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The microquasar Cyg X-1: a short review

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Abstract. We review the spectral properties of the black hole candidate Cygnus X-1. Specifically, we discuss two recent sets of multi-satellite observations. One comprises a 0.5–500 keV spectrum, obtained with *every* flying X-ray satellite at that time, that is among the hardest Cyg X-1 spectra observed to date. The second set is comprised of 0.5–40 keV *Chandra*-HETG plus *RXTE*-PCA spectra from a radio-quiet, spectrally soft state. We first discuss the "messy astrophysics" often neglected in the study of Cyg X-1, i.e., ionized absorption from the wind of the secondary and the foreground dust scattering halo. We then discuss components common to both state extremes: a low temperature accretion disk, and a relativistically broadened Fe line and reflection. Hard state spectral models indicate that the disk inner edge does *not* extend beyond $\gtrsim 40\,GM/c^2$, and may even approach as close as $\approx 6\,GM/c^2$. The soft state exhibits a much more prominent disk component; however, its very low normalization plausibly indicates a spinning black hole in the Cyg X-1 system.

Key words. accretion, accretion disks – black hole physics – X-rays:binaries

1. Introduction

After the initial discovery (Bowyer et al. 1965) of the black hole candidate Cyg X-1, Tananbaum et al. (1972) noted that, at least in the 2–10 keV band, it exhibited two distinct spectral states: a bright, spectrally soft state, and a fainter, spectrally hard state. Subsequent broad-band studies further elucidated this dichotomy. The soft state spectrum peaks between 1–2 keV, has a weak hard tail with photon spectral index $\Gamma > 2.1$, and is radio quiet. The hard state spectrum is well-described by an exponentially cutoff (folding energy 125–250 keV) broken powerlaw with 2-10 keV photon index $\Gamma < 2.1$ and a harder photon index at $\gtrsim 10$ keV, weak soft excess, and it is radio loud. Cyg X-1 spends the majority of its time in its hard state. A range of such spectra (and further references) can be found in the work of Wilms et al. (2006), which describes a multi-year radio/*RXTE* monitoring campaign of Cyg X-1.

Two extreme examples of the states are presented in Fig. 1. This figure shows April 2008 observations of a spectrally hard state, covering the bandpass of 0.5–500 keV. It is among the hardest spectra seen from Cyg X-

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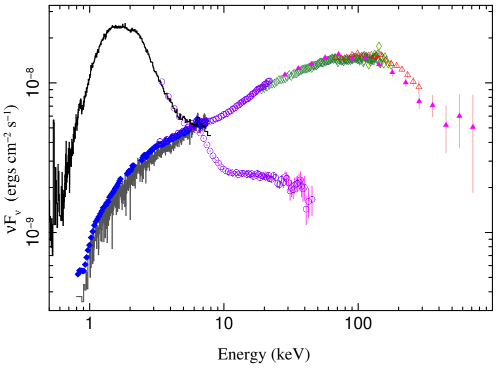

Fig. 1. Cyg X-1 in its two most extreme spectral states: the hard state dominated by a cutoff power-law spectrum extending to > 100 keV, and the soft state dominated by a thermal spectrum peaking between 1–2 keV. The above hard state is from a multi-wavelength campaign wherein Cyg X-1 was observed by *every* flying X-ray satellite. Here we display *Chandra*-HETG spectra (histogram), *Suzaku*-XIS (solid diamonds) and -GSO (hollow triangles) spectra, *RXTE*-PCA (circles) and -HEXTE (hollow diamonds) spectra, and *INTEGRAL*-SPI (solid triangles) spectra (see Nowak et al. 2011). The soft state spectra are from a simultaneous *Chandra*-HETG and *RXTE* campaign conducted in January 2011. The above spectra are presented without reference to any underlying spectral model, and are unfolded using only the spectral response of the detectors (see Nowak et al. 2005).

