Veiling by lines: the new approach to interpretation of CTTS spectra.

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THE MODEL

Generally speaking emission lines in spectra of Classical T Tauri Stars (CTTS) consist of narrow and broad components. Wide components are originated in an extended region above accretion shock front, where disk matter interacts with stellar magnetosphere (left panel of Fig.1). Narrow components are formed in the so called hot spot which is originated at CTTS's surface due to heating of stellar atmosphere by X-ray and EUV radiation from an accretion shock (right panel of Fig.1). For the first time we calculated the structure and emergent spectrum of the hot spot taking into account not only continuum, but also line emission.

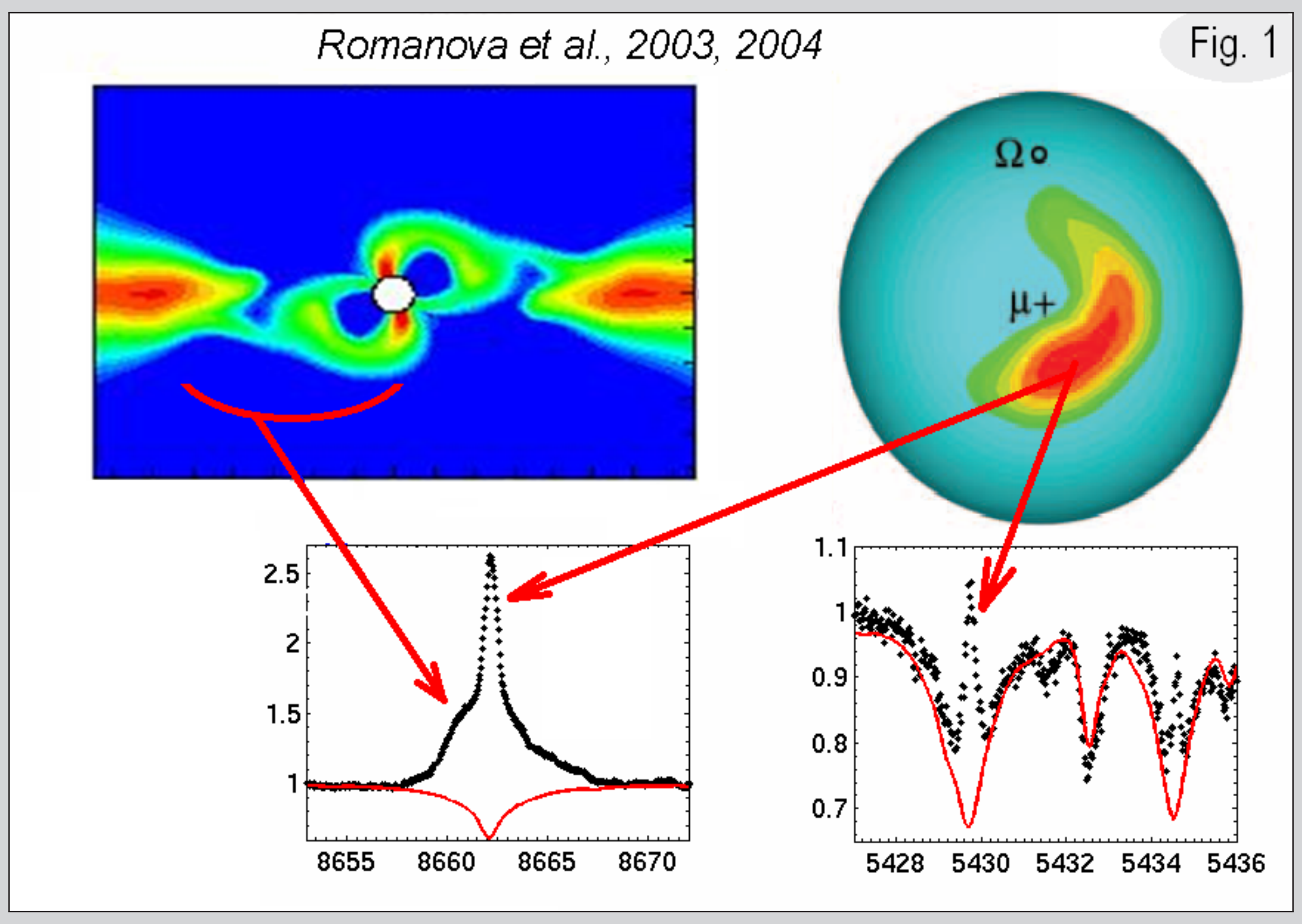

Fig. 1

Vertical structure of CTTS's atmosphere heated by external X-ray and EUV radiation was calculated in plane-parallel LTE approximation by means of modified ATLAS-9 programm (Kurucz, 1993) for a set of parameters that characterize accretion shock (pre-shock gas infall velocity V_0 and density N_0 or ρ_0) as well as underlying star (T_{eff}, $\log g$) – see Fig.2. The structure of the hot spot is primarily determined by parameter K, which we defined here as a ratio of an accretion flux $\rho_0 V_0^3/2$ to a stellar flux σT_{eff}^4. Accretion shock spectra for respective V_0 and N_0 values were adopted from Lamzin (1998) paper.

