SPECTRAL LINE FORMATION IN YY ORI AND T TAU ENVELOPES

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Summary

First results of line profile computations in a collapsing rotating envelope are discussed. As an application, an observed profile of the YY Ori star CoD -35° 10525 is compared to computed profiles. Possible similarities in the formation of YY Ori and T Tau line profiles are briefly mentioned.

I. Introduction

Line formation in spherically symmetric infalling protostellar envelopes has recently been investigated by Bertout (1977) and Grinin (1977). Both authors use the escape probability formalism to compute the emergent line profiles. Using the results of hydrodynamical calculations of the protostellar collapse (Appenzeller and Tscharnuter, 1975) to determine the temperature, density, and velocity distributions in the infalling envelope, Bertout (1977) computed profiles showing good agreement with profiles found on the low dispersion spectrograms of YY Orionis stars available at that time. Later, high dispersion spectrograms of the bright YY Ori star S CrA revealed more complex profiles. The study of these profiles allowed Wolf et al. (1977) to propose a detailed model of the emitting regions. Since it was clear that sophisticated models would be needed in order to interpret the spectroscopic data becoming available for this type of stars, I recently developed a numerical method allowing for the calculation of line profiles in axially symmetric, moving envelopes. By this method any axially symmetric velocity field can be handled in the framework of the Sobolev approximation. In the next section of this paper, I describe first results obtained for a collapsing, rotating envelope, and compare an observed H_{δ} profile of the bright YY Ori star CoD -35° 10525 (Appenzeller et al. 1977) to calculated profiles. In the last section, I comment on some computed profiles which resemble T Tauri line profiles.

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II. Emergent Line Profiles from a Rotating Infalling Envelope

Sobolev (1960) has shown that great simplifications in the line formation problem can be expected in a moving medium where velocity gradients are present. In this case, and if the gradients are large enough, photon escape from the moving envelope is primarily due to Doppler shifts. The approximation that photon escape occurs only by Doppler shift has been called the supersonic approximation. It has been used by several authors to calculate emergent line profiles from spherically symmetric envelopes in the presence of radial velocity fields. More complicated geometries and velocity fields have not been investigated until now, although the Sobolev approximation is probably the only radiative transfer approximation, besides Monte Carlo methods, which allows for the treatment of arbitrary geometries on the computers available at the present time.

Essentially, the numerical code (used here in the case of a rotating infalling envelope) works as follows. A grid of lines of sight is defined. Along each of these, one looks for the intersections with all constant radial velocity surfaces corresponding to the frequencies at which the intensities are calculated. The intensities are then computed after calculating the photon escape probability at each of the above defined intersections. A two-dimensional numerical integration is used to compute the escape probability at a given point, and a two-level atom model is assumed. The emergent flux at each frequency is then found by summation over all lines of sight. The details of this numerical method will be published elsewhere.

For the tests of the computer code and for the preliminary calculations presented here, I used a velocity field devised by Ulrich (1976), which combines infall and rotation in a simple way. The velocity at each point of the envelope is calculated by assuming that the gas particles all possess the same initial velocity of rotation, and are free-falling toward the stellar core, conserving their angular momentum. Ulrich used this model to investigate the line formation problem in the shock cooling region, which he assumed to be responsible for the Balmer emission. His results show strong similarities with observed T Tauri profiles. Rather than the shock emission I investigate here the envelope emission. Previous investigations (Bertout, 1977, Wolf et al. 1977) seem to indicate that contributions from the post-shock cooling region are not necessary to

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reproduce the observed YY Ori profiles. I therefore assume that the shock cooling region is optically thin in the Balmer lines. A detailed treatment of the radiative transfer problem through the accretion shock is required to test the validity of this assumption. Unfortunately, no computations of this nature are available at the present time.

