X-ray spectra of accretion discs with dynamic coronae

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Abstract. We compute X-ray spectra produced by *non-static* coronae atop accretion discs around black holes. The hot corona is radiatively coupled to the underlying disc (the reflector) and generates an X-ray spectrum which is sensitive to the bulk velocity of the coronal plasma, $\beta = v/c$. We show that an outflowing corona atop a neutral reflector reproduces the hard-state spectrum of Cyg X-1 and similar objects. The dynamic model predicts a correlation between the observed amplitude of reflection R and the X-ray spectrum slope Γ since both strongly depend on β. A similar correlation was observed and its shape is well fitted by the dynamic model.

INTRODUCTION

The hard X-ray spectra of galactic black holes (GBHs) and active galactic nuclei (AGN) indicate the presence of hot plasmas with temperature $kT \sim 100$ keV in the vicinity of accreting black holes (see e.g. Poutanen 1998 for a review). The plasma can be identified with a corona of a black hole accretion disc (e.g. Galeev et al. 1979; see Beloborodov 1999b for a review, hereafter B99b). The corona is likely to form as a result of magnetorotational instabilities in the disc and the buoyancy of the generated magnetic field (Tout & Pringle 1992; Miller & Stone 2000). The coronal plasma is probably heated in flare-like events of magnetic dissipation producing the variable X-ray emission. The observed power-law X-ray spectra are generated by Comptonization process. The X-rays are partly reprocessed into soft radiation by the underlying disc. The soft radiation reenters the source, providing the feedback loop that regulates the temperature of the corona (Haardt & Maraschi 1993). The geometry of the corona can hardly be derived from first principles. It might be a large cloud covering the whole inner region of the disc. It may also be a number of small-scale blobs with short life-times. The resulting X-ray spectrum is however not sensitive to the exact shape of the cloud, its density distribution, and other details. The only important parameter is the effective feedback factor (see e.g. Stern et al. 1995b) that is the fraction of the X-ray luminosity which reenters the source after reprocessing. Previous computations of the disc-corona models all assumed that the corona is static (e.g. Haardt & Maraschi 1993; see also Poutanen 1998). The model was successfully applied to Seyfert 1 AGN, however, it was found to disagree with observations of some black-hole sources in the hard state, for instance, Cyg X-1 (Gierliński et al. 1997). A possible explanation could be that the coronal plasma is moving away from the disc and emits beamed X-rays. Beloborodov 1999 (hereafter B99a) argued that the flaring plasma is likely to acquire a mildly relativistic

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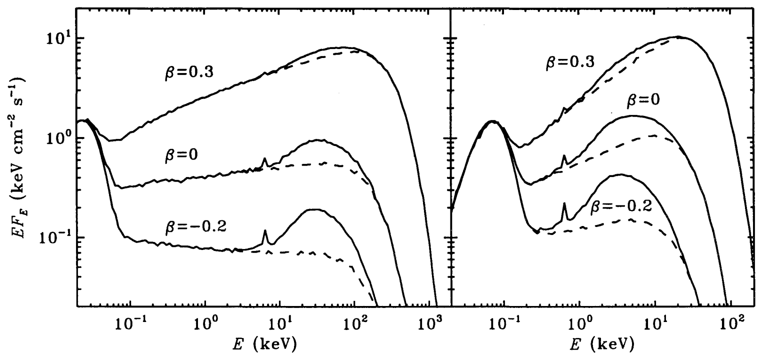

FIGURE 1. Effect of bulk motion on the emitted spectra. Here $h/r = 2$, $\tau_T = 3$, and nearly face-on inclination is assumed, $0.9 < \cos i < 1$. Left panel corresponds to the case of AGN ($kT_{bb} = 5$ eV) and right panel corresponds to GBHs ($kT_{bb} = 150$ eV).

bulk velocity $\beta \lesssim 0.5$ as a result of magnetic dissipation and/or radiative pressure in the corona. The bulk velocity may be directed away or towards the disc (and it may change) with the preferential direction away from the disc. Mildly relativistic bulk motion causes aberration of the X-ray emission and strongly affects both the amplitude of reflection, R, and the spectrum slope, Γ. Here we perform exact computations of the X-ray spectra produced by dynamic coronae. We use a non-linear Monte-Carlo code (Malzac & Jourdain 2000) which is based on the large-particle method (Stern et al. 1995a).

