On the origin of spectral states in accreting black holes

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Abstract A numerical code is developed to study radiative processes in relativistic magnetized plasmas. We account for Compton scattering, synchrotron processes, and pair-production/annihilation. For the first time, we solve coupled kinetic equations for electrons/positrons and photons without any approximations on the relevant cross-sections and compute self-consistently the resulting electron and photon distributions. We apply these simulations to model the spectral energy distributions observed in black hole X-ray binaries (BHB). In the absence of external soft photons, the synchrotron self-absorption at close to equipartition magnetic field acts as an efficient electron thermalizer, and therefore even the non-thermal electron injection can result in a nearly thermal equilibrium distribution. This mechanism reduces the need for mysterious 'thermal heating' that was invoked previously to explain thermal Comptonization spectra of BHB. It also stabilizes the spectral slope and fixes the electron temperature at 50–100 keV (when the Thomson optical depth is of the order unity). The resulting quasi-thermal synchrotron self-Compton spectra are very similar to those in the hard states of BHB. The observed hard X-ray spectra, the cutoff at 100 keV, and the MeV tail together strongly constrain the energy dissipation mechanisms. The motion of the inner edge of the accretion disk towards the black hole, resulting in the increased Compton cooling, reduces the equilibrium electron temperature and produces the power-law like distributions of both electrons and photons, which is similar to what is observed in BHB during the transition into the soft state. The energy dissipation and electron acceleration mechanism operating in all spectral states might be very similar in spite of the dramatic difference in the equilibrium photon and electron distributions.

Introduction

The physical processes giving rise to the X-ray/gamma-ray emission of accreting black hole binaries (BHB) have been a matter of debates over the last four decades. The hard state spectra, showing a strong cut-off around 100 keV, are well described by thermal Comptonization, while a weak MeV tail requires the presence of non-thermal particles. The origin of seed soft photons for Comptonization is, however, much less clear. An apparent correlation between the spectral slope and the amount of Compton reflection (Zdziarski et al. 1999) argues in favor of the accretion disk, while the observed optical/X-ray correlation (e.g. Kanbach et al. 2001) leans towards the synchrotron hypothesis. Interesting questions are then what stabilizes the spectral slope in the X-rays at $\alpha_{\rm X} \sim 0.6$–0.8 and what fixes the temperature of the emitting plasma at $kT_{\rm e}$ ~50–100 keV. Do the feedback from the cool accretion disk and the thermostatic properties of electron-positron pairs play a role here? Or does the cooling by synchrotron radiation act as a stabilizer?

In the soft state, BHB spectra are dominated by the thermal disk emission of temperature $kT_{\rm BB}$ ~0.4–1.5 keV. At higher energies the spectrum is a power-law-like and shows no signatures of the cut-off (Grove et al. 1998) extending possibly up to 10 MeV (McConnell et al. 2002). This emission is well described by Comptonization in almost purely non-thermal plasmas (e.g. Poutanen & Coppi 1998; Gierliński et al. 1999). We can ask then why the electrons are nearly thermal in the hard state and what causes such a dramatic change in the electron distribution when transition to the soft state happens? Poutanen & Coppi (1998) proposed that the two states are distinguished by the way the energy is supplied to the electrons: by thermal heating, dominating during the hard state, and by non-thermal acceleration, operating in the soft state. They have considered only Coulomb collisions as a thermalizing mechanism, which are not efficient enough in rarefied plasmas to produce a thermal distribution, if the electrons originally are non-thermal. However, in compact magnetized sources, the synchrotron boiler, involving the emission and absorption of synchrotron photons, is a more efficient particle thermalizing mechanism (Ghisellini et al. 1988).

