The Monte Carlo Simulation of the X-Ray Spectra from the Black Hole X-Ray Binaries

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Abstract. The accretion mode of the black hole X-ray binaries (BHXBs) during the intermediate state remains unclear as it corresponds to an unstable situation. In order to find possible observable clues of the accretion mode, we describe all the possible cases with the same set of parameters, and compare the differences of the X-ray spectra for different values of the parameters. Since the geometry of the accretion flow is complex, we adopt the Monte Carlo simulations to obtain output spectra. Different to previous study, the thickness of the cold gas, which is usually ignored, is taken into account. It is found that for the cases with small clouds or a large amount of clouds, the influence of the thickness are significant since the area of the side surface are comparable to the upper surface area. For the thermal component of the output spectra, or the multi-color black-body spectra, the range of the spectral index is larger. While for the power-law component due to inver Compton scattering, the flux can be increased by a few times, which means higher cooling rate of the hot gas and shorter duration of the intermediate state.

Keywords: Black hole, X-ray binary, accretion disk.

1. Introduction

As well known, the black hole X-ray binaries (BHXBs) experienced different states during the outburst, varying from the initial hard states to the intermediate state and the soft state in sequence when the luminosity keeps increasing, and then chaning inversely when the luminosity decreases. The accumulating observational data enables us to understand the accretion process around the central BH better and better.

For the hard state, the thermal soft photons/X-rays are dominated by the hard power-law/non-thermal photons/X-rays (e.g. /1/). This can be easily explained by the hot accretion flow model, in which the inner hot accretion flow is truncated by the outer cold accretion disk [2]. Since the cold disk locates far away from the central BH, the soft photons from it are inverse Compton scattered by the inner hot gas radiating outwards, increasing its energy, causing the soft thermal photons dominated by the hard photons (e.g. /3/).

When the luminosity is close to 1% of the Eddington limit, the BH system changes to the soft state. The thermal component is dominating, while the power-law component is weak with photon index higher than 2. Compare to the high-energy cutoff in the hard state, the power-law component in soft state can extend to MeV gamma-ray band. The model of standard accretion disc (SAD) plus weak corona can well explain the spectra, in which cold dense gas extends to the innermost stable circular orbit (ISCO). The radiation of SAD is efficient and in form of thermal black-body spectrum, and the corona is weak and can only upscatter a very small fraction of the soft seed photon to hard X-rays. As the corona is radiatively unefficient, either its teperature is high, or the energy distribution of the electrons is non-thermal, therefore it is easy to explain the power-law spectra that extends to MeV band.

The intermediate state is the X-ray state when BHXBs transit from soft to hard, resulting in their spectral shape and luminosity between the high and low state spectra. Such state can be categorized into two divisions—the hard-intermediate state, in which thermal soft photons/X-rays could be

dominated by the hard power-law/non-thermal photons/X-rays, or the soft-intermediate state, which is dominated by soft power-law/non-thermal photons/X-rays. (e.g., /4/).

However, in contrast to the hard and soft states, there is no widely accepted theoretical model yet. The scenarios of state transition are still on debate. On the one hand, the most natural way is the gradully reduction of the truncation radius with increasing accretion rate, in which the truncation radius changes from about 10 gravitational radius to ISCO [5]. However, this model predict critical luminosity for state transition, which is contradict to the hysteresis phenomenon, which tells the state transition happens in a relatively large range of luminosity. On another hand, according to the calculation of disk evaporation and condensing rate, an inner annulus can form at the beginning of the state transition [6]. Moreover, numerical simulations have shown that the cold clumps in the accretion flow can be induced due to instabilities and corresponding overcooling [7].

Yu et al. [8] investigated the spectra of the inhomogeneous accretion flow with Monte Carlos similuation, and they found the warp structure and the deviation from the multi-color black body specta in the thermal component may indicate the existence of the cold clumps. However, in their model, the thickness of the cloud is not considered, which means the area of the side is ignored. Since the flux of thermal emission is propotional to the surface area, their results need modification, especially when the clouds are small, or the number of clouds is large. Moreover, the hot gas is assumed homogeneous in Y17, considering the cooling effect of the cold gas, it is very likely that the hot gas are very different in different region.

In this paper, we take into account the thickness of the cold gas, as well as the radial structure of the hot gas. Although our treatment is in a simple way, the results are helpful to estimate the real case by comparing the variation of the spectra.

