ACCRETION DISKS IN ALGOLS

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ABSTRACT. Basic theoretical concepts concerning formation and properties of disks in close binary systems are reviewed and compared with observations of Algols.

0. NOTATION

Throughout this article, unless indicated otherwise, capital letters will be used for quantities in *cgs* units, while small letters for their dimensionless equivalents.

Subscript "$_1$" will be used to designate the *gainer*, and subscript "$_2$" - the *loser*. The mass ratio will be defined as $q = M_2/M_1$.

Accretion rates will be expressed in g/s, or in 10^{18} g/s. Thus $\dot{M}_{18} = 1$ will correspond to $\dot{M} = 10^{18}$ g/s $= 1.6\times10^{-8}$ $M_\odot$/yr.

1. INTRODUCTION: OBSERVATIONAL EVIDENCE

Disks in binary systems can be detected and studied in a number of ways. The following effects are observed in the continuum:

1. Contribution from the disk to the total light of the system.

2. Obscuration by the disk of the gainer. In the case of an optically thick disk, depending on geometrical parameters, this can affect more than 50 percent of the stellar light. Note that effects 1 and 2 are related. When the disk is not axisymmetric they are both phase dependent.

3. Occultation of the disk by the loser. This produces broad, usually shallow wings superposed on the stellar eclipse.

4. Occultation of the loser by the disk. Note that effects 3 and 4 are related.

The most spectacular contribution from the disk, however, is seen in the form of emission lines. The following effects are observed:

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5. Emission lines from disks are double. In the case of a Keplerian disk the half-separation of the peaks corresponds approximately to the rotational velocity of the outer parts of the disk (Smak 1981).

6. Occultation of the disk by the loser results in major variations in the profiles of the emission lines. This provides a very powerful tool for studying the velocity field and distribution of the emitting atoms (cf. Kaitchuck and Honeycutt 1982, Kaitchuck 1988).

An important point is to be made here: Different types of observations may, depending on circumstances, provide information on different parts and different properties of the disk. For example, when the disk is optically thin the emission lines are produced together with the continuum in the whole body of the disk (cf. Tylenda 1981). When the disk is optically thick, however, they must originate primarily in its chromosphere or corona.

2. INTRODUCTION: STANDARD ACCRETION DISK MODEL

In the standard theory of accretion disks (cf., e.g., Pringle 1981) it is assumed that disk is: (1) axially symmetric, (2) flat, i.e. $Z/R \ll 1$,, and (3) Keplerian, i.e. $V_t = (GM_*/R)^{1/2} \gg |V_r|$. These assumptions are sufficient to predict some of the disk's parameters regardless of the nature of viscosity responsible for the transfer of the angular momentum and for the accretion itself.

The total luminosity of the disk is

$$L_d = \frac{1}{2} \frac{G M_*}{R_*} \dot{M} . \qquad (1)$$

Since the radius of the main sequence gainer is roughly proportional to its mass, the luminosity of the disk depends primarily on M and we have: $L_d \approx 1 \times 10^{33} \dot{M}_{18}$ erg/s. Compared to stellar luminosities this implies that *the disk may contribute significantly to the total light of the system, particularly in the case of high mass transfer rates and low mass primaries*. Radiation from the disk is strongly anisotropic. The approximate relation between the luminosity of the disk at an inclination i and its average luminosity is (cf. Mayo et al. 1980)

$$L_d(i) = \langle L_d \rangle \, (1.5 \cos i + 1) \cos i , \qquad (2)$$

where $\langle L_d \rangle = L_d$ given by Eq.(1).

The flux emitted from the surface of the disk at a distance R is

$$F = \sigma T_e^4 = \frac{3}{8\pi} \frac{G M_*}{R^3} \dot{M} \left[1 - (R_*/R)^{1/2} \right] , \qquad (3)$$

with the maximum temperature to occur at $R = 49/36 \, R_*$. In Algols, the maximum temperatures are predicted to be rather low. For example, at $M_1 = 5$ M⊙ and $\dot{M} = 10^{18}$ g/s, $T_e \approx 1200$ K, while at $M_1 = 2$ M⊙ and $\dot{M}$ =

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10^{20} g/s, T_e ≈ 6000 K. Thus, *disks in Algols are expected to be quite cool.*

