13. BLACK HOLES IN BINARY SYSTEMS: OBSERVATIONAL APPEARANCES*

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Abstract. The outward transfer of angular momentum of accreting matter can lead to the formation of a disk around the black hole. The structure and radiation spectrum of the disk depends, in the main, on the rate of matter inflow $\dot{M}$ into the disk at its external boundary. Dependence on the efficiency of mechanisms of angular momentum transport (connected with the magnetic field and turbulence) is weaker. If $\dot{M} = 10^{-9}$–$3 \times 10^{-8}\ M_{\odot}$/yr, the disk around the black hole is a powerful source of X-radiation with $h\nu \sim 1$–10 keV and luminosity $L \sim 10^{37}$–10^{38} erg s^{-1}. If the flux of the accreting matter decreases, the effective temperature of radiation and the luminosity will drop. At the same time when $\dot{M} > 10^{-9}\ M_{\odot}$ yr^{-1}, the optical luminosity of the disk exceeds the solar one. The main contribution to the optical luminosity of the black hole is due to the re-radiation of that part of the X-ray and ultraviolet energy which is initially produced in the central high temperature regions of the disk and which is then absorbed by the low temperature outer regions. The optical radiation spectrum of such objects must be saturated by the broad emission recombination and resonance lines. Variability is connected with the character of the motion of the black hole and the gas flow in binary systems and possibly with eclipses. For well defined conditions, the hard radiation can evaporate the gas. This can counteract the matter inflow into the disk and lead to autoregulation of the accretion.

If $\dot{M} \gg 3 \times 10^{-8}\ (M/M_{\odot})\ M_{\odot}$ yr^{-1}, the luminosity of the disk around the black hole is stabilized at the critical level of $L_{cr} = 10^{38}\ (M/M_{\odot})$ erg s^{-1}. A small fraction of the accreting matter falls under the gravitational radius whereas the major part of it flows out with high velocities from the central regions of the disk. The outflowing matter is opaque to the disk radiation and completely transforms its spectrum. As a consequence, a black hole in a supercritical regime of accretion can appear as a bright star with a strong outflow of matter.

A black hole (collapsar) does not radiate either electromagnetic or gravitational waves (Zel'dovich and Novikov, 1967). Therefore, a black hole can be observed only through its gravitational influence on a neighboring star or on the ambient gas medium, since the gas must be accreted with great energy release (Salpeter, 1964; Zel'dovich, 1964).

In many papers, it has been proposed to search for collapsars in binary systems. It is often considered that a collapsar should appear as a 'black' object which emits no appreciable radiation. In this paper, it is pointed out that the outflow of matter from the surface of the visible component and its accretion onto the black hole should lead to observable emission. In systems with outflow of matter $\mathrm{d}M/\mathrm{d}t = \dot{M} \gtrsim 10^{-12}\ M_{\odot}$ yr^{-1}, the total luminosity of the disk around the black hole formed by the accreting matter can be comparable and even exceed the luminosity of the visible component. In the typical case, the main part of this luminosity is in the range of $h\nu \sim 100$–10^4 eV. However, as will be shown below, the optical and ultraviolet luminosities (responsible for

* This paper was presented by J. E. Pringle, in lieu of an invited talk by Ya. B. Zel'dovich. This paper is similar in form to the introductory part of a paper to be published in full in *Astron. Astrophys.*

Bradt and Giacconi (eds.), X- and Gamma-Ray Astronomy, 155–164.

the formation of a Strömgren region) are also high. Therefore, it is entirely possible that black holes are among the optical objects, soft X-ray sources and the harder X-ray sources now being intensively investigated. The radiation connected with accretion on black holes in binary systems has, in fact, distinctive features. However, they are not so astonishing as is usually assumed; thus, black holes can be hidden among the known objects. A collapsar in a binary system will be a 'black' object only if the system is remote with a weak stellar wind from the visible component.

Up to 50% of the stars are in binary systems (Martynov, 1971). A sufficiently massive ($M > 2\ M_\odot$) star, being part of a binary system is able to evolve up to the moment when it loses stability and collapses*. In this case, it is possible that an appreciable number of binary systems will not be destroyed and the stars will remain physically bound. These statements are, of course, controversial. However, if we are reminded that the total number of stars with $M > 2\ M_\odot$ which have existed in the Galaxy is of the order of 10^9 (Zel'dovich and Novikov, 1967), then it becomes reasonable to assume that the number of binary systems including a black hole can be very large, up to 10^6–10^8.