2. Model and Methods

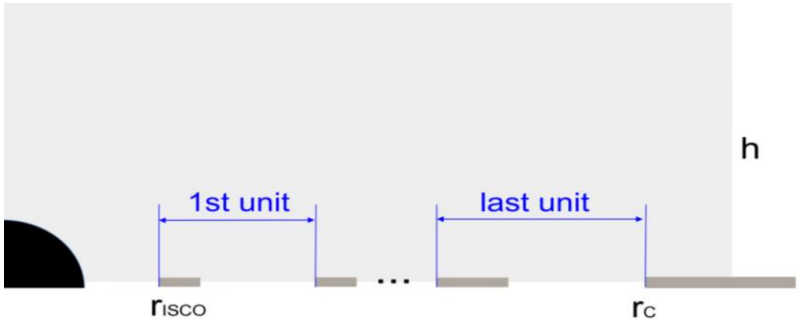


Figure 1. One-quarter cross-section schematic diagram of the toy model. The cold gas, i.e., cold gas disk and clumps, the hot accretion flow, and the BH are shown with dark gray, light gray, and black color, respectively. The unstable region, in which cold clouds form, is assume to be evenly distributed on radial direction

Our model is basically a truncated disk model as shown above, with the continuous cold disk laying outside the truncation radius r_c, and some cold clouds seeding inside the inner hot accretion flow. In order to reduce the number of parameters, we assume the clouds are evenly distributed on radial direction, and the temperature following the SAD model, in which *T* is dierctly proportional to $r^{\frac{3}{4}}$. Different to the continuous disk, the surface area of the clouds are larger due to the side surface. To calculate the area of the side surface, we assume the ratio of the vertical size of the cloud to the height of SAD is the same as the ratio of the radial size to the gap size, i.e. the covering factor *f* is the same in the radial and vertical direction. The height of the SAD is taken as the typical value, i.e., h/r=0.1. The process of state transition can be described with *f*, varying between 0 and 1. The structure of the hot accretion flow can be obtained with the global solution, however in order to investigate the influence of the cold clouds we simplify the hot accretion flow to be two layers along the radial direction, the inner part, $r < r_c$, and the outer part $r > r_c$, as the cooling rate of the cloud could be

either less or higher than SAD depending on its size. The readers are referred to Y17 for more detailed description of the model.

Considering the complex geometry of the accreting system, we use the Monte Carlo method to calculate the output spectrum of the accretion flow, which simulates a large amount of seed photons, follows the trajectory of each photon and samples the possible scattering or absorption randomly according the differential cross section. The detailed process are described as follows.

The first step is to sampling the soft seed photons, which arise from the cold gas by thermal emission. The radial position of each photon is drawn based on the luminosity distribution with the probability density of $P = \sigma T(r)^4 \Delta S_i / L$, where L is the total luminosity from the cold gas, both the cold cloud and the outer cold disk, T is the temperature at radius r that roughly proportional to $r^{-\frac{3}{4}}$ as described by the SAD model, and ΔS_i is the surface of the i-th cloud. It should be noted that the side surface of the cold clouds are also included supposing the height of the cloud is proportional to the thickness of the disk where the ratio of H/r is taken to be the same as the outer cold disk, i.e., 0.1. For simplicity, we assume the vertical covering factor is the same as that in the radial direction. After sampling the radial position, the energy of the seed photon, $h\nu_0$, can be drawn based on the black-body spectrum of temperature T(r). And then assume the direction of the seed photons is isotropic, we can start the trajectory of simulated photon.

Along the free path of the photon trajectory to infinity or the BH, the total optical depth τ due to the hot and cold gas can be calculated, which means the possibility for photon to pass through the medium without interaction is $e^{-\tau}$, and the possibility to interact with the medium is $(1 - e^{-\tau})$. If the free path is towards infinity, we collect the fraction $e^{-\tau}$ of the photon bunch as output spectrum, while if towards the BH, this fraction will be lost. The rest fraction $(1 - e^{-\tau})$ of photon bunch is kept down as weight.

For the free electrons, we assume the free-free absorption and synchrotron self-absorption to be ignorable, and therefore the interaction between the photon and electrons are only scattering. For bounded electrons in the cold gas, in addition to scattering, the bound-free absorption can considered when the photon energy is higher than the threshold. The possibility of scattering or absorption depends on the corresponding cross section for different photon energy. In our work, we assume the cold gas is neutral and the elemental abundence is the same as solar system.

