Old models for Cygnus X-1 and AGN

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Abstract

Recently, there appeared many papers devoted to the modeling of X-ray properties of Cygnus X-1 and other black hole accretion disk candidates: e.g. J. Poutanen, J. Krolik, F. Ryde, MNRAS 292 (1997) L21; E. Agol, J. Krolik, ApJ 507 (1998) 304; A. Beloborodov, in “High Energy Processes in Accreting Black Holes”, ASP Conf. Series, 161, (1999), p.295. The goal of this electronic publication is to draw attention to our old papers where many ideas of recent discussions were anticipated (hot coronae, Comptonization, photon damping of waves, particle acceleration and matter ejection from accretion disks with large scale poloidal magnetic fields, etc.)
A hot corona around a black-hole accretion disk as a model for Cygnus X-1

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Heat transfer in the region of maximum energy release of an accretion disk will take place mainly by convection, serving to enhance the turbulence and to generate a powerful acoustic flux. The hard X-rays emitted by Cyg X-1 \((E \lesssim 200 \text{ keV})\) might result from Comptonization of soft photons in a corona formed around the disk through this heating.

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With high probability, the X-rays emitted by the source Cygnus X-1 come from a black hole that is in a regime of disk accretion. The theory of disk accretion has been developed by several authors \([1]–[4]\). But difficulties arise if one seeks to explain the spectrum of Cyg X-1 on the basis of this theory. The source has a luminosity \(L \lesssim 10^{38} \text{ erg/sec} \approx 0.1 L_c\), where \(L_c = 1.3 \cdot 10^{38} M/M_\odot\) is the critical Eddington luminosity. For this luminosity the theoretical spectrum should fall off sharply in the energy range \(h\nu \approx 7 \text{ keV}\), whereas the observed spectrum extends up to energies as high \([5,6]\), as \(\approx 200 \text{ keV}\), or even beyond \([7,8]\).

To overcome this difficulty, models have been proposed \([9,10]\) wherein the properties of the radiating regions are essentially determined by the observations. An attempt has been made \([11]\) to construct a self-consistent model for Cyg X-1 that would account for the hard part of the radiation. This model, which neglects radiation pressure from the very outset, appears to have an internal contradiction in that it implies a disk as thick as its radius and drift velocity comparable to the orbital velocity.

Hard radiation up to 200-keV energy can be present in the spectrum of an accretion disk only in the event that regions with hot \((T_e \approx 10^9 \text{ K})\) electrons participate in forming the spectrum; harder photons would require still more energetic particles. In an analysis of accretion disks we have shown \([12]\) that hot regions or coronae with \(T_e \approx 10^9 \text{ K}\) will form around them.

The standard theory presupposes that radiative heat conduction is responsible for energy transfer in the vertical direction. In the region of maximum energy release, \(P \approx P_r \gg P_g\), \(\kappa = \kappa_{\text{es}}\), and the vertical structure can easily be determined analytically. The density in this region is found \([3]\) to be independent of \(z\), while the temperature declines toward higher \(z\). Such a situation will evidently be convectively unstable, since the entropy will decrease in the vertical direction. The onset of convective instability will serve to equalize the entropy. The mean density in the disk will become approximately an order of magnitude higher than the density of the disk in the standard theory.

The convective heat flow \(Q_{\text{conv}}\), the convection velocity \(v\), and the excess \(\Delta \nabla T\) of the temperature gradient above the adiabatic gradient (we shall take the mixing length \(l\) to be the half-thickness \(z_0\) of the disk) are given \([13]\) by the equations

\[
Q_{\text{conv}} = C_p \rho v(z_0/2) \Delta \nabla T, \tag{1}
\]

\[
v = \left[ \frac{Q_{\text{conv}}(1 + 4P_r/P_g)}{2 \rho C_p T} \frac{GM}{R^3} \right]^{1/3} \frac{z_0^{2/3}}{z_0}, \tag{2}
\]
\[ \Delta \nabla T = \left( \frac{4Q_{\text{conv}}}{\rho C_p} \right)^{2/3} \left[ \frac{T}{(1 + 4P_r/P - g)GM} \right]^{1/3} R z_0^{-5/3}. \]  

