ACCRETION DISK STRUCTURE IN SS CYGNI

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ABSTRACT. High-resolution Coude observations of non-axisymmetric line emission from the dwarf nova SS Cygni are presented. By subtracting the constant line component, the asymmetric line emission responsible for the observed phase shift between the absorption and emission line radial velocity curves can be isolated. The extra emission is a large fraction of the total line emission and extends to large velocities (~1500 km sec^{-1}). The phase stability of the emission demands a large-scale structure which is fixed in the frame of the binary. A magnetic origin of the excitation cannot be ruled out but is implausible. A simple explanation is that the accretion stream from the companion star is able to spill over the edge of the disk, introducing emission at non-circular velocities and most likely disturbing the upper layers of the accretion disk.

1. INTRODUCTION

Any complete model for the emission lines from quiescent cataclysmic variables must be able to reproduce not only the correct line flux ratios but answer the following questions : (1) why are the classically double-peaked emission lines in systems with moderate inclinations so rare; (2) is the line emission driven locally by viscous dissipation and/or by other means; and (3) what is the source of the frequent phase shifts between the emission lines and more trust-worthy measurers of binary orbital phase (absorption lines and/or eclipses)? The first problem has not been "solved", but the observed presence of many other sources of line emission like the the companion star (Hessman 1985, 1986) and the hot spot make it seem plausible that

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an underlying, classically double-peaked profile exists. The problem of the excitation is not so easily resolved. Simple, LTE viscous models cannot reproduce the flat Balmer decrements seen in Cataclysmic Variables without invoking extreme assumptions like the near-absence of hydrogen (Ferguson and Williams 1982) even when a wide range of possible viscous models are used (Hessman 1985). Simple photoexcitation models will have a difficult time producing the large He I emission line fluxes and the flat, singlet-to-triplet ratio.

The third problem - that of the phase shifts - is the most intriguing, for it implies that we are seeing non-axisymmetric structure(s) in the accretion disk. An up-to-date list of well-documented phase shifts in cataclysmic variables is shown in Table I. Most of these shifts have been measured from the extreme wings of the emission lines which should have come from the inner parts of the disk. Although this region of the lines should have been the best indicator of the white dwarf's orbital motion, the phase shifts are seen in roughly all of the systems for which we have independent phase information. The most obvious way to produce emission line phase-shifts is to maintain large-scale structures in the inner regions of the accretion disks. However, fluctuations in a disk which initially might have large-scale, coherent structure should be rapidly destroyed by the differential rotation of the disk. Large-scale structures may be caused by the effective gravitational potential field of the two stars and may lead to non-circular motions in the outer parts of the disk, but should be destroyed by the viscosity necessary for the mass-accretion in the inner disk where the orbital speeds are high enough to produce line emission at the observed velocities.

The purpose of this article is to present high resolution observations of the Hβ emission line in SS Cygni and to show how they constrain possible physical models for the asymmetric emission from the accretion disk. Finally, two models for the emission line regions are discussed which are capable of maintaining coherent structures: magnetic fields and the accretion stream.

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TABLE I

Observed Emission Line Phase Shifts

System	Phase Shift	Period (days)	Reference
DQ Her	0° ± 4°	0.1936	Young, et al. 1981
BV Cen	6° ± 2°	0.6101	Gilliland 1982
EX Hya	7° ± 4°	0.0682	Gilliland 1982
RU Peg	9° ± 3°	0.3708	Stover 1981
U Gem	9° ± 4°	0.1769	Stover 1981
SS Cyg	10° ± 1°	0.2751	Hessman, <u>et al.</u> 1984
EM Cyg	20° ± 4°	0.2909	Stover, <u>et al.</u> 1981
Z Cam	24° ± 6°	0.29	Szkody and Wade 1981
WZ Sge	29° ± 7°	0.0566	Gilliland 1983
LX Ser	30° ± 4°	0.1584	Young, <u>et al.</u> 1981
HT Cas	33° ± 4°	0.0736	Young, <u>et al.</u> 1981
AC Cnc	43° ± 10°	0.3004	Schlegel, <u>et al.</u> 1984
SW UMa	47° ± 10°	0.0568	Shafter, <u>et al.</u> 1986
V2051 Oph	48° ± 7°	0.062	Schoembs & Hartman 1986
Lan 10	58° ± 7°	0.3212	Horne, <u>et al.</u> 1982
UX UMa	0° to 22°	0.1967	Kaitchuck, <u>et al.</u> 1983