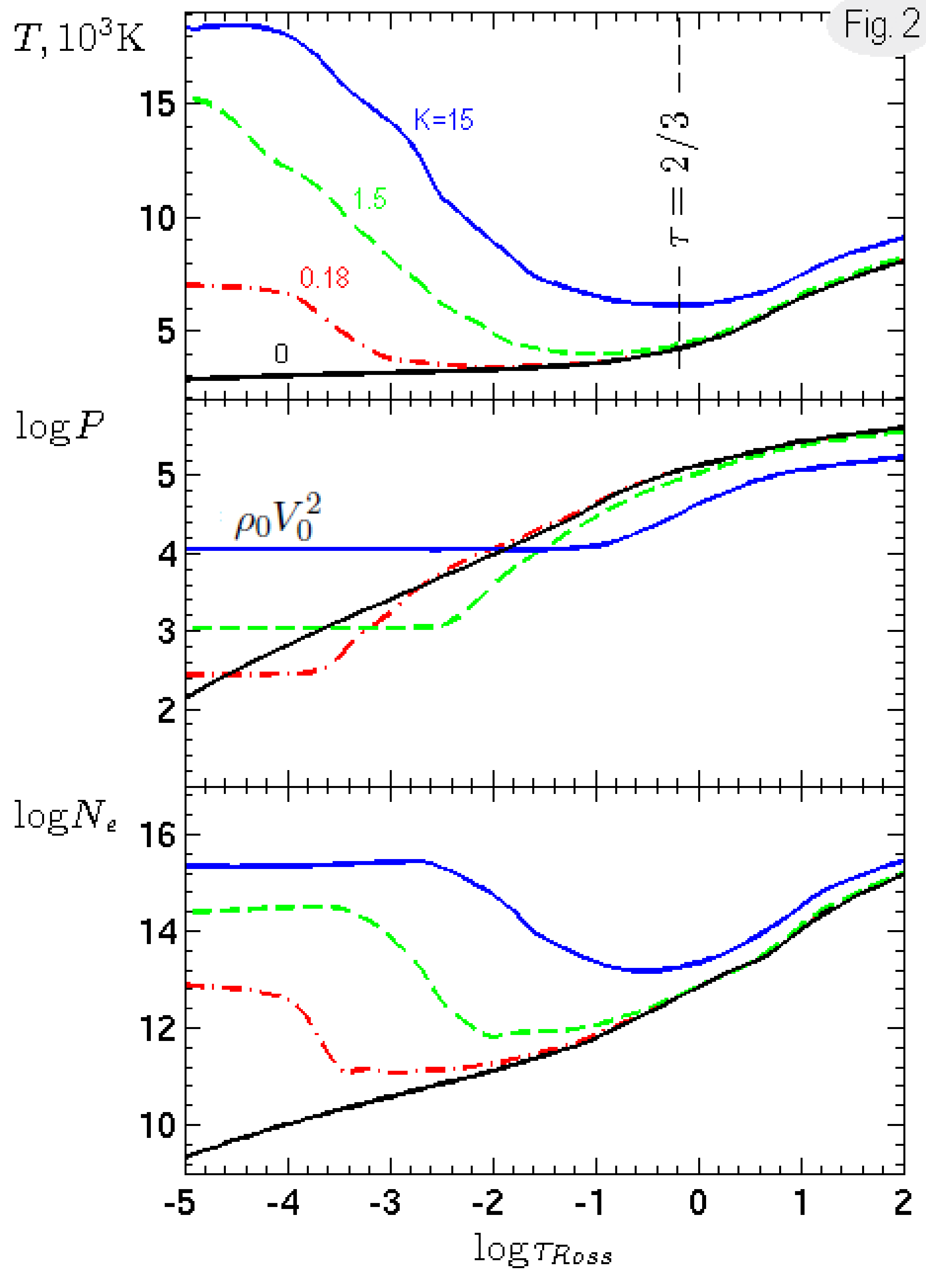

Fig. 2

Initially we calculated LTE spectrum of a hot spot in 100Å– 1.2 mkm spectral band (Dodin and Lamzin, 2012) using SYNTHE subroutine of ATLAS-9 programm. More precisely, a specific intensity $I_\lambda(\lambda, \mu)$ was calculated with spectral resolution $R =$ 600 000 for 17 values of μ from 1.0 to 0.01, where μ is a cosine of angle between the local normal to the spot's surface and the line of sight. Later non-LTE spectra of He and Ca were additionally calculated (Dodin et al., 2013) using DETAIL programm (Butler&Giddings, 1985).
To compare our calculations with observations, we assumed that on the stellar surface there was only one circular spot within which the shock parameters V_0 and N_0, were identical. Parameters that characterize the spot are stellocentric coordinates of its center and spot's relative area f. The radiation coming to the observer is the sum of the radiations from the spot and the unperturbed stellar surface – see Fig.3

