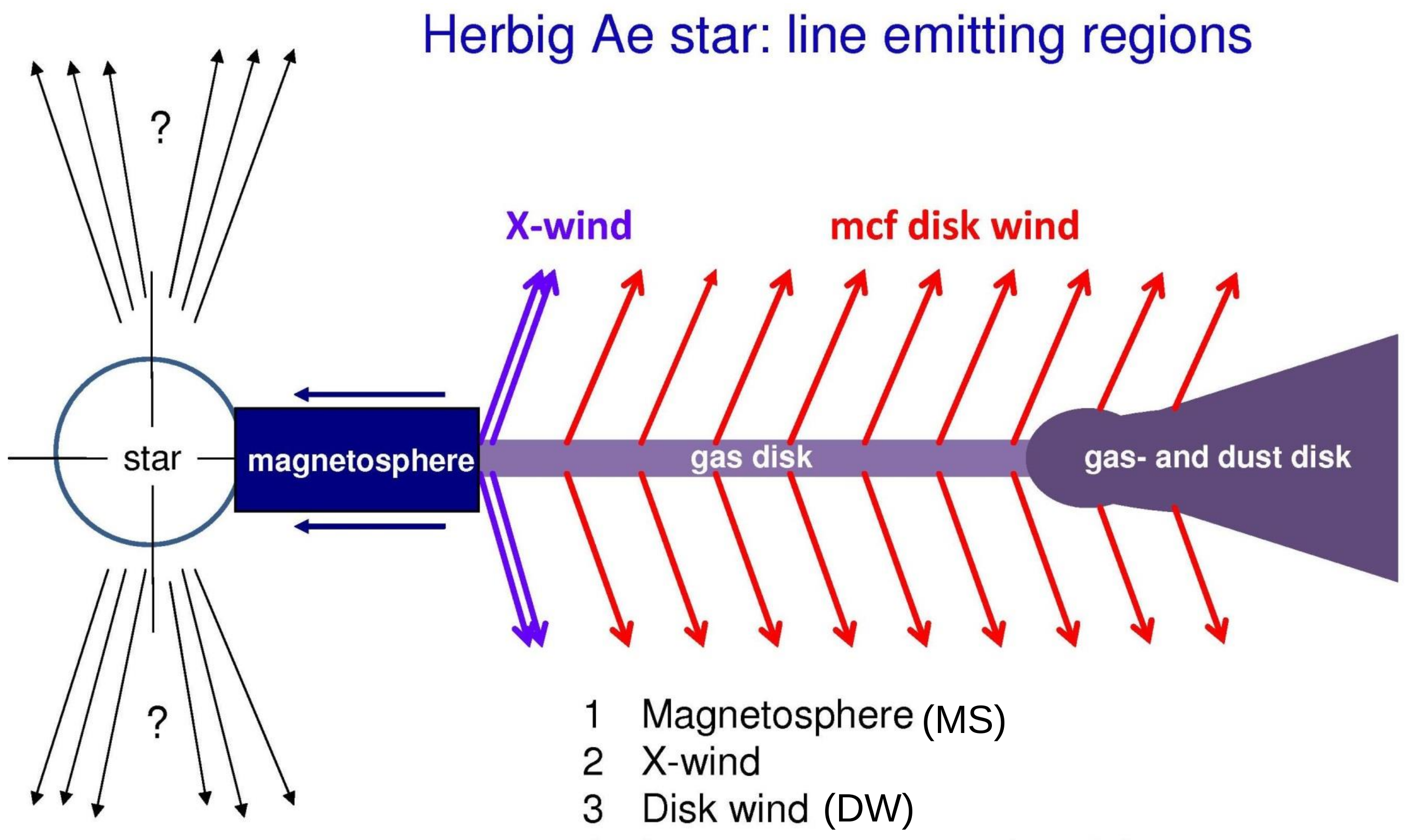
Multi-component line emission in young stars. Spectroscopy and Interferometry

L.V. Tambovtseva[1,3], V.P. Grinin[1,2,3], G. Weigelt[3], D. Schertl[3], K.-H. Hofmann[3],
R. Garcia-Lopez[3,4], A. Caratti o Garatti[3,4]

