

# On the accretion geometry of Cyg X-1 in the low/hard state

F. Eugenio Barrio,<sup>1★</sup> Chris Done<sup>1★</sup> and Sergei Nayakshin<sup>2★</sup>

<sup>1</sup>University of Durham, Department of Physics, South Road, Durham DH1 3LE

<sup>2</sup>Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, Postfach 1317, D-85741 Garching, Germany

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## ABSTRACT

We fit the broad-band *RXTE* PCA and HEXTE spectrum of Cyg X-1 from 3–200 keV with reflection models which calculate the vertical ionization structure of an X-ray illuminated disc. We consider two geometries corresponding to a truncated disc/inner hot flow and magnetic flares above an untruncated disc. Both models are able to fit the PCA 3–20 keV data, but with very different spectral components. In the magnetic flare models the 3–20 keV PCA spectrum contains a large amount of highly ionized reflection, while in the truncated disc models the amount of reflection is rather small. The Compton downscattering rollover in reflected emission means that the magnetic flare models predict a break in the spectrum at the high energies covered by the HEXTE bandpass which is *not* seen. By contrast, the weakly illuminated truncated disc models can easily fit the 3–200 keV spectra.

**Key words:** accretion, accretion discs – black hole physics – stars: individual: Cygnus X-1 – X-rays: binaries.

## 1 INTRODUCTION

The black hole binary (BHB) systems in their low/hard state have spectra dominated by a power law which rolls over at  $\sim 200$  keV. This continuum is generally well fit by thermal Comptonization models, in which low-energy photons from the accretion disc are upscattered by energetic electrons (see e.g. the review by Zdziarski 2000). To get these hard X-rays, a large fraction of the gravitational energy released by accretion must be dissipated in an optically thin environment, i.e. not in the disc itself. However, there is no consensus on how this happens, or on the geometry of this hot region. There are currently two main models, one in which the hot electrons are confined in magnetic flares above a disc which extends down to the last stable orbit around the black hole (magnetic flares), and one in which the electrons form a quasi-spherical hot flow, replacing the inner disc (truncated disc).

The magnetic flare model is motivated by the discovery that the physical mechanism for the disc viscosity is a magnetohydrodynamic dynamo (see e.g. the review by Balbus & Hawley 2002). Buoyancy could cause the magnetic field loops to rise up to the surface of the disc, so they can reconnect in regions of fairly low particle density, forming a patchy corona. Numerical simulations (although these are highly incomplete because in general the simulated discs are not radiative) do show this happening (Hawley 2000), but they do not yet carry enough power to reproduce the observed low/hard state (Miller & Stone 2000).

The truncated disc model has its physical basis in the accretion flow equations. The standard Shakura–Sunyaev disc solution as-

sumes that the accreting material is at one temperature (protons and electrons thermalize) and that the accretion energy released by viscosity is radiated efficiently. At low mass accretion rates neither of these are necessarily true. The thermalization time-scale between the electrons and protons can be long, so the flow is intrinsically a two-temperature plasma. Where the electrons radiate most of the gravitational energy through Comptonization of photons from the outer disc, the hot inner flow is given by Shapiro, Lightman & Eardley (1976). Alternatively, if the protons carry most of the accretion energy into the black hole then this forms the advection-dominated accretion flows (Narayan & Yi 1995). These are related, as in general both advection and radiative cooling are important for a hot accretion flow (Chen et al. 1995; Zdziarski 1998).

These two models of the accretion flow have very different geometries. A potential way to test the geometry is with X-ray reflection. The amount of reflection scales with the solid angle subtended by the optically thick material while the relativistic smearing of the atomic features shows how far this material extends into the gravitational potential (Fabian et al. 2000). With magnetic flares, the disc subtends a solid angle of  $2\pi$  as seen from the X-ray source, and extends down to the last stable orbit. Its reflected spectrum should be large and strongly smeared. Conversely, a truncated disc illuminated by an inner hot flow subtends a solid angle  $\leq 2\pi$ , and the reflected spectrum is small and only weakly smeared by relativistic effects.

The BHB spectra in the low/hard state show overwhelmingly that the solid angle is significantly less than  $2\pi$ , and that the smearing is less than expected for a disc extending down to the last stable orbit (Życki, Done & Smith 1997, 1998, 1999; Gierliński et al. 1997; Done & Życki 1999; Zdziarski, Lubinski & Smith 1999; Gilfanov, Churazov & Revnivtsev 1999, 2000). While this is clearly consistent

★E-mail: eugenio.barrio@durham.ac.uk; chris.done@durham.ac.uk; serg@MPA-Garching.mpg.de

with the idea that the disc is truncated in the low/hard state, the magnetic flare models can be retrieved in several ways.

First, magnetic reconnection on the Sun is known to produce an outflow in the coronal mass ejection events. In the extreme conditions close to the black hole it is possible that this outflow velocity could be large so that the hard X-ray radiation is beamed away from the inner disc (Beloborodov 1999).