Ghisellini et al. (1998) studied for the first time the combined effect of the synchrotron boiler and Compton cooling on the electron distribution and photon spectra. They considered a two-phase corona model, where half of the high-energy radiation was assumed to be reprocessed by the disk to soft photons. As the actual geometry of the emitting region is not known, we are interested in studying first pure synchrotron self-Compton models (i.e. with no external soft photons) and in computing self-consistently the electron (positron) and photon distributions. Then we would like to investigate how the additional soft photons (e.g. associated the inner radius of the cool accretion disk) affect the equilibrium distributions and compare the results of simulations with the data on BHB. The results of this study are presented by Vurm & Poutanen (2008a) and Poutanen & Vurm (2008).

Description of the code

The code solves the coupled kinetic equations for photons and electrons/positrons of the form

$$\frac{\partial f_{ph}}{\partial t} = \frac{Df_{ph}}{Dt}_{syn} + \frac{Df_{ph}}{Dt}_{cs} + \frac{Df_{ph}}{Dt}_{pp} - \frac{f_{ph}}{t_{ph.esc}} + Q_{ph}, \qquad (1)$$

$$\frac{\partial f_{e}}{\partial t} = \frac{Df_{e}}{Dt}_{syn} + \frac{Df_{e}}{Dt}_{cs} + \frac{Df_{e}}{Dt}_{pp} - \frac{f_{e}}{t_{esc}} + Q_{e}, \qquad (2)$$

and similar for positrons. Here cs, syn, and pp stand for Compton scattering, synchrotron processes and pair-production/annihilation, respectively. The quantities Df/Dt describe the rates of different processes and contain both integral and differential terms. The quantities Q_{ph} and Q_e denote sources of particles not associated with synchrotron or Compton processes, such as injection of high-energy electrons and external sources (e.g. disk) of photons. To accurately treat electron thermalization by synchrotron processes, Df_e/Dt_{syn} has to contain both first and second order differential terms, accounting for cooling and diffusion in energy. The treatment of Compton scattering over a wide energy range is not straightforward due to the very different behaviour of the process in different regimes. We have therefore adopted an approach, where we treat the process as discrete or alternatively as a continuous energy gain/loss mechanism depending on whether or not the redistribution function can be resolved by our grid. This results in the presence of both integral and up to second order differential terms (to account for diffusion/thermalization) in Df/Dt_{cs} for both photons and electrons. When necessary, the Fokker-Planck differential terms are substituted instead of the integral terms with coefficients computed exactly from the moments of the integral equation. The resulting integro-differential equations are discretized on energy and time grids and solved iteratively as three coupled systems of linear algebraic equations. The detailed description of the code and its extensive testing are presented by Vurm & Poutanen (2008b).

Model setup

We consider a black hole of mass 10 $M_\odot$ and assume the size of the active region of $R = 10R_S = 3 \times 10^7$ cm (where $R_S = 2GM/c^2$ is the Schwarzschild radius). In the following, we assume that the inner accretion flow is hot and almost spherical, corresponding to the advection dominated (e.g. Esin et al. 1997) or to the recently discovered luminous hot accretion flow solutions (Yuan & Zdziarski 2004). The gravitational energy dissipated in the vicinity of the black hole needs to be transferred to electrons which then cool and emit this energy in the X-rays. The details of the electron heating/acceleration mechanisms are unknown. These could be related to the Coulomb collisions with hot protons, collective plasma effects, magnetic reconnection as well as shocks. We assume that the electrons are injected to the active region with the power-law spectrum $Q_e(\gamma) \propto \gamma^{-\Gamma_{inj}}$ extending from Lorentz factor $\gamma = 1$ to 10^3 with the total kinetic power L_{inj}. The electron escape is regulated by fixing the equilibrium Thomson optical depth of electrons associated with protons τ_p. The total optical depth might be larger due to the produced pairs (but for parameters considered in the paper, the amount of pairs is negligible).