[1]Pulkovo Astronomical Observatory , St. Petersburg, Russia [2]The Sobolev Astronomical Institute of the St. Petersburg University, St. Petersburg, Russia
[3]Max-Planck-Institut für Radioastronomie, Bonn, Germany [4] Dublin Institute for Advanced Studies, Dublin, Ireland

Intermediate-mass young stars (Herbig Ae/Be stars) have a very complex environment consisting of accreting and outflowing matter. To determine the geometrical structure and physical properties of this environment, we develop models that are able to reproduce the spectroscopic and interferometric observables such as hydrogen line profiles as well as visibilities, differential and closure phases. For non-LTE modeling of the emission in the hydrogen lines, we use the Sobolev approximation. Fitting the spectroscopic and interferometric observables permits us to constrain the model parameters and find main contributors to the line emission of components such as the magnetosphere, disk wind and accretion disk. Modeling the infrared hydrogen line Brγ is important because it probes regions near the star, which cannot be resolved with single telescopes but with IR interferometers. In a series of publications, we present a full description of the radiative transfer problem in different regions emitting hydrogen lines and examples of the line profiles of Balmer, Paschen and Brackett series lines as well as line radiative transfer models of the Brγ line emitting region that are able to reproduce all interferometric observables, that is, the line intensity, line profile, visibilities, differential phases, and closure phases (Grinin & Tambovtseva 2011, Weigelt et al. 2011, Tambovtseva et al. 2014, Garcia Lopez et al. 2015, Caratti o Garatti et al. 2015).

Herbig Ae star: line emitting regions



1 Magnetosphere (MS)
2 X-wind
3 Disk wind (DW)
4 Inner gaseous accretion disk

Disk wind:
1 Magneto-centrifugal (mcf) disk wind
2 Conical wind
3 Disk wind due to photoevaporation