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2. OBSERVATIONS

The observations were made with the help of J. Brown in September 1983 on the 2.7m at the University of Texas' McDonald Observatory. A low-dispersion grating and a Digicon at the Coude focus gave about 225 Å of spectrum centered at Hβ at a dispersion of 8.6 Å mm^{-1} and a resolution of about 0.5 Å. Due to the low throughput of the Coude system, the 28 exposures had to be 15 minutes long. This did not, however, endanger our ability to resolve profile features in the frame of the 6.6 hr binary system. Details of the reduction process are described in Hessman (1985).

Because the ratio of the absorption line flux to the disk flux remained constant during the period of the observations, the spectra could be placed on an approximate relative flux scale. After the absorption spectrum was removed from each spectrum, the spectra were binned into 8 orbital phase bins. As one can see in Figure 1a, the emission component with the same phasing as the companion star is obvious. Sometimes obvious is the classically double-peaked profile of a simple rotating disk, but it is clear that there is an additional, asymmetric emission component. In order to isolate this additional component, the phased spectra were corrected for the assumed orbital motion of the white dwarf and the minimum line flux present in each phase bin calculated at each velocity was determined. This composite spectrum represents the constant, underlying emission of the disk due to whatever processes. A smoothed version of the constant emission line profile was then subtracted from each phase bin. The remaining emission line profiles represent the non-constant fraction of the asymmetric emission responsible for the observed 10° phase shift (Figure 1b).

3. MODELS FOR THE ASYMMETRIC LINE EMISSION

Any successful model for the asymmetric line emission from the accretion disk in SS Cyg must satisfy the following constraints : (1) the emission must be locked in phase with the orbit; (2) a substantial fraction of the emission must be at high velocities; and (3) the mechanism must have little memory of the disk's

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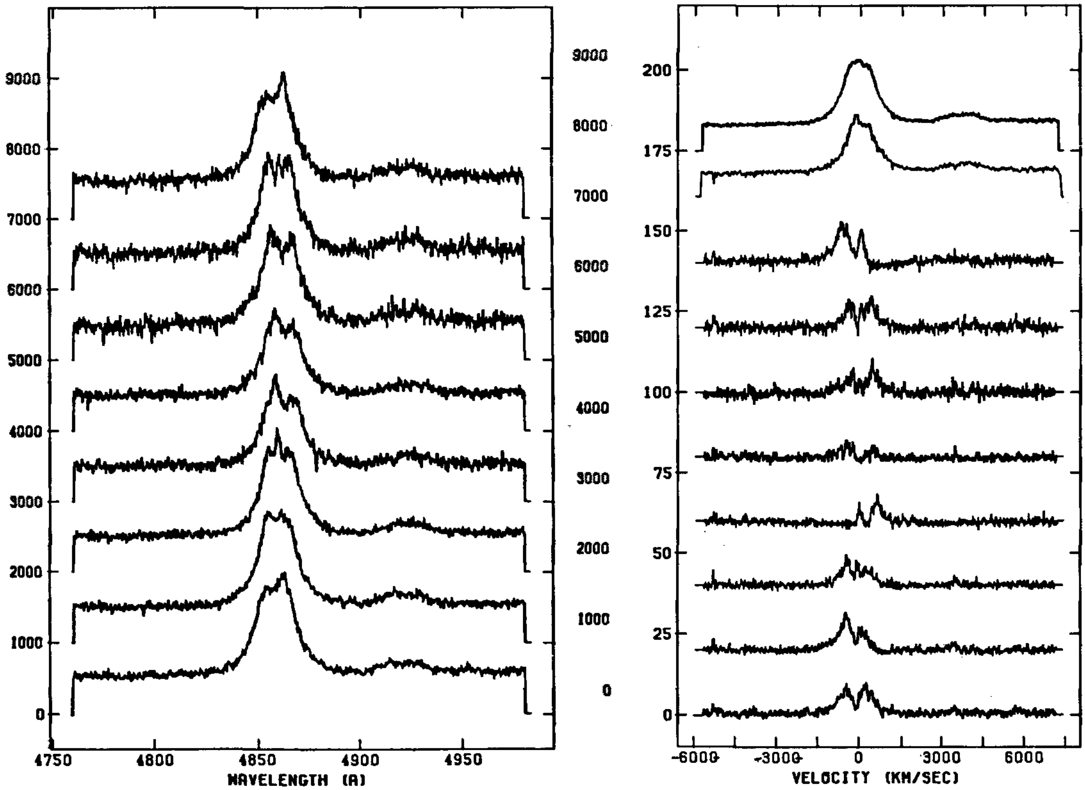

