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Unification of Spectral States of Accreting Black Holes

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Abstract

Several galactic black holes show transitions between spectral states. The nature of these transitions is not fully understood yet. None of the dynamical accretion disk models can fully describe spectral transitions. In this paper we present a unifying radiation transfer model that can fit the spectral data in both states. Since Cyg X-1 has the best available data, we focus here on modeling this object. We fit individual broad-band (from 1 keV up to 4 MeV) spectral data for the "hard" and "soft" states of Cyg X-1 using an emission model where a central Comptonizing corona/cloud is illuminated by the soft photon emission from a cold, outer disk that does not penetrate much in to the corona. We assume that the energy is injected to the corona by two channels: a non-thermal one that injects energetic (> MeV) electrons into the coronal region, and a thermal one that heats injected and ambient electrons once they cool sufficiently to form a Maxwellian distribution, i.e., we consider a hybrid thermal/non-thermal model. The process of photon-photon pair production is included in the model, and the number of pairs produced in the coronal region can be substantial.

Using simple scaling laws for the luminosity of the cold disk, the thermal dissipation/heating rate in the corona, and the rate of energy injection from a non-thermal source, all as functions of radius of the corona, we explain the hard-to-soft transition as the result of a decrease in the size of the corona and the inner radius of the cold disk by a factor ~ 5. For the case of Cyg X-1, we show that the bolometric luminosity of the source (mass accretion rate) does not change significantly during the transition, and thus the transition is probably the result of a disk instability.

1. Observations of Galactic Black Holes

Galactic black holes radiate X-rays and γ-rays in one of several spectral states. Recently, it has become clear that in the soft state, the power-law spectrum (with typical energy spectral index $\alpha \sim 1.5$) extends to photon energies $\sim m_e c^2$ without any obvious break [1-3]. The black hole spectra in the hard state instead show a cutoff at $\sim$ 100 keV [3-5] and can be fit quite well with thermal Comptonization models up to energies $\sim$ 300 keV. However, there is evidence in the COMPTEL and BATSE data that the hard state spectrum of Cyg X-1 show high energy excess at $\sim$ 500 keV [6, 7]. This excess can be interpreted as a signature of non-thermal electrons in the X/γ-ray source [8, 9]. This excess can also be explained in terms of a multi-zone models where thermal electrons have significantly different temperatures [7, 10, 11].

While the data in any one state can be fit quite successfully by one of the models mentioned above, none of the models proposed thus far can fit data from both states. Esin *et al.* [12] explain the spectral transitions in terms of the advection dominated disks. Their prediction that electron temperature in the soft state should be smaller than that in the hard state (because of the significant increase in the number of ambient soft photons) is in perfect agreement with our findings. However, their model does not explain X/γ-ray spectra that extend unbroken to $\sim$ 1 MeV, since they do not consider non-thermal particles. The soft state power-laws were also explained in terms of bulk Comptonization in a converging flow [13]. This model would require, however, a significant increase in the accretion rate to account for the significant decrease in the radiative efficiency of the spherical converging flow, which does not appear to be the case, at least for the most recent hard-soft transition of Cyg X-1. The observed signatures of Compton reflection with an iron edge smeared out by relativistic effects [14] and the possible extend of the power-law spectrum up to $\sim$ 10 MeV [15] would be difficult to explain in such a scenario.

Since fully dynamical (accretion disk) models are still highly uncertain, in our model, we instead concentrate on the radiative processes that lead to the formation of the observed broad-band spectra of accreting black holes. We propose a "radiative" model (as opposite to dynamical) which is based on the hybrid thermal/non-thermal pair model and can explain both the soft and hard spectra of galactic black holes in a unified way.