Vertical structure of disks has been studied extensively within the α-disk theory, in particular with application to disks in cataclysmic variables (e.g. Meyer and Meyer-Hofmeister 1982). Resulting models give an information about the geometrical thickness as well as the optical thickness. Using such models (Smak 1984) we find that in the case of relatively cool disks in Algols the following approximate formula can be used to estimate the *geometrical* thickness at the density level of 10^{-10} g/cm^3:

$$Z_0/R \approx 0.07 \left[\dot{M}_{18} \, [1 - (R_1/R)^{1/2}] \right]^{0.18} . \qquad (4)$$

For the *optical* thickness we find that, depending on parameters, disks in Algols should be either optically thick (when M is high and R is large) or moderately thin. Even in the latter case, however, the optical thickness in the disk plane must be high.

A complete picture of accretion must include also the *boundary layer* between the innermost part of the disk and the equatorial parts of the star. The amount of energy to be dissipated in the boundary layer depends on the star's rotational velocity. In the case of a non-rotating star it is given also by Eq.(1). It can be shown that the boundary layer must be thin (in the z-coordinate) and narrow (in the r-coordinate). If the boundary layer is assumed optically thick then its effective temperature can be estimated (after Pringle 1977) in the case of Algols to be comparable to that of the gainer. Detailed models developed for cataclysmic binaries (for references see Smak 1987) show, however, that the structure of the boundary layer can be much more complex and that in some cases it can be very hot and optically *thin, extending considerably in the vertical direction. No attempts so* far have been made to check whether such hot, corona-like boundary layers could not also be present in Algols and be partly responsible for the presence of high excitation lines (e.g. Plavec 1983, 1988, Plavec and Dobias 1983, Peters and Polidan 1984).

Several of the predictions made above are indeed consistent with the results of analysis of disks in very long period Algols (e.g. RZ Oph and KU Cyg; cf. Olson 1987, 1988, Olson and Hickey 1983) which are of Type 1 (cf. next Section) and to which this standard model is presumably well applicable. So far, however, no theoretical models are available for other types of disks, or disk-like structures present in Algols.

3. DISK FORMATION

3.1. Particle Trajectories

Disks are formed in close binary systems as a result of mass transfer from the loser. Calculations of simple particle trajectories (Lubow and Shu 1975 and references given therein) lead to identification of two critical radii: (1) the distance of closest approach of the stream to the gainer r_{min}; and (2) the radius of a circular, Keplerian orbit with an angular momentum being the same as that of the stream particles r_h. Both of them are functions of the mass ratio only and always $r_{min} < r_h$.

3.2. Conditions and Mechanisms of Disk Formation

Depending on the radius of the gainer the following three types of situation are to be considered:

Type 1: $r_1 < r_{min}$

Type 2: $r_{min} < r_1 < r_h$

Type 3: $r_h < r_1$.

In *Type 1*, starting with an initial situation, when the mass transfer is just turned on, the formation of a disk can be described as follows. Since the stream trajectory intersects itself after one revolution, there will be collisions between stream particles, leading to the dissipation of the radial and vertical velocity components, with the angular momentum being conserved. Without viscous interactions the final configuration would be a Keplerian ring with radius r_h. Due to viscosity, however, the ring will spread inward and outward, the outer radius of the disk r_d being controlled by the tidal interactions. The steady state configuration then will be just the standard accretion disk described in Section 2.

The situation appears different in *Type 2* and *Type 3*. In both cases the stream must originally collide with the gainer. Two pictures have been proposed to describe the formation of a disk in this case. Olson (1980) considered a model in which the stream penetrates fairly deeply into subphotospheric layers of the gainer. Due to inefficient cooling only part of the impact energy is dissipated in a shock front, while the rest is absorbed and distributed in the equatorial belt on the trailing side of the gainer. As a result, the equatorial parts expand forming a *bulge*. This model is likely to be more applicable to Type 3 where the stream collides with the stellar surface nearly vertically.