The electrons injected into an active region are cooled by synchrotron emission and Compton scattering. The synchrotron radiation is strongly self-absorbed up to tens of harmonics, and therefore the cooling depends strongly on the high-energy tail of the electron distribution. The seed photons for Compton up-scattering can be provided by the synchrotron as well as by the external sources, the cool accretion disk being the most natural one. The importance of synchrotron processes is determined by the ratio $\eta_B = U_B R^2 c / L_{inj}$, where $U_B = B^2/(8\pi)$ is the magnetic energy density (with $\eta_B \sim 0.1$ corresponding to an equipartition of the magnetic and other energy densities). The external soft photons are modelled as a blackbody of temperature T_{BB} determined from the Stefan-Boltzmann law $L_{disk} = 4\pi R^2 \sigma_{SB} T_{BB}^4$. The cooling by external photons depends on the ratio $f = L_{disk}/L_{inj}$. The total power $L = L_{disk} + L_{inj}$ is larger than the total photon luminosity, as the escaping electrons take some energy.

The equilibrium electron distribution is determined by the competition between cooling and thermalization due to synchrotron self-absorption and Compton scattering. For strongly magnetized sources, we expect the electrons to attain a nearly thermal distribution, while in the opposite case, electrons are able to cool before thermalizing, having thus a significant power-law-like tail. Varying the inner radius of the cool outer disk changes the supply of soft photons and has a strong impact on both electron and photon distributions. The closer the disk is to the active region, the stronger is Compton cooling, the lower the equilibrium electron temperature and the more pronounced power-law tail in both distributions.

Synchrotron self-Compton models

Variable electron injection slope

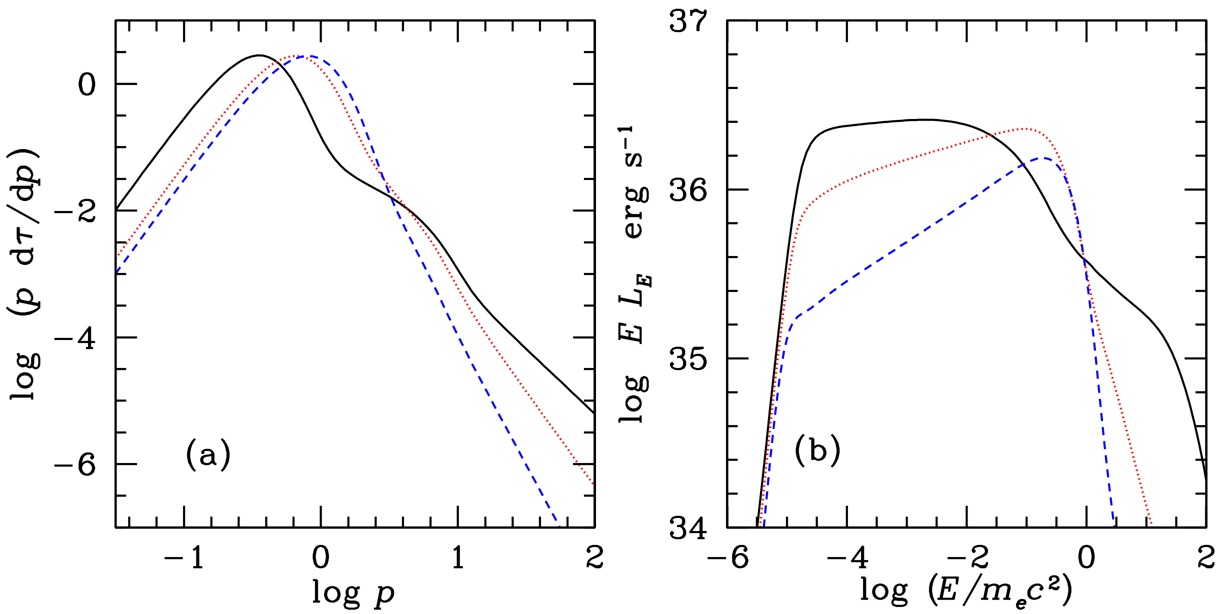

Fig.1: Equilibrium (a) electron distributions (Thomson depth per log of momentum $p = \sqrt{\gamma^2 - 1}$) and (b) photon spectra for different injection slopes: $\Gamma_{\rm inj} = 2$ (black), $\Gamma_{\rm inj} = 3$ (red) and $\Gamma_{\rm inj} = 4$ (blue). Other parameters: $\tau_{\rm p} = 1.5$, $L = 10^{37}$ erg/s, $\eta_{\rm B} = 1$, no external radiation ($f = 0$). The Maxwellian parts of the distributions correspond to electron temperatures 21, 63 and 87 keV, respectively.