An alternative explanation for the lack of reflection and smearing is that the inner disc or top layer of the inner disc is completely ionized. There are then no atomic features, and the disc reflection is unobservable in the 2–20 keV range as it appears instead to be part of the power-law continuum (Ross & Fabian 1993; Ross, Fabian & Young 1999). However, these models with passive illumination of the disc require a fairly sharp transition between the extreme ionization and mainly neutral material (Done & Życki 1999; Done, Madejski & Życki 2000; Young et al. 2001). Such a transition can be produced as the disc *responds* to the intense X-ray illumination. There is a thermal ionization instability which affects X-ray illuminated material in pressure balance, which can lead to a hot, extremely ionized skin forming on top of the rest of the cooler, denser, mainly neutral disc material (Field 1965; Krolik, McKee & Tarter 1981; Kallman & White 1989; Ko & Kallman 1994; Rózańska & Czerny 1996; Nayakshin, Kazanas & Kallman 2000, hereafter NKK; Rózańska & Czerny 2000; Nayakshin & Nayakshin 2001; Ballantyne, Ross & Fabian 2001). Such X-ray illuminated disc models can fit the 2–20 keV data from BHB with reflection from a disc which subtends a solid angle of  $2\pi$  and extends down to the last stable orbit around a black hole (Done & Nayakshin 2001b).

While the truncated disc and magnetic flare/X-ray illuminated disc models are indistinguishable with current data in the 2–20 keV range, they are very different at higher energies. In the magnetic flare models, a lot of the 2–10 keV ‘continuum’ is actually ionized reflection, so the true continuum level is lower than in the truncated disc models, in which reflection is small. At higher energies, where reflection is negligible, the lower continuum level for the magnetic flare models leads to a smaller predicted flux in the 100–200 keV range than for the truncated discs (Done & Nayakshin 2001a). Here we fit both truncated disc and magnetic flare/X-ray illuminated disc models to the 3–200 keV PCA/HEXTE spectrum of the hard/low state spectra of Cyg X-1. We show that the truncated disc models provide an excellent fit to these data, but that the magnetic flare/X-ray illuminated disc does not, as it dramatically underpredicts the 100–200 keV spectrum.

Similar conclusions were independently reached by Maccarone & Coppi (2002) from fits to the Cyg X-1 broad-band spectrum. However, they approximated the reflection from magnetic flares by highly ionized, single zone reflection models rather than the full complex ionization reflection models used here. Here we are able to show explicitly that the complex ionization magnetic flare models do not fit the high-energy spectrum, while the truncated disc models do.

## 2 MODELS

We use the complex ionization reflection code, XION, described in NKK which computes the self-consistent vertical ionization structure of an X-ray illuminated disc in hydrostatic equilibrium at a given radius. The reflected and diffuse (line and recombination continua) emission from this are smeared by the relativistic effects expected from a disc, and then these spectra are summed over all radii to get the total disc reflected emission for any given source/disc geometry. These models have been tabulated for use in XSPEC for a central sphere/truncated disc geometry, assuming that the hot inner flow has

emissivity  $\propto r^{-3}$ , and starts at the radius where the optically thick disc truncates (Nayakshin et al., in preparation). They have also been tabulated for a magnetic flare geometry, which results in much stronger illumination of the disc and so gives a deeper ionized skin (Nayakshin 2000). With magnetic flares, the luminosity of the flares is assumed to scale as the local disc flux, so that  $f_x/f_{\text{disc}}$  remains constant with radius. These tabulated models are hereafter referred to as XION-DISC (truncated disc) and XION-FLARES (magnetic flares). The free parameters are the mass accretion rate (this determines the unilluminated disc structure i.e. the starting density as a function of height),  $f_x/f_{\text{disc}}$  which determines the depth of the ionized skin, and the shape of the illuminating spectrum ( $\Gamma$  and  $E_{\text{cut}}$  assuming an exponentially cut-off power law). For the truncated disc models there is also the inner radius of the accretion disc,  $R_{\text{in}}$ , which controls the amount of relativistic smearing of the iron line features.

The XION code includes Compton up and downscattering by electrons in the disc. Compton upscattering can be very important in smearing the iron features in ionized discs (Ross et al. 1999), while Compton downscattering determines the high energy rollover in the reflected spectrum (Lightman & White 1988). However, the approximations used for Compton scattering in the XION code become progressively less accurate at higher energies (NKK). The appendix discusses how we merge the more accurate high-energy Compton downscattering of the standard XSPEC PEXRIV based reflection models (Magdziarz & Zdziarski 1995) with the XION results.

The code does not include time-dependant effects. These may well be important, but have the tendency to produce a broader (and lower) range of ionization states than those expected in hydrostatic equilibrium (Nayakshin & Kazanas 2002; Collin et al. 2003). The observed spectra appear to *require* a sharp transition between an extreme ionization skin (iron completely ionized) and underlying neutral material (e.g. Done & Życki 1999), and simulations also show that only extreme ionization can effectively mask the reflection signature (Done & Nayakshin 2001a). Thus it seems unlikely that including time-dependance would improve the match between the observed spectra and the X-ray illuminated disc models.

## 3 SPECTRAL FITTING

We used the hardest spectra seen from multiple observations of the Cyg X-1 hard/low state (Gilfanov et al. 1999). We extracted the data using the REX data analysis script with the bright source background from the top layer of PCA detectors 0 and 1. Previous work has shown that this configuration gives a good fit to the Crab data with 0.5 per cent systematic error for RXTE Epoch 3 data (Wilson & Done 2001). We extracted the simultaneous HEXTE data from cluster 0. In fits with both the PCA and HEXTE data we allow a normalization offset between the two instruments to take into account the cross-calibration uncertainties. We use XSPEC version 11 (Arnaud 1996) and quote all error bars as  $\Delta\chi^2 = 2.7$ , corresponding to 90 per cent confidence limits on 1 parameter, and fix the absorbing column to  $N_H = 6 \times 10^{21} \text{ cm}^{-2}$  (Balucinska-Church et al. 1995).