SET UP

For definiteness, consider a cylinder of radius r and height h located atop the accretion disc. The cylinder may be associated with a hot outflow covering the disc or a heated magnetic tube in a compact flare. The plasma in the cylinder is assumed to have a constant density and it is heated homogeneously with a constant rate. The plasma moves through the cylinder with a velocity β directed normally to the disc. The electrons are assumed to have a Maxwellian distribution with a temperature T_e in the plasma rest frame. T_e is calculated from the heating=cooling balance. We assume that reprocessed radiation is the main cooler of the hot coronal plasma and neglect soft radiation generated viscously inside the accretion disc. We assume that the reflecting material of the disc is sufficiently dense so that the ionization parameter $\xi \lesssim 10^3$ and the ionization effects are weak. Then the albedo is small, $a \sim 0.2$, and most of the X-rays impinging the disc are reprocessed. We assume that the reprocessed flux has a quasi-blackbody spectrum (possibly diluted) with a constant temperature T_{bb}. In the simulations, we consider two cases: $kT_{bb} = 150$ eV and $kT_{bb} = 5$ eV, representing the typical temperatures in GBHs and AGN, respectively. We start a simulation from an initial (non-equilibrium) state and follow the evolution of the plasma and radiation in the cylinder until a steady state is achieved. The model has four parameters: (i) Thomson optical depth τ_T (defined along

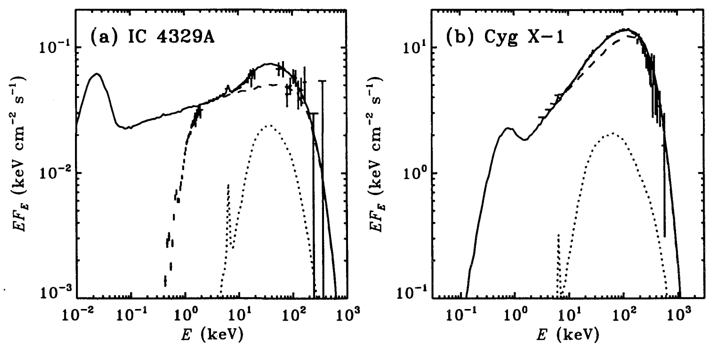

FIGURE 2. Right panel: Spectrum of Cyg X-1 as observed by Ginga and CGRO/OSSE in September 1991 (crosses, set 2 from Gierliński et al. 1997). The solid curve is the model spectrum for $\tau_T = 3$, $h/r = 1.25$, $\beta = 0.3$ at inclination $i = 50°$. Left panel: Spectrum of the Seyfert 1 galaxy IC4329A observed by ROSAT, Ginga, and CGRO/OSSE (crosses, from Madejski et al. 1995). The solid curve is the model spectrum for $\tau_T = 3$, $h/r = 2$, $\beta = 0.1$ at inclination $i = 40°$. In both panels, dotted curves give the reflected components, dashed curves show the intrinsic Comptonized spectra.

the height of the cylinder), (ii) height to radius ratio of the cylinder h/r, (iii) bulk velocity β and (iv) blackbody temperature T_{bb}. Given these parameters the code computes the emitted spectrum as a function of the disc inclination i. Details of the computations are given in Malzac, Beloborodov & Poutanen (2001, hereafter MBP).

THE EFFECTS OF BULK MOTION

Fig. 1 illustrates the effects of bulk motion on the emitted spectra. In the case of $\beta = 0.3$ (plasma moves away from the disc), the observed Comptonized luminosity is enhanced as a result of relativistic aberration. The X-rays are beamed away from the disc, and the reprocessed and reflected luminosities are reduced. The low feedback leads to a hard intrinsic spectrum. In the case of $\beta = -0.2$ (plasma moves towards the disc), the Comptonized luminosity is beamed towards the disc and the reprocessed and reflected components are enhanced. The high feedback leads to a soft intrinsic spectrum. Since τ_T is fixed in Fig. 1, a high (low) feedback leads to low (high) coronal temperature. This causes the shift of the spectral break to lower energies with decreasing β. The dynamic corona model reproduces the broad-band spectra of black hole sources. For illustration, we show in Fig. 2 the model and observed spectra of Cyg X-1 and the bright Seyfert 1 galaxy IC4329A.