A soft electron injection with $\Gamma_{\rm inj} > 3$ leads to efficient thermalization, because the synchrotron emission of the majority of electrons is strongly self-absorbed. This also reduces the amount of soft photons resulting in rather hard radiation spectra, with the photon energy index $\alpha_{\rm X} = 0.7$–0.9 and cut-off at ∼100 keV, which is similar to the hard state of BHB. A harder injection spectrum leads to more power in the nonthermal tail and more seed photons for Comptonization, which causes a drop in the electron temperature (see Fig. 1a). A curious secondary 'bump' also develops at $\gamma \sim 3$. The synchrotron emission produced by these electrons is still strongly self-absorbed, while the energy losses and gains stay close to each other for an extended energy interval (Katarzynski et al. 2006). One can show that the ratio of energy loss and gain rates for relativistic power-law electrons emitting in self-absorbed regime is approximately $\frac{\dot\gamma_c}{\dot\gamma_h} = \frac{5}{\Gamma_{\rm e}+2}$, where $\Gamma_{\rm e} = \Gamma_{\rm inj} + 1$ is the index of the steady-state power-law electron distribution. Observe that for $\Gamma_{\rm e} = 3$ (i.e. for $\Gamma_{\rm inj} = 2$) the heating and cooling rates are balanced, however, such an equilibrium is unstable (Rees 1967). The Comptonized spectrum for hard injection $\Gamma_{\rm inj} = 2$ is much softer than the hard state spectra, even without any contribution to the cooling from the disk. This strongly constrains the electron injection mechanism in these sources.