(3)

Hence we readily find that the excess \( \Delta \nabla T \) in the temperature gradient amounts to no more than 20\% of \( \nabla T \), while the convection velocity is \( v = 3 \cdot 10^8 \) cm/sec for \( r = 10r_g \), a value close to the velocity \( v_s \) of sound in this region. The heat flow is carried mainly by convection \( (Q \approx Q_{\text{conv}}) \); because of the high density the radiative flux is equal to \( \approx 20\% \) of the total flux.

In the convective disk the flow \( Q_{\text{ac}} \) of acoustic energy in the vertical direction is given [14] by

\[ Q_{\text{ac}} \approx \rho v^3 (v/v_s)^5 \approx 10^{21-22} \text{erg} \cdot \text{sec}^{-1} \cdot \text{cm}^2, \]  

(4)

and is a quantity of the same order as the total energy flux. An amount of order \( (P_g/P_r)Q_{\text{ac}} \) is expended in heating the outer layers to an optical depth \( \tau < 1 \). One other mechanism serves to heat these layers [12]. A particle in a region near the surface of the disk that is transparent to radiation will be subject to the influence of radiation from the whole disk, and not only to the local radiation pressure gradient. The force of the radiation pressures will accelerate particles in the transparent region above the disk. Calculations of the equations of motion for particles subject to radiative, centrifugal, and gravitational forces show that in the region with \( \tau < 1 \) the particles (protons and electrons) will acquire vertical velocities corresponding to the temperatures \( (1 \cdot 8) \cdot 10^8 \) K of protons for \( L \approx 0.1L_c \). Turbulent relaxation of the particle motions in the corona will tend to equalize the mean energies of the ions and electrons and to form a quasi-Maxwellian particle velocity distribution. Thus the combined action of the two heating mechanisms we have described will produce around the accretion disk a hot corona with \( T_e \approx 10^9 \) K for \( L \approx 0.1L_c \). The existence of an analogous corona has been postulated phenomenologically by Price and Liang [10].

We now estimate the density \( \rho_{co} \) of the corona and the amount of material it contains. Since the gas pressure varies continuously with transition from the photosphere to the corona, we readily find that at the base of the corona

\[ \rho_{co} \approx \rho_s T_s/T_{co} \approx 10^{-2} \rho_s \approx 10^{-5} \text{g/cm}^3, \]  

(5)

where \( \rho_s, T_s \) denote the density and temperature in the photosphere of the disk for the parameters of the source Cyg X-1 in the region of maximum energy release. The surface density of the corona is determined by the condition \( \tau_{es} \approx 1 \) and is \( \approx 2 \text{g/cm}^2 \), which is more than an order of magnitude lower than the density of the opaque disk.

The hot corona readily affords an explanation of the peculiarities of the Cyg X-1 spectrum. The soft X-rays at \( h\nu \lesssim 7 \) keV, which comprise \( \approx 70\% \) of the total flux, are formed in the photosphere of the opaque disk. Some of the radiation (\( \approx 10\% \)) will pass through the hot corona, and Comptonization will generate hard radiation up to \( h\nu \approx 3kT_e \approx 200 \) keV, which will amount to \( \approx 30\% \) of the total flux. In Cyg X-1 the luminosity varies around \( L = 0.1L_c \). Under these conditions the region of the disk with \( P_r \gg P_g \), where convective heating is important, will be spatially small and will convert \( \approx 10\% \) of the soft radiation flux, in accord with the requirements that the observations impose on the model.