2. Hybrid Thermal/Non-Thermal Pair Model (HPM)

The model is based on the pair plasma code of Coppi [16]. The model incorporates the following processes: Compton scattering (using exact the Klein-Nishina cross-section and redistribution function), pair-production and annihilation, Coulomb scattering, and bremsstrahlung. Compton reflection from the cold matter of an arbitrary ionization state is accounted for using angular dependent Green functions [17]. Our model is a single-zone model. (All particle and distributions are assumed to be isotropic and homogeneous in the coronal region.) The input parameters of the model are: (*i*) the thermal compactness, $l_{\rm th} = L_{\rm th}/r_{\rm c} \cdot \sigma_{\rm T}/(m_{\rm e}c^3)$ which characterizes the heating rate of electrons (pairs); (*ii*) the analogous non-thermal compactness, $l_{\rm nth}$, which characterizes the rate of injection of relativistic electrons, (*iii*) the soft photon compactness, $l_{\rm s}$, which represents the fraction of the cold disk luminosity that enters the X/gamma-ray source (corona), (*iv*) $\Gamma_{\rm inj}$, the power-law index of the non-thermal electron injection spectrum, (*v*) $\tau_{\rm p}$ the proton (Thomson) optical depth (ie., the optical depth due to background electrons), and (*vi*) $T_{\rm bb}$, temperature of the soft black body radiation. Here $r_{\rm c}$ is the radius of the corona.

Instead of introducing (ad hoc) a number of zones with different temperatures, we propose the model where electrons are not thermal, but the electron distribution is computed self-consistently balancing electron cooling (by Compton scattering and Coulomb interactions), heating (thermal energy source), and acceleration (non-thermal energy source). Both the electron and positron energy distributions are assumed to consist of a Maxwellian distribution of arbitrary temperature plus a non-thermal tail of arbitrary shape (which is again solved for self-

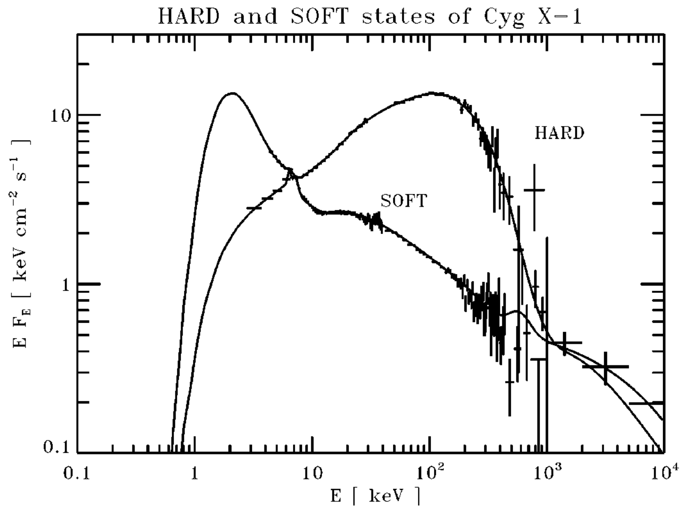

Fig. 1. Best fits to the two spectral states of Cyg X-1 using the hybrid thermal/non-thermal pair model. The hard state data are simultaneous observations by Ginga, OSSE, and COMPTEL (June 1991). The best fit model has the following parameters $l_{\rm nth} = 1.3$, $l_{\rm s} = 1$ (frozen), $l_{\rm th} = 11$, $\tau_{\rm p} = 1.47$, $T_{\rm bb} = 0.13$ keV (f), and Compton reflection amplitude $R = 0.3$, give a χ^2/dof=56/78. The soft state data are from the XTE/PCA and OSSE (June 1996). The model spectrum corresponds to the fit parameters: $l_{\rm nth} = 5$ (f), $l_{\rm s} = 34$, $l_{\rm th} = 3$, $\tau_{\rm p} = 0.23$ (f), $T_{\rm bb} = 0.39$ keV, $R = 1.1$, giving a χ^2/dof=180/169. In both cases the power-law index for non-thermal electron injection was fixed at $\Gamma_{\rm inj} = 2.4$. Spectra cut off at low energies due to interstellar absorption with column density $N_H = 0.6 \cdot 10^{22}$ cm^{-2}.