REFLECTION AND SPECTRAL INDEX

There are two parameters that are commonly used to quantify the shape of the observed X-ray spectra: Γ, the slope of the primary Comptonisation spectrum in the 2-10 keV range, and R, the amplitude of reflection. The R is defined so that $R = 1$ for an isotropic

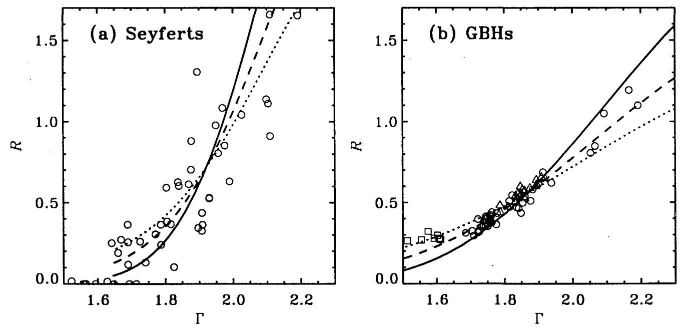

FIGURE 3. Left panel: The observed R–Γ correlation for Seyfert galaxies (data from Zdziarski et al. 1999). The curves show the model with $\mu_s = 0.6$, $\tau_T = 3$, $a = 0.15$ at three different inclinations. Right panel: The $R-\Gamma$ correlation for GBHs (data from Gilfanov et al. 2000). The model curves have $\mu_s = 0.45$, $\tau_T = 3$, $a = 0.15$. In both panels, solid, dashed, dotted curves correspond to $i = 30^\circ, 60^\circ, 70^\circ$.

point source illuminating an infinite slab. Both R and Γ expected from a dynamic corona can be evaluated using a simple analytical model (B99a). We here improve the model by accounting for additional attenuation of reflection by scattering in the corona. The amplitude of reflection is given by

$$R(\mu) = \frac{(1-\beta\mu)^3}{(1+\beta\mu_s)^2} \left\{ \mu_s \left(1 + \frac{\beta\mu_s}{2} \right) + \frac{(1-\mu_s)\left[1+\beta(1+\mu_s)/2\right]}{(1+\beta)^2} \, e^{-\tau_T(1-\mu_s)} \right\}, \qquad (1)$$

where $\mu = \cos i$, i is the inclination angle, and the geometrical parameter $\mu_s \approx (h/2)/\sqrt{r^2+(h/2)^2}$ describes the geometry of the blob. In equation (1), the reflected luminosity is represented as a sum of two parts: the first one is reflected outside the cylinder base and does not experience any attenuation and the second one is reflected from the base and it is partly attenuated, depending on τ_T. When μ_s approaches unity (or $\tau_T \to 0$), the attenuation is not important and equation (1) becomes equation (3) in B99a. In MBP we show that formula (1) is in good agreement with the results of exact simulations. The spectral index Γ can be evaluated using a simple relation between Γ and the amplification factor A (B99b)

$$\Gamma = C(A-1)^{-\delta}. \qquad (2)$$

Equation (2) is a good approximation for models with kT_e in the range between 50 keV and 300 keV (see Fig. 7 in MBP). From our simulations we find $C = 2.19$, $\delta = 2/15$ for GBHs ($kT_{\rm bb} = 150$ eV) and $C = 2.15$, $\delta = 1/14$ for AGN ($kT_{\rm bb} = 5$ eV). The amplification factor ($A = D^{-1}$ where D is the feedback factor) is determined by the geometrical parameter μ_s, the energy-integrated albedo of the disc, a, and the plasma velocity β (B99a)

$$A = \frac{2}{(1-a)(1-\mu_s)} \frac{\gamma^2(1+\beta)^2(1+\beta\mu_s)^2}{1-\beta^2(1+\mu_s)^2/4}. \qquad (3)$$

Combining equations (2) and (3) we get Γ as a function of the corona parameters.

A correlation between R and Γ was found in individual objects observed at different epochs as well as in a sample of sources (Fig. 3). Equations (1-3) give $R(\beta)$ and $\Gamma(\beta)$ predicted by the dynamic corona model for given μ_s, τ_T, a. Variations in β result in $R-\Gamma$ correlation with a shape similar to the observed correlation (see Fig. 3). Note that the correlations for AGN and GBHs cannot be fitted with the same value of μ_s. It might indicate different geometries of the coronae in GBHs and AGN.

CONCLUSIONS

We performed Monte-Carlo simulations of X-ray production by coronae atop accretion discs. The disc-corona model agrees with the data if the hot plasma moves with a mildly relativistic velocity away from the accretion disc. The spectrum of Cyg X-1 is reproduced by the model with $\beta = 0.3$, confirming the estimate of B99a. The observed $R-\Gamma$ correlation is well explained by varying β. It suggests that β may be the main parameter controlling the X-ray spectrum. The results of the simulations are in good agreement with the analytical description of B99a,b. We improved the analytical model by accounting for the attenuation of the reflection component by the hot plasma atop the disc.

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