The changes in the spectrum as the luminosity of Cyg X-1 varies [6,15,16] exhibit the following characteristic behavior. As the total energy flux rises, the radiation in the soft part of the spectrum \( (h\nu \lesssim 7 \text{keV}) \) increases, but in the hard range \( (h\nu \gtrsim 10 \text{keV}) \) it remains almost constant, or perhaps may even decrease slightly. We shall assume that the variations in the luminosity are associated with fluctuations in the power of accretion. As the mass flow \( \dot{M} \) rises in the region with \( P_r \gg P_g \) the fraction of the acoustic flow \( (4) \) expended in heating the corona will decrease:

\[ (P_g/P_r)Q_{\text{ac}} \sim \dot{M}^{-1}. \]  

(6)
For $L \approx 0.1L_c$, when acoustic heating predominates, the rise in $\dot{M}$ may cause some decrease in the heating of the corona and in the amount of hard radiation. At the same time the flux in the soft range is determined by the radiation of the disk photosphere and will increase with $\dot{M}$. It is worth noting that in strong bursts of luminosity, when $L$ reaches about $0.3L_c$, the heating will begin to be governed by radiation-pressure forces, so the temperature of the corona and thereby also the power of the hard radiation should increase along with the rise in $\dot{M}$ and in the total energy flux.

The observational evidence for the spectrum at $h\nu > 150$ keV is considerably less reliable than for the soft range. For instance, Baker et al. [8] have measured the radiation to $h\nu \approx 10$ MeV, but find an observed signal of only $\approx 1\%$ of the background (they also report a deficiency of $\gamma$-ray photons in the direction of Cyg X-1). In the range up to 600 keV, Haymes and Harnden [7] find a break in the spectrum at $h\nu \approx 150$ keV, and the spectral index $\alpha$ changes from $\alpha = 1.9$ at $h\nu < 124$ keV to $\alpha = 3.1$ at $h\nu > 154$ keV.

Even if a corona with $T \simeq 10^9$ K is present in the disk accretion model, radiation cannot be formed at $h\nu = 200 - 2000$ keV. Electrons with $T_e = 10^{10}$ K or fast nonthermal electrons would be needed for that purpose. There are in fact two ways to form such fast electrons. Both would require the presence of a magnetic field in the disk. A magnetic field could exist in the disk either through twisting of the lines of force by differential rotation [3,17,18], or through infall onto the black hole of magnetized material having a small angular momentum [19]. In the latter case a poloidal magnetic field would be generated.

In the binary system containing the source Cyg X-1, some of the material flowing from the giant star is dispersed in space near the system. The attraction of the black hole will not only produce an accretion disk. A small proportion of material having a low angular momentum will fall into the black hole and be decelerated in the disk. If this deceleration takes place at radii of $(10 - 30)r_g$ and if a thin collisionless shock wave is formed (as is very likely in the presence of an azimuthal magnetic field) wherein the kinetic energy is transformed into thermal energy and $T_e \approx T_i$, then hot electrons with $T = 10^{10} - 10^{12}$ K will appear. The inverse Compton mechanism of interaction of the disk radiation with these electrons can lead to the generation of hard radiation with $h\nu \approx 200 - 2000$ keV or even higher energies.

Another mechanism for producing fast particles is analogous to the pulsar process. If magnetized matter with low angular momentum falls into the black hole (in addition to the disk accretion), a strong poloidal magnetic field will arise [19]. By analogy to pulsars [20], rotation will generate an electric field of strength $E \approx -(v/c)B$ in which electrons are accelerated to energies $\varepsilon \approx R(v/c)Be \approx 3 \cdot 10^4[B/(10^7 \text{ Gauss})]$ Mev where $v/c \approx 0.1$ and $R \approx 10^7$ cm is the characteristic scale. In a field $B \approx 10^7$ Gauss, such electrons will generate synchrotron radiation with energies up to $\approx 10^5$ keV. Just as in pulsars, it would be possible here for $e^+e^-$ pairs to be formed and to participate in the synchrotron radiation.

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Models for the X-ray brightness fluctuations in Cygnus X-1 and active galaxy nuclei

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The X-ray brightness fluctuations induced in Cyg X-1 and active galaxy nuclei by convection and turbulence in the sub-photospheric layers are discussed in terms of the disk-accretion and supermassive-star models. The variability time scales should be comparable with those observed, but in the case of supermassive stars and disks it is difficult to obtain the observed amplitude of the fluctuations.

