HARD X-RAY–EMITTING BLACK HOLE FED BY ACCRETION OF LOW ANGULAR MOMENTUM MATTER

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ABSTRACT

Observed spectra of active galactic nuclei and luminous X-ray binaries in our Galaxy suggest that both hot (∼10^7 K) and cold (∼10^6 K) plasma components exist close to the central accreting black hole. The hard X-ray component of the spectra is usually explained by Compton upscattering of optical/UV photons from optically thick cold plasma by hot electrons. Observations also indicate that some of these objects are quite efficient in converting gravitational energy of accretion matter into radiation. Existing theoretical models have difficulties in explaining the two plasma components and high intensity of hard X-rays. Most of the models assume that the hot component emerges from the cold one because of some kind of instability, but no one offers a satisfactory physical explanation for this. Here we propose a solution to these difficulties that reverses what was imagined previously: in our model, the hot component forms first and afterward it cools down to form the cold component. In our model, the accretion flow initially has a small angular momentum, and thus it has a quasi-spherical geometry at large radii. Close to the black hole, the accreting matter is heated up in shocks that form because of the action of the centrifugal force. The hot postshock matter is very efficiently cooled down by Comptonization of low-energy photons and condensates into a thin and cool accretion disk. The thin disk emits the low-energy photons which cool the hot component. All the properties of our model, in particular the existence of hot and cold components, follow from an exact numerical solution of standard hydrodynamical equations—we postulate no unknown processes operating in the flow. In contrast to the recently discussed advection-dominated accretion flow, the particular type of accretion flow considered in this Letter is both very hot and quite radiatively efficient.

Subject headings: accretion, accretion disks — black hole physics — hydrodynamics — methods: numerical — X-rays: general

1. INTRODUCTION

There is general agreement that the observed properties of Galactic black hole candidates and of active galactic nuclei (AGNs) could be best explained in the framework of accretion disks around black holes. However, no theoretical accretion disk model could explain all the basic properties of these sources. In particular, the best known model, the standard Shakura & Sunyaev (1973) disk (SSD) model, predicts a temperature of accreted matter far too low to explain the hard X-ray emission (hv ≥ 10 keV) that is observed. The observed hard X-ray emission could be explained by postulating the existence of a very hot plasma, with electron temperature $T_e = 10^9$ K, in which soft photons emitted by the SSD are boosted to higher energies by the inverse Compton effect. The question is, How does such a hot plasma form in black hole accretion flows?

The very popular disk-corona (DC) model (Liang & Price 1977; Haardt & Maraschi 1993) postulates the existence of the $T_e = 10^9$ K plasma in the form of a hot corona above the cold disk. Because the physics of DC models is largely ad hoc, a typical specific DC model contains a set of free tunable parameters. Also, more recent studies that consider magnetic flares as a source of corona activity (Di Matteo 1998; Beloborodov 1999) are far from self-consistency.

In the Shapiro, Lightman, & Eardley (1976) hot, optically thin accretion disk model, ions are heated by viscous dissipation of their orbital energy and inefficiently cooled by the Coulomb interaction with electrons. Thus, the ions have temperature close to the virial temperature, $10^{11}–10^{12}$ K. Electrons are very efficiently cooled by a variety of radiative mechanisms, and this reduces their temperature to about $10^9–10^{10}$ K, which is sufficient for explanation of the hard X-ray radiation. The Shapiro et al. (1976) model is, however, violently thermally unstable, and therefore it cannot describe objects that actually exist.

Detailed models of black hole optically thin accretion flows in which cooling is dominated by advection (ADAFs) have been recently constructed in many papers (see recent reviews in Abramowicz, Björnsson, & Pringle 1998 and Kato, Fukue, & Mineshige 1998). ADAFs are hot, with the electron temperature about $10^9–10^{10}$ K, and underluminous, $L \ll L_{\text{Edd}}$. Here $L_{\text{Edd}} = 1.3 \times 10^{38}(M/M_\odot)$ ergs s$^{-1}$ is the Eddington luminosity corresponding to the black hole mass $M$. No ADAF solution is possible above a limiting accretion rate that is roughly about $0.1M_{\text{Edd}} = 0.1L_{\text{Edd}}c^2$. In some black hole sources, however, observations point to accretion rates and radiative efficiencies that are much too high for the standard ADAF model to explain (see review in Szuškiewicz, Malkan, & Abramowicz 1996). On the theoretical side, no satisfactory model of an SSD-ADAF transition has been worked out, and in order to account for the presence of cold matter together with hot ADAF plasma, one still uses phenomenological arguments (see Kato & Nakamura 1998).

