THEORETICAL MODELLING OF ALGOL DISKS

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ABSTRACT. A brief review of various theoretical approaches to model accretion disks is presented. Emphasis is given to models that determine self-consistently the structure of a disk together with the radiation field. It is argued that a proper treatment of the vertical structure is essential for calculating theoretical spectra to be compared with observations. In particular, it is shown that hot layers above an accretion disk (sometimes called disk "chromospheres" or "coronae"), whose presence is indicated by recent UV observations of strong emission lines of highly ionized species, may be explained using simple energy balance arguments.

1. Introduction

While most workers in the field generally agree that the circumstellar matter in Algol-type binaries forms some kind of disk-like structure, there is no general consensus about detailed physical properties of such disks. The contemporary theory of accretion disks is rather successful in explaining observed properties of various objects, ranging from active galactic nuclei, quasars, cataclysmic variables, to disks around T Tauri stars and protostars. For a general review of accretion disk theory see the excellent textbook by Frank, King and Raine (1985) and references cited therein.

It is thus natural to expect that our understanding of Algol disks should benefit from the development of accretion disk theory. However, it has become clear that a too literal application of results found for other objects, as for instance for cataclysmic variables, may be rather misleading. In particular, recent UV observations of Algol and W Ser binaries revealed the presence of strong emission lines of highly ionized species, which most likely imply the existence of extended hot regions above the accretion disks. This was discussed, together with

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problems of applicability of the canonical disk model to Algol type binaries, by Plavec (1980, 1985).

The present paper is devoted primarily to the question of which modifications of the canonical disk theory are necessary in order to be able to model Algol disks.

2. Degrees of Sophistication of Disk Modelling

It is perhaps helpful to start by stressing that there are basically two types of theoretical modelling, namely that approached from the "stellar interior" viewpoint, and that approached from the "stellar atmospheric" point of view. The former usually treats a *dynamical* problem, and its goal is primarily the *evolution* of the system. Yet, radiation is usually treated only approximately. In contrast, the main objective of the latter is *spectroscopic diagnostics*. Its importance results from the fact that radiation, apart from being the only information about a distant object we have, is often also a prominent energy balance agent. Therefore, details of radiative transfer are viewed as an essential part of the physical description. Since most recent theoretical studies of accretion disks belong to the first category, my objective here is to stress above all the studies dealing with spectroscopic diagnostics.

In virtually all studies, the radial structure is assumed to be given by the canonical model (Shakura and Sunyaev 1973; Lynden-Bell and Pringle 1974; Pringle 1981), which assumes a cylindrically symmetric Keplerian disk. The disk is usually divided into a set of concentric rings, assuming that each ring behaves like an independent plane-parallel radiating slab. The emergent spectrum of a disk is then calculated as an appropriate sum of contributions from the individual rings. Obviously, the quality of the overall model depends on the degree of sophistication of calculating emergent radiation from the individual rings.

From the point of view of spectroscopic diagnostics, the existing approaches can be divided into several categories, ordered here by increasing complexity:

i) Superposition of blackbodies. This is the simplest approximation, first suggested by Lynden-Bell (1969). At a given distance from the central star, r, the local effective temperature is given by

$$T_{\rm eff}^4(r) = \frac{3Gm_*\dot{M}}{8\pi\sigma r_*^3}\, x^{-3}(1-x^{-1/2});\; x = r/r_* \quad , \qquad (1)$$

where m_* and r_* are the mass and the radius of the central star, $\dot{M}$ is the mass accretion rate, and G and σ the gravitational and Stefan-Boltzmann constants, respectively. The emergent flux from the ring with radial distance r is then given by $B_\nu(T_{\rm eff})$, where B_ν is the Planck function at frequency ν.

ii) Somewhat better approximation can be achieved by using classical model atmosphere fluxes instead of blackbody fluxes (Mayo, Wickramasinghe, and Whelan 1980; Wade 1984). Both latter approaches have recently been extensively tested by Wade (1988), who concluded that neither blackbody nor stellar atmosphere models reflect the physics of disks. Wade based his conclusion on a comparison between theoretical predictions and observations. There are, however, also several fundamental objections to the above approaches, namely a) a disk need not be optically thick, which is the implicit assumption underlying both approaches; b) the effective temperature is not the only parameter that determines the emergent radiation; and c) a disk is neither a vertically homogeneous layer in thermodynamic equilibrium (which is needed to get blackbody emergent radiation), nor does it have the same vertical structure as a classical stellar atmosphere.