The outflow of matter from the surface of the visible companion – the stellar wind – is one of the main properties of stars. Depending on the type of star, the rate of mass loss ranges from $2 \times 10^{-14}\ M_\odot\ yr^{-1}$ for the Sun up to $10^{-5}\ M_\odot\ yr^{-1}$ for the nuclei of the planetary nebulae, Wolf-Rayet stars, MI supergiants and O stars of the main sequence (Pottash, 1970). In binary systems, an additional strong matter outflow connected with the Roche limiting surface is possible. At a definite stage of evolution, for example after leaving the main sequence, the star begins to increase in size so that, after filling the Roche cavity, an intensive outflow of matter occurs mostly through the inner Lagrangian point (Martynov, 1971).

What will be the consequences of a black hole in a binary system with a visible companion which has strong matter outflow? Some fraction of the matter flowing out from the normal star must come into the sphere of influence of the gravitational field of the black hole, accrete onto it and as the final result, fall under its gravitational radius (Figure 1). In a regime of free radial falling (initially the matter was at rest and there was no magnetic field) the cold matter accretes onto the black hole without any energy release and noticeable observational appearance (Zel'dovich and Novikov, 1967). However, in a binary system, the matter flowing out from the normal star and falling onto the black hole has considerable angular momentum relative to the latter, which prevents the free falling of the matter. At some distance from the black hole, centrifugal forces are comparable to the gravitational forces and the matter begins to rotate in circular orbits. The matter is able to approach the gravitational radius only if there exists an effective transport mechanism of angular momentum outward.

The magnetic field, which must exist in the matter inflowing into the disk, and turbulent motions of the matter, give rise to the transfer of the angular momentum outward. The efficiency of the mechanism of angular momentum transport is charac-

* It is possible that M_{min} considerably exceeds $2\ M_\odot$ (Zel'dovich and Novikov, 1967).

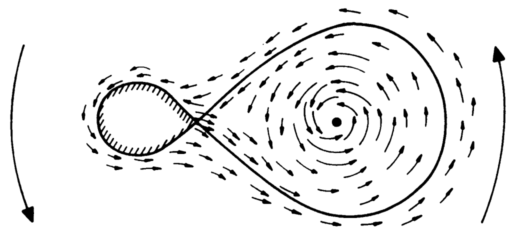

Fig. 1a-b. Two regimes of matter captured by a collapsar; (a) the normal companion fills up its Roche cavity, and the gas outflow goes mainly through the inner Lagrangian point; (b) the companion's size is much less than the Roche cavity; the outflow is a stellar wind. The matter loses part of its kinetic energy in the shock wave; there after the gravitational capture of accreting matter becomes possible.

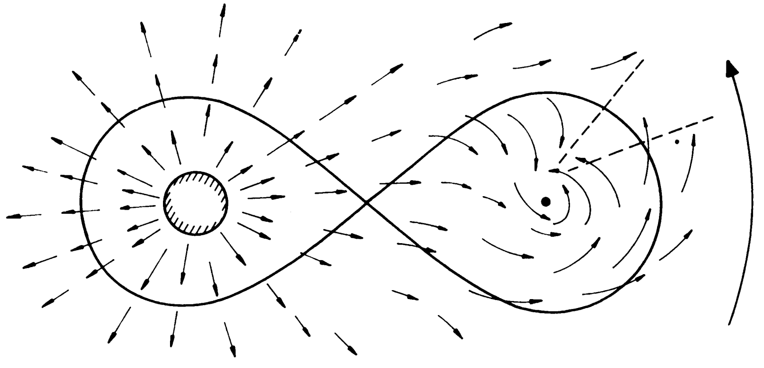

Fig. 1b.

terized by the parameter

$$\alpha = \frac{v_t}{v_s} + \frac{H^2}{4\pi \varrho v_s^2}$$

where

$$\frac{\varrho v_s^2}{2} = \frac{3}{2}\frac{\varrho kT}{m_p} + \varepsilon_r$$

is the matter thermal energy density, ε_r is the energy density of radiation, v_s is the sound velocity, and v_t is the turbulent velocity. In the following, we take $\alpha \lesssim 1$ (see Shakura and Sunyaev, 1972).