A model of the inhomogeneous inner region of an accretion
disk was proposed by Krolik (1998). In this model the accretion flow consists of clouds moving in a hot, magnetized intercloud medium, which can principally explain the emission of hard X-rays. Such a structure could result from a dynamical photon bubble instability in radiation pressure-supported disks (Spiegel 1977; Gammie 1998). Due to a significant complexity in describing the inhomogeneous medium, the model contains a number of phenomenological assumptions. In particular, the assumption of stability of such a configuration is questionable.

Motivated by the above difficulties of the existing models for black hole accretion flow in explaining the coexistence of the hot and cold components, we have constructed a new model that has the following properties. (1) Both very hot, hard X-ray-emitting gas and sufficiently cool gas, consistent with the detection of the fluorescent iron line, are present very close to the central black hole. (2) A significant part (up to \( \sim 50\% \)) of the total luminosity (\( \sim 10^{-1} \) to \( \sim 10^{-2}L_{\text{edd}} \)) of the object is emitted in hard X-rays. (3) Flow is stationary and globally stable for large accretion rates (\( M \sim M_{\text{edd}} \)).

The key element of the model is that accretion matter initially has a low angular momentum. We keep in mind two kinds of objects in which low angular momentum accretion onto a black hole may occur.

1. Black holes, which are fed by accretion from winds blowing from the OB star in binary systems (Illarionov & Sunyaev 1975a). The most popular object of this kind is the X-ray binary Cygnus X-1 (see Liang & Nolan 1984).

2. Luminous X-ray quasars and AGNs, in which the central supermassive black hole is fed by the matter that is lost from stars of the slowly rotating central stellar cluster (Illarionov 1988).

In its basic respects, the geometry of our model closely resembles that of the DC model. Our model is different from that recently discussed by Esin, McClintock, & Narayan (1997), although they both stress the importance of cooling by inverse Comptonization.

### 2. LOW ANGULAR MOMENTUM ACCRETION

Let us consider matter with a low characteristic specific angular momentum \( \ell \), accreted quasi-spherically onto the central black hole. By low \( \ell \), we mean that which corresponds to the Keplerian orbit with radius \( r_\ell = 2G\ell c^2 / \ell \) in the range \( 3r_\ell \lt r \lt 100r_\ell \). Here \( r_\ell = 3 \times 10^8 (M/M_\odot) \) cm is the gravitational radius of a black hole with mass \( M \). Matter with angular momentum smaller than that in the indicated range could not form an accretion disk around the Schwarzschild black hole because the innermost stable orbit around such a hole is localized at \( r = 3r_\ell \). Matter with \( \ell \) higher than in the indicated range could form an accretion disk that extends from the black hole to large radial distances, \( r \geq 100r_\ell \); this would correspond to the previously studied SSD.

At large radii, \( r \gg r_\ell \), the low angular momentum accretion flow closely resembles spherical Bondi accretion (Bondi 1952). Approximated models of spherical accretion onto a luminous X-ray central source were studied by several authors (e.g., Ostriker et al. 1976; Bisnovatyi-Kogan & Blinnikov 1980). It was shown by Igumenshchev, Illarionov, & Kompaneets (1993) that inside of the Compton radius \( r_c = 10^3 (10^5 K T_c) r_\ell \), where the Compton temperature \( T_c \) is determined by the “average” photon energy of the source, accretion is almost spherical and supersonic. Our model shows that at smaller radii \( r \sim r_\ell \), the flow significantly deviates from the spherical accretion. Fluid elements tend to cross the equatorial plane at the radius that corresponds to the Keplerian orbit for the angular momentum of the element. This leads to formation of shocks above and below the equatorial plane at \( r \sim r_\ell \). By crossing the shocks, protons reach the virial temperature \( T_v \approx 10^{12} (r / r_\ell) \) K. In the presence of soft photons from the thin accretion disk, electrons in the postshock region are efficiently cooled by inverse Comptonization. These cold electrons also efficiently cool protons via Coulomb collisions. Such a plasma undergoes a runaway cooling due to the intensive bremsstrahlung-Compton processes at layers, in which the Compton \( \gamma \)-parameter reaches the order of unity. At these layers, protons lose most of their thermal energy, and the plasma condenses into the thin and cold disk.

The thin disk spreads to very large radii, \( r \gg r_\ell \), because of the viscous diffusion (von Weizsäcker 1948; also see Pringle 1981) from the region of condensation at \( r \sim r_\ell \). It is convenient to consider two different parts of the thin disk. The inner part, \( r \leq r_\ell \), is an accretion disk in which matter moves inward and angular momentum is transported outward. Matter mainly enters the black hole through this thin accretion disk, which means that radiative efficiency of the system is as high as in the standard SSD model (\( \approx 6\% \) for the Schwarzschild black hole).