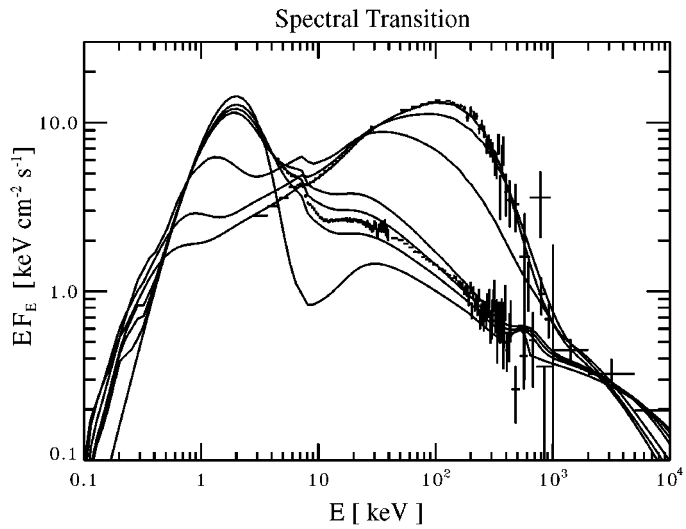

Fig. 2. Simulations of the spectral transitions by the HPM. The starting point is the best fit to the hard state data ($r = 6$). Using the simple scaling laws (see § 4) for $l_{\rm s}, l_{\rm th}, l_{\rm nth}$, we obtain the sequence of spectra covering the transition between the hard and soft states as a function of the inner disk radius, r. From top to bottom (at 100 keV), the curves correspond to the inner disk radius of 6, 4, 2, 1.2, 1.15, 1.1, 1.0, respectively. The spectra at $r \sim 1.1 - 1.15$ are quite close to the observed soft state spectrum.

consistently; in general, it is *not* a power law). The code used in these simulations is incorporated into XSPEC. Although it is simple, this one-zone model appears to be able fit black hole spectra very well.

3. Spectral States

We fit the hybrid pair model to the broad-band data of Cyg X-1 in both hard and soft states using XSPEC. The simultaneous hard-state observations by Ginga, OSSE and COMPTEL [4, 6] are analyzed together. For the soft state, publically available XTE/PCA and OSSE data from June 1996 are analyzed. The data together with the best fit models are presented in Figure 1.

We interpret the spectral transition as a result of decrease of the inner radius of the cold accretion disk (and corresponding decrease in the size of the coronal region). In the hard state, the inner radius of the cold disk is far away from the black hole (at $\sim 30 - 50{\rm GM/c^2}$). Almost all the energy is dissipated thermally in the hot central cloud/corona. In addition, we assume that there is a source of non-thermal electrons (an "accelerator") situated close to the black hole which pumps energetic electrons into the corona. Its contribution to the total luminosity is of order of 10%. The X/gamma-ray source is photon starved since the luminosity of the outer cooler part of the accretion flow is small and the covering factor of the hot corona is quite small too (see, e.g., [18]). Amplitude of the Compton reflection is relatively small, $R \sim 0.3$ [4, 19]. Under these conditions, electrons have an almost Maxwellian distribution with a weak power-law tail. This results in the hard spectrum produced by thermal Comptonization with a small contribution from the non-thermal tail at energies above $\sim m_e c^2$.

In the soft state, the situation is very different. The optically thick cool disc moves inward and receives the majority of the dissipated energy. The thermal energy dissipation in the corona is now a factor of $\sim$ 10 lower than the soft luminosity (from the accretion disk) entering the corona. The non-thermal electron luminosity (which we take to be constant) is larger than the thermal dissipation rate. The electron distribution can be represented by a thermal distribution with a lower temperature (relative to the hard state) of $\sim$ 20 keV and significant power-law tail. Most of the power is now in non-thermal electrons. The resulting spectrum is a black body from the cold accretion disk, followed by a "soft excess" due to Comptonization by the thermal population of electrons (pairs), and then a power-law (Comptonization by non-thermal electrons) which extends up to $\sim kT_{\rm bb}\gamma^2_{\rm max}$ (here $\gamma_{\rm max}$ is the maximum electron energy). Note that since most of the observed X-rays are produced in *one* scattering off non-thermal electrons, we expect no significant time lags between hard and soft photon energies (as would be the case for thermal Comptonization).

