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Circumstellar rings, flat and flaring discs

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Abstract. Emission lines formed in the circumstellar envelopes of several type of stars can be modeled using first principles of line formation. We present simple ways of calculating line emission profiles formed in circumstellar envelopes having different geometrical configurations. The fit of the observed line profiles with the calculated ones may give first order estimates of the physical parameters characterizing the line formation regions: opacity, size, particle density distribution, velocity fields, excitation temperature.

1. Rings and flaring discs

In optically thick regions, more than 90% of the emitted energy in a given line can be considered produced in a limited region of the circumstellar disc. This is the case of Fe II in Be stars (Arias et al. 2005), but also hydrogen Balmer, Paschen series if their formation region has the aspect of an expanding ring. In both circumstances, the emitted radiation can be estimated using an equivalent isothermal ring with uniform semi-height H, whose surface density equals the radial column density. If the particle density has a distribution $N(R) \sim R^{-\beta}$, the radius of the ring is then $R_r/R_* = [(1-\beta)/(2-\beta)][1-(R_i/R_e)^{\beta-2}]/[1-(R_i/R_e)^{\beta-1}]$, where $R_{i,e}$ are the internal and external radii of the line forming region. The ring can be considered having expansion V_{exp} and rotation V_Ω velocities, both represent averages of the respective velocity fields (Arias 2004). The emitted flux is simply $F_\lambda = \int_{\mathcal{S}(i)} I_\lambda(x,y)\mathrm{d}x\mathrm{d}y$ where $\mathcal{S}(i)$ is the aspect-angle effective emitting surface projected on the sky and $I_\lambda(x,y)$ is:

$$\left.\begin{aligned} I^a(x,y,v-v_r) &= I^*(x,y)e^{-\frac{\tau^f(v-v_r)}{\mu(x,y)}} + S[1-e^{-\frac{\tau^f(v-v_r)}{\mu(x,y)}}] \\ &\ \text{(stellar emission absorbed by the front side)+} \\ &\ \text{(front side emission)} \\ I^b(x,y,v-v_r) &= S[1-e^{-\frac{\tau^t(v-v_r)}{\mu(x,y)}}]e^{-\frac{\tau^f(v-v_r)}{\mu(x,y)}} + S[1-e^{-\frac{\tau^f(v-v_r)}{\mu(x,y)}}] \\ &\ \text{(rear emission absorbed by the front side)+} \\ &\ \text{(front side emission)} \end{aligned}\right\} \quad (1)$$

with $\tau_v = \tau_o\Phi(v-v_r)$ and $v_r(x,y) = \pm\{V_{exp}(R)[1-(\frac{x}{R})^2]^{\frac{1}{2}} \pm V_\Omega(R)\frac{x}{R}\}\sin i$, where (f,r) stand for 'front' and 'rear' sides of the ring. The signs in the radial velocity v_r are chosen according to the quadrant; v is the Doppler displacement in the observed emission line profile, $\mu(x,y) = \cos$(ring-normal;observer), i inclination of the ring-star system, τ_o is the radial opacity of the ring in the line center and

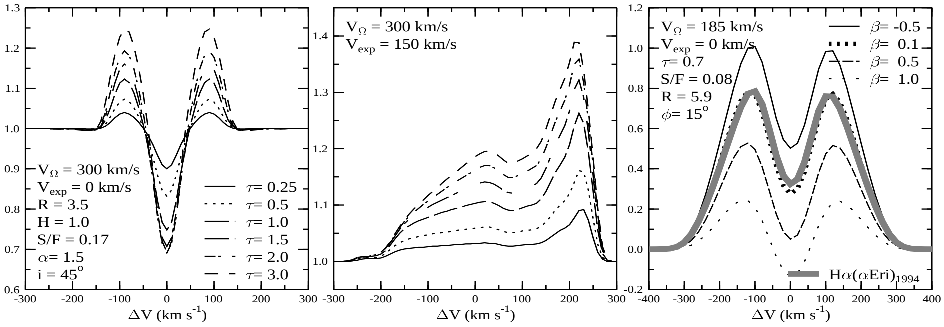

Figure 1. a) Line profiles for a ring with $V_{exp}=0$ and the indicated parameters. b) 'Steeple' line profiles produced by rings with same parameters as in a) but $V_{\rm exp}\neq 0$. c) Line profiles due to flaring discs treated as rings, for several β and opening angle $\phi=15^o$. $\beta=0.1$ closely fits Hα of α Eri in 1994 (a flat ring would require $H=3.8$; $\beta=-0.1$)