Synchrotron self-Compton models

Variable magnetization

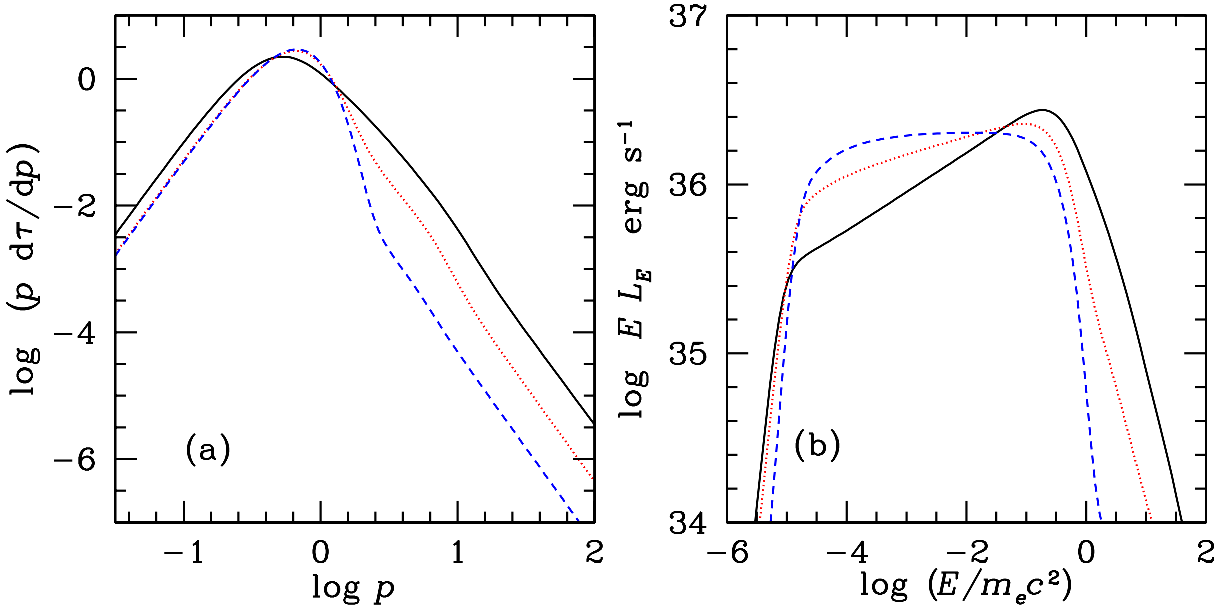

Fig.2: Equilibrium (a) electron and (b) photon distributions for variable $\eta_{\rm B}$: $\eta_{\rm B} = 0.1$ (black), $\eta_{\rm B} = 1$ (red), $\eta_{\rm B} = 10$ (blue). Other parameters: $\Gamma_{\rm inj} = 3.0$, $\tau_{\rm p} = 1.5$, $L = 10^{37}$ erg/s, no external radiation. Equilibrium $T_{\rm e}$ are around 60 keV.

The efficiency of electron thermalization and synchrotron cooling depends on magnetization $\eta_{\rm B}$. At small $\eta_{\rm B}$, electrons cool to rather low energies before thermalizing, resulting in a higher normalization of the power-law part of the distribution. At high $\eta_{\rm B}$, the (synchrotron) cooling rate increases and the normalization of the power-law decreases. At the same time, the synchrotron thermalization operates more efficiently and the thermal part of the distribution persists to higher energies. As magnetic field gets stronger, synchrotron emissivity increases resulting in softening of the Comptonized spectrum. For $\eta_{\rm B} \lesssim 1$ (and $\Gamma_{\rm inj} > 3$), the thermal Comptonization spectrum is very stable with $\alpha_{\rm X}$ ~0.7–0.9.

The hard X-ray spectra with $\alpha_{\rm X} < 0.7$ and a high-energy cutoff at ~100 keV observed e.g. in Cyg X-1, require low $\eta_{\rm B} < 0.1$ or large $\Gamma_{\rm inj} > 4$ (or much larger than the assumed $R = 10R_{\rm S}$ size, which would reduce the magnetic field strength, $B \propto 1/R$, for fixed $\eta_{\rm B}$ and $L_{\rm inj}$). If the MeV tail with $\alpha_{\rm MeV} \approx 2$ is produced by the non-thermal electrons in the same physical region as the rest of the emission, it constrains the injection slope to be $\Gamma_{\rm inj} < 2\alpha_{\rm MeV} = 4$. In the soft state, the MeV tail is even harder $\alpha_{\rm MeV} \approx 1.6$, and therefore $\Gamma_{\rm inj} < 3.2$. If the injection is similar in both states, the only possible explanation for the very hard X-ray spectra is low $\eta_{\rm B}$, which rules out magnetic reconnection as the energy dissipation mechanism. Any additional soft photons from the disk will make the spectrum softer, putting stronger constraints on $\Gamma_{\rm inj}$ and $\eta_{\rm B}$. The thermostatic properties of the SSC mechanism (not the feedback from the cool disk) fix $T_{\rm e}$ and stabilize $\alpha_{\rm X}$.