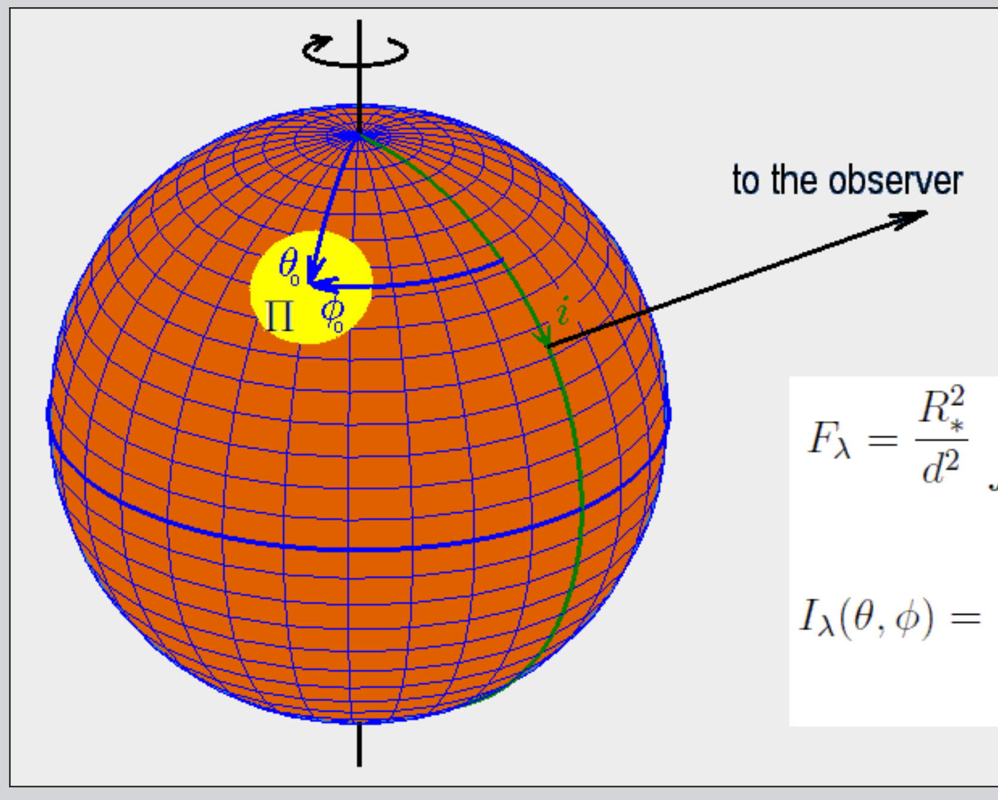

Fig. 3

$$F_\lambda = \frac{R_*^2}{d^2} \int I_\lambda \, \mu \, \sin\theta \, d\phi \, d\theta,$$

$$I_\lambda(\theta, \phi) = \begin{cases} I_\lambda^{star}, & \text{if } (\theta, \phi) \notin \Pi \\ I_\lambda^{spot}, & \text{if } (\theta, \phi) \in \Pi \end{cases}$$

COMPARISON WITH OBSERVATIONS

We used high resolution optical spectra of CTTS, adopted from VLT and KECK archives, to compare the theory with observation. Even in the model of a circular homogeneous spot, there are 9 free parameters that characterize the star (T_{eff}, $\log g$, the equatorial rotational velocity V_{eq}, the inclination i of the rotation axis to the line of sight), the accretion flow (V_0, N_0) and, finally, the spot itself (f, θ_0, ϕ_0). But it appeared that there are a number of spectral features that are sensitive to different parameters, what makes possible to pick up model's parameters relatively easy and fit observed spectra almost unambiguously – see Dodin et al. (2013) for details. For example relative intensity of He II 4686 line depends almost solely on infall gas density: the larger N_0 the smaller EW of the line – see middle panels of Fig.4 and 5. By the way, we found that in 8 out of 9 investigated CTTS pre-shock gas density N_0 is $\geqslant 10^{13}$ cm^{-3}.