Figure 1. (a) The Hβ emission line of SS Cygni with the absorption spectrum removed and binned into 8 equal phase bins. Note the narrow emission component apparently due to the companion star. (b) The same spectra but with the minimum emission component (second from the top) removed; the top spectrum is the average spectrum. Note that the extra emission is a substantial fraction of the total line emission and that it often extends to velocities around 1500 km s^{-1}.

evolution, since repeated dwarf nova eruptions have not measureably changed the phase shift and the same shift is seen even during the late decline from an eruption (Hessman, et al. 1985).

3.1 Non-Circular Motions

Non-Keplerian orbits in the disk have been invoked for a wide variety of reasons. In the outer parts of the disks, the effective gravitational potential field of the binary will certainly produce small, non-circular motions, but the pertubations should dissappear in the inner disk where one would expect the viscosity to circularize the orbits. A possible way out of this dillemma is to invoke shocks or hydralic jumps (Michel 1984) which - if they can be maintained - may impose non-circular motions on the gas in the disk. However, without a theory of such shocks, it is difficult to say whether or not they would be successful at reproducing the observed line emission.

3.2 Magnetic Fields on the White Dwarf

There is little doubt that a magnetic field of some unknown strength must be present in the white dwarf. Even if the field is unable to affect the structure of the main body of the disk (unlike the fields in the AM and DQ Her systems), it is possible for a large field to exist which is capable of determining only the form of the innermost disk and boundary layer. Imagine a dipole field $B=B_*(r_*/r)^3$ which is able to disrupt the disk at a radius defined by

$$\frac{\dot{M}}{4\pi r^2}\,\frac{GM}{r_m} = \frac{B_*^2}{8\pi}\left|\frac{r_*}{r_m}\right|^6$$

or, expressed in appropriate units,

$$r_m = 7.4\times10^8\ \mathrm{cm}\ (M\ /\ M_\odot)^{-1/4}\ (\dot{M}\ /\ 10^{-10}\ M_\odot\ \mathrm{yr}^{-1})^{-2/7}\ \times$$
$$\times\ \ (r_*\ /\ 5\times10^8\mathrm{cm})^{12/7}\ (B_*\ /\ 10^4\mathrm{Gauss})^{7/4}$$

How could such a weak field produce the observed asymmetric line emission? Certainly, the accretion poles of the magnetic white dwarf could produce enough hard radiation to excite the line radiation (ignoring for now the problem of the flat Balmer and He

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I singlet-triplet decrements). If, in addition, the magnetic pole is tilted with respect to the orbital axis, the degree of asymmetry in the line fluxes could be produced. As a simple example of what effect such a model might have on the line profiles, consider the line intensity distribution of the form

$$I_o\, r^{-2}\ (1 - \cos(\phi - \phi_o))$$

for which an analytic form for the final disk line profile can be obtained (Hessman 1985). This model intensity distribution mimics what one would expect from the tilted magnetic field model. The resulting line profiles can be treated exactly like the observed ones (by removing the constant profile component): the results are shown in Figure 2. The agreement with the observations is fairly good, given the signal-to-noise of the observations and the crudity of the model.

The major problem with this explanation is that the magnetic field model predicts the white dwarf should be spinning up. The timescale for spin-up can be crudely written as

$$\tau_{spinup} \approx \Omega_*/\dot{\Omega}_* = 2\pi\, I_{wd} \,/\, P_{orb}\, M\, GMr_a$$

where I_{wd} is the moment of inertia of the white dwarf. For typical parameters, $\tau_{spinup} \approx 425{,}000$ years, which is a very short time. The observed stability of the phase shift in SS Cygni implies that the white dwarf must be rotating very slowly. Thus, if the magnetic field model is correct, we must be very fortunate indeed to have caught the white dwarf immediately after it began to experience accretion.