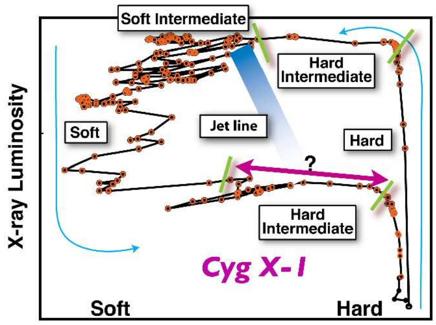

Fig. 2. Hardness-intensity diagram of a black hole transient outburst (based upon GX 339–4; Belloni et al. 2005; Homan et al. 2005; adapted from `www.issibern.ch/teams/proaccretion`). Transients begin faint, hard, and radio loud; they evolve to brighter states while remaining hard; they soften and become radio quiet (often preceded by a radio ejection event); they then fade, harden, and become radio loud once more. Cyg X-1, which is persistently emitting in the X-ray band, occupies only a small portion of this diagram at fractional Eddington luminosities of ≈ 2%, near the so-called radio loud/radio quiet transition "jet line".

1; a description of these spectra can be found in Nowak et al. (2011). Also shown are spectra from simultaneous *Chandra*-HETG/*RXTE*-PCA observations, covering the 0.5–40 keV range of a spectrally soft state. In terms of *observed* flux, the 0.1–50 keV flux of the soft state is 3.9×10^{-8} erg cm^{-2} s^{-1}, while the *observed* 0.5–300 keV flux of the hard state is 4.9×10^{-8} erg cm^{-2} s^{-1}. However, making plausible corrections for absorption and extrapolating the spectra to determine bolometric luminosities, this is at 2.2% $L_{\rm Edd}$ and this hard state is at 1.6% $L_{\rm Edd}$. (The Eddington luminosity, $L_{\rm Edd}$, used here assumes a distance of 1.86 kpc and a mass of 15 $M_\odot$; Reid et al. 2011; Orosz et al. 2011.) That is, whereas we directly observe most of the flux in the hard state, nearly 2/3 of the soft state flux is *unobserved* due to both absorption and bandpass limitations.

As has been noted by previous researchers, the range of bolometric luminosities traversed by Cyg X-1 spans only a factor of ≈ 3–4 (Wilms et al. 2006, and references therein). This is somewhat narrow compared to most black hole transients. Furthermore, Cyg X-1 also traverses a narrower range of colors than many black holes, never exhibiting a purely disk-dominated spectrum without a hard tail (e.g., like the simple disk-dominated spectrum of 4U 1957+11; Nowak et al. 2008). Black hole transients often follow color-intensity diagrams as shown in Fig. 2, spanning ≳ 3 orders of magnitude in luminosity, and wider extremes of color variations. Cyg X-1, however, exists on an especially interesting portion of this 'q-diagram' — moving between the radio quiet/soft ⇔ radio loud/hard-intermediate state transition near ≈ 2% $L_{\rm Edd}$.

The hypothesized emission components in the Cyg X-1 system include an accretion disk, a Comptonizing corona (with either a ther-

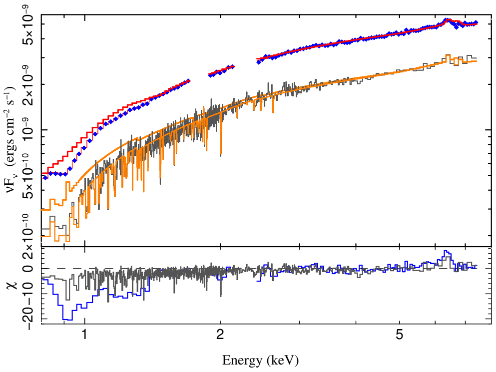

Fig. 3. Simultaneous *Suzaku*-XIS (diamonds) and *Chandra*-HETG (histogram) spectra fit with a simple phenomenological model consisting of a disk, powerlaw, a relativistically broadened line, and a narrow line, modified by ionized absorption (see Hanke et al. 2009 and Nowak et al. 2011). Furthermore, the HETG spectra are modified by dust scattering. One set of models, and all of the residuals, are shown with both the ionized absorption and dust scattering absent.

mal, or hybrid thermal/non-thermal electron distribution; Coppi 1999) that upscatters photons from the disk, a radio emitting jet that might also contribute to the X-ray (Markoff et al. 2005), and relativistically smeared reflection/fluorescence from the disk. The important questions are, what are the relative contributions of these components, and how do they and the system geometry change between the two state extremes?