Fig.1

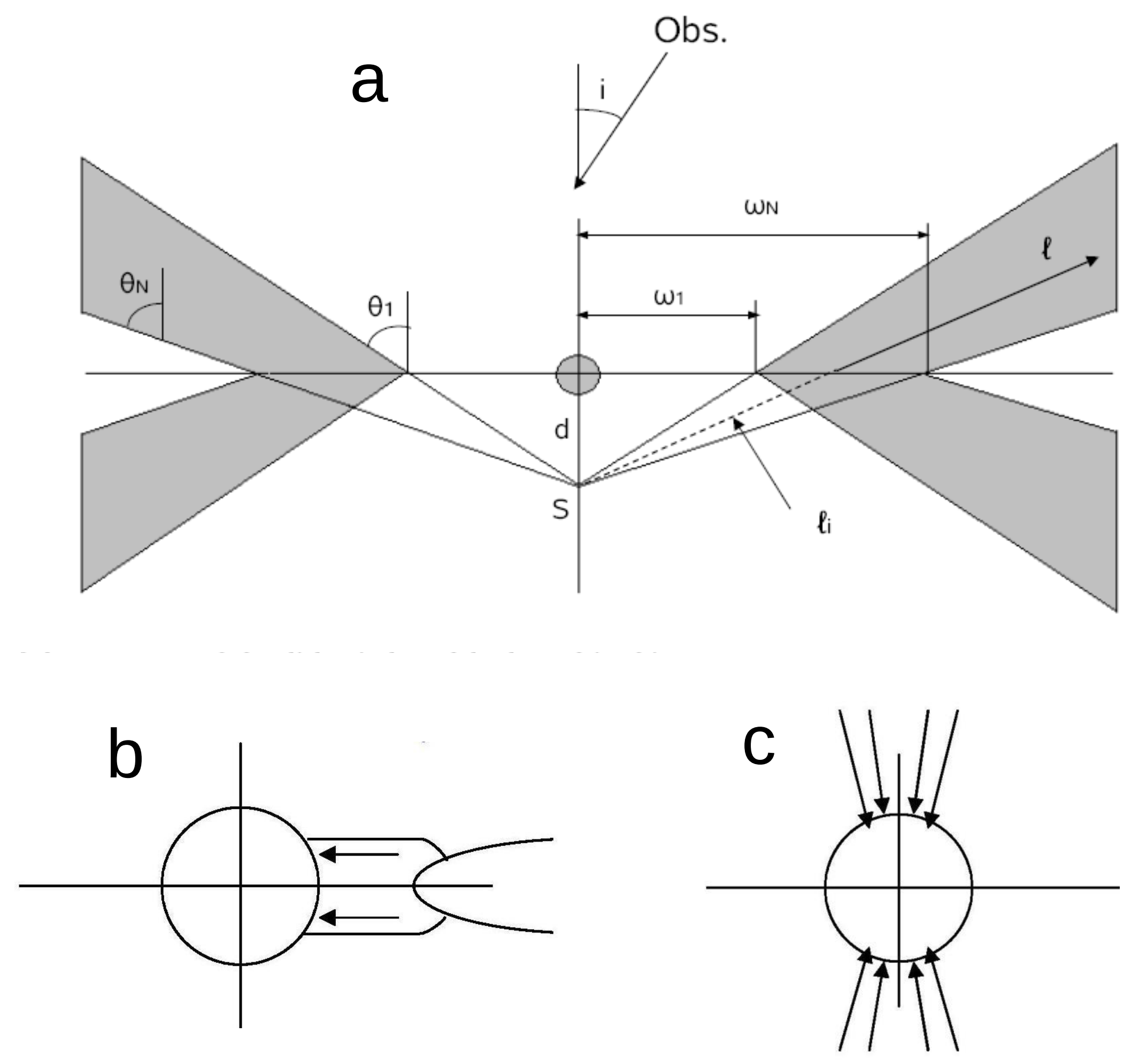
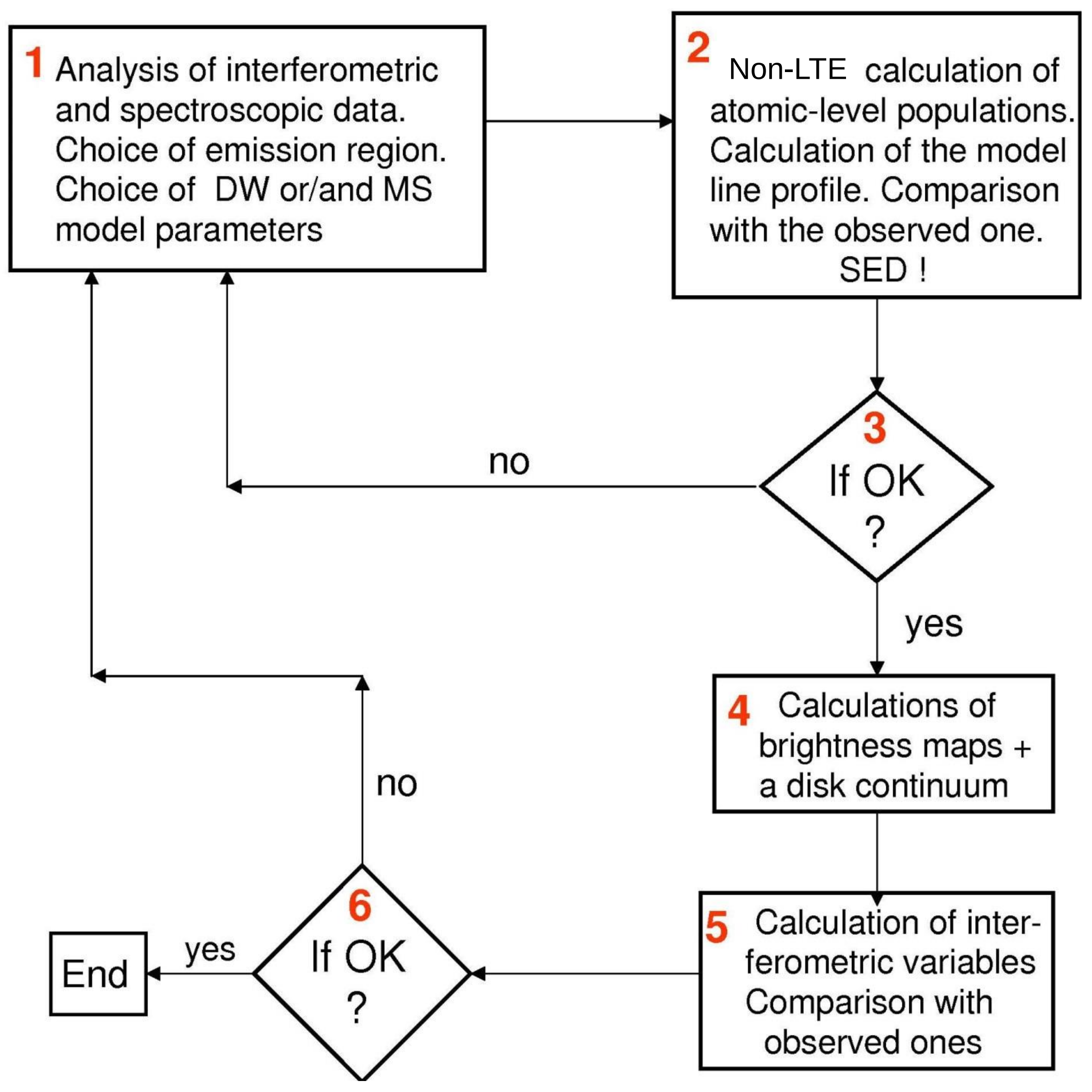