Synchrotron self-Compton models
Variable optical depth / luminosity

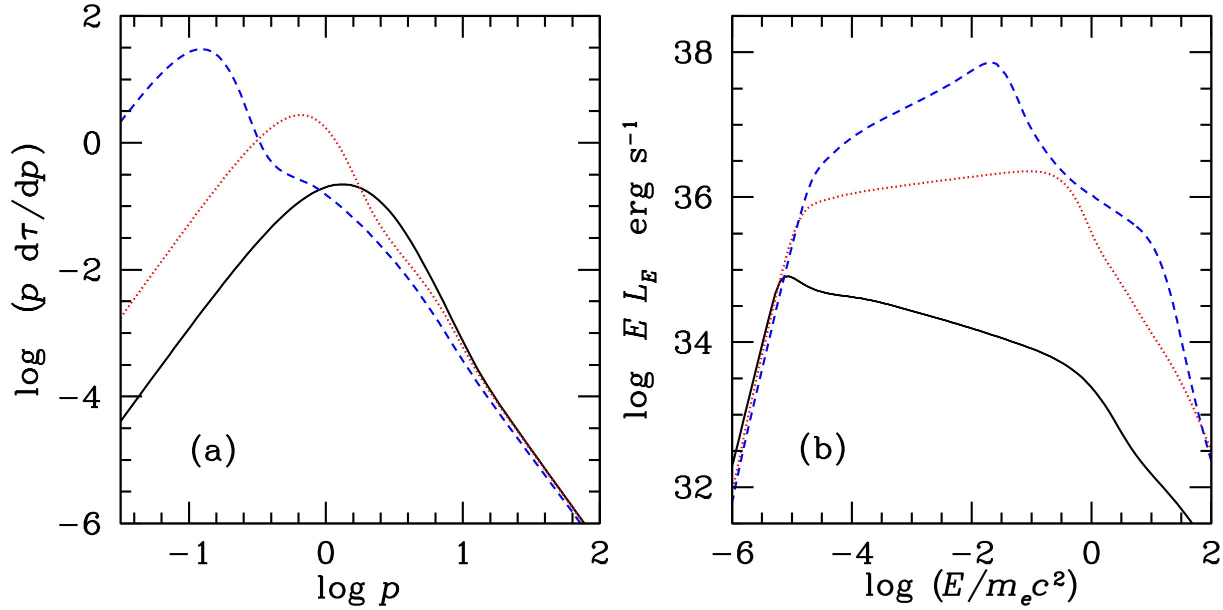

Fig.3: Equilibrium (a) electron and (b) photon distributions for variable L (and $\tau_{\rm p}$): $L = 10^{36}$ (black), 10^{37} (red), 10^{38} erg s^{-1} (blue), which results in different optical depths in the steady-state (for fixed escape time) $\tau_{\rm p} = 0.15$, 1.5, 15, respectively, with the equilibrium electron temperatures of ∼160, 67 and 2.7 keV.

Now we fix the electron escape time from the system and vary the source luminosity, which results in changing the equilibrium optical depth. At high L, larger $\tau_{\rm p}$ causes equilibrium electron temperature to drop, which leads to stronger synchrotron absorption reducing the number of seed photons for Comptonization. This, in turn, results in the harder photon spectra produced by saturated Comptonization and a weak high-energy tail, very similar to the ultrasoft spectra of BHB. At lower $L \sim 10^{36}$ erg s^{-1}, smaller $\tau_{\rm p} = 0.15$ and higher equilibrium temperature of ∼160 keV lead to a stronger synchrotron cooling and softer Comptonized spectra of $\alpha_{\rm X} \approx 1.25$.