2. Messy astrophysics

Often neglected in models of Cyg X-1 are two important components that directly bear upon fits of the low temperature disk component in the hard state. First is the fact that Cyg X-1 has an O-star secondary with a highly ionized wind that leads to pronounced ionized absorption (Hanke et al. 2009). This absorption is spectrally resolved by *Chandra*-HETG but not by *Suzaku*-XIS spectra (Nowak et al. 2011). Second is the fact that foreground dust scattering acts as a loss term for the 1″ spatial resolution *Chandra* spectra, but not for 2′ spatial resolution *Suzaku* spectra. For the latter, the emis-

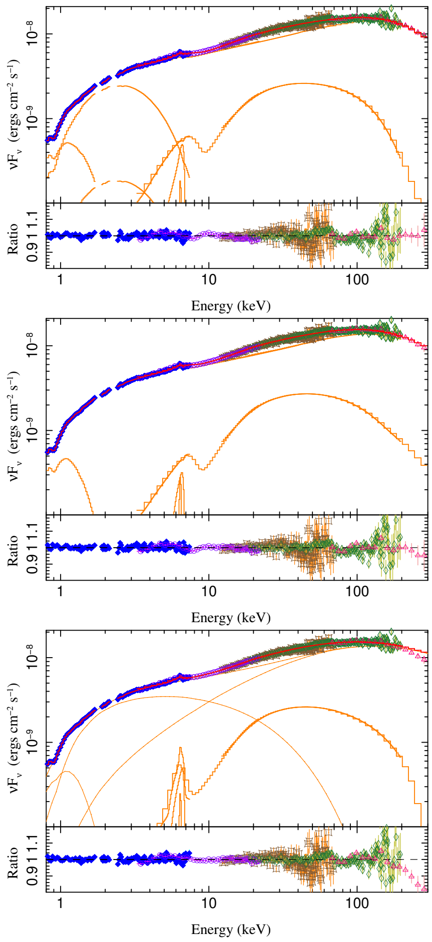

Fig. 4. Cyg X-1 hard state *Suzaku*/*RXTE* spectra, fit with different models. (Model components shown individually: seed photons, Compton spectrum, synchrotron, SSC, disk, reflection, broad and narrow lines.) Top: thermal Comptonization with a high seed photon temperature. Middle: non-thermal Comptonization with a low seed photon temperature. Bottom: jet model dominated by synchrotron and SSC emission. All models also have: a low temperature disk, relativistically broadened reflection and Fe fluorescence line, and a narrow Fe line. Disk and broad Fe line parameters are consistent with the disk extending very close to the innermost stable circular orbit (Nowak et al. 2011).

sion scatters back into the line of sight, albeit time delayed, from an extended dust scattering halo (see Xiang et al. 2011, for models of the

Cyg X-1 halo, and use of the halo time delay to derive a distance consistent with the radio parallax measurements of Reid et al. 2011).

Both of these components must be included in the fits, as demonstrated in Fig. 3 (Nowak et al. 2011).

3. Hard state spectra

There are a number of questions as to the physical mechanisms responsible for the hard state spectrum of Cyg X-1. The emission is typically attributed to a hot corona upscattering photons from an accretion disk; however, the geometry of this configuration is still debated. Does the corona lie central to a truncated outer thin disk (Dove et al. 1997), or, if the corona is driven outwards by radiative pressure (e.g., Beloborodov 1999), could it instead overlay the inner disk? Can an optically thick, geometrically thin disk extend inward nearly to the innermost stable circular orbit (Miller et al. 2006)? Is the hard state corona comprised primarily of electrons with a thermal population (Poutanen & Vurm 2009), or can it have a substantial contribution from a non-thermal electron population (Ibragimov et al. 2005)? Alternatively could the X-rays be comprised of a combination of direct synchrotron and synchrotron self-Compton (SSC) emission from a jet, in addition to coronal emission (Markoff et al. 2005; Maitra et al. 2009)?

In Fig. 4 we present a number of these possibilities, which fit nearly equally well: a thermal corona, a non-thermal corona, and a jet plus corona model (Nowak et al. 2011). All three models, however, have aspects in common. There is spectral hardening above 10 keV that is *partly*, but *not solely*, attributable to reflection. The spectra require a low temperature disk (peak temperature 150–250 eV) with normalization sufficiently low to indicate a disk inner radius $\lesssim 40\,GM/c^2$ (or even consistent with $6\,GM/c^2$). In addition to the narrow Fe line there is a broad Fe line, also with parameters indicating a disk inner radius of 6–40 GM/c^2.