Fig. 2 Geometry of the disk wind (**a**) and magnetosphere (**b, c**)


1 Analysis of interferometric and spectroscopic data. Choice of emission region. Choice of DW or/and MS model parameters

2 Non-LTE calculation of atomic-level populations. Calculation of the model line profile. Comparison with the observed one. SED !

3 If OK ?

no

yes

4 Calculations of brightness maps + a disk continuum

5 Calculation of interferometric variables Comparison with observed ones

6 If OK ?

no

yes

End

Fig. 3 Modeling strategy

Calculation of the line profile (block 2 from Fig.3)

Step 1:

The magneto–centrifugal disk wind is a main contributor to the line emission. We divide it by several streamlines (SL) (Fig. 2a) and solve mass continuity equations for each of them. As a result, we obtain a density and velocity distribution along of each SL.

Tangential and poloidal velocity components are

$$u(\omega) = U_K(\omega_i)(\omega/\omega_i)^{-1}$$

$$V(l) = V_0 + (V_\infty - V_0)(1 - l_i/l)^{\beta}$$

$U_K(\omega_i)$ is the Keplerian velocity at a footpoint ω_i

V_0, V_∞ are initial and terminal velocities for the i-th streamline

Step 2: We solve a system of the stationary equations:

$$\boxed{\frac{dn_i}{dt} = R_i + Q_i = 0}$$

n_i is the population of the *i*-th level,
R_i and Q_i are terms describing radiational and collisional exitations and deactivations of *i*-th level

$$R_i = -n_i\left(\sum_{j=i}^{i-1}(A_{ij} + B_{ij}J_{ij}) + \sum_{k=i+1}^{\infty} B_{ik}J_{ik} + B_{ic}WJ^*_{ic}\right) + \\ + \sum_{k=i+1}^{\infty} n_k(A_{ki} + B_{ki}J_{ik}) + \sum_{j=1}^{i-1} n_j B_{ji} J_{ij}$$

$$Q_i = -n_i\left(n_e(q_{ic} + \sum_{i\neq j} q_{ij}) + B_{ci}WJ^*_{ic}\right) + \\ + n_e \sum_{j\neq i}^{\infty} n_j q_{ji} + n_e n^+ C_i + n_e^2 n^+ Q_{ci}$$

Step3: We compute a source function and intensity of the disk-wind radiation

$$S(r) = \frac{2h\nu^3}{c^2}\left(\frac{n_k(r)}{n_i(r)}\frac{g_i}{g_k} - 1\right)^{-1}$$