Another model is that involving a *splash* when part of the stream material bounces off the stellar surface (cf. Kaitchuck et al. 1985). Some support for such a model comes from hydrodynamical calculations performed by Różyczka and Schwarzenberg-Czerny (1987) for the stream-disk collision. They find that when cooling is relatively ineffective the stream is indeed "reflected" from the target. The splash model can be explored a little bit further with the particle trajectories technique. Very crudely we can assume that the radial velocity component is only partly dissipated during collision while the tangential component remains unaffected. Figures 1 and 2 show two examples of such trajectories corresponding to Type 2 and Type 3.

In *Type 2* we have a situation qualitatively similar to Type 1. The reflected material retains its original excess angular momentum and therefore the formation of a disk appears as natural as in Type 1. But once such a disk has been formed the stream collides with its outer parts and the condition $r_1 < r_{min}$ appears no longer important! In other words, *Types 1 and 2 are expected to differ during the disk*

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formation phase and - possibly - whenever the accretion rate is strongly variable, but should be qualitatively similar under steady state accretion conditions.

In *Type 3* the angular momentum of the stream is, to begin with, too low to form any permanent, axisymmetric disk so that the reflected material must sooner or later land on the star. Therefore *in Type 3 only a quasi-disk structure is expected, with sub-Keplerian velocities, and - presumably - with a considerable asymmetry between the trailing and leading sides.*

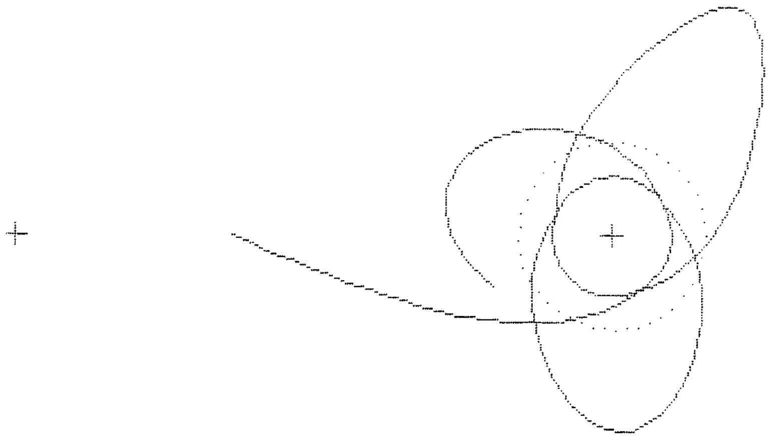

Figure 1. Particle trajectories with a "splash" from the surface of the gainer calculated for the mass ratio q = 0.25, the radius of the gainer r_1 = 0.10, and the "reflection coefficient" of 0.75. The dotted circle has radius r_h.

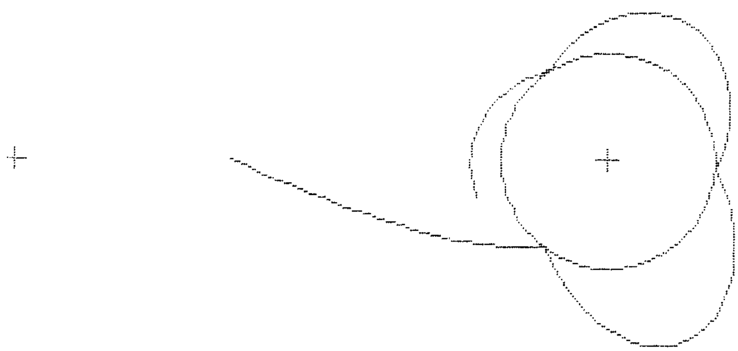

Figure 2. Same as in Figure 1 but with r_1 = 0.18.

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Note concerning terminology: As it was pointed out during the Colloquium by Professor Plavec, the commonly used term "*sub-Keplerian*" is, unfortunately, misleading and incorrect. What is discussed here (and observed in some binaries) amounts to the fact that the tangential velocity is smaller than the *circular*, Keplerian velocity (at the same radial distance). In the simple, two-body approximation, this implies that the particle must be near the apastron of its elliptic, *Keplerian* orbit.

3.3. The Stream

The structure of the stream was studied by Lubow and Shu (1975, 1976) who calculated, in particular, the density distribution. It turns out that the cross section of the stream is generally comparable to the vertical thickness of the disk (as discussed in Section 2). The finite cross section of the stream has two important consequences. First, the subdivision into three types discussed in Section 3.2, cannot be sharp. Secondly, and perhaps more importantly, it appears that, depending on the combination of parameters involved, substantial fraction of *the stream material can fly above (and below) the disk*.

