Spectral synthesis of inner gaseous protoplanetary disks with PHOENIX

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Abstract

The inner gaseous regions of protoplanetary disks are of special interest in the formation and evolution of planets and stars because they are the likely birthplaces of planets and serve as the accretion reservoir for young stars. The study of inner disks may give rise to a better understanding of the dynamics, physical and chemical structure, and gas content of the region. As a first step, we have developed a 1D disk radiative transfer package as an extension to the well established multi-purpose stellar atmosphere program `PHOENIX`. The solution of the equations of momentum and energy conservation as well as the radiative transfer equation is adopted for the physical conditions in and the geometry of disks. Comparison of detailed models with high-resolution spectra will enable us to constrain the structure, dynamics, and gas content of disks, and thus give new insights on the physical processes governing star and planet formation.

Introduction

The inner regions of protoplanetary disks are the proposed birthplaces of planets and thus of special interest for the understanding of planet formation. The investigation of the inner gaseous parts of these regions by means of spectral line diagnostics may therefore yield insights in the physical and dynamical conditions under which planetary systems form. The interest in this field has even increased ever since the first planets around other stars have been found. The large number of planets at orbital radii < 5 AU points at the possibility of planetary migration in the early phases of planetary systems. This further underlines the necessity for the investigation of inner disk properties.

Contrary to the outer dust disks, inner disks are dominated by gas and therefore show spectral line features. Because of the small spatial extent of the inner disks at the distances of the nearest star-forming regions (~ 30 mas at 150 pc), resolving these parts at high spectral resolution is very challenging. However, high-resolution disk integrated spectra can be obtained for example with NIRSPEC (e. g. Najita et al. 2003) or CRIRES. In case of disks that are tilted against the line of sight of the observer, the differential rotation of the disk can be utilized to separate disk radii in velocity.

With our newly developed accretion disk radiative transfer code, we expect to be able to constrain the gas and dust content in the disk, the mass accretion rate and structure (e. g. temperature and density stratification).

Standard accretion model

We adopt the standard accretion model for geometrically thin disks, i. e. $H \ll R$ (Shakura & Sunyaev 1973). Matter is assumed to rotate with Kepler velocity and viscous shear decelerates inner and accelerates outer parts leading to accretion of matter and outward transportation of angular momentum. Turbulent cells smaller than the disk height H are the proposed origin of kinematic viscosity. The height averaged kinematic viscosity is usually described by

$$\bar{w} = \alpha c_s H \quad (= \nu \text{ in the literature}), \tag{1}$$

where $0 \leq \alpha \leq 1$ is the angular momentum transfer efficiency. Inner disks usually have values of $\alpha \approx 0.001 \ldots 0.01$. Typical mass accretion rates of $\dot{M} = 10^{-8}\ M_\odot/yr$ imply disk column densities of ≈ 100 g cm^{-2} at 1 AU for $\alpha = 0.01$ (D'Alessio et al. 1998)

Model calculations

In a first step, we use a 1D disk ring structure approximation. The disk is divided into rings and each ring is assumed to be plane-parallel and to have the same physical properties from its inner to its outer radius. Radiative transfer and disk structure are calculated vertically from the disk's midplane to the top layer. Gas and dust are in chemical equilibrium and dust is assumed not to settle in the disk.