3.3 Spill-over from the Accretion Stream

The idea that the accretion stream can penetrate into the inner parts of the disk has been proposed many times for a variety of reasons. Bath, Edwards, and Mantle (1983) tried to quantify this effect by assuming the stream penetrates but is stripped away by the disk at a rate

$$\frac{\partial \dot{M}}{\partial r} = \beta\ \Sigma\ \sin\theta\ v_{Kepler}$$

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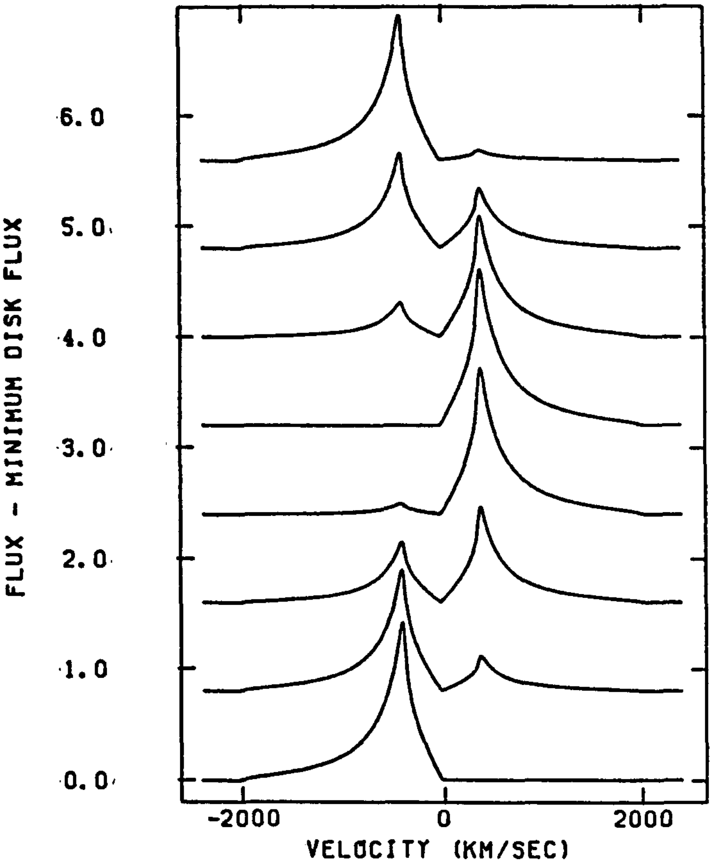

Figure 2. Model spectra for the emission line profiles given the intensity distribution r^{-2} $[1 - \cos(\phi-\phi_o)]$. The profiles have had the minimum component removed, just as in Figure 1b.

where θ is the angle between the velocity vectors of the stream and the disk, Σ is the disk surface mass density, and β is a fudge factor describing the efficiency of the stripping. This parameterization implies that the interaction takes place with the entire body of the disk. The former assumption requires very little material in the disk or a large mass-transfer rate through a geometrically thin accretion stream in order for large amounts of stream material to penetrate through the main body of the disk.

While the main body of the accretion stream from the secondary star might be stopped by the initial interaction with the disk, it is possible that part of the stream may be able to skim over the surface of the disk. Lubow and Shu (1976) calculated the vertical height of the stream and showed that it might very well be somewhat larger than the scale height of the disk, leading to a very complicated interaction and the formation of a "bow-shock" between the disk and the spill-over. More recently, Smak (1986) has argued from the phasing and velocities of the "hot spot" components in the emission lines that the accretion stream in dwarf novae systems is sometimes fully stopped by the disk when the latter is thick but spills over when the disk becomes thinner. Frank, King and Lasota (1986) have invoked stream spill-over as a necessary ingredient in their model to explain the X-ray "dipper" sources in LMXB's.

The major problem with this model is, of course, that the highly hypersonic interaction of the stream spill-over with the disk can only be realistically calculated using 3-D numerical hydrodynamical simulations. In an effort to see how the spill-over could affect the line profiles, it is instructive to take the simplest possible case : assume some fraction of the stream passes relatively unhindered over the disk rim and subsequently follows a particle trajectory appropriate for its inital velocity - assumed to be that of the main body of the stream - and its height above the disk - a free parameter which depends mostly on the relative heights of the disk and stream at the disk edge. If one further assumes that the Mach number of the disk, M_{disk}, is constant (which amounts to the requirement that $M_{disk} \approx r/h \approx v_\phi/v_r$ is constant throughout the disk), the relative heights of the disk and stream reminent can be calculated as a functions of time and is shown in Figure 3a for the case $\underline{M}_{disk}=100$. Note how the trajectory of the stream takes the material away from the disk initially (due to the initial velocity assumed), but that the stream material eventually comes crashing down onto the disk. Since even the particle trajectories imply that some of the stream material should be stripped during the passage of the stream over the disk, I have assumed that the amount of stripped matter depends linearly upon the relative heights of the stream and disk. However, the line profile results do not depend sensitively on the choice of the stripping model. In any case, the stream must crash into the disk at the point where it tries to climb up the surface of the disk.