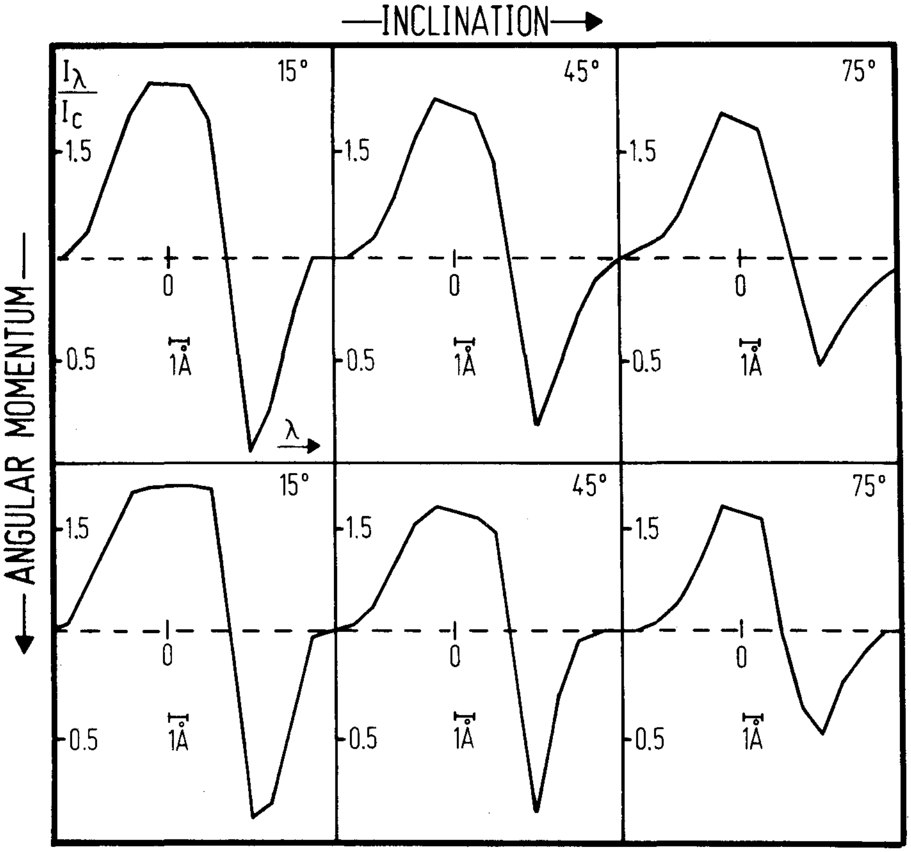

Fig. 1: Line formation in a collapsing rotating envelope. See text for explanations.

In Figure 1, calculated profiles are shown for two different values of the angular momentum and three values of the inclination angle. The other parameters are the same for all profiles and correspond to those of a "standard" 1 $M_\odot$ protostar at the end of its hydrody-

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namical evolution. The radius of the core was assumed to be 10^{11}cm, and the envelope extent is 5 x 10^{11}cm. Both core effective temperature and envelope temperature are taken to be 5000 K. The number of atoms in the lower line quantum state was assumed to vary like the density as a function of radius, and was taken to be 10^{3}cm^{-3} at the shock, corresponding to a pre-shock density of about 10^{-11}g cm^{-3}. The line absorption coefficient therefore decreases monotonically outwards like $r^{-3/2}$. The wavelength of the line is 4102 Å, and the collisional de-excitation rate is 10^{-3}. In the first row, the value of the angular momentum is such that all the infalling matter can still impact the stellar core. In the second row, a disk of 5 x 10^{11} cm is formed around the core. For these first calculations, I assumed the disk to be infinitely thin, so that disk contribution to the line profile is due only to the equatorial discontinuity in the velocity field, not to a density larger in the disk than in the envelope. For each series of profiles corresponding to a given value of the angular momentum, a decreasing line strength is found for increasing inclination towards the equatorial plane. This is due to the tangential component of the velocity field, which acts to reduce the velocity gradient in the line of sight direction as one moves toward greater inclination values, thus reducing the escape probabilities. The broadening of the emission component with increasing angular momentum is due to both the stretching out of the constant radial velocity surfaces and to the contribution from the disk.

As a first application of this model, I consider the observed H_δ profile of the YY Ori star CoD -35° 10525 (Appenzeller et al.,1977). In Figure 2, I compare this profile (a) to two calculated profiles. The first of these, (b), was computed using basically the code described by Wolf et al. (1977), and assuming a radial infall. In the model proposed by Wolf et al., the central absorption is due to the outer layers of the envelope. The reader is referred to the original work for a discussion of the model.
In the case of CoD -35° 10525, the central absorption feature is slightly red displaced, which indicates that the outer envelope layers - where absorption of Lyman line radiation is effective - are still collapsing. The following parameters were used for the profile calculation: the core radius is 10^{11}cm, the envelope radius is 5.10^{11}cm, the number of atoms in the lower line quantum state is 10^{2}cm^{-3} at the core, decreasing as $r^{-3/2}$. This corresponds roughly to a density of 10^{-12}g cm^{-3} just above the shock. The envelope