The picture of accretion with the formation of a disk around a black hole is the most probable (Gorbatsky, 1965; Prendergast and Burbidge, 1968; Lynden-Bell, 1969; Shakura, 1972). The particles in the disk due to the friction between the adjacent layers lose their angular momentum and spiral into the black hole. Gravitational energy is released during this spiraling. Half of this energy increases the kinetic energy of rotation and the second half turns into thermal energy and is radiated from the disk surface. The total energy release as well as the spectrum of the outgoing radiation are determined mostly by rate of accretion, i.e., by the rate of inflowing of matter into the disk*. The distinctive parameter is the flux of the matter $\dot{M}_{cr}$ at which the total energy released by the disk $L=\eta c^2\dot{M}$ is equal to Eddington's luminosity $L_{cr}=10^{38}$ $(M/M_{\odot})$ erg s^{-1}, which in turn is characterized by the equality of the force associated with the radiation pressure on the completely ionized matter and the gravitational attraction forces (η is the efficiency of gravitational energy release; in the case of Schwarzchild's metric $\eta=0.06$; in a Kerr black hole η can attain 40%). For a black hole having a mass M, the critical flux is equal to

$$\dot{M}_{cr} = 3 \times 10^{-8}(M/M_{\odot})\, 0.06/\eta \quad M_{\odot}\ \mathrm{yr}^{-1}.$$

There is no particular reason for considering a rate of accretion exactly equal to $\dot{M}_{cr}$. A subcritical regime of the disk accretion is possible as well as a flux of matter into the disk exceeding many times the critical value.

At essentially subcritical fluxes $\dot{M}\sim 10^{-12}$–10^{-10} $M_{\odot}$ yr^{-1}, the luminosity of the disk is of the order of $L=10^{34}$–10^{36} erg s^{-1}. Maximal surface temperatures $T_{eff}\simeq 3\times 10^5$–$10^6$ K are expected in the inner regions of the disk, where the main fraction of energy is released. This energy, radiated mainly in the ultraviolet and soft X-ray bands, is absorbed in the interstellear medium. Therefore these sources are inaccessible for observations**.

The observed radiation of the disk is formed in the upper layers of its atmosphere. The local spectrum F_ν depends on the distance from the black hole and the distribution of the matter along the Z-coordinate. The form of the local spectrum reduces to one of the four characteristic distributions (Figure 2). The integral spectrum (Figure 3) is determined by the expression $J_\nu = 2\pi\int F_\nu(R)R\mathrm{d}R$.

For the disk accretion, one typically expects for $h\nu<kT_{max}$, a weak dependence of the radiation intensity on the frequency, $F_\nu\sim\nu^{-\beta}(-1/3<\beta<1)$. As a result, the optical luminosity of the black hole may be appreciable. Our estimates show (Shakura and Sunyaev, 1972) that for black holes with $M=10\ M_{\odot}$, even if $\dot{M}=10^{-9}\ M_{\odot}$ yr^{-1}, one may expect an optical luminosity of the order of the solar luminosity.

In fact, the optical luminosity can be much higher, since it is connected with the reradiation of the hard radiation of the hot central regions of the disk by the outer cold layers. The thickness of the disk increases with distance from the black hole (Figure 4). This is why the outer regions of the disk must effectively absorb the X-ray flux from central regions of the disk and reradiate the absorbed energy in the ultraviolet and optical bands. Thus, from 1.0% to 10% of the total luminosity of the disk

* The efficiency α of the angular momentum transport mechanism is assumed to be constant along the disk (v_t and H vary in accordance with the change of ϱv_s^2). The observational appearance of the disk, i.e., the spectrum of its radiation and the effective temperature of its surfaces does not strongly depend on the chosen value of α. However at supercritical accretion this dependence becomes dominant.

** However they may sufficiently contribute to the galactic component of soft X-ray background and to the thermal balance of interstellar medium. Their radiation must ionize and heat neutral interstellar hydrogen.