iii) The next category comprises models constructed assuming optically thin, vertically homogeneous disks. The emergent spectrum is then calculated by solving a simplified radiative transfer; the optically thin approximation enables one to write analytical expressions for the emergent flux (Williams 1980; Tylenda 1981; Schwarzenberg-Czerny 1981; Williams and Ferguson 1982). Recently, a modification of this approach has been elaborated by Williams and Shipman (1988), who considered an approximate non-LTE approach, using a variant of the escape probability formalism. The obvious drawback of these methods is the approximation of an optically thin disk, which need not be generally valid.

iv) Finally, in the last category are models that aim at determining the vertical structure. Several studies deal with the vertical structure of accretion disks, however do not treat the radiation properly (Meyer and Meyer-Hofmeister 1982, 1983; Cannizzo and Wheeler 1985; Cannizzo and Cameron 1988). These studies belong to the "stellar-interior" type modelling discussed above. Vertical structure of accretion disks, with self-consistent treatment of radiative transfer, has been considered by Kriz and Hubeny (1986), Shaviv and Wehrse (1986), and by Adam et al. (1988).

3. Vertical Structure of Accretion Disks

Let us first recall the basic equations that govern the vertical structure. Assuming that the radial component of gravity of the central object is balanced by the centrifugal force of the Keplerian rotation, one may write the equation of vertical hydrostatic equilibrium as

$$\frac{dp}{dz} = g(z)\rho \quad , \qquad (2)$$

where z is the geometrical distance from the central plane, P and ρ are the pressure and density, respectively, and

$$g(z) = Qz = (Gm_*/r^3)z \qquad (3)$$

is the (z-dependent) effective vertical gravity. Here the neglected terms are of the order of $(z/r)^2$.

The second basic equation is the energy balance equation. The net energy generated per unit volume is given by

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$$D_{mech} = (9/4)Q\nu_v\rho, \qquad (4)$$

which is derived assuming that energy is released through the radial shear of the Keplerian motion; ν_v is the viscosity per unit mass, which is the most uncertain part of the theory. The dissipated energy has to be balanced by the net radiation loss per unit volume, D_{rad},

$$D_{rad} = D_{mech}. \qquad (5)$$

The approaches belonging to the category of stellar-interior type studies treat D_{rad} very approximately, basically by means of the diffusion approximation (Mihalas 1978). It is well known that the diffusion approximation is valid only for large optical depths. On the other hand, emergent radiation reflects physical conditions at optical depths of the order of unity. This is the fundamental reason why models based on diffusion approximation cannot predict the emergent radiation satisfactorily. Moreover, experience gained from classical stellar atmosphere models teaches us that details of radiative transfer are important for determining the global temperature structure of the atmosphere. D_{rad} is generally given by

$$D_{rad} = 4\pi \int_0^\infty [\eta(\nu,z) - \kappa(\nu,z)J(\nu,z)]d\nu \quad , \qquad (6)$$

where η and κ are the monochromatic emission and absorption coefficients, respectively, and $J(\nu,z)$ is the mean intensity of radiation. The latter is determined by the radiative transfer equation, viz.

$$\mu \frac{dI(\nu,\mu,z)}{dz} = - \kappa(\nu,z)I(\nu,\mu,z) + \eta(\nu,z) \quad , \qquad (7)$$

where $I(\nu,\mu,z)$ is the specific intensity of radiation, μ is the cosine of the polar angle. These equations have to be complemented by definition expressions for the absorption and emission coefficients.

Resulting equations form a highly coupled, non-linear set which closely resembles that describing classical stellar atmospheres. The most important differences are i) depth-dependence of gravity in the case of disks; and ii) the energy equation for stellar atmospheres simply reads $D_{rad} = 0$, which is equivalent to the condition of the total radiation flux being constant throughout the atmosphere.

The above set of structural equations has been solved, for conditions corresponding to accretion disks around dwarf novae, by Kriz and Hubeny (1986). They developed a modification of the complete linearization method devised originally for classical stellar atmospheres (Auer and Mihalas 1969). They found that for moderate and low values of the mass accretion rate, large parts of the disk are optically thin in the visible and UV continua, while for higher values of the accretion rate the disk is optically thick. In other words, they demonstrated that making the ad hoc assumption that the disk is either optically thin or optically thick may lead to considerable errors in the predicted emergent radiation.

4. Gray Model

As in the classical stellar atmospheres, a gray model, which is constructed using some appropriately defined frequency-averaged opacities, may serve as a guide to the general nature of the results to be expected from more realistic calculations. Also, the gray model serves as an excellent starting approximation for a subsequent iterative method, as for instance the complete linearization.