At the outer part of the disk, \( r \approx r_\ell \), angular momentum is transported outward, removing its excess from the accretion flow to large radii.

### 3. NUMERICAL METHOD

To study details of the model briefly described in the previous section, we have simulated the low angular momentum accretion of weakly magnetized plasma onto a black hole with the help of two-dimensional time-dependent hydrodynamical calculations. Our code is based on the PPM hydrodynamical scheme (Colella & Woodward 1984) and solves nonrelativistic Navier-Stokes equations in spherical coordinates, assuming the azimuthal symmetry. We calculate separately the balance of the internal energies of electrons and protons for the electron-proton plasma. The energies of electrons and protons are coupled through the Coulomb collisions. Electrons are cooled by bremsstrahlung and Compton mechanisms. The cold and thin accretion disk at the equatorial plane emits soft photons needed for the Compton cooling. The thickness of the disk is not resolved in our models. We approximately calculate the energy release in the disk and the corresponding radiation flux, which directly affects the efficiency of the Compton cooling, using the standard SSD model. In the model, the accretion rate in the cold disk equals the condensation rate of the hot plasma into the disk, which is directly calculated in numerical simulations.

We neglect the multiple photon scattering processes when calculating the Compton cooling of plasma. This approximation is quite reasonable for the optically thin flows (\( \tau \approx 1 \)), which are characteristic for our models. We do not solve the transfer equation for radiation emitted by the thin disk. However, we calculate the radiation density (which is used to find the plasma energy losses) at each point above and below the disk by integrating the direct radiation from the disk surface.

In our simulations, protons are heated by shocks, adiabatic compression, and viscous dissipation. We take into account all the components of the viscous stress tensor corresponding to shear in all directions. The bulk viscosity is not considered. The kinematic viscosity coefficient is taken in the standard \( \alpha \)-paramterization form: \( \nu = \alpha c / \Omega_k \), where \( \alpha \) is a constant, \( c \) is the isothermal sound speed, and \( \Omega_k = (r / r_\ell)^{3/2} c / \sqrt{2} r_\ell \) is the
Keplerian angular velocity. We use $\alpha = 0.1$ in numerical models. No artificial numerical viscosity was used in the calculations.

At the outer boundary, we assume a supersonic matter inflow with the spherically symmetric–distributed density and the specific angular momentum distributed in the polar direction consistently with rigid rotation: $\ell(\theta) = \ell_{\text{max}} \sin^2(\theta)$. The parameter $\ell_{\text{max}}$ determines (roughly) the maximum radius, $r_g = 2\ell_{\text{max}}/c^2$, inside which the condensation of the hot plasma to the thin disk takes place. For convenience, we will use the parameter $r_g$ rather than $\ell_{\text{max}}$ when describing results of numerical simulations. At the inner boundary $n_{\text{in}} = 3r_g$, and at the equatorial plane, where the condensation occurs, we assume total absorption of the inflowing matter.

4. RESULTS AND DISCUSSIONS

We follow the evolution from an initial state until a time when a stationary flow pattern is established. Models show a strong dependence on two parameters: accretion rate $M$ and $r_g$. We have calculated several models with different $M$'s and $r_g$'s. Two examples of stationary accretion flows with $r_g = 30r_g$ and two different $M$'s ($M = 0.25$ and $0.5M_{\text{Edd}}$) are presented in Figure 1. One can clearly see two stationary shock structures, which are developed in each model. The structures are more compact for larger $M$. The nature of the inner shock at radial distances $r < r_g$ above and below the equatorial plane has already been discussed in § 2. In these shocks, the supersonic accretion flow is slowed down before condensation to the thin disk. We expect that, in the hot postshock plasma, the inverse Comptonization of soft photons emitted from the thin disk provides the main contribution to the hard X-ray luminosity of this type of accretion flow. In this region, the maximum proton temperature $T_p \approx 10^{11}$ K and the electron temperature $T_e \approx 10^7$ K in both models shown in Figure 1. The distribution of $T_e$ in the postshock region is quite uniform.