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1. One noteworthy property of the X-ray source Cygnus X-1 is the variability of its flux on time scales ranging from milliseconds to a fraction of a second [1]. This variability is generally attributed to the presence of a turbulent accretion disk in the Cyg X-1 system. In particular, the flux variations have been explained by the rotation of a hot spot [2,1] or alternatively, by the onset of instability in a zone where radiation pressure predominates [3,5].

In this letter we shall consider another model for the variability. We shall outline more fully what properties of the flux variations are to be expected on the accretion disk model as a direct result of the presence of turbulence, and how convective instability should develop in a region of high radiation pressure [6,7]. Acoustic waves generated in the convection zone will escape into optically thin layers, and will not only induce variable soft X-rays in the photosphere, but will also be responsible for variable heating of the corona. Comptonization of the photospheric radiation by the hot electrons under conditions where both temperature and density are variable will lead to flux variations in the hard range, \( h\nu > 5 \text{ keV} \). This X-ray fluctuation mechanism, involving the emergence of waves into transparent layers, evidently is of the same wave nature as the variability of the ultraviolet excess in stars experiencing intensive convection, such as T Tauri and UV Ceti.

2. The waves escaping into the transparent layers and producing variable radiation in the photosphere and corona will occupy a rather narrow frequency band. Physically, the reason for this circumstance is that media with a high radiation pressure and a nonuniform distribution of plasma along the \( z \) coordinate (across the disk) will serve as efficient filters, isolating a characteristic frequency range from the broader spectrum generated by convection and turbulence. Waves of low frequency and a wavelength exceeding the scale height of the atmosphere will not escape outside but will induce oscillations of the coronal atmosphere as a whole. On the other hand, under conditions where radiation pressure predominates, high-frequency waves will experience very severe damping because of radiative friction, and their role in heating the corona will be insignificant. High frequencies may, however, appear in the observations either through nonlinear transformation of low-frequency waves or due to inadequate processing of the observational data [8].

We have examined elsewhere [9] the propagation of waves through a medium with strong radiation pressure, followed by their escape into the atmosphere. Waves emerging into the transparent layers will have a phase and group velocity equal to the velocity of sound in gas, \( v_g = (\gamma P_g/\rho)^{1/2} = (\gamma RT)^{1/2} \), where \( \gamma = 5/3 \) or \( \gamma = 1 \) according as scattering or absorption predominates, \( \mathcal{R} \) is the gas constant, and the temperature \( T \) of the equilibrium atmosphere is...
approximately equal to the temperature $T_e$ of the photosphere. The characteristic frequency $\omega_c$ of waves emerging into the atmosphere is given by the expression

$$\omega_c = \left(\frac{\gamma}{RT}\right)^{1/2} g \left(1 - \frac{H}{H_c}\right) \sec^{-1}. \quad (7)$$

For the accretion disk model, the gravitational acceleration $g$ at radius $r$ is equal [10] to

$$g = \frac{GM}{r^2} \frac{h_0}{r}, \quad (8)$$

where the characteristic thickness is

$$h_0 = 3 \frac{L}{L_c} R_0 \left[1 - \left(\frac{R_0}{r}\right)^{1/2}\right], \quad (9)$$

and $R_0$ is the radius of the inner edge of the disk. The quantity $H/H_c = \kappa_0 H/gc$ represents the ratio of the radiation pressure force to the gravity; $\kappa_0$ is the opacity, including both absorption and scattering [9]. In a spherically symmetric star of luminosity $L$ and radius $R$ we will have $g = GM/R^2$, $H = L/4\pi R^2$, and $H/H_c = L/L_c$, where $L_c = 4\pi c GM/\kappa_0$ is the Eddington limiting luminosity.