First we fit the PCA data alone with the old, single ionization parameter reflection models so that we can compare the new reflection models with previous fits. We use the REL-REPR model of Życki et al. (1998), which is based on the publically available PEXRIV reflection but includes the self-consistently produced iron line emission and relativistic smearing. We assume a power-law continuum model, and also include neutral, unsmeared reflection, which can arise from the companion star or outer accretion disc (Ebisawa et al. 1996). This gives a value of  $\chi^2_{\nu} = 30/39$ ; the amount of reflection

from the accretion disc is low, with  $\Omega/2\pi = 0.13 \pm 0.08$ , implying a truncated disc.

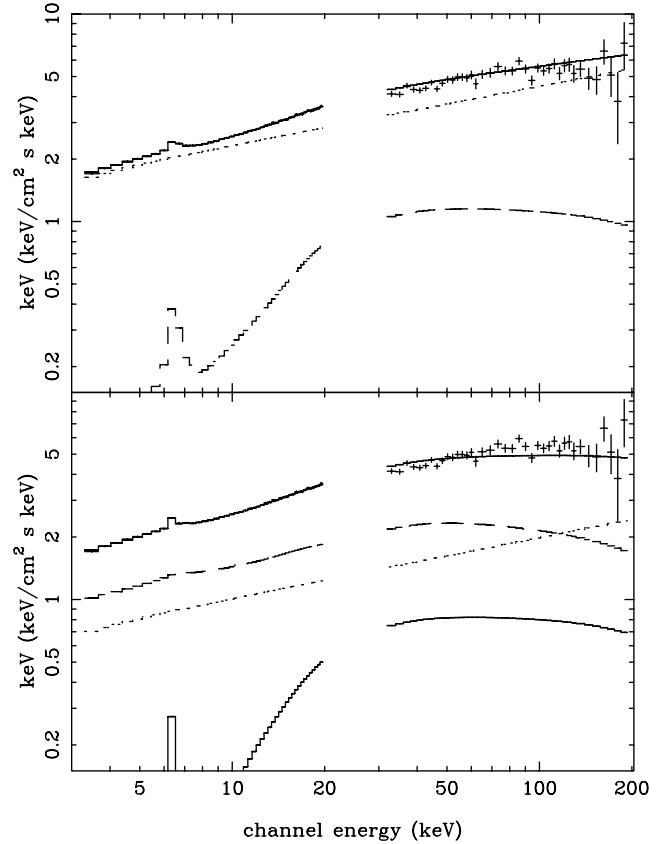
We then replace the single ionization accretion disc reflection with the XION-DISC model. The simplest version of this truncated disc geometry assumes that the hot inner source is spherical, and starts where the cool disc truncates. This results in a model in which  $\Omega/2\pi$  is fixed at  $\sim 0.3$ , rather larger than is inferred from the simple reflection models above, and so gives a somewhat larger  $\chi^2_v = 53/40$ . If instead we allow the amount of reflection to be smaller than this (e.g. if the hot source has a flattened rather than a spherical geometry) then we get  $\chi^2_v = 43/39$  for  $f_x/f_d = 6$ . This is a worse fit by  $\chi^2$  of 13 than that for the single ionization zone reflection models (REL-REPR, above). The two models give different fits because even a weakly illuminated disc produces a low optical depth ionized skin. This reflects some small fraction of the incident continuum at low energies (see Fig. A1, later, in the appendix), changing the curvature of the reflected continuum.

We then use XION-FLARE to model the magnetic flare geometry in which  $\Omega/2\pi$  is fixed at 1 and the inner disc extends down to 3 Schwarzschild radii. This gives  $\chi^2_v = 47/41$  (both the solid angle of reflection and the inner disc radius are fixed, leading to 2 fewer degrees of freedom). This confirms the results of Done & Nayakshin (2001b) that magnetic flares can give as good a fit to the data below 20 keV as a truncated disc. The PCA data are consistent with the presence of a large amount of ionized reflection, i.e. with a disc which subtends a large solid angle to the X-ray source and extends down to the last stable orbit.

However, these two very different reflection models should give very different spectra at higher energies. Reflection *must* rollover at high energies due to Compton downscattering in the disc. Fig. 1 shows the truncated disc (upper panel) and magnetic flare (lower panel) PCA fits extrapolated to the HEXTE data. The truncated disc model has little reflection, so there is little rollover in the total spectrum. By contrast, the magnetic flare models have a lot of highly ionized reflection, so the contribution of the Compton downscattering rollover is important. Plainly there is no such rollover in the HEXTE data, and the magnetic flare description of the PCA data strongly underestimates the higher energy spectrum. This is made even more marked by the fact that a power law is an overestimate of the high energy continuum: a true Comptonized continuum has a thermal cut-off at 150–200 keV (Gierliński et al. 1997). By contrast, the truncated disc models can qualitatively describe the high-energy data.

While this argues strongly against a large ionized reflection component in the data, true spectral fitting is required to show conclusively that this is the case. We do joint fits of the PCA and HEXTE data, using the Comptonization model, COMPPS, of Poutanen & Svensson (1996) rather than a power law for the continuum. In all the fits we also allow this also to illuminate the companion star, producing a neutral, unsmoothed reflection component. The PCA and HEXTE flux give a luminosity of  $\sim 10^{37}$  erg s $^{-1}$ , or  $\sim 0.01 L_{\text{Edd}}$ . This is  $\sim 3\times$  lower than the luminosity seen in a *BeppoSAX* observation, where the seed photon temperature was observed to be  $\sim 0.15$  keV (Di Salvo et al. 2001). Hence we fix the seed photons for Compton scattering at a temperature of  $3^{-1/4} \times 0.15 = 0.1$  keV.