After sampling the position of the interaction with the escaping probability, we simulate the interaction. If the scattering occurs, we first draw the velocity of the isotropic electron with Maxwellian distribution of corresponding temperature, and then draw the energy and direction of the scattered photons with the differential cross section of Compton scattering. If the absorption happens, emission lines will be produced with the probability of the fluorescence yield, otherwise the photon trajectory stops. For the emission line, its weight is the same as that of the photon before absorption, and its direction should be isotropic.

When the photon after interaction is derived, we calculate its escaping probility, as well as its new weight, and sample the interaction again. By repeating the process once and once again, we can simulate the fate of each seed photon. The seed photon will be followed until its weight is ignorable or it is absorbed. And after sampling millions of seed photons, we can obtain smooth output spectra.

3. Results

The output spectra consist of three parts, the thermal emission from the cold gas that directly escaping without scattering, the power-law component due to the inverse Compton scattering of the seed thermal photons, and the reflection from the illumination of the hard X-rays on the cold gas. Generally, the third component is usually weak, and the spectrad is dominated by the thermal component in the soft X-ray band, and by the inverse Compton scattering component in the hard X-ray band. As shown in the following figures, the spectra are characterized by a thermal peak and a power-law with cutoff.

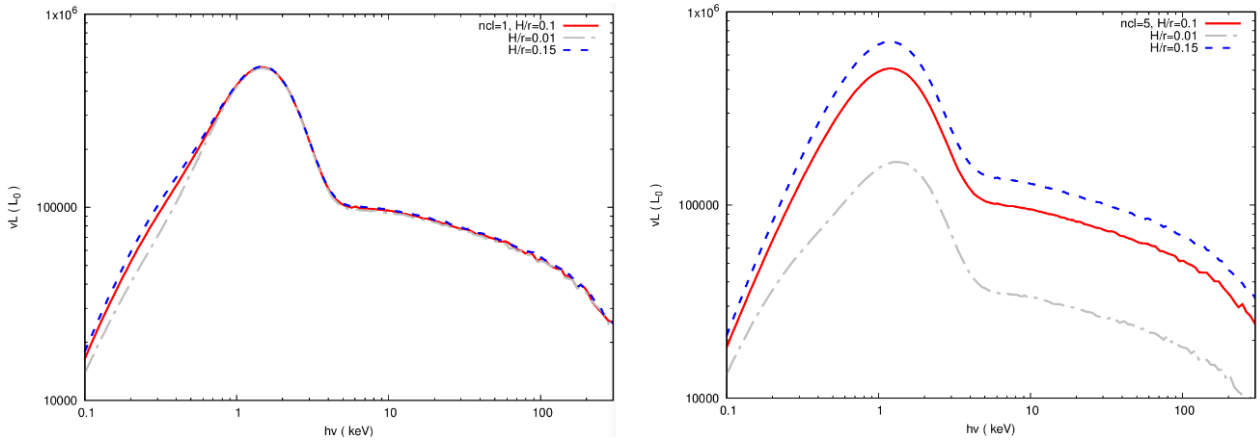


Figure 2. Influences of the thickness of the cold clouds. The left panel shows the case with only one cloud, and the right panel shows the case with 5 clouds. The different type of lines represent the cases with different ratios of the thickness to radius

Different to Y17, the thickness of the cold cloud is included. Its influences on the output spectra are shown in Fig. 2. It can be seen that for the case with one cloud where the side surface is much less than the upper and lower surface, the influence of thickness is small. The minor difference is from the side surface of larger radius because of the larger surface although lower temperature. The difference between the power-law component are subsequently almost the same as the spectra of inverse Compton scattering are determined by the peak of seed thermal emission. While when the number of clouds increases, the side surface becomes larger and larger. As a result, the influence of thickness becomes significant. It can be seen from the right panel that the flux of the output emission increases a lot with the cloud thickness.