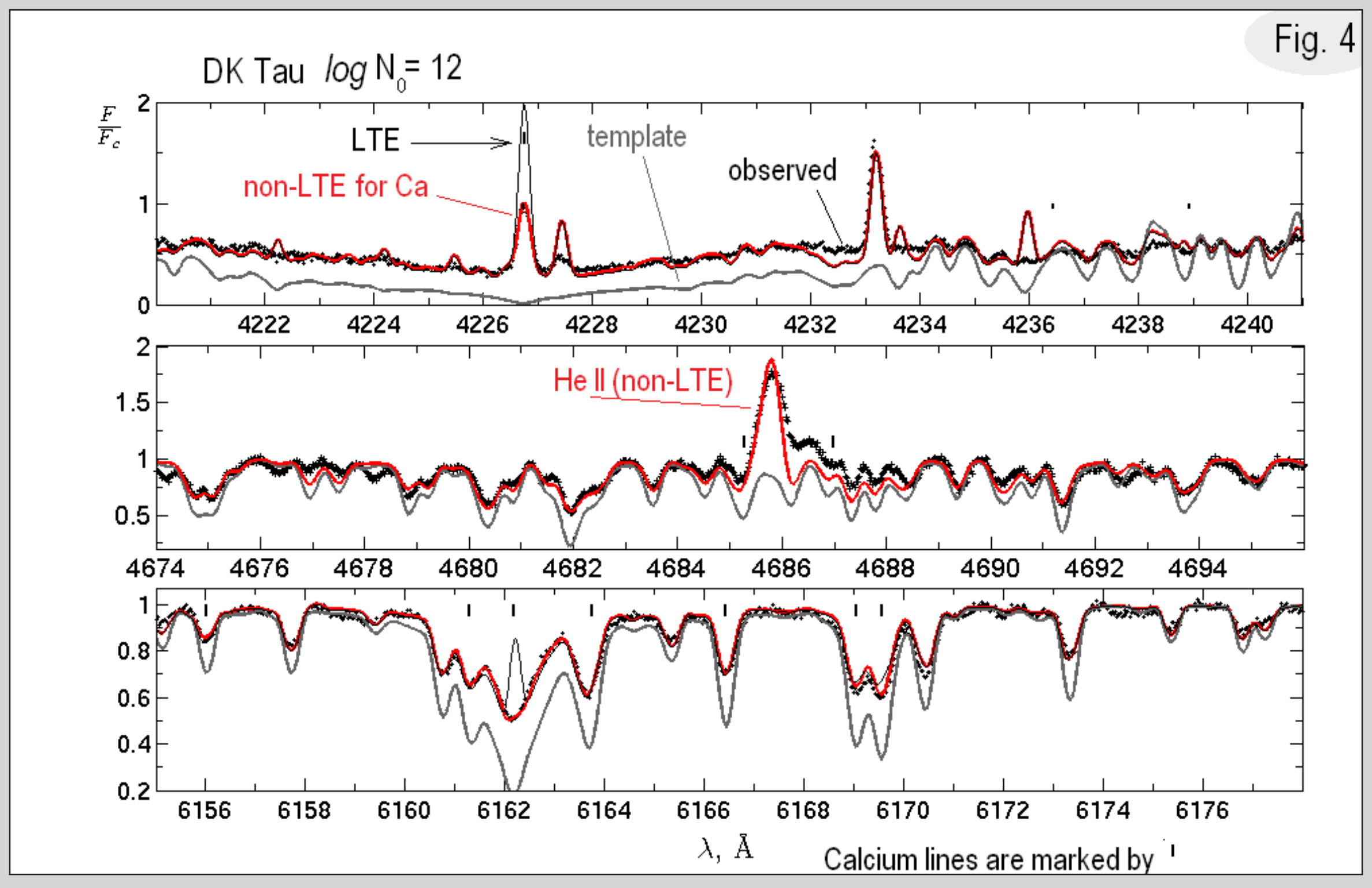

Fig. 4

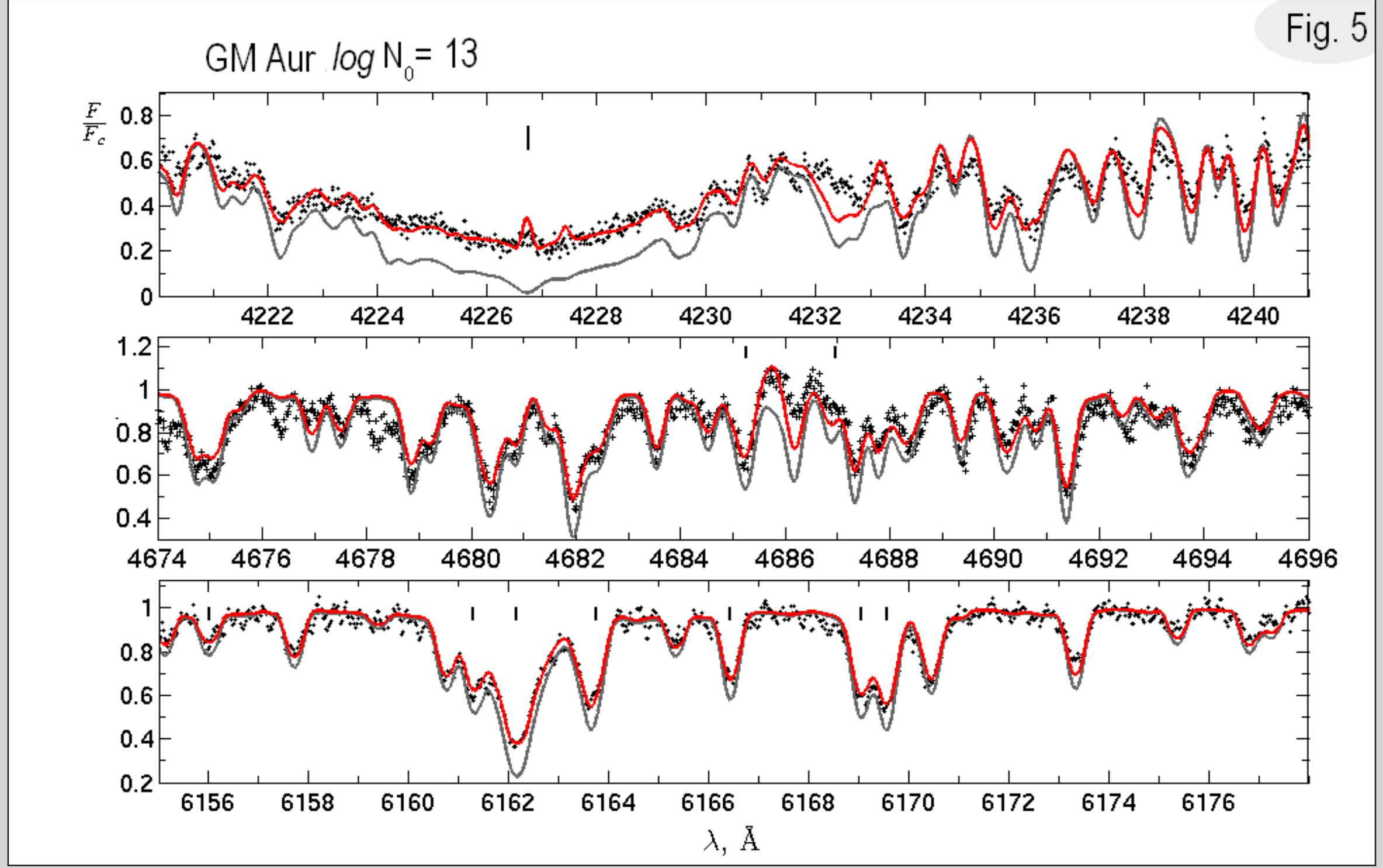

Fig. 5

Variation of spot's position relative to the Earth, caused by a stellar rotation, results in variations of the narrow emission component position inside respective absorption line – see the left panel of Fig.6. The effect is sensitive to i, θ_0, ϕ_0 and V_{eq} parameters. As an example the right panel of the figure illustrates sensitivity of theoretical profile of Ca I 6162 line on ϕ_0 parameter.

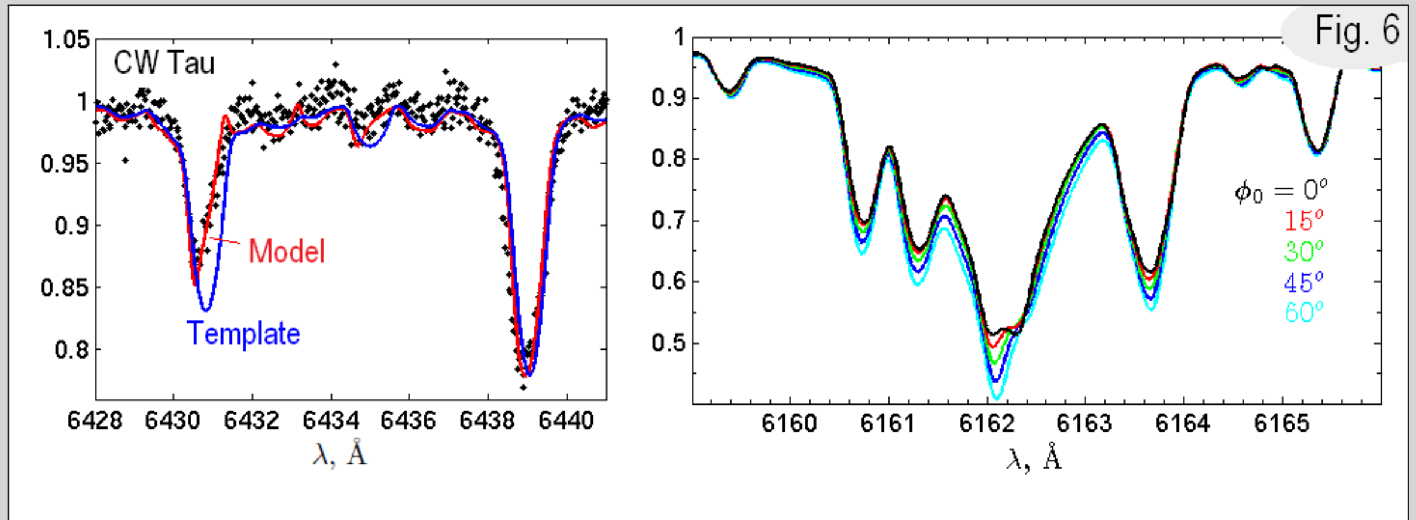

Fig. 6

Fig.4 and Fig.5 demonstrate that our models fit observed spectra good enough, such as non-LTE effects are very important for Ca I lines in the case of CTTSs with relatively low N_0.
At the same time we found that it is not possible to fit observed intensites of Ca I and Ca II lines simultaneously in the frame of homogenious hot spot model. One can overcome the difficulty if to assume that the spot with high velocity and density of the accreted gas is surrounded by an accretion zone with lower N_0 and V_0. Fig.7 illustrate this on the example of TW Hya. Note that theory predicts that real spots are inhomogenious – see the right panel of Fig.1