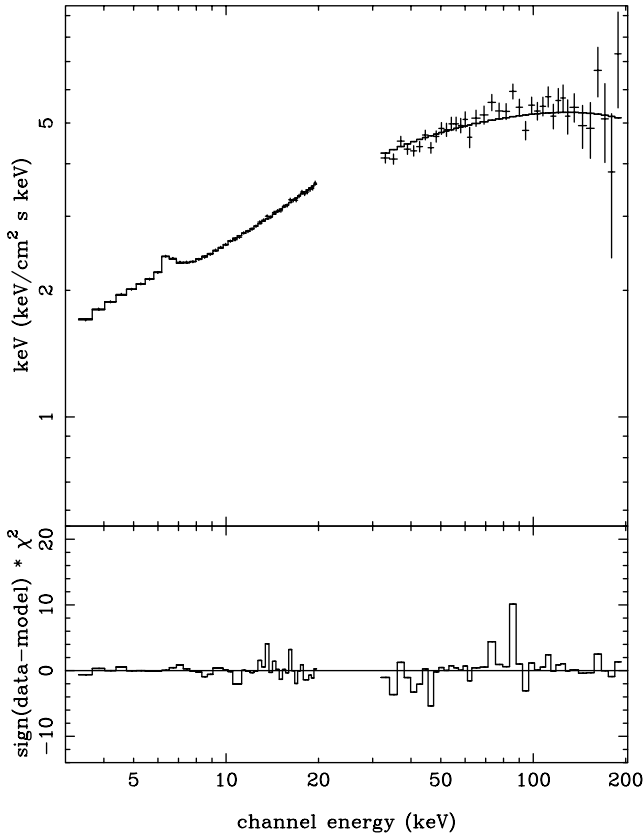
We first assume that the Comptonizing region is spherically symmetric, illuminated by isotropic seed photons to produce a generic, isotropic Comptonized continuum (geometry flag set to 0). This gives an adequate fit of  $\chi^2_v = 114/77$  where this continuum is assumed to form a spherical central source which then illuminates a truncated disc (i.e. with hardwired solid angle of  $\Omega/2\pi = 0.3$ ). Allowing the reflection amount to vary (as in a flattened source) gives



**Figure 1.** The upper panel shows the PCA fit to a power law and truncated disc model extrapolated through the HEXTE data, while the lower panel shows this for the magnetic flares. Both figures have the power law continuum as a dotted line, while the dashed line is the reflected component from the accretion disc. The intrinsic continuum level for the truncated disc is much higher than for magnetic flares as the magnetic flares have a large contribution of reflected emission in the PCA. The reflected continuum has a *rollover* at  $\sim 100$  keV, so the extrapolated high energy spectrum is dominated by the intrinsic continuum and the magnetic flare model predicts a much smaller HEXTE flux than the truncated disc. Both fits have comparable  $\chi^2$  in the PCA, but the magnetic flares underpredict the high energy data while the truncated disc model matches fairly well. Both fits include neutral, unsmoothed reflection from the companion star/outer disc (lower solid line in the bottom panel) but is too small to be seen in the truncated disc model. This figure can be seen in colour in the online version of the journal on *Synergy*.

a much better fit with  $\chi^2_v = 86/76$ . We show the unfolded spectrum and residuals from this model in Fig. 2, where the continuum parameters are  $\tau \sim 0.75$  and  $kT_e = 200$  keV. By contrast, assuming the isotropic continuum is above the disc, as appropriate for magnetic flares, gives a very poor fit, with  $\chi^2_v = 259/78$  (Fig. 3) for a continuum with  $\tau \sim 0.75$  and  $kT_e \sim 210$  keV.

However, both these fits are subtly inconsistent as the continuum model assumed isotropic seed photons for the Compton scattering rather than having them arise from the disc. Anisotropic seed photons lead to anisotropic Compton continua (e.g. Haardt & Maraschi 1993), so a fully self-consistent picture should include the continuum anisotropies which arise from the two different geometries. There is a fairly large range of incident angles for the seed photons in the truncated disc geometry so we expect any anisotropies to be small (so the isotropic continuum models above should be a good approximation), but the magnetic flares are illuminated preferentially from below. For a Comptonizing plasma with optical depth