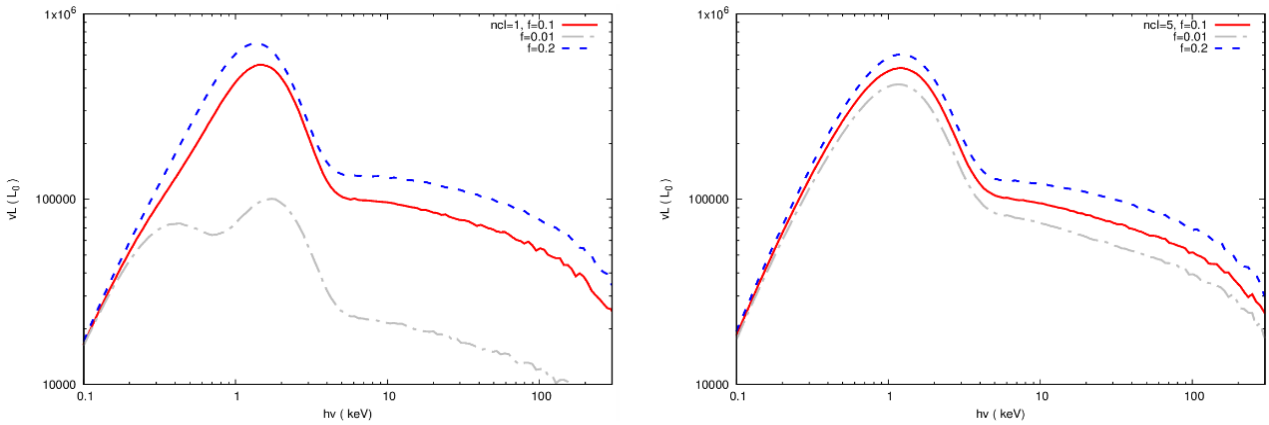


Figure 3. Influences of the covering factor. The left panel shows the case with one cloud and the right panel shows the case with 5 clouds. The cases with f=0.01, 0.1, 0.2 are presented with grey dash-dot, red solid, and blue dashed lines, respectively

The influence of the covering factor is shown in Fig. 3. Similar to Y17, when the cloud is small and the gap between the cold gas is large enough, two thermal peaks of the cloud and outer cold disk appear, otherwise the thermal component will be similar to the multi-color black body of SAD. It can be seen that the thermal and power-law component increases together, which means the cooling rate of the hot gas increases as the soft seed photon strengthens. Compare the red lines in the left and right panel, it can also be seen that the thermal component is steeper and the power-law component is stronger when the cloud number is higher and the covering factor is the same. On the one hand, this is because of the emission from the side surface of the clouds, which adds up the seed photons of higher temperature. On the other hand, the emission from the inner clouds locates in the inner region of the hot gas, which increases the possibility of up scattering.

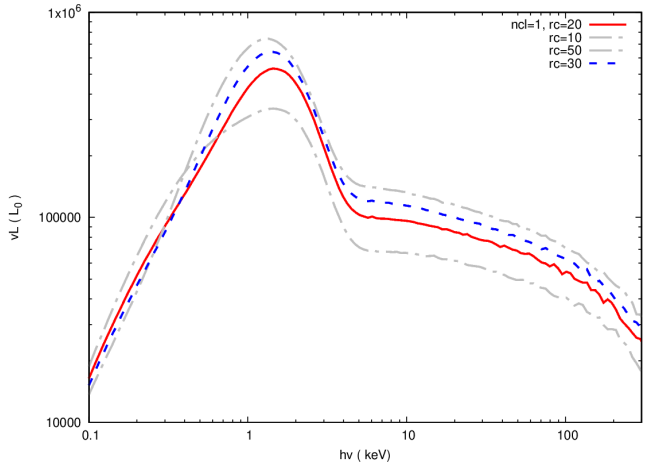


Figure 4. Influence of the truncation radius

The influences of the truncation radius is shown in Fig. 4. For given covering factor, the larger truncation radius implies larger clouds and therefore stronger radiation. It is interesting to compare the cases with largest and smallest truncation radius, as shown by the grey dash-dot lines. Because the inner radius of the outer cold disk is smaller, the contribution from the continous disk becoes more significant while the thermal peak reduces, producing a much flatter themal spectrum.