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temperature was assumed to be constant at 10^4 K, and the core effective temperature is 4×10^3 K. The collisional de-excitation rate is 10^{-3}. The number of absorbers in the outer layers contributing to the central absorption was arbitrarily taken to be $8 \times 10^{-2}\mathrm{cm}^{-3}$. Using this value, the observed depth of the absorption could be reproduced. The maximum infall velocity in this calculation is 515 km s^{-1}. The largely redshifted emission component at about 500 km s^{-1} is produced in the region very close to the core, where photoionization due to the Lyman continuum radiation escaping from the shock cooling region is important. The observed peak could be reproduced by assuming that the mean molecular weight was $\mu = 0.56$ over a shell of 10^8cm around the core. No recombination emission was needed to reproduce the main emission component on the red side of the line.

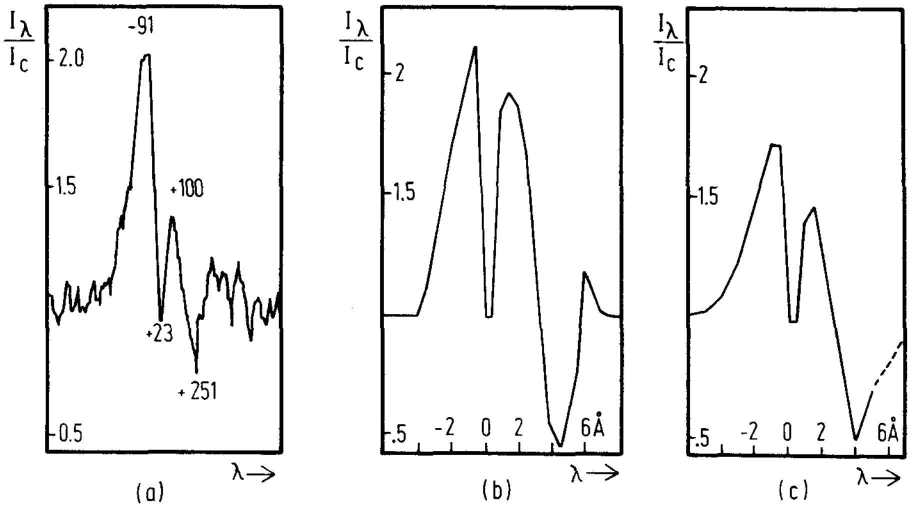

Fig. 2: (a) Observed H_δ profile of CoD -35° 10525. The numbers indicate the radial velocities of the profile feature, in km s^{-1}.

(b) Computed profile assuming radial infall. The profile parameters are given in the text.

(c) Computed profile assuming infall and rotation. The parameters are given in the text.

There are two main criticisms which can be raised about this calculated profile: the blue wing is not well reproduced by the model, and the observed profile is less symmetrical than the computed one, i.e. the observed main emission component is less intense on the red side than on the blue side of the central absorption component. From

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the profiles shown in Figure 1, it is tempting to interpret these discrepancies in terms of rotation. To illustrate this point, I reproduced in Figure 2 (c) the profile of Figure 1 corresponding to the lower case of angular momentum and to an inclination of 75°. I added the same central absorption as calculated in the case excluding rotation. Although the parameters of the computed profile including rotation have not been adjusted for reproducing this particular line, the qualitative agreement with the observed profile is better than in the case without rotation. Since ionization in the precursor region is not taken into account in the calculations including rotation, profile (c) does not show the red secondary emission at 500 km s^{-1}.

III. YY Ori and T Tau Line Profiles

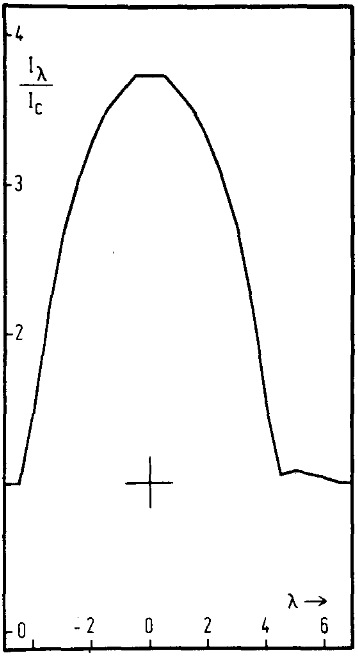

Fig. 3: Profile calculated assuming radial collapse, but not showing the usual red displaced absorption. See text.