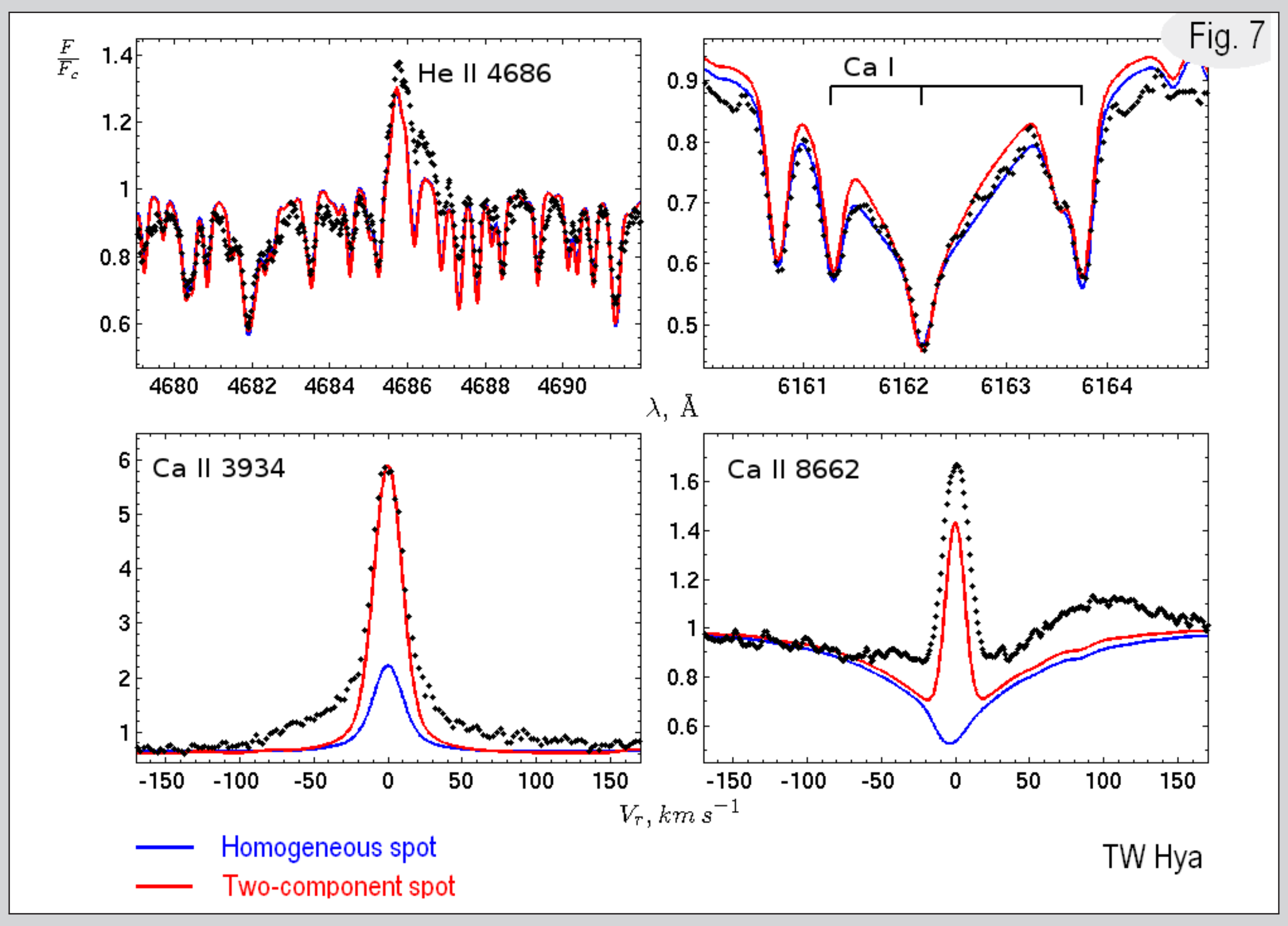

Fig. 7

WHY VEILING BY LINES IS IMPORTANT

It has long been known that the depths and EWs of photospheric lines in CTTS spectra are smaller than those for main-sequence stars of the same spectral types presumably due to superposition of emission continuum onto stellar spectrum. $r_\lambda = (EW_0 - EW)/EW$ value is commonly used as a quantitative characteristic of the veiling, where EW and EW_0 are the equivalent widths of a photospheric line in the spectra of CTTS and a template star of the same spectral type respectively. To characterize the veiling in a particular spectral range, one provides the value of r_λ obtained by averaging of r-values of the individual lines falling within this range. To reproduce observed veiled spectra of CTTS and to derive accretion parameters ($\dot{M}_{ac}$, L_{ac} etc.) it is widely used hot spot model of Calvet & Gullbring (1998), which assumed that the spot radiates in continuum only.
As can be seen from the left panel of Fig.6 spot's emission lines fill in respective photospheric lines in different extent even within narrow spectral band. So neglecting with veiling by lines results not only in overestimation of veiling continuum intensity (and e.g. $\dot{M}_{ac}$), but also in non-monotonic behavior of "its" SED – see Fig.8 and 9 (Dodin & Lamzin, 2013), which also illustrate that veiling by lines is especially important in CTTS with relatively large spot's filling factor f but low N_0.