Spectral transitions and the role of disk photons

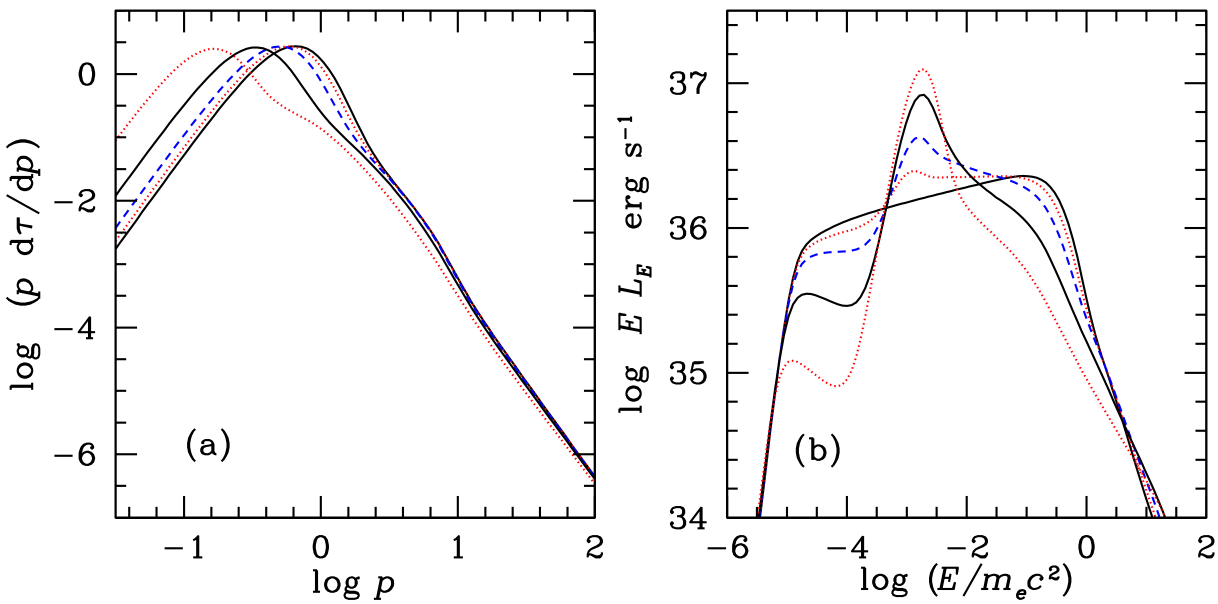

Fig.4: Equilibrium (a) electron and (b) photon distributions for different ratios between the power from external soft photons (disk) and the injected power : $f = 0, 0.1, 0.3, 1, 3$ (for constant total power L).

The spectral transitions are most probably accompanied by the change in the geometry of the accretion disk. The cool outer disk moves towards the central black hole causing an increasing flux of the soft photons to the central hot flow (Esin et al. 1997, Poutanen et al. 1997; Poutanen & Coppi 1998). We follow this approach here. We start from $f = 0$, which gives the spectra similar to the hard state, and increase the ratio $f = L_{\rm disk}/L_{\rm inj}$ gradually. For simplicity we keep here the total power L constant. The results are presented in Fig. 4. The increasing flux of the soft photons leads to faster Compton cooling and shifts the equilibrium electron temperature to lower values making the non-thermal part more pronounced. The resulting photon distribution changes from the hard, thermal Comptonization dominated spectrum to the one dominated by the disk blackbody, with a non-thermal tail extending to tens of MeV. The MeV tail becomes flatter at high f, because of a less significant absorption due to the pair-production on the 100 keV photons.