If we assume the stream material is excited only by the radiation from the central disk and is stripped as soon as it settles down onto the disk, the observed line profile from the stream as a function of phase can be easily calculated and is shown in Figure 4a. Potentially large amounts of emission can be produced at velocities of a few v_{orb} – about 250 km s^{-1} or so in SS Cygni.

A very different possibility is that the stream material is shock-heated by the collision with the thin, upper atmosphere of the disk. The cooling time of such a hot gas could be much longer than an orbital period, so that – in an equilibrium – the emitted energy would be balanced by the input energy represented by the kinetic energy flux from the disk's atmosphere. The density of the upper atmosphere can be (somewhat over-)estimated using the same simple model for the disk, i.e. assuming that $\underline{M}_{disk}$ = constant. The equation of mass conservation for a steady disk and the local Keplerian velocity gives us a simple relation for the density in an isothermal disk

$$\rho(r,z) = \frac{\dot{M} \; \underline{M}_{disk}^{2}}{2\pi^{3/2} \; r^{2} \; v_{\Phi}} \exp\left[-(z \, \underline{M}_{disk}/r)^{2}\right]$$

The energy emitted by the stream is simply related to the flux of kinetic energy due to the impacting disk atmosphere. The line

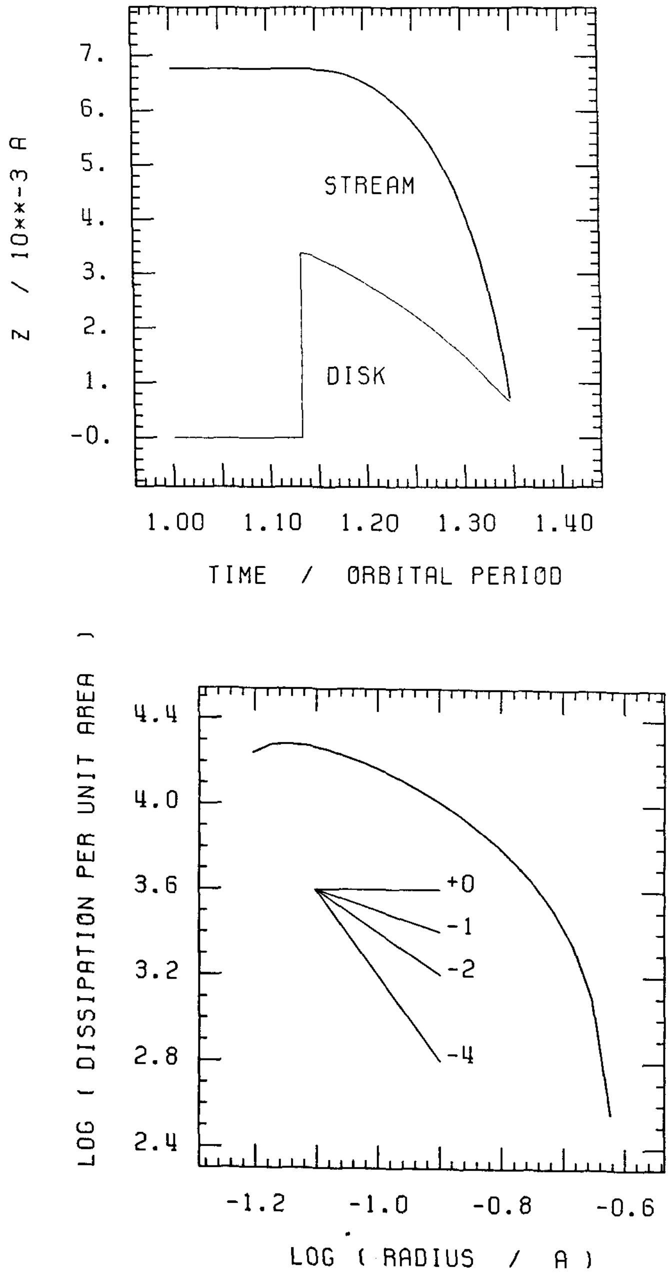

Figure 3. (a) The assumed trajectory of the accretion stream relative to an accretion disk with a constant Mach number M_{disk}=100. (b) The kinetic energy dissipation rate per unit area of the disk due to the assumed stream stripping law.