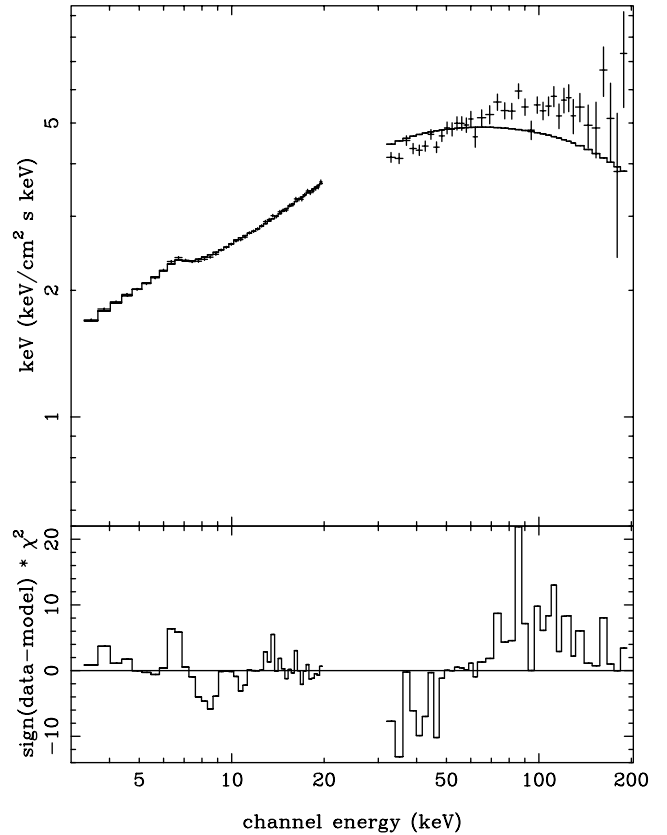


**Figure 2.** The PCA and HEXTE data fit to a Comptonized continuum plus illuminated truncated accretion disc model XION-DISC, plus neutral, unsmear reflection from the companion star/outer disc. The upper panel shows the unfolded spectrum while the lower panel shows residuals to the fit. This figure can be seen in colour in the online version of the journal on *Synergy*.

of order unity and temperature of  $\sim 200$  keV (Sunyaev & Titarchuk 1980; Gierliński et al. 1997) then this seed photon anisotropy can have a marked effect on the spectrum (Haardt & Maraschi 1993; Poutanen & Svensson 1996). We use the COMPPS code to simulate the anisotropic continuum expected from hot plasma forming a slab above a disc (Poutanen & Svensson 1996). This approximates the magnetic flare geometry in the limit when the radial size of the flare is much bigger than its height. Any general magnetic flare geometry should give rise to a continuum which is somewhere between the isotropic Comptonized spectrum; the anisotropic slab (the COMPPS cylinder, or hemisphere geometry, is more anisotropic than the slab as it assumes only seed photons from below the flare rather than allowing disc photons to also enter through the side of the flare).

We refit the data with the magnetic flare reflection model using this anisotropic slab continuum. This gives an even worse fit than before, with  $\chi^2 = 531/78$ , where the continuum has  $\tau \sim 1$  and  $kT_e = 85$  keV. The reason the fit is so poor is that the seed photon anisotropy leads to a break in the spectrum, such that the low-energy spectrum is harder than the high energy spectrum (Haardt & Maraschi 1993; Haardt et al. 1993). The low-energy spectrum then predicts even less high-energy emission than for isotropic seed photons. Fig. 4 shows the unfolded spectrum and residuals from this model.

The energy at which the anisotropy break occurs depends on the seed photon temperature (Haardt & Maraschi 1993), and the strength of the break will depend on the detailed geometry of the flare (its radius-to-height ratio) but qualitatively any hot plasma illuminated



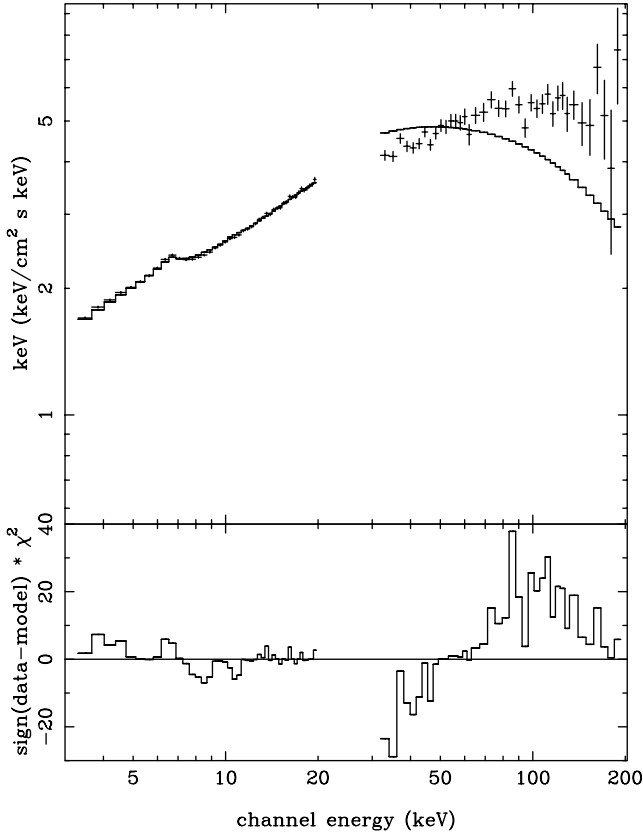
**Figure 3.** As for Fig. 2, but with the XION-FLARE model for reflection from an X-ray illuminated untruncated disc. The large amount of reflection with its rollover at  $\sim 100$  keV means that the slope of the HEXTE spectrum is predicted to be considerably steeper than that of the PCA, while the observed HEXTE data have a rather similar slope. This figure can be seen in colour in the online version of the journal on *Synergy*.

from below produces a continuum which is anisotropic in the sense that there is a steepening of the high energy spectrum as seen by an observer. The limit where this break is below the PCA bandpass requires an uncomfortably low disc temperature of  $\leq 10$  eV, and leads to the same poor fit as obtained for isotropic seed photons with magnetic flare reflection ( $\chi^2 = 259/78$ ).

#### 4 DISCUSSION

The data clearly show that the 2–20 keV spectrum from the low/hard state of Cyg X-1 does *not* contain a large fraction of highly ionized reflection. This rules out models which have static magnetic flares above an untruncated disc, unless the flares have a spectrum which is much harder than that predicted by a single temperature Comptonization model.