Note that we do not resolve in our calculations the regions close to the thin disk surface, in which the main part of energy of the matter being condensed is released and where the Comptonized spectrum is formed. We are limited in space resolution by the sizes of numerical cells, but the scale of the condensation region is much less than the cell’s sizes. This lack of resolution can be demonstrated by the estimation of the $\gamma$-parameter, calculated as the integral $\gamma = \int (kT_e/m_e c^2) dr$, where $\gamma$ is the Thomson optical depth and the integration is taken in the $z$-direction from the equatorial plane to the outer boundary. For the larger accretion rate model, $M = 0.5M_{\text{Edd}}$, the maximum value of $\gamma$ is only of order of 0.1, whereas the optical depth in vertical direction does not exceed 0.5. The spectrum of the escaping radiation is most probably formed at layers with $\gamma \approx 1$ and $\tau = 1$, and its hardness is determined by the temperature of these layers. To resolve the layers in which the spectrum is formed, one should increase the resolution of numerical scheme at more than 10 times in comparison with the present one (we currently use $n_x \times n_y = 150 \times 100$). As an alternative approach, we propose to study the vertical structure of the condensation region using a one-dimensional numerical scheme with the boundary conditions taken from the two-dimensional models.

Radiative shocks of the discussed type could be thermally unstable (see Saxton et al. 1998), and their instabilities may drive quasi-periodic oscillations with a timescale of order of $10r_g/c$, which could explain the observed high-frequency variability in the X-ray flux (Cui et al. 1997).

The outer shock shapes depend mainly on $M$ and vary from
an oblate spheroid to a torus (see Fig. 1). The formation of this shock is connected to the presence of the centrifugal barrier: supersonically moving matter is stopped at \( r \approx r_g \) by the centrifugal force. In the preshock region, between the outer boundary and the outer shock, the viscous transport of angular momentum is not important because of the supersonic accretion velocities. Slowing down of matter inflow on the outer shock makes the viscous transport of angular momentum important in the outer postshock region. The angular momentum is effectively transported outward there. This outward transport, from the rapidly rotating inner parts to the slowly rotating outer ones, is balanced by the inward advection of angular momentum by the inflowing matter. This balance, as well as the efficient cooling of plasma via the Compton mechanism, plays a significant role in limiting the size of the outer postshock region and creation of the stationary shock structures. We found that in the case in which the Compton cooling is (artificially) switched off, no stationary solutions of this type are possible.

Note that the shock structures found in our simulations that describe initially almost spherical accretion with low angular momentum are physically quite different from the hypothetical ones whose existence in the opposite case of a disklike accretion with high angular momentum has been suggested by Abramowicz & Zurek (1981) on general grounds and demonstrated in terms of simple toy models by Fukue (1987) and Abramowicz & Chakrabarti (1990). Whether these toy model shocks could exist in realistic disklike flows with high angular momentum is a matter of controversy. A claim by Chakrabarti and collaborators (see Lanzafame, Molteni, & Chakrabarti 1998, and references therein) that global solutions with shocks of the mentioned type do exist was not confirmed by other authors who constructed global solutions with the same \( M, \alpha \), and \( \dot{M} \), but found no shocks (see reviews by Narayan, Mahadevan, & Quataert 1998 and Kato et al. 1998).

The dependence of the flow structure on the parameters \( r_g \) and \( M \) can be used for explanation of the observed spectral variability of Galactic black hole candidates. For example, the change of spectral state from “hard” to “soft” in the case of Cyg X-1 (see Tanaka & Lewin 1995) can be explained in terms of variation of \( r_g \). In the hard state (small \( r_g \)), most of the accreting matter goes through the inner shocks at radius \( \approx 10r_g \). In this case, a significant part of radiation comes in hard X-rays. In the soft state (large \( r_g \)), the accretion matter comes to the thin disk at radius \( \approx 100r_g \). Close to the black hole, accretion takes place mainly through the thin disk. Obviously, hard X-ray emission is suppressed in this case.

Both parameters \( r_g \) and \( M \) are very sensitive to conditions of mass exchange between binary companions in the case of a wind-fed accretion (Illarionov & Sunyaev 1975b). A small change in the velocity of the wind of an OB star companion leads to a significant variation of both \( r_g \) and \( M \) with amplitudes that could explain the observed variability.

5. Conclusion

A new model of accreting black holes has been proposed, which self-consistently explains the existence of two-component (hot and cold) plasma in the vicinity of black holes. The model assumes that at large radial distances, the accretion flow has a quasi-spherical geometry and a low characteristic angular momentum. The main parameters of the model are the accretion rate and the amount of angular momentum carried by accretion flow. The model can naturally explain, without phenomenological assumptions, the origin of hard X-ray excess observed from the stellar mass black holes (Galactic black hole candidates) as well as the supermassive black holes (quasars and AGNs). More hydrodynamical and radiative transfer simulations are needed to construct detailed spectra of accreting black holes, which will be compared with observations.

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