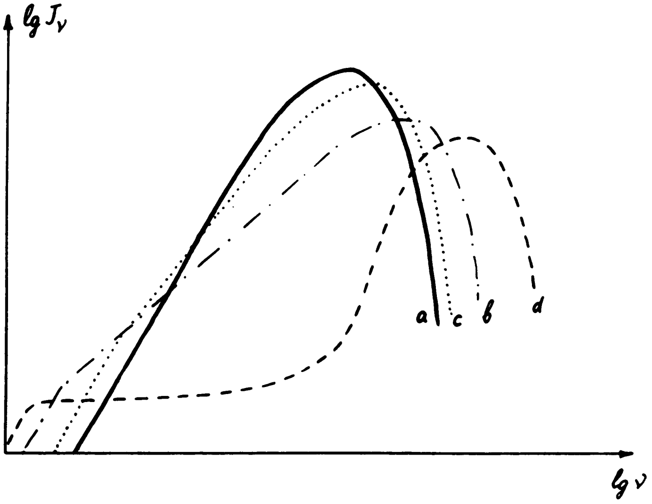

Fig. 2. Characteristic local spectra of radiation in the disk atmosphere: (a) black body spectrum $\varepsilon_r = bT^4$, (b) radiation spectrum of an isothermic homogeneous medium where the main contribution to the opacity is given by scattering $\varepsilon_r = cT^{2.25}$, (c) the same in an isothermic exponential atmosphere, $\varepsilon_r = dT^{2.5}$, (d) the spectrum forming as a result of Comptonization $\varepsilon_r = eT^4$. The intensity is chosen in such a way that the energy density of radiation ε_r is equal in all four cases. The change of effective radiation temperature is easily seen. (Details are given in Shakura and Sunyaev, 1972).

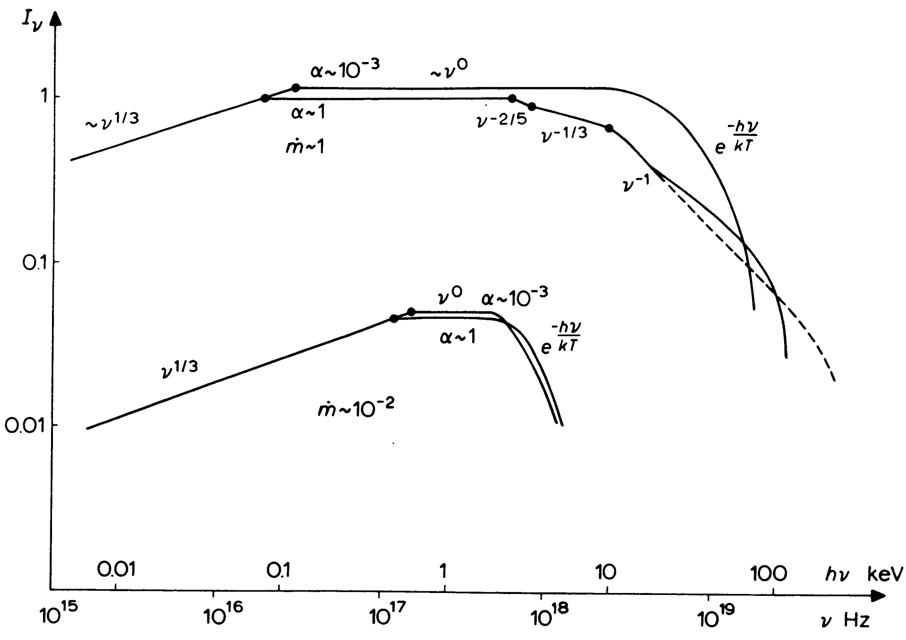

Fig. 3. An integral radiation spectrum of the disk for $M = M_\odot$, $\dot{M} = \dot{M}_{cr}$ and different α. The spectrum of an opaque disk at low α is analogous to the bremsstrahlung radiation spectrum of optically thin plasma, i.e. to the spectra of Sco-X1 type thermal X-ray sources.

can be reradiated (Shakura and Sunyaev, 1972). The hard radiation must be reradiated mainly in the lines of the different elements.

