Studying the Accretion Disks in Black Hole X-ray Binaries with Monte-Carlo Simulations

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Abstract. Understanding the properties of the hot corona is very important for studying the accretion disks in black hole X-ray binary systems. Using the Monte-Carlo technique to simulate the inverse Compton scattering process between disk photons and electrons in the hot corona, we have produced two table models in the XSPEC package. Applying them to the broad-band BeppoSAX observations of the black hole candidate XTE J2012+381, we demonstrate the power of this table model. Our results indicate that the electron distribution in the corona has a powerlaw shape with a spectral index around 4 and the size of the corona is just several tens of gravitational radius and the inclination angle of the disk is around 60 degrees.

INTRODUCTION

The spectrum of a black hole X-ray binary system usually consists of two components (see Zhang, et al. 1997 for a review and references therein): blackbody-like component and powerlaw-like component. The blackbody-like component turns off above 20 keV and is believed to be emitted from the accretion disk. The powerlaw-like component can extend up to 200 keV and is believed to be produced in a hot corona around the black hole through the inverse Compton scattering process between the disk photons and electrons in the corona. This process can be described by the Kompaneets’s equation, which is a non-linear diffusion equation and very difficult for analytical solutions.

Analytic solutions have been worked out by Sunyaev and Titarchuk (1980) and Titarchuck (1994) based on these assumptions: 1) uniform corona with either spherical or disk geometry; 2) seed photons are emitted in the center of the corona; 3) the seed photon distribution follows the Wien form; 4) the thermal temperature of electrons in the corona is much higher than the Wien temperature of the seed photons. However, some or all of these assumptions are not appropriate for black hole binary systems.

In the X-ray astronomy community, the multi-color blackbody (Mitsuda et al., 1984; Makishima et al., 1986; diskbb in XSPEC) plus a powerlaw model has been employed traditionally to fit the energy spectra of the black hole X-ray binary systems; this model is non-physical and unreasonable as we pointed out in our previous paper (Zhang et al., 2001).

In this paper, we use the Monte-Carlo technique to simulate the inverse Compton process in the corona; two powerful table models (as the standard model in XSPEC package) have been built up based on our simulation results. Using these table models to fit the data on XTE J2012+381 with BeppoSAX, we estimated several physical parameters of the accretion disk and corona.
MONTE-CARLO SIMULATIONS

In our simulations, we assume that the accretion disk is the Keplerian disk, and during the accretion process, the potential energy loss of the accreted material is radiated away in blackbody radiation. Therefore, the temperature distribution along the accretion disk is \( T \propto r^{-3/4} \). The corona may take either spherical or disk geometry; the electron density distribution in the corona may be either uniform or non-uniform (take the powerlaw for non-uniform distribution); and the electron energy distribution in the corona may take either thermal form or non-thermal form (powerlaw).

Our simulation results can be summarized as following: 1) for a given electron temperature, the scattered photon spectrum in the high energy band is determined by the optical depth of the corona (FIGURE 1.a); 2) the shape of scattered photon spectrum in the low energy band is related to the geometrical size of the corona (FIGURE 1.b); 3) for the same properties of disk and corona, the ratio between the flux of soft component and that of the hard component is related to the inclination angle of the accretion disk (FIGURE 1.c); 4) the high energy portions of the spectra are very different for different electron energy distributions in the corona, even though the low energy portions are quite similar (FIGURE 1.d).

Based on our simulation results, we have built up two different table models for thermal and powerlaw electron energy distributions respectively. The table models consist of the following parameters: temperature of the inner boundary of the accretion disk \( (T_{in}) \), thermal electron temperature \( (K_T) \) or the electron powerlaw index \( (\Gamma_e) \), size of the corona \( (\text{Size}) \), scattering optical depth of the corona \( (\tau) \), inclination angle of the accretion disk, and normalization parameter \( (K_{BB}) \) which is added by the XSPEC automatically.

APPLICATION TO XTE J2012+381

The two models are applied to model the BeppoSAX broad-band data on the black hole candidate XTE J2012+381. FIGURE 2 shows the modeling results with diskbb + powerlaw model in XSPEC and the results with our table models. During the rising phase of the outburst, the powerlaw component was very strong (Sun et al., 2001)(FIGURE 2(a)). For the BeppoSAX observation during the rising phase we have analyzed, the observed spectrum can be fitted reasonably well using diskbb + powerlaw model with photon index around 2.4 (FIGURE 2(b)). When fitting with our table model for the thermal electron case, the fit to the high energy data above 10 keV is not acceptable (FIGURE 2(c)) and thus the thermal model is rejected. However, when fitting with our table model for the powerlaw electron distribution, the result is comparable to the that with the diskbb + powerlaw model. The powerlaw index for electron energy distribution is around 4, the size of corona is around several tens of gravitational radius and the inclination angle of the disk is around 60 degrees (FIGURE 2(d)).