The gray models of accretion disks were constructed by Kriz and Hubeny (1986), who used them as starting solutions for their method, by Shaviv and Wehrse (1986), and by Adam et al. (1988). All these authors solved the gray problem numerically. Nevertheless, it is possible to derive some simple analytic expressions that represent generalization of corresponding classical stellar atmospheric results. A more complete account is given elsewhere (Hubeny, in preparation); here I present only a brief outline.

Introducing the mass-depth variable, m, the first and the second moments of the transfer equation read

$$\frac{dH}{dm} = \kappa_J J - \kappa_B B \quad ; \quad \frac{dK}{dm} = \kappa_H H \quad , \tag{8}$$

where J, H, K are the frequency integrated moments of the specific intensity, B is the Planck function, and κ_J, κ_B, κ_H are the absorption mean, Planck mean, and flux mean opacity, respectively (for definitions of these opacities refer, e.g., to Mihalas 1978). The energy equation (5) may be written

$$\frac{dH}{dm} = - E\nu_V(m) \quad , \quad \text{with} \quad E = (9/4)Q \quad . \tag{9}$$

When writing $\nu_V(m)$ we stress that viscosity generally depends on depth, although the form of this dependence need not actually be known.

Combining Eqs. (8) and (9), and introducing Eddington factors f_K=K/J, and f_H=H(0)/J(0), we get after some algebra

$$T^4(m) = \frac{3}{4} T_{eff}^4 \left\{ \gamma_J [\gamma_H/\surd 3 + \tau_H - \psi] + \frac{1}{3M\kappa_B(m)} \frac{\nu_V(m)}{\bar{\nu}_V} \right\} \quad , \tag{10}$$

where γ_J and γ_H are factors of the order of unity, defined by

$$\gamma_J = \kappa_J/(3\kappa_B f_K) ; \qquad \gamma_H = \surd 3 \; f_K(0)/f_H \; ; \tag{11}$$

τ_H is the optical depth associated with flux mean opacity, $\bar{\nu}_V$ is the m-averaged viscosity and M the total column mass;

$$M = \int_0^\infty \rho dz \quad ; \quad \bar{\nu}_V = \int_0^\infty \nu_V(z) dm/M \tag{12}$$

and function ψ is given by

$$\psi(m) = \int_0^m \kappa_H(m')\mu(m')dm' \; ; \text{ with } \; \mu(m) = \int_0^m \nu_V(m')dm'/(\bar{\nu}_V M) . \tag{13}$$

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One may simplify Eq. (10) further by putting $\gamma_J = \gamma_H = 1$ (i.e., invoking the Eddington approximation and assuming $\kappa_J = \kappa_B$), next assuming $\kappa_H = \kappa_R$, κ_R being the Rosseland opacity, and finally assuming the Rosseland opacity to be weakly dependent on depth. One gets

$$T^4 = \frac{3}{4} T_{eff}^4 \left[1/\sqrt{3} + \tau(1-\tau/2\tau_{max}) + \frac{1}{3\epsilon\tau_{max}} \frac{\nu_v(m)}{\bar{\nu}_v} \right] , \quad (14)$$

where τ has now the meaning of Rosseland optical depth, τ_{max} is the total optical depth, and $\epsilon = \kappa_B/\kappa_R$. This result is a generalization of the well-known gray temperature distribution for stellar atmospheres. Apart from a relatively unimportant correction term, approximated here by $(1-\tau/2\tau_{max})$, the main difference is the last term in the square brackets. As we shall see, this term is crucial for understanding the behavior of disks at small optical depths

5. Formation of Hot Layers

The existence of high-temperature layers at large z (or small optical depth) can be readily deduced from Eq. (14). Letting $\tau \to 0$, and assuming first a depth-independent viscosity, we get

$$T(0) = T_{eff} \left[\sqrt{3}/4 + (4\epsilon\tau_{max})^{-1} \right]^{1/4} . \quad (15)$$

The surface temperature exceeds T_{eff} if either τ_{max} or ϵ or both are sufficiently small. Since τ_{max} is given basically by the adopted mass accretion rate $\dot{M}$, and can then be either large or small, the crucial factor is ϵ.