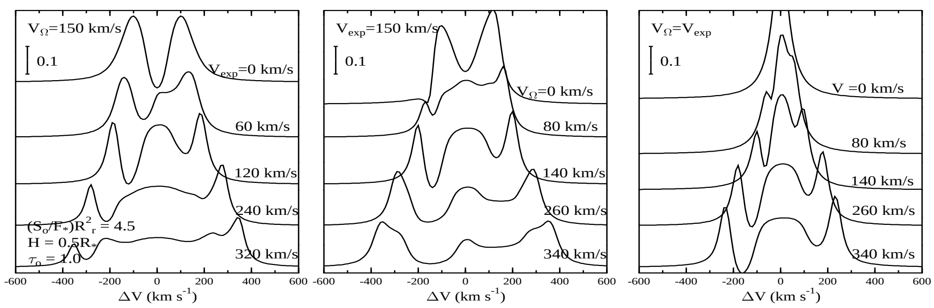

Figure 2. Three-peak line profiles produced by rotating+expanding rings

$\Phi(v)$ is the intrinsic absorption line profile. The line source function is: $S_\lambda(\tau_{\rm o})=S_o$ for $\tau_o\leq 1$; $S_o\tau_{\rm o}^p$ for $\tau_o>1$ [$p\simeq 1/2$ for Gaussian $\Phi(v)$] and $B_{\lambda_o}(T_{\rm e})$ for $\tau_o\geq(B_{\lambda_o}/S_o)^2$ (Mihalas 1978, Chap.11). S_o depends on the nature of the line transition: collision-, photoionization-, mixed-dominated. Using S_o as done in Cidale & Ringuelet (1989) we can determine the excitation temperature (Arias et al. 2005). Thus, the free parameters to fit the observed emission line profiles are: S_o/F_*, τ_o, R_r, H, i, V_Ω, V_{exp} and density distribution β (or $\alpha=2-\beta$). The shape of the line profiles reduce strongly the space of free parameters, mainly those of the velocity field and the ratio between τ_o and H. Line intensities are sensitive to $(S_o/F_*)R_r^2$ and R_r to the temperature, which in turn determines S_o/F_*. Figure 1a shows line profiles obtained for the indicated parameters of the ring with $V_{exp}=0$, which are typical for *'shell'* lines. The same ring parameters are used for Fig. 1b, but $V_{exp}=150$ km/s. The line profiles are of the *'steeple'* type seen frequently in Fe II lines. Flaring discs can be treated in the same way as cylindrical ones, except that the surface density, and hence τ_o depends on the coordinate perpendicular to the equator (Vinicius et al. 2005). A fit of the Hα line of α Eri in 1994 with a flaring disc of opening angle $\phi=15^o$ is shown in Fig. 1c, where are also shown line profiles for different β-values. Several three-peak emission line profile are shown in Fig. 2 produced in regions treated

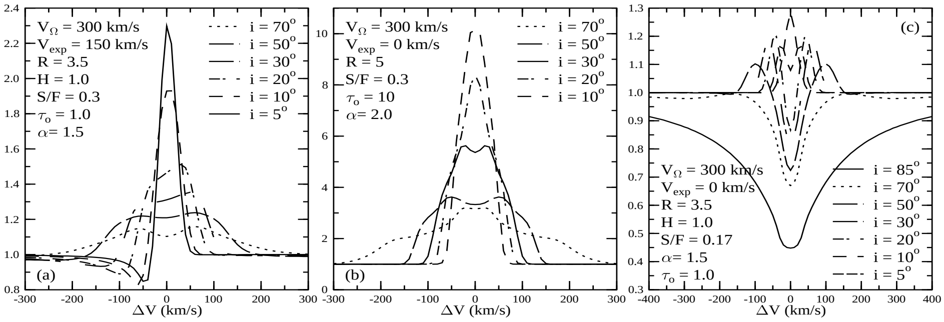

Figure 3. Emission line profiles obtained with discs. a) P Cyg like profiles. b) Bottle shaped. c) Broadening due to v_1 at $i \rightarrow 90^o$

as equivalent expanding rings. Due to the Doppler shifts, the central emission components are produced by the front and rear sides of ring sectors where the radial velocity is $v_r \simeq 0$.

2. Discs

The main difference in the treatment of discs with respect to that for rings is in the velocity dependence of the intrinsic absorption line profile. It has been shown by Horne & Marsh (1986) that for a Gaussian $\Phi(v)$ the Doppler width of the profile is enlarged by a "turbulent" term due to the differential rotation in the disc towards the observer's direction. The wavelength dependent opacity is then proportional to $exp\{-(1/2)[(\lambda-\lambda_D)/(\Delta_D \times \delta)]^2\}$, where $\lambda_D = \lambda_o(v_o/c)$ and:

$$\left.\begin{array}{lcl} v_o & = & [V_\Omega(R)\sin\theta + V_{exp}(R)\cos\theta]\sin i \\ \delta & = & [1+(\lambda_o v_1/c\Delta_D)^2]^{1/2} \\ v_1 & = & [\frac{1}{2}V_\Omega(R)\sin\theta + V_{exp}(R)(2-\beta)\cos\theta]\cos\theta\tan i\sin i \end{array}\right\} \quad (2)$$

where θ is the azimuthal angle. For large values of H, v_1 acts as a non-negligible broadening agent of the effective Doppler line width. Different examples of line profiles obtained with discs seen at several inclination angles are shown in Fig 3. The parameters used in Fig 3a can suite for P Cyg type line profiles, while Fig 3b reproduce the bottle shaped emission line profiles seen frequently in Be stars. The *'bottle'* shaped profiles can be obtained also with rings. They are produced by the τ_o^p opacity dependence of the source function due to its non-local energy supply. The broadening of the effective Doppler line by v_1 is depicted in Fig 3c ($i = 85^o$). Other related subjects can be found in http://www2.iap.fr/users/zorec/.

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