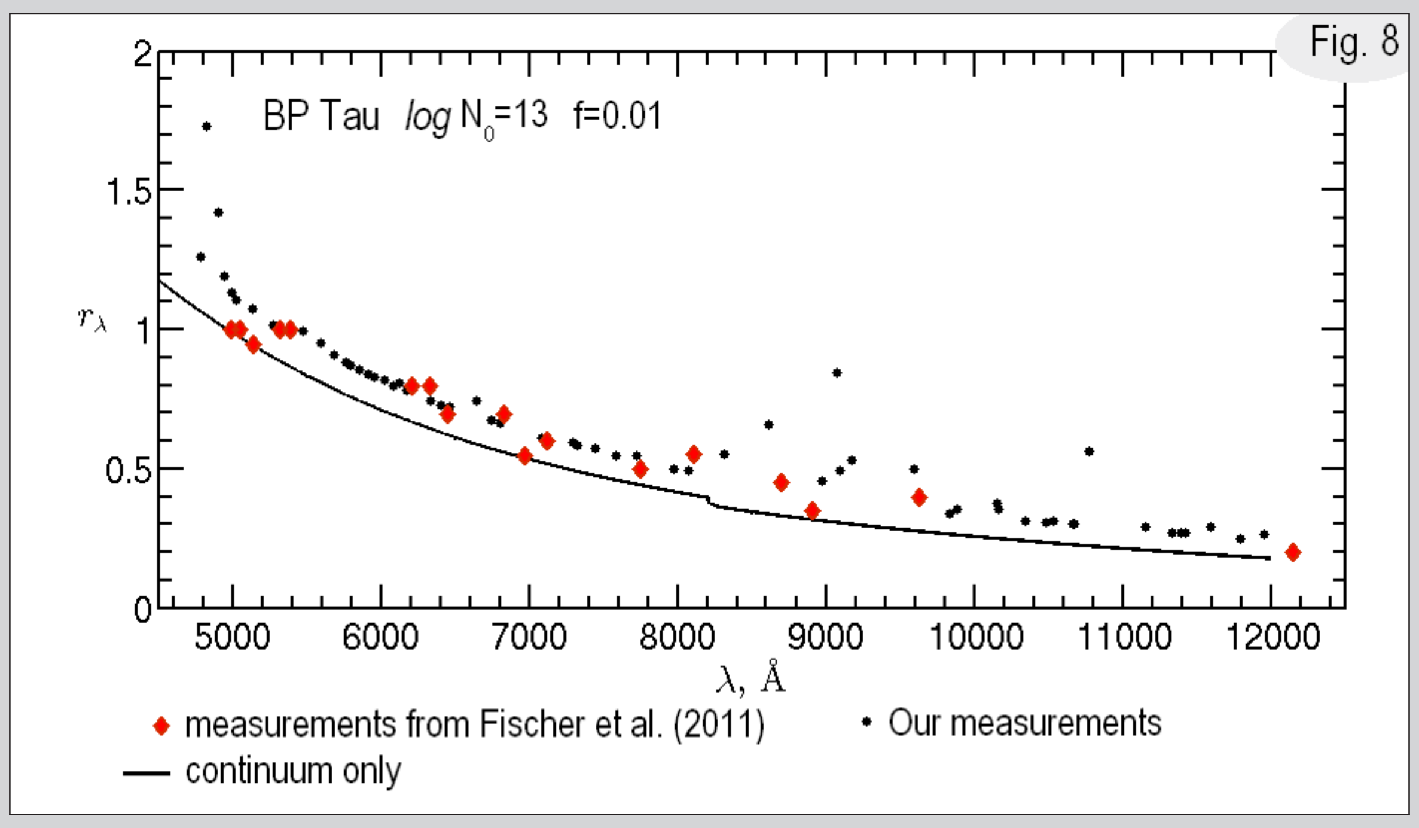

Fig. 8

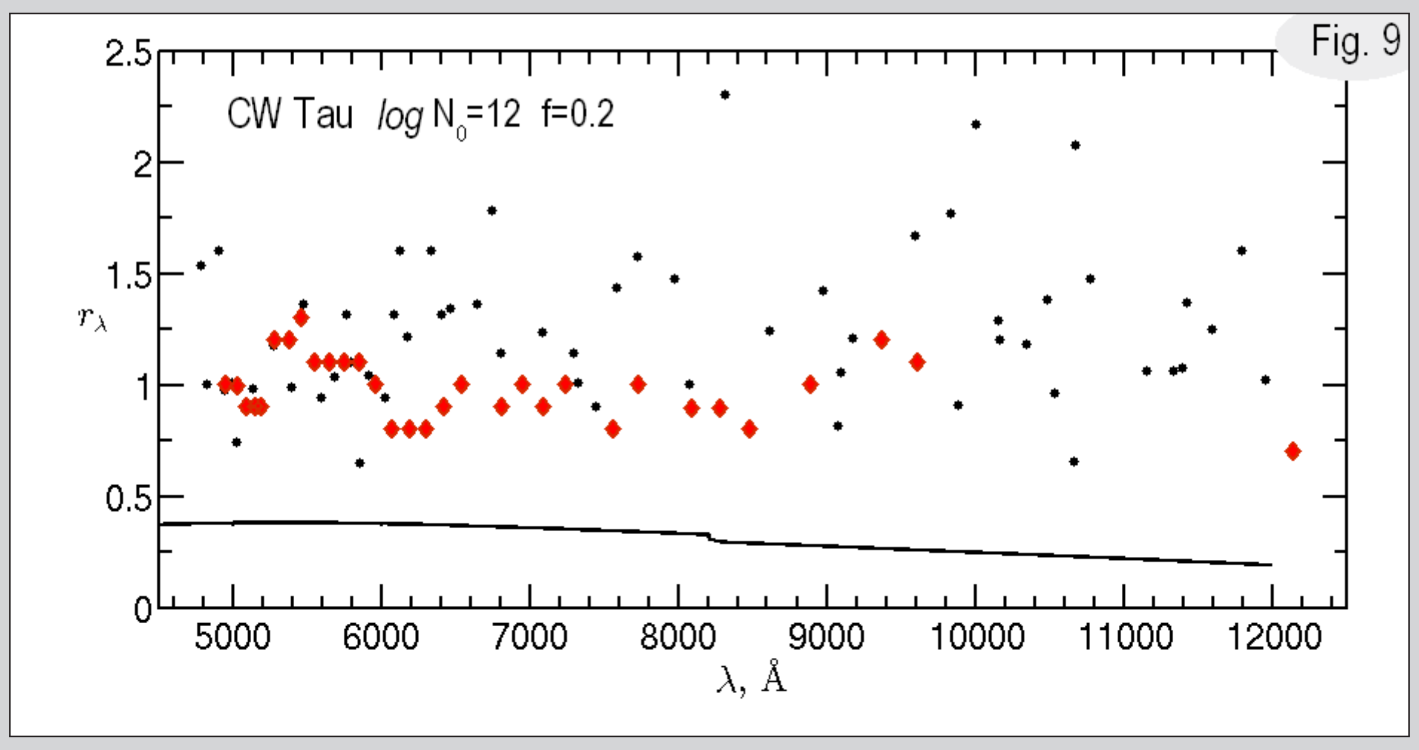

Fig. 9

As far as our models fit both line and continuum spectrum of CTTS one can use observed spectra normalized to continuum level for the comparison with calculations. Thus one can derive parameters of hot spot model without using poorly known A_V and extinction law toward CTTSs: errors of 0.5 in A_V can lead to an uncertainty up to 1 order of magnitude in estimating of $\dot{M}_{ac}$ (Ingleby et al., 2013). What is more in the frame of our approach one can found $A_\lambda(\lambda)$ as well as stellar radius and $\dot{M}_{ac}$ if to have additionally CTTS spectra $F_\lambda(\lambda)$ calibrated in absolute units, i.e. in erg s^{-1} cm^{-2} Å^{-1}.
Broad and narrow components of CTTS emission lines are originated in regions with very different physical conditions, geometries, and velocity fields. As a result they have to be modeled independently of each other. For this reason, when the calculated intensities and profiles of one of the components are compared with observations, the uncertainty due to the *a priori* unknown contribution from the second component arises. This problem is especially serious for the broad line components: since they are formed in the moving gas of CTTS magnetospheres (Kurosawa and Romanova 2012), the currently used separation of the components by decomposing the observed line profile into two Gaussians cannot be considered as a serious basis for comparing the calculations with the observations. At the same time, our calculations reproduce well the profiles of most lines of neutral metals, for example, Ca I, implying that there is virtually no broad component in these lines. If one will determine the hot-spot spectrum using such lines, then the profile of the broad component can also be found by subtracting the calculated profiles from the observed ones. For example such an approach has revealed a broad component in the He II 4686 line for the first time – see Fig.10.

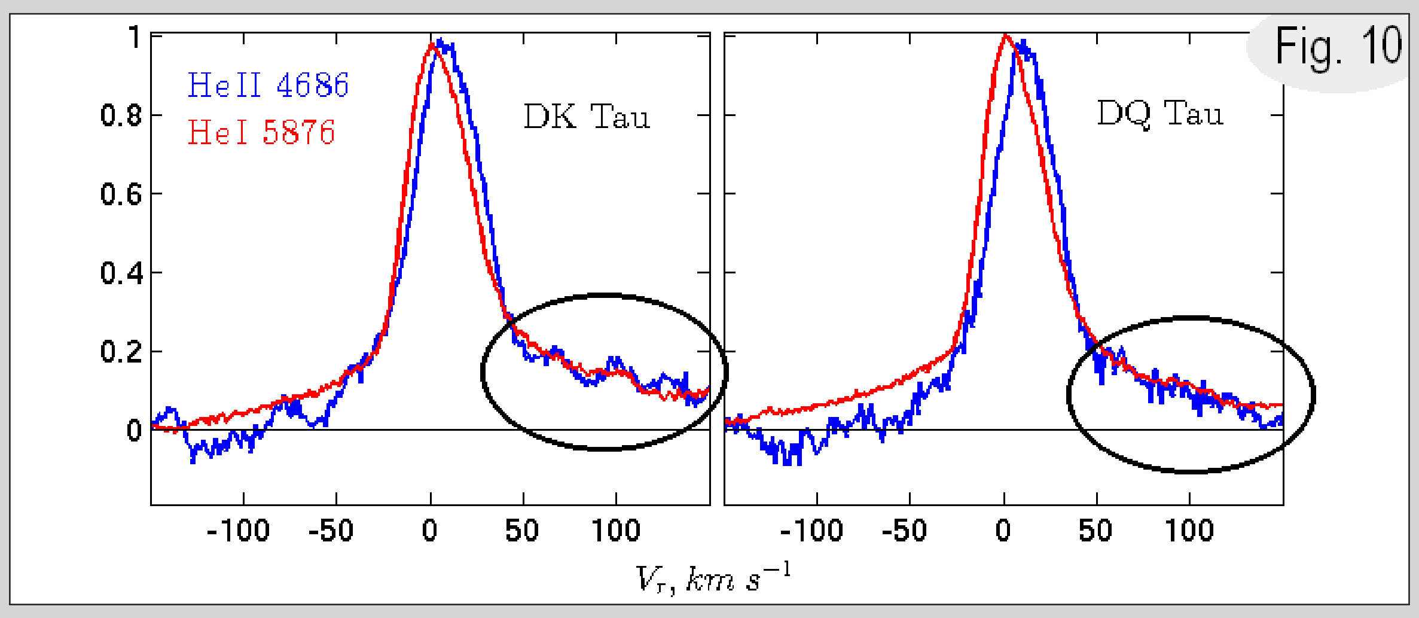

Fig. 10

The main goal of modeling the spot spectrum is to determine what the shape of the accretion spot on the stellar surface is and how V_0 and N_0 are distributed within it. This problem can be solved by Doppler imaging based on the dependence $I_\lambda = I_\lambda(\mu)$ calculated in the frame of our approach in the widest spectral range for a large set of parameters characterizing the accretion shock and the star itself. Presented results are the first steps in this direction.

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