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profiles in such a case are shown in Figure 4b. Note how a totally different phase shift is produced by this excitation mechanism.

If some stripping mechanism is chosen, the kinetic energy of the stripped stream material will heat the upper disk atmosphere. Part of this dissipation will be reflected in line emission. Thus it is interesting to compare how the amount of stream dissipation per unit surface area of the disk compares with the $r^{-1.5}$ to r^{-2} distribution of line intensity observed in cataclysmic variables. Our choice of stripping laws is, of course, highly arbitrary, but the dissipation in the simple model does show the highly peaked distribution characteristic of the emission lines and has the right power-law distribution (Figure 3b). As an added bonus, the characteristics of a shocked, (by normal standards) dense, emission line region are just those needed to explain the flat Balmer and He I decrements and this mechanism works even if the underlying accretion disk is optically thick.

There are two major problems with this model for the extra emission : (1) the particle trajectory paths cannot come close enough to the central mass to explain the emission at velocities approaching 1500 km s^{-1}; and (2) the plausibility of the model rests on the assumption that the stream can indeed survive past the "bow-shock" at the main disk-stream intersection. Answers to these questions will have to wait for more detailed observations of the emission line components as well as fully 3-dimensional hydrodynamical calculations.

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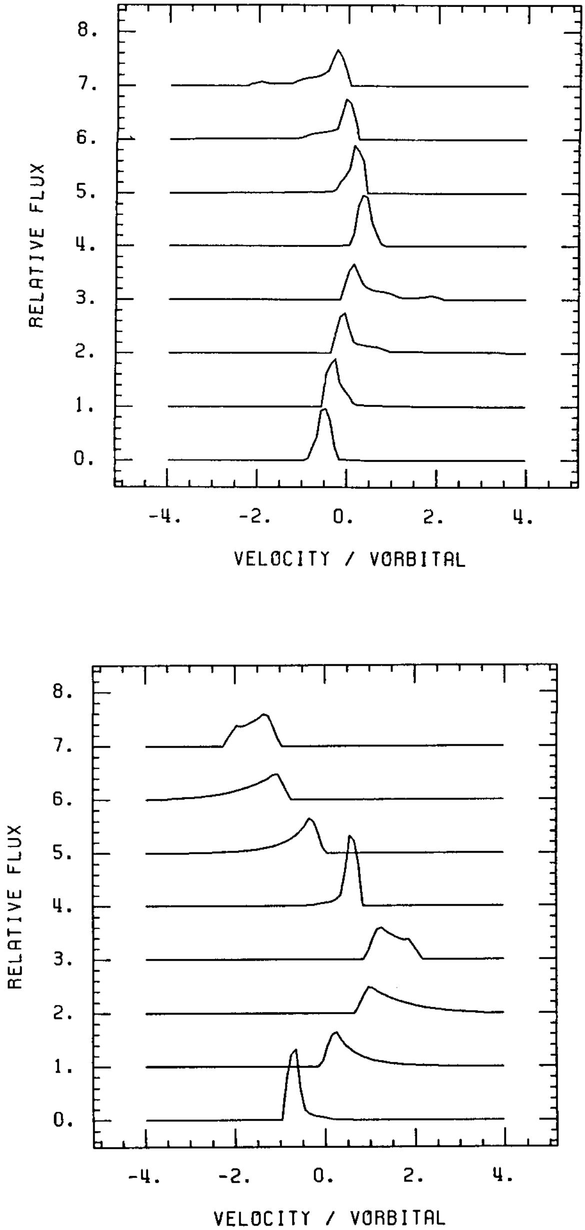

Figure 4. The line profiles due to the stream as functions of orbital phase: (a) assuming the material is excited by the radiation from the central disk; and (b) assuming the stream emission is proportional to the incident kinetic energy flux of the disk's upper atmosphere.

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