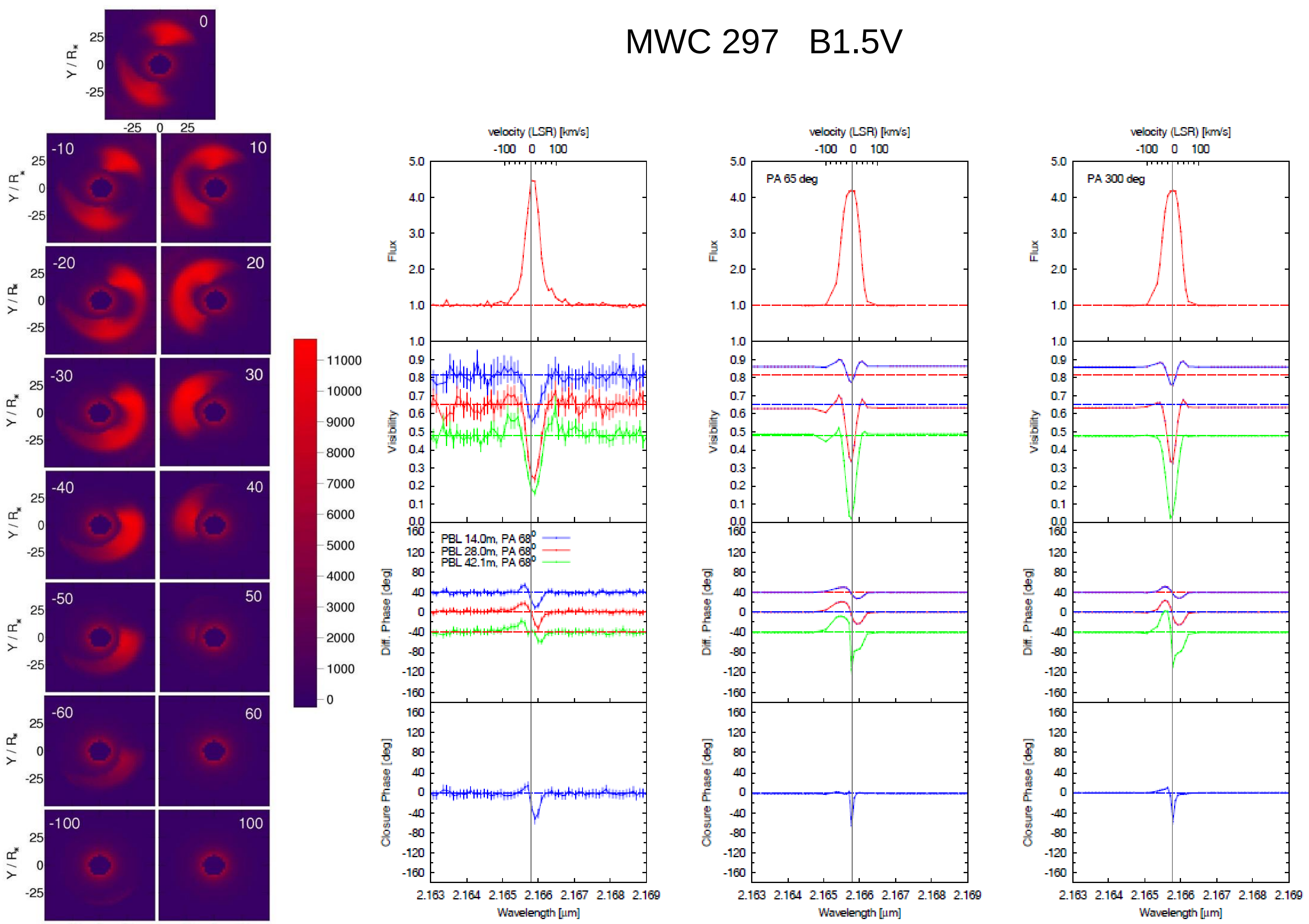
$$I_w(\nu) = \int_A I_w(\nu, x, y)\,dxdy$$

$$I_w(\nu, x, y) = \int_{z\min}^{z\max} S(\vec{r})\varphi\left(\nu - \nu_0 \frac{\vec{V}_z(\vec{r})}{c}\right) e^{-\tau(\nu,\vec{r})}\kappa(\vec{r})\,dz$$