4. Spectral Transitions

We model the changes in the source during the spectral hard-to-soft transition by using simple scaling laws for the soft compactness, $l_{\rm s}$, thermal compactness, $l_{\rm th}$, and non-thermal compactness, $l_{\rm nth}$, as well as for proton optical depth, $\tau_{\rm p}$, and covering fraction of the cold disk around hot corona, R. Assume that thermal dissipation in the corona vanishes when inner radius of the cold accretion disk $r = 1$ (arbitrary units), and the radius of the cold disk in the hard state is $r_{\rm hs} > 1$. Now, further assume that the radius of the corona is constant in units of the inner radius of the accretion disk (which is, probably, not exactly the case, see [18]). The sum of soft luminosity from the disk, $L_{\rm s} \propto 1/r$, and the thermal dissipation rate in the corona, $L_{\rm th} \propto 1 - 1/r$, should remain approximately constant during transition (required to fit the data). A decrease in radius r during the transition thus gives the following dependences on r for the model parameters:

$$
\begin{aligned}
l_{\rm s}(r) &= l_{\rm s}^{\rm hs} \left(\frac{r_{\rm hs}}{r}\right)^2 , \\
l_{\rm th}(r) &= l_{\rm th}^{\rm hs} \frac{r_{\rm hs}}{r} \frac{1 - 1/r}{1 - 1/r_{\rm hs}} , \\
l_{\rm nth}(r) &= l_{\rm nth}^{\rm hs} \frac{r_{\rm hs}}{r} .
\end{aligned} \qquad (1)
$$

The quadratic dependence of l_s on r follows from the fact that $L_s \propto 1/r$ and compactness $l \propto L/r$. The thermal luminosity decreases when inner radius of the disk decreases, while the thermal compactness parameter l_{th} grows at large r and the rapidly decreases when r is close to 1. We assume here that proton optical depth follows the (ad hoc) relation $\tau_p = \tau_p^{hs} r/r_{hs}$. (The exact form does not appear to be very important.) Since the amplitude of the Compton reflection is higher in the soft state, we take $R = R_{hs}(r/r_{hs})^{0.8}$. The temperature of the soft photon black body can be computed, of course, from the soft luminosity and the size of accretion disk $T_{bb} = T_{bb}^{hs}(r/r_{hs})^{-3/4}$. The whole sequence of spectra for different r between $r = r_{hs} = 6$ and $r = 1$ is shown in Figure 2. The spectral shape changes dramatically in a very narrow interval of radii between $r = 2$ and $r = 1$, where the thermal energy dissipation in the corona decreases significantly.

5. Summary

We present an emission model that unifies the hard and the soft state of accreting black holes. We show that even when the total source luminosity (the mass accretion rate) is constant, the broad-band source spectrum can significantly change its shape simply due to redistribution of the energy release between the cold outer disk and a hot central corona. (Note that the energy injection rate into non-thermal particles required to explain the soft state spectrum as well as the MeV tail in hard state is also assumed to remain constant during the transition.)

When inner radius of the cold accretion disk is large (tens of GM/c^2), most of the power is dissipated in a central cloud/corona-like structure (the inner hot accretion disk). The Comptonization by mostly thermal electrons produces a spectrum which cuts off at ~ 100 keV, and a weak power-law tail (due to non-thermal population of electrons) extending up to MeV energies. This is the hard state.

In the soft state, most of the power is dissipated in the cold disk, and emerges in form of blackbody-like spectrum. The thermal energy supply to the corona becomes negligible. The emerging spectrum thus consists of a black body, a power-law (produced by non-thermal Comptonization) extending up to MeV energies, and a "soft excess" at a few keV (produced by Comptonization in a cool thermal plasma with temperature of order ~ 20 keV). Note that the temperature and density of the thermal plasma are not free parameters and are determined self-consistently in the model. In both states, Compton reflection bump changes the intrinsic spectrum significantly from ~ 5 to 100 keV.

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