FIGURE 3 shows the results of inner disk radius inferred with different models. When modeling with diskbb + powerlaw model and diskbb + compTT model, the inner disk radius inferred directly from the normalization of diskbb model are very small compared to the results obtained with our table model. The results after the radiative transfer correction (see Zhang et al. 2001 for detail) are consistent with the results of our table model reasonably well.
CONCLUSION AND DISCUSSION

According to our simulation results and data analysis, the X-ray spectral shape in the low energy band might be related to the size of corona and the electron energy distribution may be inferred from the spectral shape in the high energy band. Two powerful table models have been built up based on our simulation results and the physical parameters can be obtained directly when modeling the data with these table models.

According to the fitting results with our table models, the electron energy distribution in the corona of XTE J2012+381 during the rising phase seems to have a powerlaw form rather than the thermal form and the size of the corona is just several tens of gravitational radii and the inclination angle of the disk is around 60 degrees.

The reason that the size of the corona may be determined from the X-ray data is because in our model the seed photons for the inverse Compton scattering come from the disk, whose temperature is a function of the distance from the central black hole. The relatively small size of the corona indicates that most of the hard X-ray photons come from the region very close to the black hole.

Another interesting result is that the spectral fitting is quite sensitive to the disk
FIGURE 2. Panel (a) shows the ASM light curve of the black hole candidate XTE J2012+381 during its burst in 1998 and the dotted lines in the plot indicate the times of BeppoSAX observations we have analyzed. The first observation is in the rising phase in which the hard component is relatively strong and the other two observations are in the soft state in which the hard component is very weak. Panel (b) shows the modeling result for the first observation with diskbb + powerlaw model. The best fit parameters are: $T_{\text{in}} = 0.77 \pm 0.002$ keV, $K_{\text{BB}} = 887 \pm 10.0$, $\Gamma = 2.4 \pm 0.03$, and the Chi-Squared is 1368 with 553 degrees of freedom. Panel (c) shows the modeling result with our table model for thermal electron distribution in the corona. The best fit parameters are: $T_{\text{in}} = 0.6 \pm 0.02$ keV, $KT = 52 \pm 6.2$ keV, $Size = 19 \pm 1.7R_g$, $\tau = 0.6 \pm 0.06$, and the Chi-Squared is 3109 with 548 degrees of freedom. Panel (d) shows the modeling result with our table model for powerlaw electron distribution in the corona. The best fit parameters are: $T_{\text{in}} = 0.76 \pm 0.002$ keV, $\Gamma_e = 4$, $Size = 49 \pm 6.2R_g$, $\tau = 0.09 \pm 0.003$, $\theta = 59^0 \pm 3.6^0$, and the Chi-Squared is 1564 with 552 degrees of freedom.

Inclination angle. This is because the observed flux from the disk depends strongly upon the inclination angle, while the hard X-ray flux is almost isotropic, especially for the case of spherical corona. Unfortunately the inclination angle and the geometrical factor (opaqueness of the corona) may be coupled together in the spectral fitting if the quality of the data is not good enough. If the inclination angle of the system is determined independently, e.g., with optical photometry observations or radio measurements of jets, the shape of the corona may be constrained reliably with X-ray spectral fitting.

Determining the value of the inner disk radius is very important in understanding the
FIGURE 3. Inner disk radius ($R_{in}^2 \propto K_{BB}$) inferred with different models. These three data points correspond to the three observations indicated in FIGURE 2(a). When modeling with diskbb + powerlaw model and diskbb + compTT model, the results inferred directly from the soft component are quite small compared to the results inferred from our table model and the results after the radiative transfer correction.

physics of the accretion disk and the black hole angular momentum (Zhang, Cui and Chen 1997). The normalization parameter inferred with our table model, which is proportional to the square of the inner disk radius (Makishima et al., 1986), is significantly different from that determined with the simple diskbb + powerlaw or diskbb + compTT model without radiative transfer correction. This is because the corona, though optically thin in most cases, scatters some of the photons emitted from the disk and make the observed soft component different significantly from the original disk emission.

Therefore modeling broad-band X-ray continuum spectra with physically consistent and accurate models provides a powerful tool in determining the properties of accretion disks and coronae in black hole X-ray binaries. However such studies require high quality and broad-band data, which may be provided by BeppoSAX, Chandra and XMM currently. Future data from Integral, Swift and especially the Constellation X-ray missions will provide significant breakthroughs in this field.

Currently, we have not included non-uniform corona and other geometry in our table models. The general relativistic effects and Doppler effects (Zhang, et al., these proceedings) are also not taken into account in our table model currently. All of these will be our future work.

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