Strong recombinational fluorescence of hydrogen must be observed with no apparent ionization source and possibly also lines of highly ionized heavy elements. All these lines must be broad because the matter in the disk has large rotational velocities ($\gtrsim 100$ km s^{-1}). The density of matter in the disk is high and forbidden lines should be absent.

Considerable ultraviolet luminosity of the disk can lead to the formation of Strömgren region which distinguishes a black hole from normal optical stars with similar optical luminosity. In certain conditions, the hard radiation of the central regions of the disk can heat the matter in the outer regions up to high temperatures and evaporate the disk, decreasing the inflow of matter into the black hole. Such an autoregulation of accretion can essentially influence the luminosity of the disk around the black hole.

When the rate of accretion increases, the luminosity grows linearly, and the effective temperature of radiation rises (Figures 5 and 6). At fluxes $\dot{M} = 10^{-9}$–10^{-8} $M_{\odot}$ yr^{-1}, the black hole is found to be a powerful X-ray star with luminosity $L = 10^{37}$–10^{38} erg s^{-1} and an effective temperature of radiation $T_{\text{eff}} \simeq 10^7$–$10^8$ K. The star radiates also in the optical and ultraviolet spectral bands. In a close binary system, a significant part of the X-radiation of the black hole can hit the surface of the normal star and be reradiated by its atmosphere, which can lead to an unusual optical appearance in such a system (Shklovsky, 1967; Shakura and Sunyaev, 1972). This effect is observed now in Hz Her = Her X1 system (Lutiy *et al.*, 1972).

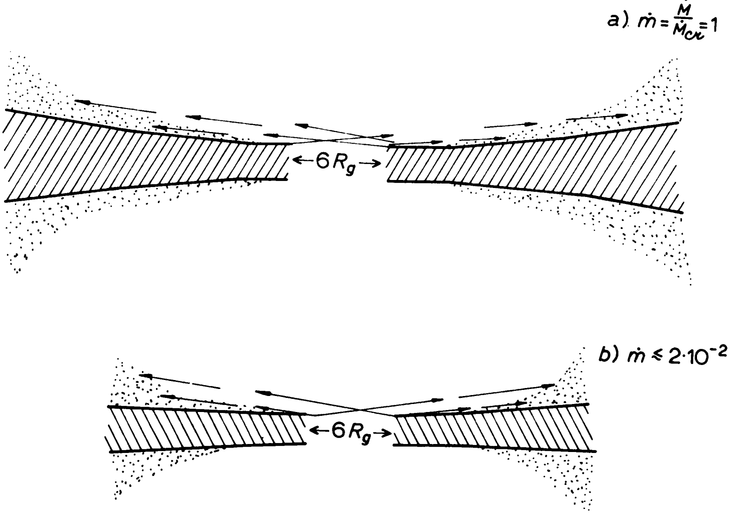

Fig. 4. Dependence of the thickness of the disk on the distance from the black hole: (a) $\dot{M} = \dot{M}_{cr}$, (b) $\dot{M} < 10^{-2} \dot{M}_{cr}$. In the central zone where $R < 3R_g$, Newtonian theory is not applicable. The trajectories of X-ray and ultraviolet quanta leading to evaporation and heating of the matter in the outer regions of the disk are indicated by the arrows. The disc corona formed by hot evaporated matter is denoted by points.

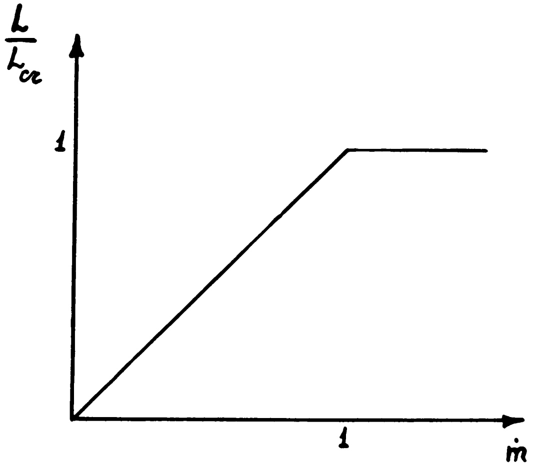

Fig. 5. Dependence of luminosity of the disk around the collapsar on the flux of the matter entering the external boundary.