Then, while the central part of the stream collides with the outer parts of the already existing disk, its outer parts may reach and collide with the central star. This appears the most promising mechanism to explain the existence of hot, highly turbulent circumstellar material (cf. Plavec 1983, 1988, Plavec and Dobias 1983, Peters and Polidan 1984).

4. CONFRONTATION WITH OBSERVATIONS: THE r_1 *vs.* q DIAGRAM

Since the classical times of Joy and Struve it is well known that observations of double emission lines in the spectra of Algols provide rich information on the presence and structure of their disks. The most recent extensive survey by Kaitchuck and Honeycutt (1982b) and Kaitchuck et al. 1985) confirmed an earlier result by Struve and Huang about the existence of three types of systems: (a) with *permanent disks*, (b) with *transient disks*, and (c) *without disks*.

At this point it is worth to emphasize that observations refer actually to the *emission lines*. Their absence or variability must obviously be related to the variable parameters of the disk, but the nature of this relationship is far from being obvious. In particular, the absence of emission lines may not necessarily indicate that there is no disk or disk-like structure in the system.

The three observed types appear *correlated* with the three types discussed in Section 3.2. Figure 3 shows a plot of all systems from the survey by Kaitchuck et al. in the r_1 *vs.* q diagram (where r_1 is the dimensionless radius of the gainer). As we can see, the correlation is not too strong but certainly well established: For example, most systems with *permanent disks* are located below the r_{min} line, i.e. belong to *Type 1*, nearly all those *without disks* are above the r_h line, i.e. belong to *Type 3*, etc. Of course, we could argue that some

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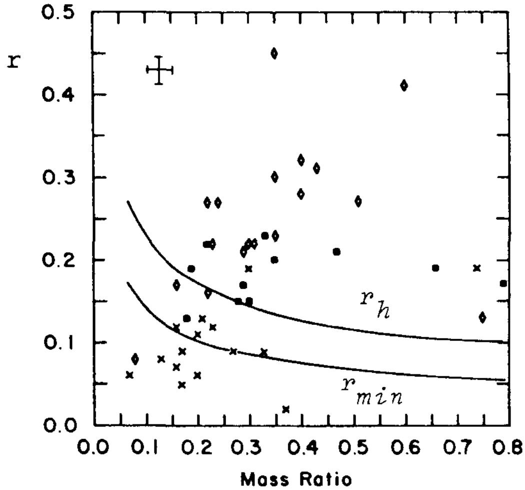

Figure 3. Location of Algols in the r_1 *vs.* q diagram (after Kaitchuck *et al.* 1985). Crosses are systems with permanent disks, squares - with transient disks, and diamonds - without disks. The two critical lines are discussed in the text.

scatter in the r_1 *vs.* q diagram near the r_{min} line should be expected as a natural consequence of the finite cross section of the stream.

The existence of this correlation, its loose nature, and - to begin with - the very presence of the three types of systems pose questions which are far from being trivial:

1. Why should there be any such correlation? In view of the general discussion of Section 3.2 we would expect disks or disk-like structures to present in all three types of systems. In particular, we would expect to be no qualitative difference at least between Types 1 and 2. Could it be then that the correlation refers only to the regions of emission line formation but not to the disks themselves?

2. What is responsible for the transient nature of disks in some systems or, more generally, for the strong variability of the emission line intensities? Here we can consider two possibilities:

(a) *Disks are unstable.* This has been the traditional explanation. It is not clear, however, what kind of instability - if any - would be involved here. Further studies of the structure of quasi-disks or bulges are badly needed to explore this possibility.

(b) *Disks never reach steady-state conditions due to strongly variable accretion rates.* This is much more promising since, indeed, many Algols show highly variable mass transfer rates, the most spectacular example being U Cep.