One way to get some spectral hardening, which is expected in a magnetic flare geometry but is neglected in our modelling, is for the flares to Comptonize some fraction of the reflected photons. The reflected photons are from the disc, so they are intercepted by the hot electrons in the flares in the same way as the soft seed photons, and are Compton upscattered to form a hard continuum. With flares covering most of the disc this can then make a 50–100 per cent increase to the flux at 200 keV (Petrucchi et al. 2001). A covering fraction of unity for the flares (slab corona geometry) is normally ruled out for the low/hard spectra as this produces many non-reflected, thermalized photons from the hard X-ray illumination. These are also



**Figure 4.** As for Fig. 3 (reflection from XION-FLARE), but with the anisotropic Compton continuum expected from X-ray emission regions above an accretion disc. The fit is even worse than for isotropic emission as the Compton continuum has a break to a steeper spectrum at high energies due to the anisotropic illumination of the seed photons from the accretion disc. Note the change in scale for the  $\chi^2$  panel compared to Figs 2 and 3. This figure can be seen in colour in the online version of the journal on *Synergy*.

Comptonized by the corona, leading to spectral indices which are too soft to explain the low/hard state (Pietrini & Krolik 1995; Stern et al. 1995; Zdziarski et al. 1998). However, a covering fraction of  $\sim 0.5$  might give enough Compton scattering of reflection to produce the required  $\sim 50$  per cent excess emission at 200 keV, while also allowing enough seed photons to escape to produce the required hard continuum.

The problems that the magnetic flare models have in matching the high energy flux are exacerbated by the anisotropy break which should be present in the continuum in this assumed geometry, but which has never been convincingly observed (Gierliński et al. 1999). If the magnetic flares are to fit the high energy data then the anisotropy break must be hidden by having a multiple temperature Comptonized continuum. At some level there *must* be a distribution of electron temperatures: it is almost inconceivable that a single temperature distribution can be maintained, especially as the sources are variable so the flare spectra probably evolve with time (e.g. Poutanen & Fabian 1999). A multiple-temperature continuum gives another way to boost the high-energy flux so that we do not necessarily need to strongly Comptonize the reflected continuum. However, it still seems somewhat contrived that a combined complex continuum plus complex ionization reflection spectrum should so precisely mimic a simple single temperature continuum, truncated disc reflection.

By contrast, a truncated disc/hot inner flow geometry at low mass accretion rates is compatible with the observed hard continuum, lack of anisotropy break, low amount of reflection and relativistic smearing. It can also explain the low temperature and luminosity of the direct emission from the disc (e.g. Esin et al. 2000). This geometry can also give a qualitative explanation for a range of observed correlations if the truncation radius decreases with increasing (average) mass accretion rate. The disc penetrates further into the hot flow, increasing the seed photon flux intercepted by the hot inner flow, leading to a softer continuum spectra. This changing geometry gives a larger solid angle subtended by the disc, leading to an increasing amount of reflection (Poutanen, Krolik & Ryde 1997; Zdziarski et al. 1999; Gilfanov et al. 1999, 2000), and relativistic smearing (Życki et al. 1999; Gilfanov et al. 2000; Lubiński & Zdziarski 2001). The variability power spectra are also affected as they contain characteristic frequencies which are most probably linked to the inner edge of the disc, so this can explain the correlated increase in break and quasi-periodic oscillation frequency (e.g. the review by van der Klis 2000; Churazov, Gilfanov & Revnivtsev 2001). Lastly, the collapse of an inner hot flow when it becomes optically thick gives a physical mechanism for the state transition (Esin, McClintock & Narayan 1997). The caveats are only that the truncation mechanism and hot flow structure are not well understood theoretically, and that there are quantitative problems in reproducing the correlation between the amount of reflection and spectral shape (Beloborodov 2001).

Thus, if one were to choose between relatively straightforward models, then the truncated disc is definitely favoured by our analysis while the magnetic flare model is ruled out. However, the straightforward solutions may be too simple to describe the complexity of accretion disc structure near the black hole. The role and magnitude of secondary effects (Comptonization of the reflection component; multi-temperature nature of flares) not taken into account in our modelling needs to be clarified in the future with detailed calculations.