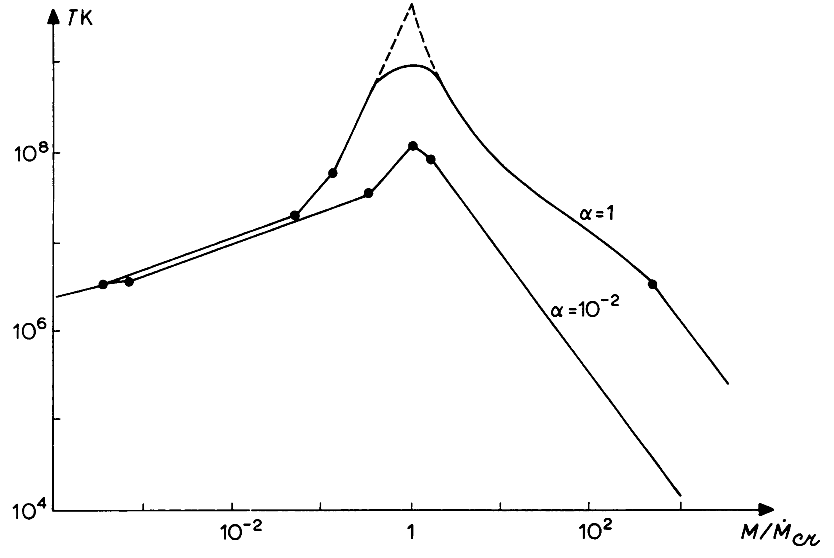

Fig. 6. Maximal effective temperature of the radiation from the disk as a function of the flux of matteri nflowing into it for the different efficiencies α of mechanisms of the angular momentum transfer.

Aperiodic variability of certain properties such as fluctuations of brightness, principally connected with the variability of infalling matter flux and its non-homogeneity, should distinguish some collapsars. In remote systems, a collapsar in the perigee of its orbit gets into the more dense matter flux outflowing from the visible component. Therefore, periodic variability of luminosity (non-sinusoidal in general) should be expected. Moreover, eclipses of radiation of the central source by the disk itself are possible when it is viewed edge-on, if its plane does not coincide with the plane of rotation of the system. Such an orientation of the disk must take place, for example, when the matter flows through the inner Lagrangian point from a non-synchronously rotating star, whose axis of rotation is inclined with respect to the plane of rotation of the system. Taking into account the eclipse of the X-ray source by the adjacent star and by the disk, the number of eclipses amounts to 3 for each period of rotation. If the plane of the disk coincides with the plane of the system, then only the disk can be occulted or darkened, whereas on the other side of the orbit, the thin disk covers only an insignificant fraction of the star surface. However, the most typical characteristic of the black hole in a close binary system should be its X-ray radiation. The detection of compact X-ray stars having a mass $M > 2\ M_{\odot}$ in binary systems will be the proof of existence of black holes in the Galaxy.

For a neutron star, we can estimate (in order of magnitude) that the energy release of infalling matter per gram is the same as for a black hole ($\eta \sim GM/R_{ns}c^2 \sim 10$–$20\%$). However, the accretion on a neutron star in a binary system has its own peculiarities. In the case of a neutron star without a magnetic field, the disk extends to its surface. One half of the entire energy released is radiated by the surface of neutron stars in the form of X-ray quanta having energy less than 10 keV. Compton interaction of radiation and matter in the disk decreases the maximum photon temperature in the disk to $T_{\rm eff} \sim 2 \times 10^7$ K, whereas in the neighborhood of a black hole regions having temperatures up to 10^9 K are possible, in principle.

Accretion on a rotating neutron star with a magnetic field, the direction of which does not coincide with the axis of rotation, can lead to the phenomenon of an X-ray pulsar (Shvartzman, 1971b).

At subcritical inflow of matter into the Roche cavity of the black hole, we may assume that the main part of the inflowing matter is accreted. In supercritical regimes, both in the case of a black hole and of a neutron star* (there is no fundamental difference here), a qualitatively different picture should be realized. An effective outflow of matter under the influence of radiation pressure appears to take place in the region surrounding the black hole. The outflow begins close to the radius at which the forces associated with radiation pressure and gravitation, pressing the matter into the disk plane, are comparable. Only the critical flux of the matter can go under the radius $R = 3R_g$ where $R_g = 2GM/c^2$. The remaining gas is ejected outwards by radiation pressure.