Spectral transitions in Cygnus X-1

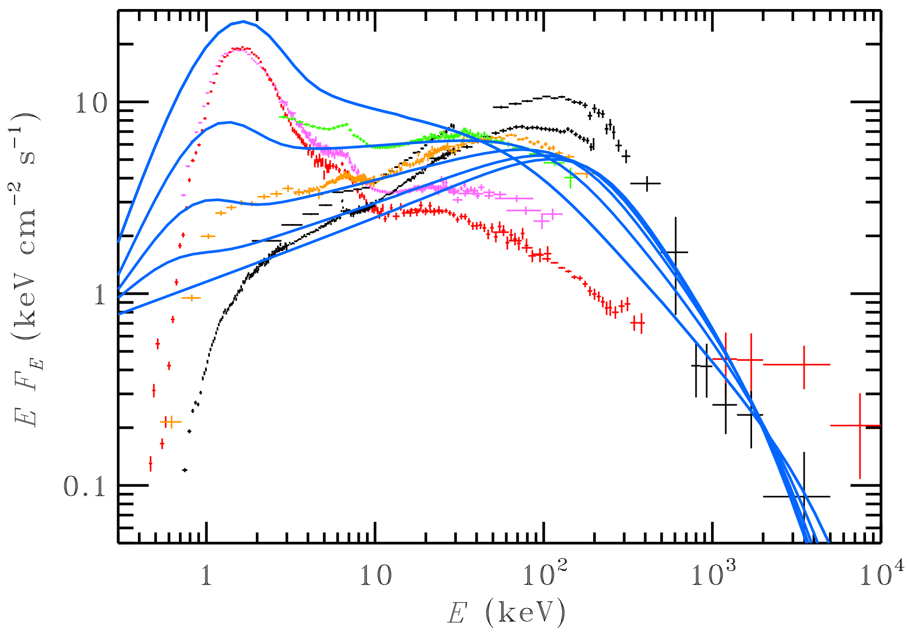

Fig.5: Spectral states of Cyg X-1 (crosses show the unfolded spectral data presented by Zdziarski et al. 2002) and the model spectra. Model parameters: $L_{\rm inj} = 5 \times 10^{37}$ erg s^{-1}, $\Gamma_{\rm inj} = 3.5$, $\tau_{\rm p} = 2$, $\eta_{\rm B} = 0.1$ and $f = 0, 0.03, 0.1, 0.3, 1, 3$.

We now try to reproduce the transitions observed in Cyg X-1. For that we fix $L_{\rm inj} = 5 \times 10^{37}$ erg s^{-1} to give the photon luminosity of $\sim 3 \times 10^{37}$ erg s^{-1} typical for Cyg X-1 in the hard state, and consider $\tau_{\rm p} = 2$, $\Gamma_{\rm inj} = 3.5$, $\eta_{\rm B} = 0.1$ which produce a rather hard X-ray spectrum for $f = 0$ and an MeV tail at the same time. We vary the disk luminosity while keeping $L_{\rm inj}$ constant. This leads to the transition shown in Fig. 5. As we do not aim here to provide detailed fitting of the data, the Compton reflection bump is not added to the model spectra, which explains partially the deviation between the model and the data. The deficit in high-energy (>1 MeV) photons in the soft state results from our fixed $\Gamma_{\rm inj}$, while in reality the injection seems to harden. We also did not account for the fact, that some fraction of the disk photons can propagate directly to the observer and $L_{\rm inj}$, R, and $\tau_{\rm p}$ do not need to be constant. In spite of all these simplifications, this toy model reproduces the observed trend rather well.

We stress again that the dramatic changes in the electron and photon distributions are produced by varying a single parameter f, while the electron injection is kept constant. This is different from the earlier model of Poutanen & Coppi (1998), where also the ratio of the electron thermal heating to the efficiency of acceleration was varied.

Conclusions

1. The hard state of BHB can be well described by the quasi-thermal SSC mechanism. The feedback from the cool disk is not needed to stabilize the spectral slope and the electron temperature. Electrons can be injected to the active region with the power-law spectrum, but the synchrotron self-absorption thermalizes them efficiently. This mechanism reduces the need for mysterious 'thermal heating' that was invoked previously to explain thermal Comptonization spectra of BHB. The hard X-ray spectra of BHB with photon energy indices $\alpha_{\rm X} \lesssim 0.7$ require either soft electron injection with $\Gamma_{\rm inj} > 4$ or rather low magnetization $\eta_{\rm B} < 0.1$ or large size $R \gg 10R_{\rm S}$. If the MeV tail is produced in the same physical region as thermal Comptonization spectra, injection with $\Gamma_{\rm inj} < 4$ is required, which is only marginally consistent with the constraints from the X-ray slope. In that case, magnetic reconnection can be ruled out as a source of energy.
2. At high optical depth of the emitting region $\tau_{\rm p} \gtrsim 10$, in the absence of disk radiation, the spectrum is close to saturated Comptonization, peaking at a few keV. This Wien-type spectrum might be associated with the ultrasoft state of BHB. At low $\tau_{\rm p}$, the electrons are hotter and the spectra are softer due to the efficient synchrotron cooling.
3. The spectral state transitions in BHB can be reproduced by varying the ratio of injected soft luminosity and the power dissipated in the hot phase, which could be caused by varying the radius of the inner cool disk. The increasing Compton cooling causes dramatic changes in the electron distribution from almost purely thermal one to nearly non-thermal. The photon distribution also changes from quasi-thermal SSC to the non-thermal Comptonization of the disk photons.

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