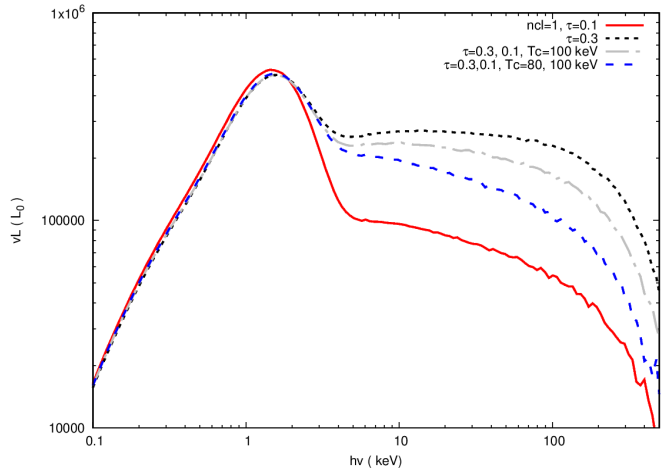


Figure 5. The output spectra for different distribution of the hot gas. As an example, there is only one cloud for all the cases. Here the hot gas is divided into two layer, the inner layer locate at $r < r_c$ and the outer layer $r > r_c$. The red and black lines correspond to homogeneous hot gas but with different optical depth. The grey line corresponds to the case where the temperature is the same but the inner hot gas is denser with $\tau = 0.3$ and the outer gas is rarer with $\tau = 0.1$. The blue dashed line is similar to the grey line but the inner denser gas is of lower temperature

The influence of the structure of hot gas is shown in Fig. 5. Compare the red solid and black dotted lines, i.e. the cases with $\tau = 0.1,0.3$ respectively, the optial depth can significantly increase the flux of power-law component and can play roles to adjust the spectral index. It is easy to understand as the probability for the soft seed photons to be upscattered is proportional to $e^{-\tau}$. Compare the grey dash-dot and blue dotted lines, it can be seen that the temperature of the inner hot gas is very effective to adjust the steepness of the power-law component.

4. Discussion

In Y17, it is found that the aapearance of the cloud leads to the reduction of spectral index in the soft X-ray band of the multi-temeperature black-body spectra. When the surface area of the cloud is considered, the thermal emission from the clouds are stronger, which means the spectral index could even be higher than that of SAD. When the gap between the cloud and the outer disk is large, there

would appear a warp between the thermal peaks of the cloud and the out disk in the soft X-ray spectra, as has been shown in Y17. Since the thermal emission of the cloud is stronger, the thermal peak due to the cloud is higher, and the warp could become more significant.

Moreover, in our calculation, the temperature of SAD is assumed without considering in detail the interaction between the cloud and hot gas, such as thermal conduction, illuminating, etc.. Since the interface between the hot gas and cloud is larger, the heating effect is more efficient, which means the temperature of the cloud should be higher than that of SAD, making the variation of spectral index and warp structure more significant.

For some cases, in addition to the multi-color black-body and the power-law components, a second thermal component is needed to fit the observational data. Here in our model, the cloud can naturally explain the origin of the second thermal component. Since the exsitence of the clouds is also possible to generate wider Fe iron line, it would be interesting to further check the iron line in these cases.

When the thermal seed emission get stronger, the inverse Compton scattering would lead to stronger hard X-ray emission if the hot gas remains the same. As known from observations, when the hard-to-soft state transition starts to occur, the hard X-ray reach maximum, as shown at the right top corner of the q shape in the hardness-intensity diagram. This implies that there is a critical conditions for the variation of the hot and cold gas. The condensing rate of hot gas to cold gas per unit time is higher than the accretion rate, although the accretion rate of the hot gas keeps increasing during the transition. Otherwise, the hot gas is able to maintain its temperature and density, and the corresponding hard X-ray would keep increasing when hard-to-soft transition happens.

As shown in our results, both the temperature and the density of the hot gas can change the spectral index of the power-law X-ray spectra. It is interesting to compare the energy transfer during the state transition. From our results it can be seen that if the temperature and length scale of the hot gas remain the same, the density of the hot gas should decrease by 10 times, as the optical depth should change from about 1 to about 0.1, while if the density remain the same, the temperature decreases, the variation of twice would be engough to explain the variation of spectral index.

It should be noted that when the gas change from hot phase to cold phase, significant thermal energy are released. These part of energy may participate the energy balance, maintaining the temperature as the soft seed photons increases. In this case, when some gas change from one hundred keV to about one keV, the thermal energy decreases by 50 times or more. Without considering the variation due to the accretion rate, if a few percent of the hot gas condense to cold gas, the released thermal energy is enough to increase the internal energy of the rest hot gas by one time.

Combine the above two points, it would be interesting to further explore the state transition. If the spetral variation is due to the temperature, the condensing of only a few percent of the hot gas is enough to explain the spectral variation. However, this is unlikely, as the optical depth remain almost the same. If it is due to variation of the density, it seems to be a problem that a large amount of thermal energy are released. In fact, this should not be a problem. These energy may triger the formatio of outflow, which would effectively take away the hot gas, as well as the thermal energy.

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