Solution of the Radiative Transfer Equation in Rotating Atmospheres and in Winds

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Abstract. We present a method for solving the radiative transfer equation appropriate for its solution in the circumstellar environment of B[e] stars. The problem is solved in two dimensions in axial symmetry. The velocity field in the radiative transfer is included using the Lorentz transformation, which allows us to solve it in the fast polar wind as well as in the slow equatorial wind.

1. Introduction

The currently adopted model of the circumstellar environment of B[e] stars is a two-component (two-stream) stellar wind model Zickgraf et al. (1985). The hot and fast radiation driven wind is present along the rotation axis, while the cool, dense, and slow wind is near the equator. The disc-like structure can be formed along the equator in this case.

The radiative transfer problem is a bit more complicated in this situation compared to a quiet horizontally homogeneous stellar atmosphere. We need a method which is able to describe both the stellar photosphere and the wind region and which can solve the radiative transfer equation for small as well as relatively large velocity gradients.

We present such a method for solving the radiative transfer equation (RTE) here. We assume axial symmetry, which is a good approximation for B[e] stars, since the solution is relatively fast and the geometry of the problem is well described. The nonrelativistic velocity fields are the second assumption made in this method. Since relativistic velocities are not observed in B[e] stars, this assumption does not restrict us. A detailed description of our method is published in Korčáková & Kubát (2005a).

2. Description of the method

We assume axial symmetry in our model and choose a modified spherical grid. To obtain a better description of the disc geometry and of the velocity field in the fast polar wind region, the grid is finer near the equatorial plane and near the pole (Fig. 1, left panel).

To reduce a 3D problem to a 2D one we solve the radiative transfer equation in a set of longitudinal planes (Fig. 1, right panel). The whole radiation field is obtained by rotating the planes around the axis of symmetry (Fig. 2., left panel).
In every plane the transfer problem is solved using a combination of the short and long characteristic methods (Fig. 2., right panel).

The ray starts and ends at the grid circle, so it is possible that it intersects more cells. This allows us to describe the global character of the radiation field better than with the short characteristic method. The transfer equation is then solved by parts along the selected rays

\[
I_B = I_A e^{-\Delta \tau_{AB}} + \int_0^{\Delta \tau_{AB}} S(t) e^{-[(\Delta \tau_{AB}) - t]} dt. \tag{1}
\]

The quantities used have their usual meaning. The interval $AB$ is a section of the ray within each cell. We assume the source function and the opacity to change linearly within this interval.
Figure 3. **left panel:** The line profiles from a rapidly rotating star with an extended atmosphere. **right panel:** Hα line profiles which include stellar wind for three values of parameter $\beta = 0.5, 1, 2$. For comparison, the line profile affected by a decelerating velocity field is also plotted.

In every cell we assume a constant velocity and we only allow a change of velocity at the cell boundary. This approximation allows us to solve the static equation of the radiative transfer inside the cells. At the cell boundaries we perform a transformation of frequency (we can neglect the transformation of intensity).

### 3. Selected results

Basic tests of this method and its comparison with another independent stellar atmosphere model are presented in Korčáková & Kubát (2005a). Here we show the most relevant results for the case of the B[e] phenomenon.

**stellar rotation:** The symmetry of our method allows us to include gravity darkening as well as differential rotation of stars. In Fig. 3 (left panel) we show the results for a rapidly rotating star with an extended atmosphere (for details see Korčáková & Kubát 2005b). The line profiles are calculated with gravity darkening ($+\text{grav}$), differential rotation ($+\text{dif}$) included, or excluded ($-\text{grav}$, $-\text{dif}$). The lines indicated by “$-\text{velocity}$” are obtained by neglecting the velocity field in the solution of the RTE. The velocity field is present only in the flux calculation in this case.

**stellar wind:** The line profiles influenced by stellar wind are plotted in Fig. 3 (right panel). A hot main sequence star with a thin atmosphere is chosen as the test star (see Korčáková & Kubát 2005a), which is the reason why the P Cygni profile is not obtained.

**accretion disc:** The possibility to solve the disc-like structure is tested on a model of a cataclysmic variable (Korčáková et al. 2005). Corresponding intensity map is shown in the Fig. 4.
4. Conclusion

We present a method for solving the radiative transfer equation in axial symmetry with a velocity field. This method naturally includes both the optically thick stellar photosphere and the optically thin wind region. The advantage of this method is in the simultaneous solution of the fast polar wind as well as the slow equatorial wind.

This new method will be used for an interpretation of B[e] star observations especially using data from the Ondřejov 2m telescope (see Kučerová et al., these proceedings).

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References

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Figure 4. The theoretical intensity map of an edge on accretion disc.