3. To calculate the characteristic frequencies of the fluctuations for Cyg X-1, we shall adopt the convective accretion-disk models given in a previous paper [7] and by Shakura et al. [11]. For a black hole of mass $M = 10M_\odot$, we find that in both models as the luminosity rises from $0.1L_c$ to $0.3L_c$ there is little change in the characteristic frequency $\omega_c$ corresponding to the equilibrium temperature, as given by Eq. (1); the values of $\omega_c$ are confined [9] to the range 5-40 msec. Note that if a corona with $T_c \approx 10^2 T_e$ is present, waves whose frequency is $\omega = \omega_c$ or even somewhat lower will be able to escape. The frequency range mentioned is in good accord with the observed time-scales of variability. Our mechanism can yield fluctuations weakly correlated in time, and can simulate the white noise derived from observational analysis [8] of the brightness fluctuations of Cyg X-1.

Despite the good agreement between the theoretical time characteristics and the observations, analysis of small oscillations in our model still does not suffice to explain the amplitudes of the variability we observe, because pulsations should, in general, occur independently in regions whose size is comparable with the velocity of sound multiplied by the pulsation period, or about one-tenth the diameter of the zone of maximum energy production. Small pulsations should accordingly be smoothed out. However, the mechanism we are proposing could operate in a highly nonlinear regime. Strong nonlinearity of the waves would be expected in the light of theoretical estimates [7], and is essential to the very existence of the corona. The frequencies obtained from linear analysis correspond to the characteristic growth times of strong nonlinear flares. This problem awaits further theoretical treatment. Indeed, we would point out that not even the observational situation is fully clear [8].

An evaluation of the proportion $\eta$ of the acoustic flux that emerges into the corona and produces heating shows [9] that as the luminosity rises by a factor of 3 from $0.1L_c$ to $0.3L_c$, the value of $\eta$ will drop by a factor of 5-10. Thus, in accord with our previous suggestion [6,7], as the luminosity increases the power of the corona will remain approximately the same, or may even decline somewhat. This situation will prevent the hard X-ray flux ($h\nu > 5$ keV) of Cyg X-1 from changing appreciably as the total luminosity varies, in agreement with the observations [12].

4. Multicolor photometry of the nuclei of certain galaxies has revealed the presence of comparatively short-period brightness fluctuations in the nucleus of the Seyfert galaxy [13,14] NGC 4151 ($\approx 130$ days) and in the BL Lacertae object [15] OJ 287 ($\approx 180$ days). There is presently no consensus as to the nature of active galaxy and quasar nuclei. Three models have been explored
[16,17]: a) a dense star cluster; b) a supermassive star; c) disk accretion onto a massive black hole. The variability mechanism proposed here can operate in the two models b and c, for in both cases the subphotospheric layers will be strongly convective, resulting in the formation of a corona with variable heating. Using Eq. (1) to estimate the characteristic period of the fluctuations along with the standard model for a supermassive star [18] we find that for a mass $M = 10^8 M_\odot$ and a radius $100 R_g$ ($R_g = 2GM/c^2$ is the gravitational radius), the period corresponding to $\omega_c$ would be $\approx 160$ days, a value consistent with observation. On the accretion disk model, such a period would prevail in the zone of maximum energy production [9] for a black hole of $M = 10^8 M_\odot$, if the luminosity $L = 0.1 L_c$. In galaxy nuclei the fast component typically exhibits an approximately constant period in conjunction with sharp changes in phase [15], a behavior which, it would seem, accords with a convective wave origin for such fluctuations.

It is worth emphasizing, however, that both in the supermassive star model and in the model of an accretion disk around a supermassive black hole, the ratio of the radiation pressure to the gas pressure is far higher than in the case of accretion onto a black hole of stellar mass. Acoustic waves will therefore be damped much more strongly. Our calculations indicate [9] that in this event the emergent acoustic flux will comprise no more than 1% of the flux generated at large optical depth - well below the variability amplitude observed. The supermassive star model would be supported if strictly periodic brightness oscillations of constant phase were detected, associated with the rotation or with pulsations of such a star as a whole, as might be the case [14] for NGC 4151. But analysis of observations of several variable nuclei does not reveal any strict periodicities [19]. Most likely the observed variability should be modeled by a random process [20] (see, however, Ozernoi et al. [21]). The model of a dense star cluster with frequent supernova outbursts offers the best fit, in our opinion, to the irregular variability of galaxy nuclei.

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