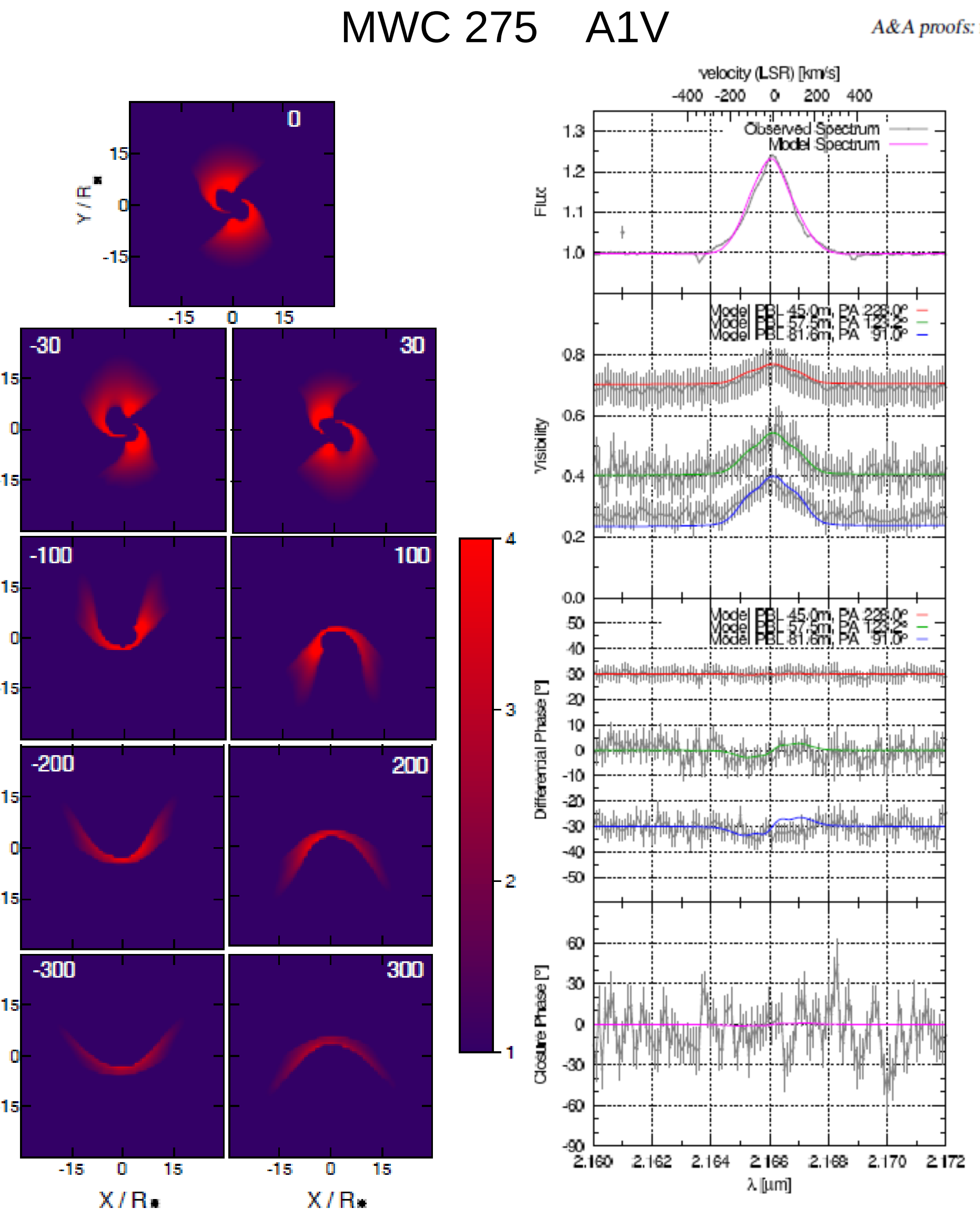
$$|\vec{r}| = (x^2 + y^2 + z^2)^{1/2}$$

x, y, z are coordinates centered on the star, with the z axis along the LOS and the x and y axes in the sky plane