5. THE V_d *vs.* P RELATION

The rotational velocity of the disk V_d, as defined by the separation of the two peaks in the emission line profile, is correlated with the orbital period (cf. Batten 1973 and earlier references therein). Indeed, in the case of a Keplerian disk we have the following relation:

$$V_d^3 = \frac{2\pi\ G\ M_1}{P} (1 + q)^{-1/2} r_d^{-3/2} , \qquad (5)$$

where r_d is the dimensionless radius of the disk, corresponding to V_d. The observed correlation, based on all types of binaries, including cataclysmics, Algols, and very long period systems like ϵ Aur, has the form:

$$4.6 \log V_d \text{ [km/s]} = 11.9 - \log P \text{ [d]} . \qquad (6)$$

Different slope and the tightness of this correlation imply that

1. M_1 must be correlated with P, which is very likely, and
2. the factor $(1 + q)^{-1/2} r_d^{-3/2}$ must be nearly independent of q and either constant or correlated with P. Concerning its dependence on q, we may note that it could indeed be rather weak if r_d/r_{Roche} = *const.* This could well be in the case of standard accretion disks, such as those presumably present in cataclysmic variables and in long period Algols of Type 1.

The most important unanswered question, however, is *why disks or quasi-disks of Type 2 and Type 3 should obey the relation defined by Type 1 disks?*

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DISCUSSION

Kaitchuck commented on the relation between the rotational velocity of disks (as measured by the separation of the emission peaks) and the orbital periods of the systems in which they are found. He has revised and added to the data compiled by Batten (Binary and Multiple Systems of Stars, Pergamon Press 1973, pp. 214-5) and found that, with improved data, the relation is even better defined. The interesting point is that, in systems of the longest and shortest periods the disks have Keplerian velocity distributions, while in intermediate-period systems they do not. He also asked about the assumptions under which the multiple "splashes" illustrated in Smak's Figures 1 and 2 were computed. Smak replied that the tangential-velocity component (i.e. angular momentum was supposed to be conserved, while a fraction x of the radial component is dissipated. The calculations shown were made with x = 0.25, but similar results can be obtained for x = 0.5.

Livio commented that recent results from three-dimensional computations (Astrophys. J. in press) of the impact of a stream on a disk confirmed that matter could flow above and below the disk. In some circumstances he also found a "splash". If the mass-transfer rate increased, the initial effect was to decrease the radius of the disk. This radius, however, would then increase beyond the value it had in the quiescent phase, and finally slowly decay. He suggested that an important, though difficult observation, would be to measure changes of the disk radius in order to identify increases in the rate of mass-transfer.

Olson commented on the importance of ram pressure, as shown by R.K. Ulrich and H.L. Burger (Astrophys. J. **206**, 509, 1976). The ram pressure can be very large near the centre of the stream, which could indeed penetrate the star. If the density-profile of the stream is Gaussian, however, the edges might give only a "splash". It could be that the emission lines come from this low-density "splash", while the bulges observed photo-metrically are evidence of penetration. Budding pointed out that the calculations for U Cep by K.H. Prendergast and R.E. Taam (Astrophys. J. **189**, 125, 1974) showed a central high-density axi-symmetric region in the disk, but that the low-density regions, in which the emission lines would originate were not axi-symmetric. Peters remarked that observations gave her the impression that a dense disk does deflect even the central portions of a thick stream. Shell-type lines that display red-shifts relative to the photosphere, which she identified as the spectrum of the stream, are more easily visible in the spectra of partially-eclipsing or non-eclipsing systems than in those of totally-eclipsing systems (cf AU Mon, CX Dra, H.R. 2142), as if the disk interferes with the flow in the orbital plane, diverting material so that it falls on the gainer near the latter's poles. She also suggested that variable rates of mass transfer could be observed in AU Mon. The period of this system is about 411^d, and the out-of-eclipse brightness fluctuates ($\Delta V \sim 0^m\!.3$). When the star is faint (out-of-eclipse) the gas-stream spectrum is 8 to 10 times stronger than when the star is bright. Lines from highly ionized species (N V, Si IV), however, are stronger when the star is brighter.

Wilson commented on the importance of self-gravitation of large disks in systems such as β Lyr. The mass-distribution in a disk is very different from a concentrated point mass. Moreover, the structure of the disk is determined by the small difference between gravity and centrifugal force. Even a small change in the gravity field, therefore, can have a large effect on the equipotentials. Smak agreed that these effects are important for a system like β Lyr, but stated that self-gravity of the disk can be shown to be negligible for many ordinary Algols.

Comments stimulated by Smak's remarks on RZ Oph will be found in the record of general discussion on p.323.