At first sight, one might argue that ϵ should be roughly given by

$$\epsilon \simeq \langle \frac{\kappa_\nu}{\kappa_\nu + \sigma_\nu} \rangle , \quad (16)$$

i.e., by some appropriate frequency average of the ratio of pure absorption to the total extinction (absorption + scattering). This follows from the fact that the Planck mean opacity contains only pure absorption, while the Rosseland (or flux mean) opacity contains total extinction. Going outward, κ_ν decreases more quickly than σ_ν (since σ_ν is proportional to n_e, the electron density, while κ_ν is proportional to n_e^2), the total opacity is then more and more dominated by electron scattering, and consequently ϵ goes to zero. As a result, the temperature increases indefinitely. Physically, this temperature increase arises due to the fact that energy is dissipated at all depths (recall the assumption of depth-independent viscosity), but the gas at small optical depths only <u>scatters</u>; it does not absorb or emit radiation, i.e., it possesses no efficient mechanism to reradiate the dissipated energy.

This is precisely the argument raised by Shaviv and Wehrse (1986) and Adam et al. (1988), although they used somewhat different language. They also suggested a way to avoid an indefinite temperature

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rise, which can be easily seen in our formalism: The critical last term of Eq. (14) contains $\nu_V(m)/\nu_V$, so that letting $\nu_V(m)/\nu_V$ decrease with vertical distance more rapidly than ϵ prevents an unreasonable temperature rise.

However, the argument of Shaviv and Wehrse and Adam et al. is not quite correct. I maintain that the temperature need not necessarily increase indefinitely even in the case of depth-independent viscosity. The key point is that the intuitive Eq. (16) is incorrect. The correct definition of ϵ follows from Eq. (10), namely that $\epsilon\tau_{max}=\kappa_B(m)M$. Now, the Planck mean opacity is determined predominantly by frequency regions of high opacity, i.e., by strong resonance lines. Physically this means that it is not correct to say that regions with $\tau \ll 1$ are poor emitters; these layers in fact emit radiation in strong resonance lines, such as H I, Mg II, C II, Al III, Si IV, C IV, N V, etc., each line being an efficient cooler for a certain temperature range. These lines have thus a two-fold significance: they serve as efficient coolers; and they represents a powerful diagnostic indicator.

The temperature structure of the most superficial layers can also be estimated by a somewhat different approach borrowed from the theory of solar and stellar coronae (see, e.g., McWhirter et al. 1975; Athay 1976; Jordan and Brown 1981; Böhm-Vitense 1987 and references therein). In regions that are optically thin even in lines, the net radiative cooling term D_{rad}, defined generally by Eq. (6), may be written

$$D_{rad} = n_e n_H \phi(T) \quad , \tag{17}$$

where n_H is the hydrogen number density, and $\phi(T)$ is a universal function depending only on temperature, called radiative loss function (Cox and Tucker 1969; McWhirter et al. 1975). For rough estimates, the function ϕ may be parametrized as $\phi = \phi_0 T^\beta$. Assuming now the α-model for viscosity, i.e., $\nu_V = \alpha P/\rho$, we get for D_{mech} from Eq. (4)

$$D_{mech} = (9/4)Q^{1/2}\alpha P \quad . \tag{18}$$

A stable solution $D_{rad} = D_{mech}$ exists only if the following thermal stability criterion (Athay 1976) is fulfilled

$$\frac{d}{dT}\left(\frac{D_{mech}}{\rho}\right) < \frac{d}{dT}\left(\frac{D_{rad}}{\rho}\right) \quad . \tag{19}$$

Equations (17) - (19) yield the stability condition

$$\beta > 2, \tag{20}$$

and the temperature gradient, assuming for simplicity complete ionization of the gas,

$$\frac{dT}{dz} = \frac{\gamma}{2(\beta-2)}\, z \quad , \quad \text{with} \quad \gamma = Q\mu m_H/k \quad , \tag{21}$$

where μ is the mean molecular weight, m_H the mass of hydrogen atom, and k the Boltzmann constant. The temperature is then

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$$T(z) - T(z_0) = \gamma(z^2 - z_0^2)/(\beta - 2) \quad . \tag{22}$$

Since stable solutions exist only for $\beta > 2$, the temperature can only increase with vertical distance. The condition $\beta > 2$ means that the cooling function has to increase rather rapidly with temperature. This is generally the case for $T \leq 15000$ K, and for $30000 \leq T \leq 10^5$ K (see, e.g., Böhm-Vitense 1987). For higher temperatures, the radiative loss function is more or less constant or even decreases with T, and thus a simple balance between D_{rad} and D_{mech} is no longer possible. Another energy loss mechanism becomes effective, namely a conductive heat transport.