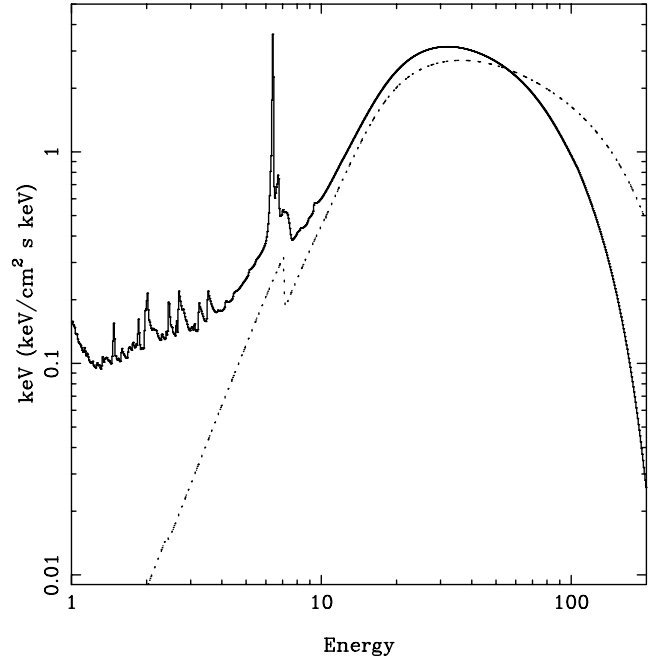
## REFERENCES

- Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
- Balbus S. A., Hawley J. A., 2003, Lect. Notes Phys., 614, 329
- Ballantyne D., Ross R., Fabian A. C., 2001, MNRAS, 327, 10
- Balucinska-Church M., Belloni T., Church M. J., Hasinger G., 1995, A&A, 302, L5
- Beloborodov A. M., 1999, ApJ, 510, L123
- Beloborodov A. M., 2001, Adv. Sp. Res., 28, 411
- Chen X., Abramowicz M. A., Lasota J.-P., Narayan R., Yi I., 1995, ApJ, 443, L61
- Churazov E., Gilfanov M., Revnivtsev M., 2001, MNRAS, 321, 759
- Collin S., Coupé S., Dumont A.-M., Petrucci P.-O., Różańska A., 2003, A&A, 400, 437
- Di Salvo T., Done C., Życki P. T., Burderi L., Robba N. R., 2001, ApJ, 547, 1024
- Done C., Nayakshin S., 2001a, ApJ, 546, 419
- Done C., Nayakshin S., 2001b, MNRAS, 328, 616
- Done C., Życki P. T., 1999, MNRAS, 305, 457
- Done C., Mulchaey J. S., Mushotzky R. F., Arnaud K. A., 1992, ApJ, 395, 275
- Done C., Madejski G. M., Życki P. T., 2000, ApJ, 536, 213
- Ebisawa K., Ueda Y., Inoue H., Tanaka Y., White N. E., 1996, ApJ, 467, 419
- Esin A. A., McClintock J. E., Narayan R., 1997, ApJ, 489, 865
- Esin A. A., Kuulkers E., McClintock J. E., Narayan R., 2000, ApJ, 532, 1069

- Fabian A. C., Iwasawa K., Reynolds C. S., Young A. J., 2000, *PASP*, 112, 1145
- Field G. B., 1965, *ApJ*, 142, 431
- Gierliński M., Zdziarski A. A., Done C., Johnson W. N., Ebisawa K., Ueda Y., Philips F., 1997, *MNRAS*, 288, 958
- Gierliński M., Zdziarski A. A., Poutanen J., Coppi P. S., Ebisawa K., Johnson W. N., 1999, *MNRAS*, 309, 496
- Gilfanov M., Churazov E., Revnivtsev M., 1999, *A&A*, 352, 182
- Gilfanov M., Churazov E., Revnivtsev M., 2000, in Zhao G., Wang J. J., Qiu H. M., Boerner G., eds, *Proc. SGSC Conf. Ser. Vol. 1, 5th Sino-German Workshop on Astrophysics*. China Science & Technology Press, Beijing, p. 114
- Haardt F., Maraschi L., 1993, *ApJ*, 413, 507
- Haardt F., Done C., Matt G., Fabian A. C., 1993, *ApJ*, 411, L95
- Hawley J., 2000, *ApJ*, 528, 462
- Kallman T. R., White N. E., 1989, *ApJ*, 341, 955
- Ko Y.-K., Kallman T. R., 1994, *ApJ*, 431, 273
- Krolik J. H., McKee C. F., Tarter C. B., 1981, *ApJ*, 249, 422
- Lightman A. P., White T. R., 1988, *ApJ*, 335, 57
- Lubiński P., Zdziarski A. A., 2001, *MNRAS*, 323, L37
- Maccarone T. J., Coppi P. S., 2002, *MNRAS*, 335, 465
- Magdziarz P., Zdziarski A. A., 1995, *MNRAS*, 273, 837
- Miller K. A., Stone J. M., 2000, *ApJ*, 534, 398
- Narayan R., Yi I., 1995, *ApJ*, 452, 710
- Nayakshin S., 2000, *ApJ*, 534, 718
- Nayakshin S., Kallman T. R., 2001, *ApJ*, 546, 406 (NK)
- Nayakshin S., Kazanas D., 2002, *ApJ*, 567, 85
- Nayakshin S., Kazanas D., Kallman T. R., 2000, *ApJ*, 537, 833 (NKK)
- Petrucchi P. O., Merloni A., Fabian A. C., Haardt F., Gallo E., 2001, *MNRAS*, 328, 501
- Pietrini P., Krolik J. H., 1995, *ApJ*, 447, 526
- Poutanen J., Fabian A. C., 1999, *MNRAS*, 306, 31
- Poutanen J., Svensson R., 1996, *ApJ*, 470, 249
- Poutanen J., Krolik J. H., Ryde F., 1997, *MNRAS*, 292, L21
- Ross R. R., Fabian A. C., 1993, *MNRAS*, 261, 74
- Ross R. R., Fabian A. C., Young A. J., 1999, *MNRAS*, 306, 461
- Różańska A., Czerny B., 1996, *AcA*, 46, 233
- Różańska A., Czerny B., 2000, *A&A*, 360, 1170
- Shapiro S. L., Lightman A. P., Eardley D. M., 1976, *ApJ*, 204, 187
- Stern B. E., Poutanen J., Svensson R., Sikora M., Begelman M. C., 1995, *ApJ*, 449, 13
- Sunyaev R., Titarchuk L., 1980, *A&A*, 86, 121
- van der Klis M., 2000, *ARA&A*, 38, 717
- Wilson C. D., Done C., 2001, *MNRAS*, 325, 167
- Young A. J., Fabian A. C., Ross R. R., Tanaka Y., 2001, *MNRAS*, 325, 1045
- Zdziarski A. A., 1998, *MNRAS*, 296, L51
- Zdziarski A. A., 2000, in Martens H., Tsuruta S., Weber M. A., eds, *IAU Symp. 195, Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas*. Astron. Soc. Pac., San Francisco, p. 153
- Zdziarski A. A., Poutanen J., Mikolajewska J., Gierliński M., Ebisawa K., Johnson W. N., 1998, *MNRAS*, 301, 435
- Zdziarski A. A., Lubiński P., Smith D. A., 1999, *MNRAS*, 303, 11
- Życki P. T., Done C., Smith D. A., 1997, *ApJ*, 488, L113
- Życki P. T., Done C., Smith D. A., 1998, *ApJ*, 496, L25
- Życki P. T., Done C., Smith D. A., 1999, *MNRAS*, 305, 231