In Figure 3, I show a profile which was computed assuming a simple radial collapse and using the same parameters as in the profile of Figure 2 (b) except for the following differences. There is no absorption in the outer layers, i.e. no central absorption feature. Furthermore, the extent of the envelope was decreased by a factor 2.5, i.e. the cut-off radius is now twice the core radius. To compensate for the loss of geometrical emission, the optical depth in the envelope was increased by a factor of 10 and the collisional deexcitation rate was assumed to be 2 x 10^{-3}. The resulting profile does not show the usual YY Orionis redward absorption feature. This is due to the combination of two effects: the smaller cut-off radius reduces the absorption in the 3-4 Å range,

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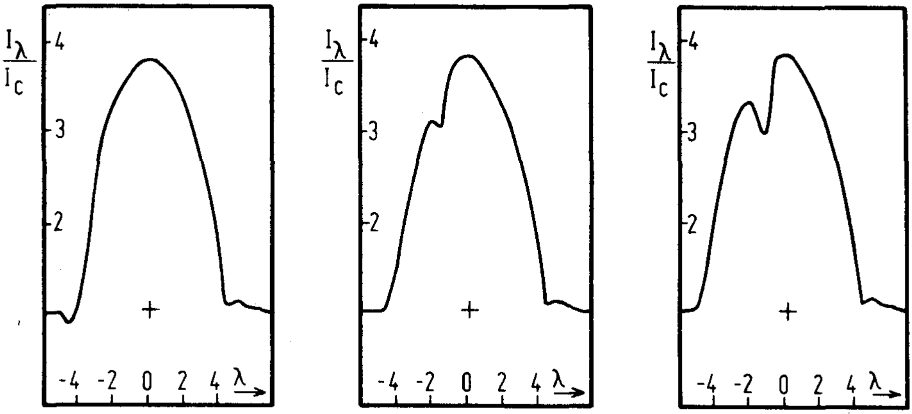
and the source function is large enough to compensate for the absorption in the shells close to the core. Note that a profile computed with the same parameters, but assuming an *expanding* decelerating envelope, rather than collapsing, would have the *same shape*, with the difference that it would be reflected about the line center axis. On a spectrogram, the difference between such profiles would be difficult to detect. In fact, the only difference is a more extended wing on the profile side corresponding to the flow motion.



(a) (b) (c)

Fig. 4: Same profiles as in Fig. 1, with an additional absorbing outer shell moving outwards. Three different expansion velocities are shown.

In Figure 4, the profile shown on Figure 3 has been recalculated, adding an absorbing, outflowing shell around the infalling envelope. Three different outflow velocities are shown. The resulting profiles bear some resemblances to profiles observed in T Tauri stars, for example in AS 209, RU Lupi, and T Tauri itself (c.f. Kuhi 1964). A possible explanation for the existence of an absorbing, outflowing shell in the outer part of the envelope might be given by the model of Wolf et al. (1977). Therefore, it seems that qualitatively YY Ori and T Tau line profiles could be obtained in essentially the same way, i.e. by assuming that the bulk of the stellar envelope is infalling, while some outer layers or clumps of matter are driven away by radiative pressure effects. However, one should be

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aware that the profiles shown on Figures 3 and 4 have been calculated as a matter of example, and without any reference to a particular star or to a precise physical model. More observational material, especially high dispersion spectroscopy extending over long periods of time, is needed in order to try a detailed interpretation of YY Ori and T Tau line profile variations.

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DISCUSSION of the paper by BERTOUT:

SURDEJ: At those very great distances from the stellar core, where all velocity gradients drop down, and where the medium accounts mainly for the absorption component (central one) in your line profiles, is still the Sobolev approximation a reasonable one?

BERTOUT: Castor (1970) derived 2 validity criteria for the Sobolev approximation which essentially states that the escape probability formalism can be used as long as the thermal velocity of the gas is small compared to the macroscopic flow velocity. This condition holds even in the outer layers of the protostar. But of course you cannot approach indefinitely the line center.

SURDEJ: I do not agree with these criteria.

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