4. Soft state spectra

Soft state spectra, from a January 2011 *Chandra*-HETG plus *RXTE*-PCA observation, are shown in Fig. 5. There is an absence of radio emission, implying a quenched jet component. (Ionized absorption is also mostly absent.) Otherwise, the soft state spectrum contains the same components as the hard state, albeit in different proportions. Here the disk is of higher temperature (peak $kT \approx 470$ eV), and is clearly dominant. A hard tail remains, which we here model with purely non-thermal Comptonization. A relativistically broadened line and smeared reflection are also indicated.

As has been discussed by Gou et al. (2011), the normalization of the disk component (here, the seed photons for Comptonization) is rather small, given recent distance and mass estimates (Reid et al. 2011; Orosz et al. 2011), *and* assuming a color-correction factor of 1.7 for the disk spectrum. Gou et al. (2011), using a fairly narrow range of masses around $\approx 15\,M_\odot$ and inclinations near 27°, claim a near maximally spinning black hole. Taking a wider range of inclinations and masses, however, still implies some degree of spin to achieve the low disk normalization, unless the black hole is at the lowest end of mass ranges from the literature.

If Cyg X-1 is rapidly spinning, then it is possible that the hard state can have an inner disk radius of $\approx 10\,GM/c^2$ (consistent with our hard state spectral fits), and yet have an inner disk radius a factor of several times smaller in its spectrally soft state.

5. Discussion

VALENTÍ BOSCH-RAMON: You mentioned that Cyg X-1 remains in the lower horizontal branch of the hardness-luminosity q-diagram. What about the blob detected in the radio by Fender et al.? Wasn't it coming from a state transition in the higher branch?

MICHAEL NOWAK: Whether or not ejection events typically also accompany the state transition from spectrally soft/radio quiet to spectrally hard/radio loud is still an open question. That being said, there's no evidence that

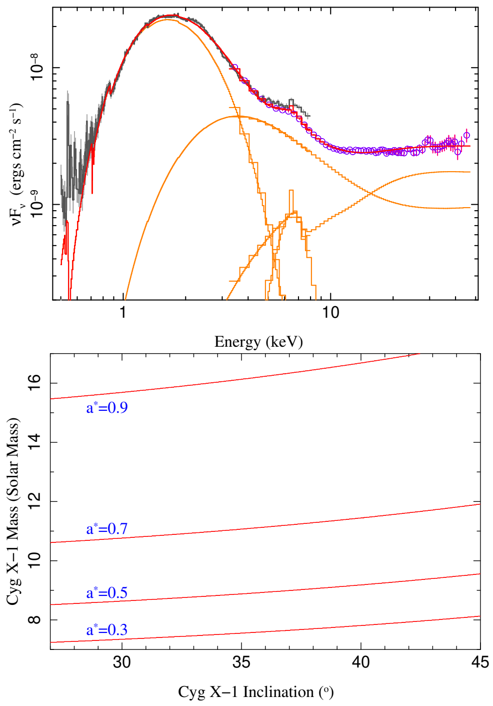

Fig. 5. Top: The soft state *Chandra*-HETG and *RXTE*-PCA spectra of Cyg X-1 fit with a non-thermal Comptonization model with a dominant, high temperature seed photon spectrum from a disk. Individual model components are shown, including the required relativistically smeared reflection/Fe fluorescence. Bottom: Based upon the fitted disk normalization, a simple estimate of the implied Cyg X-1 black hole spin in dimensionless angular momentum units vs. black hole mass and system inclination. We assume a disk temperature color correction of 1.7 and a 1.86 kpc distance.)

Cyg X-1 has been on the "upper" hard/soft transition branch (unless the two branches are *very* close to each other in terms of bolometric flux for Cyg X-1).

JÖRN WILMS: The flare was discussed by Wilms et al. (2007, ApJ, 663, L97). Cyg X-1 was close to a transition from its soft state to its hard state, and the radio flare followed the X-ray flare by ≈ 7 minutes.

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