## APPENDIX A: A COMPARISON OF XION AND PEXRIV REFLECTION

The main objective of the XION code is to accurately calculate the vertical ionization structure of the X-ray illuminated disc, so the atomic physics/photoionization calculations are treated in great depth while Compton scattering is approximated in the same manner as in Ross & Fabian (1993). These approximations are adequate at lower energies, where the energy shifts from Compton scattering are small, but become progressively worse at higher energies where downscat-



**Figure A1.** The solid line shows the lowest ionization XION reflected spectrum from a power law continuum with  $\Gamma = 1.7$ , with exponential rollover at 300 keV. We use the XION-FLARE model, so the disc subtends a solid angle of  $2\pi$ , and assume an inclination of  $30^\circ$ . The dashed-dotted line shows the reflected spectrum calculated under the same conditions using the PEXRIV model. XION-FLARE predicts much more reflected flux at low energies as even at the lowest tabulated ionization there is still a residual, low optical depth, ionized skin which reflects a small fraction of the continuum. The difference in shape at high energies and the slight difference in normalization at 20–30 keV is due to the approximate treatment of Compton downscattering in the XION code and the different assumed illumination. This figure can be seen in colour in the online version of the journal on *Synergy*.

tering is large. By contrast, the standard PEXRIV reflection model in XSPEC treats Compton scattering very carefully (Magdziarz & Zdziarski 1995), but has very crude ionization balance and does not include any vertical structure (Done et al. 1992).

The two codes should give comparable results when the vertical structure is unimportant i.e. when the X-ray illumination is very small. Fig. A1 shows a comparison of the two codes with XION-FLARES at  $f_x/f_d = 0.02$  and  $\dot{m} = 0.001$  (the lowest tabulated values) for a magnetic flare geometry at inclination of  $30^\circ$ . The dotted line shows the comparable PEXRIV results ( $\Omega/2\pi = 1$ ,  $\xi = 0$ , inclination of  $30^\circ$ ). The continuum for both is an illuminating power law of index  $\Gamma = 1.7$  with exponential rollover at 300 keV. The differences are obvious. At low energies these are expected as the XION code has a residual ionized skin in even a weakly illuminated disc. One would have to extend the grid in XION to even lower values of the ‘gravity parameter’ to render effects of the skin completely negligible in the soft X-ray range. The ionization effects should nevertheless be very small at high energies where the two codes should yield very similar results. However, the Compton hump extends to much higher energies in PEXRIV than in XION, and the normalization is different by a factor of 1.3 at 20 keV.

The difference in normalization is mainly due to the difference in illumination law used. Magdziarz & Zdziarski (1995) have specific intensity  $\propto 1/\cos \theta$ , while XION assumes a single ray, incident on to the surface at  $45^\circ$ . The first form of the illumination law is

appropriate for an optically thin *full* corona (with a covering fraction equal to unity) which is now known not to work for Cyg X-1 (Gierliński et al. 1997); the use of a fixed value of  $\theta = 45^\circ$  in XION, on the other hand, stems from the necessity to keep the XION runtime to a manageable minimum. Thus both illumination laws are not expected to be strictly correct in reality and are approximations good to some 10–20 per cent. Also, XION is a table model so linear interpolation from the nearest tabulated parameter values can introduce some inaccuracy.

The deficit of photons at  $\sim 200$  keV is a more serious problem. It is mainly due to the energy grid of XION only extending to 200 keV, again from the need to keep the XION runtime to a manageable level. However, it is these high energy continuum photons (which are included in PEXRIV) which are downscattered to form the reflected continuum above 30 keV. Thus XION as tabulated here gives too few reflected photons at high energies compared with PEXRIV.

An ideal model would accurately calculate *both* the ionization structure and Compton scattering for a broad range of parameters and do it *fast*. Because such a model is not feasible, due to computer limitations, we use the ionization structure of XION at low energies ( $< 20$  keV) and the Compton downscattering calculations of PEXRIV at high energies ( $> 30$  keV), having matched the normalization of the PEXRIV reflection to that of XION at 20 keV. The gap in good data between 20–30 keV means that the two different models can be used for the PCA and HEXTE data, respectively, rather than having to interpolate between them.

For a single-temperature Compton continuum fit to the data above 10 keV in this approach with the XION-DISC model gives  $\chi^2_v = 62/59$ . By comparison, the reflection model built into the COMPPS code (which is based on PEXRIV) has  $\chi^2_v = 65/59$  showing that the matching condition is adequate.

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