The essential picture is then very similar to the normal solar or stellar coronae. In contrast to the stellar case, where identifying a proper heating mechanism is a non-trivial task; in accretion disks we have, at least in principle, a straightforward source of dissipated energy due to viscous shear at all heights above the central plane. The problem is rather to avoid too high temperatures.

Constructing detailed models of accretion disk coronae would certainly be very difficult. The basic obstacle is a poor knowledge of viscosity. The situation is even worse here than in the canonical theory, because we need to know the dependence of viscosity on vertical distance, which is essential for detailed modelling of superficial hot layers. However, the mere existence of high-temperature regions above the accretion disks seems to be physically quite reasonable.

6. Concluding Remarks

The above analysis demonstrated that the hot layers producing highly ionized lines may exist, but did not say anything about how dense those layers will actually be, i.e., how strong we expect the emission lines to be. To this end, the detailed vertical structure has to be determined, following the methodology outlined above.

In the case of Algol disks, there are also other phenomena, not discussed here, that should be taken into account. In contrast to, say, cataclysmic variables, the central star in Algol disks has much larger dimensions, and therefore not only contributes significantly to the total emergent radiation from the system, but also plays an active role in irradiating the disk and then contributing to the energy balance in the disk.

The essential complication follows from the fact that the Algol disks are seen more or less edge-on. This means that the usual procedure of calculating the emergent flux by summing contributions from individual rings cannot safely be applied here. Instead, we have to solve the radiative transfer equation along a set of lines of sight, using the calculated vertical structure of the individual rings (the so-called 1 1/2 - D problem). Or better yet, we must devise suitable numerical schemes to treat a 2-D (vertical + radial) transfer of radiation in the disk self-consistently.

The project outlined in this paper is ambitious, but I feel this effort will be rewarded. Progress in spectroscopic diagnostics of

Algol disks contributes not only to our understanding of Algols themselves, but also to the theory of accretion disks in general.

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DISCUSSION

Smak commented that he had once hoped that computations of disk models for cataclysmic variables would help us to understand Algols, but he had become aware of many difficulties. Everyone who computes models in the "stellar-interior" spirit commits some great sins - especially in the treatment of regions where convection is inevitable. Everyone uses mixing-length theory, but the mixing scale is comparable to the disk thickness, and the theory does not work at z = 0, where gravity virtually disappears. Hubeny agreed and added that there was little point in refining the treatment of viscosity and continuing to use mixing-length theory. Nevertheless, the new so-called λ-operator method provided some very nice ways of treating multi-dimensional radiative transfer.

Guinan, noting that cataclysmic variables appear to have a conical wind emerging perpendicular to the orbital plane, asked if Hubeny would expect a similar phenomenon in Algols. Hubeny thought not, although there could be a wind from the star. Since gravity increases in the disk with z, conditions would not favour formation of a wind. Guinan pointed out that we observe only eclipsing Algols. We should look for a system that we could observe at an inclination of about 45°, that could be matched in period and masses with an eclipsing system, and then look for evidence of a wind. Hubeny agreed, suggesting that some Be stars might be candidates. Honeycutt agreed that IUE observations of low-inclination nova-like cataclysmic variables provide good evidence for winds. He pointed out that in the eclipsing nova-like systems, the radial size of the emission-line region is generally smaller than the continuum region, which implies that the emission lines arise, partly at least, from a wind-like configuration above and below the continuum disk. So far, the only Algol for which a similar comparison has been made is U Cep, in which the line-emitting region is larger. There is thus no (optical) evidence for winds in Algols, but Honeycutt thought the comparison should be attempted for more active systems.

Plavec, while he agreed with almost everything Joe Smak had said (p.107), sensed an undertone of underestimation of the knowledge and intelligence of "observers" who try to interpret the observed phenomena. The concepts of "extended envelope" and "circumstellar shell" were never clearly defined and now we are attempting to replace them by physically more meaningful concepts such as "accretion disk", "stellar wind", "chromosphere" and "corona". But in Algols the observed phenomena do not seem to match the theoretical structures. Therefore Hubeny's work (and that of Livio, Wehrse and Shaviv) is very important.

Several references to supersonic turbulence led Bolton to point out that the word "turbulence" had been used in different ways in the context of stellar atmospheres. He used the word to refer to any line-broadening mechanism that has a functional $\Delta\lambda/\lambda$ dependence and operates on scales larger than microscopic effects and smaller than the system. "Microturbulence" could refer to scales small compared with the depth of a stellar atmosphere, and "macroturbulence" to scales comparable with that depth. In disks, supersonic microturbulence would be hard to understand, but it might be easier to understand supersonic motions that are coherent on the scale of disk thickness.

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