The integral luminosity of such objects is limited by the value of the critical Eddington luminosity. The band of the electromagnetic spectrum where this energy is mostly radiated, depends strongly on the density of the outflowing matter. The density of the matter, in turn, is a function of the ratio $\dot{M}/\dot{M}_{\rm cr}$ and the efficiency α of the transport mechanism of angular momentum which determines the velocity of the outflowing gas. If $\dot{M}$ exceeds $\dot{M}_{\rm cr}$ only slightly and $\alpha \sim 1$, the emission of the disk is reradiated by the outflowing gas practically without change of the spectral properties, i.e., the object

* Critical accretion on a neutron star must lead to its collapse after 3×10^7 yr.

is a source of X-ray radiation as before. If the ratio $\dot{M}/\dot{M}_{cr}$ increases and α decreases, the opacity of the outflowing matter grows, the radiation of the disk is re-emitted as quanta of smaller energy. If $\dot{M} > 10^3 \dot{M}_{cr} (\alpha M_{\odot}/M)^{2/3}$, a black hole turns into a bright optical star. The less the parameter α the greater the effective radius of the radiating envelope.

Since the angular momentum of the ejected matter must be preserved, a strongly anisotropic outflow of matter can be observed. The hot plasma is ejected with great velocity into a narrow cone of angles near the axis of rotation. The optical depth of the outflowing gas in this cone is not great and at certain orientations of the binary system relative to the observer, the X-ray radiation of the black hole together with the optical should be observed.

The observational appearance of a black hole in a strongly supercritical regime of accretion can be characterized as follows: the luminosity is fixed by the Eddington critical limit $L_{cr} = 10^{38}\ (M/M_{\odot})$ erg s^{-1}; the major portion of the energy is radiated in the ultraviolet and optical regions of the spectrum; in the upper, rarefied layers of the outflowing matter, broad emission lines are formed. There is a strong mass outflow from a hot star with velocities $V \sim \alpha 10^5\ (\dot{M}_{cr}/\dot{M})^{1/2}$ km s^{-1}, and the star is surrounded by a colder disk where the accreting matter enters the collapsar. Eclipses of the black hole by the normal component are possible as well as an eclipse of the star by the matter outflowing from the black hole. The latter is opaque with respect to Thomson's scattering at great distances away from the black hole ($R_t \sim 10^{10}$–10^{12} cm). In the radio range, the hot outflowing matter becomes opaque far from the binary system. It can be a source of appreciable thermal radiation with a smooth dependence of intensity on the frequency ($J_\nu \sim \nu^{2/3}$).

In the radio range, for both subcritical and supercritical accretion, non-thermal radiation mechanisms connected with the existence of the magnetic fields (which may achieve $H \sim 10^5$–10^7 G) and beams of the fast outflowing particles can also appear.

Apparently, the 'Quiet' disk, radiating only due to thermal mechanisms, can really exist at low values of the parameter α. If $\alpha \sim 1$, the new important effects (connected with turbulent convectivity; plasma turbulence; reconnection of magnetic field lines through neutral points, leading to solar type flares; the acceleration of particles) and nonthermal radiation can appear. The flares and hot spots on the rotating disk surface must lead to the short term fluctuations of radiation flux in some spectral bands. The variability may have both a stochastic nature (Schvartzman, 1971a) and may be quasi-periodic. The quasiperiod of these fluctuations must be of the order of rotational period $t \sim 2\pi R/v_\varphi \sim 6 \cdot 10^{-4} (R/3R_g)^{3/2} (M/M_{\odot})$ s and depends on the distance of the hot spot from the collapsar. Minimal quasiperiod in the case of Kerr metric is 8 times less than in the case of non-rotating black hole with equal mass (Sunyaev, 1972).

Acknowledgements

The authors wish to thank Ya. B. Zel'dovich, A. F. Illarionov, D. Ya. Martynov and

L. R. Yangurasova for consultations and the participants of the 1972 winter school on astrophysics in Arhyz for numerous discussions.

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