a constant high accretion rate. Assuming a typical black hole mass of $M = 10M_\odot$, the luminosity span of Cyg X-3 corresponds to $\sim 0.06-0.2L_E$, comparable to some of the more luminous black hole systems. The transition to the hard state would then have to take place at $\sim 0.1L_E$. Such high transition luminosities are observed in transient systems where hysteresis is present. Cyg X-3 is, however, a persistent source and does not show any hysteresis. The transitions between the hard to soft and the soft to hard state always take place at the same luminosity, indicating a direct relationship between spectral state and accretion rate. For the transition to take place at a luminosity corresponding to $0.03L_E$ which is the case in e.g. Cyg X-1 and LMC X-3 [31], both persistent systems like Cyg X-3, the mass of the compact object in Cyg X-3 would have to be as high as $30M_\odot$ (for L to equal $0.03L_E$ in its intermediate state). With this assumption, the luminosity span in Cyg X-3 corresponds to $0.02-0.07L_E$, comparable to that of Cyg X-1. The track in the colour-luminosity diagram assuming a black hole accretor of mass $30M_\odot$ is shown in Fig. 6b.

The results of [29] thus favour a massive black hole accretor in Cyg X-3. A value of $M = 30M_\odot$ corresponds to the state transition taking place at $L = 0.03L_E$, in agreement with values observed in other sources and consistent with present theoretical models for advective flows. A massive black hole is consistent with the results of [7] who derive a mass for the compact object of 7–$40M_\odot$ for a range of Wolf-Rayet masses from 5 to $20M_\odot$ and inclinations $30° - 90°$, for the mass function $f(m) = 2.3M_\odot$. Interestingly, recent results from mass measurements of the only other Wolf-Rayet X-ray binaries so far discovered, IC 10 X-1 [36, 37] and NGC 300 X-1 [38, 39], suggest that the compact object in both cases is a black hole and in at least one of them, IC 10 X-1, the most probable mass is 24–33 $M_\odot$.

ACKNOWLEDGMENTS

The author acknowledges support from the Anna Greta and Holger Crafoord Foundation.

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