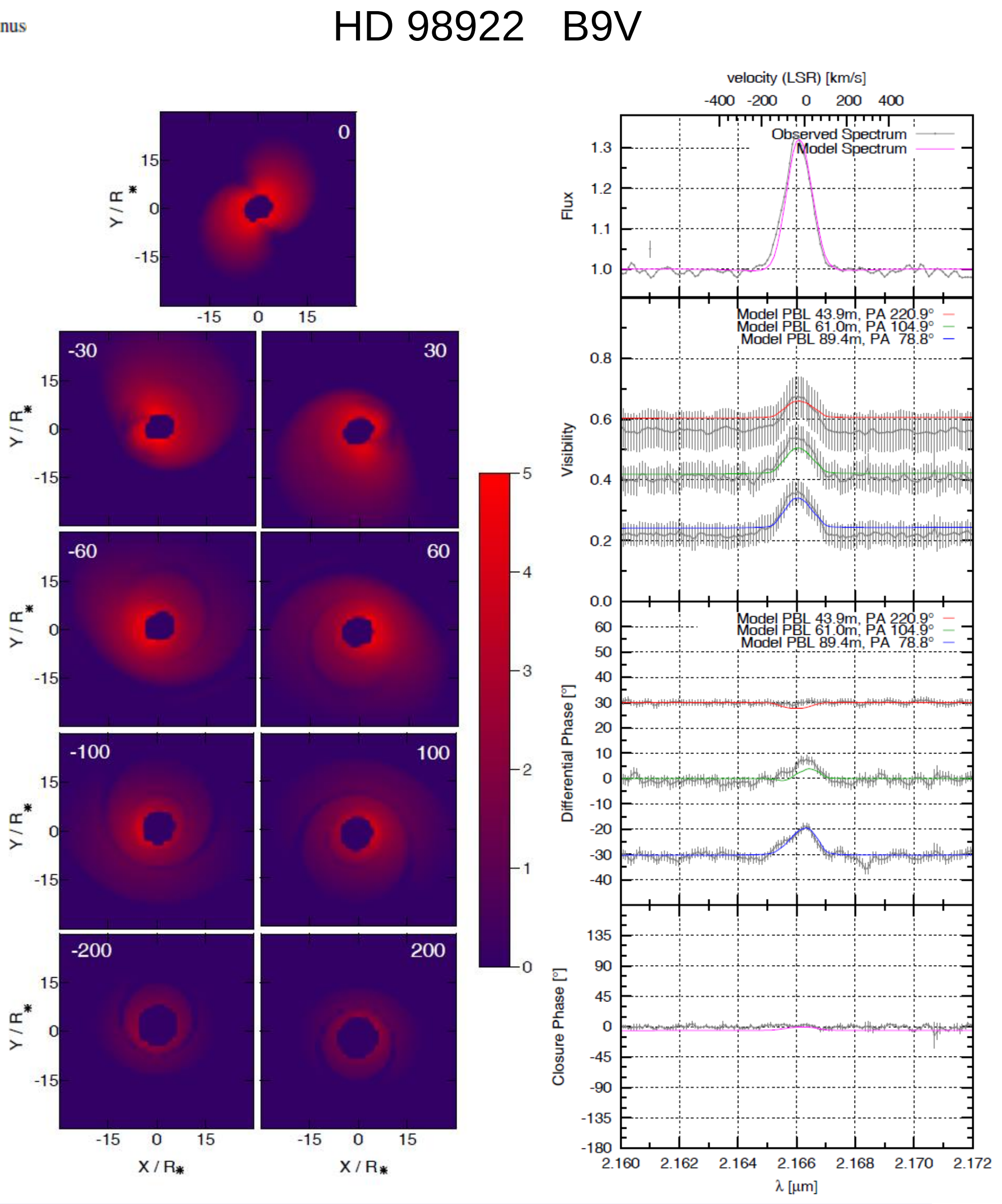
MWC 297 B1.5V



MWC 275 A1V



HD 98922 B9V



To consider the role of disk winds in the formation of the emission spectra of intermediate–mass young Herbig AeBe stars, we have performed non-LTE computations of the hydrogen emission lines. Level populations were computed in the Sobolev approximation, and we computed the radiation intensity from the disk wind at the spectral-line frequencies via exact integration over the spatial coordinates assuming a complete redistribution in frequency in the associated coordinate system.

Our computations demonstrate that the disk-wind region contributes substantially to the radiation in hydrogen lines of all series considerd (Balmer, Paschen and Brackett). The intensities and shapes of the profiles depend on the wind geometry and kinematics. Using various parameters of the wind models and inclinations, we are able to obtain a large variety of profile shapes.

These lines are also formed in the magnetosphere regions with accreting matter near Herbig Ae stars, but our computations show that this region does not dominate in the spectra of such stars. Nevertheless, this region should also be taken into account when computing line profiles, since it can appreciably affect the hydrogen line profiles.

Modeling both the IR hydrogen line Brγ and all available interferometric observations allows us to constrain the wind parameters and makes it possible to extract additional information about the disk+star system, such as the disk inclination.

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e-mails: **lvtamb@mail.ru** **grinin@gao.spb.ru**