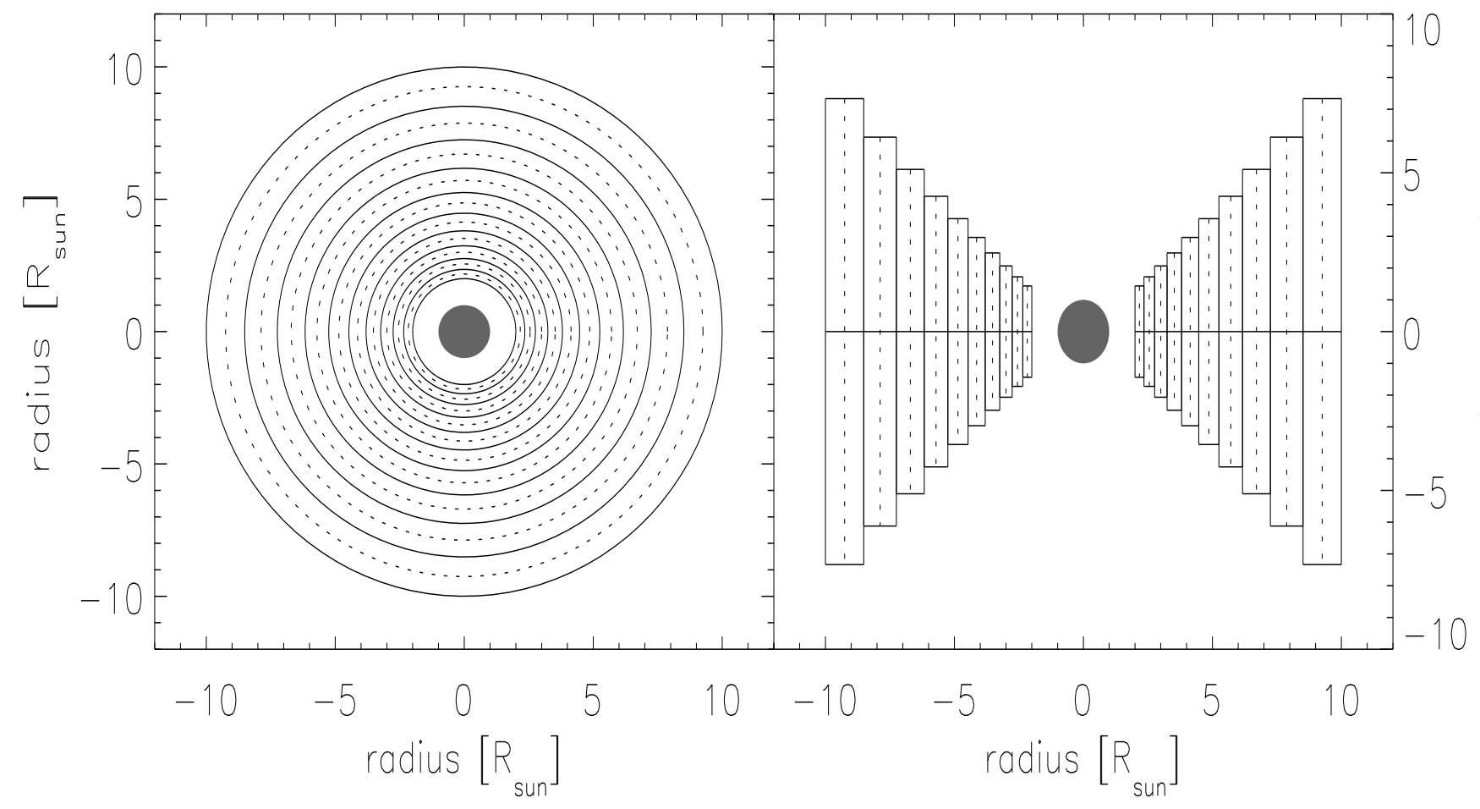

Figure 1: Disk structure as adopted for our numerical calculations.

Basic program input parameters are the radius $R_\star$ and mass $M_\star$ of the central star, the distance R between star and disk ring, the mass accretion rate $\dot{M}$ in the disk, and the Reynolds number Re as a measure for the mean kinematic viscosity $\bar{w} = \sqrt{GM_\star R}/Re$.

The iterative calculation of a disk ring model atmosphere starts by either constructing a gray start model for disks (after Hubeny 1990) or using a given `PHOENIX` model. We have further adopted the following conservation and constraint equations:

Hydrostatic equilibrium: This equation has to be used in a form to account for the varying surface gravity, i. e.

$$\frac{dP}{dm} = \frac{GM_\star}{R^3} z \quad . \tag{2}$$

Differentiating (2) once more and using $dz/dm = -1/\rho$ yields:

$$\frac{d^2P}{dm^2} = -\frac{c_s^2}{P}\frac{GM_\star}{R^3} \quad . \tag{3}$$

We take $c_s^2 = P/\rho$ as given function of depth (from previous iteration) and use inner and outer boundary conditions:

$$P'(M_0) = 0 \quad \text{and} \quad P(m_1) = \frac{m_1 c_s^2}{H_g f\left(\frac{z - H_r}{H_g}\right)} \tag{4}$$

where $f(x) = (\sqrt{\pi}/2)\exp(x^2)\mathrm{erfc}(x)$, H_r is the radiation and H_g the gas pressure scale height.

Radiative transfer: Only small changes are necessary here. We need an isotropic inner boundary condition in the short characteristic radiative transfer solution of the form

$$I(-\mu, M_0) = I(\mu, M_0) \tag{5}$$

instead of a diffusion approximation in the lowest atmosphere layer. Here M_0 is the midplane column mass density.

Energy conservation: Unlike ordinary stellar atmospheres, mechanical energy is released in disk atmospheres in every layer. Therefore, the flux is not conserved and we have to consider energy equilibrium of the form

$$E_{\mathrm{mech}} = E_{\mathrm{rad}} + E_{\mathrm{conv}} \quad , \tag{6}$$

where we neglect the convective energy E_{conv} because of the small optical depths. In every layer we need to equate

$$E_{\mathrm{mech}} = \frac{9}{4}\frac{GM_\star}{R^3} w\rho \qquad \text{and} \tag{7}$$

$$E_{\mathrm{rad}} = 4\pi \int_0^\infty (\eta_\nu - \chi_\nu J_\nu)\, d\nu \quad . \tag{8}$$

Using the first moment of the radiative transfer equation we receive the gradients of the mechanical and radiative fluxes:

$$\frac{dH_{\mathrm{mech}}}{dm} = -\frac{9}{16\pi}\frac{GM_\star}{R^3} w \quad \text{and} \quad \frac{dH_{\mathrm{rad}}}{dm} = \kappa_J J - \kappa_B B \tag{9}$$

Integration of the second moment of the radiative transfer equation and introduction of the Eddington factors $f_K = K/J$ and $f_H = H_0/J_0$ leads to an Unsöld-Lucy temperature correction scheme

$$\Delta T(m) = \frac{\pi}{4\sigma T^3}\Bigg[\frac{\kappa_J}{\kappa_B}\left(\frac{\Delta H(0) f_K(0)}{f_K f_H} + \frac{1}{f_K}\int_0^m \kappa_H \Delta H(m')dm'\right) - \frac{1}{\kappa_B}\frac{d\Delta H(m)}{dm}\Bigg] \tag{10}$$

Irradiation: Also irradiation from the central star is considered. As input source serves one or a combination of black body spectra of given effective temperatures. A `PHOENIX` spectrum can also be used as input. Discrete rays that receive radiation from the star are determined and assigned a fraction of the flux incident to the disk. The irradiation geometry is shown in Figure 2.

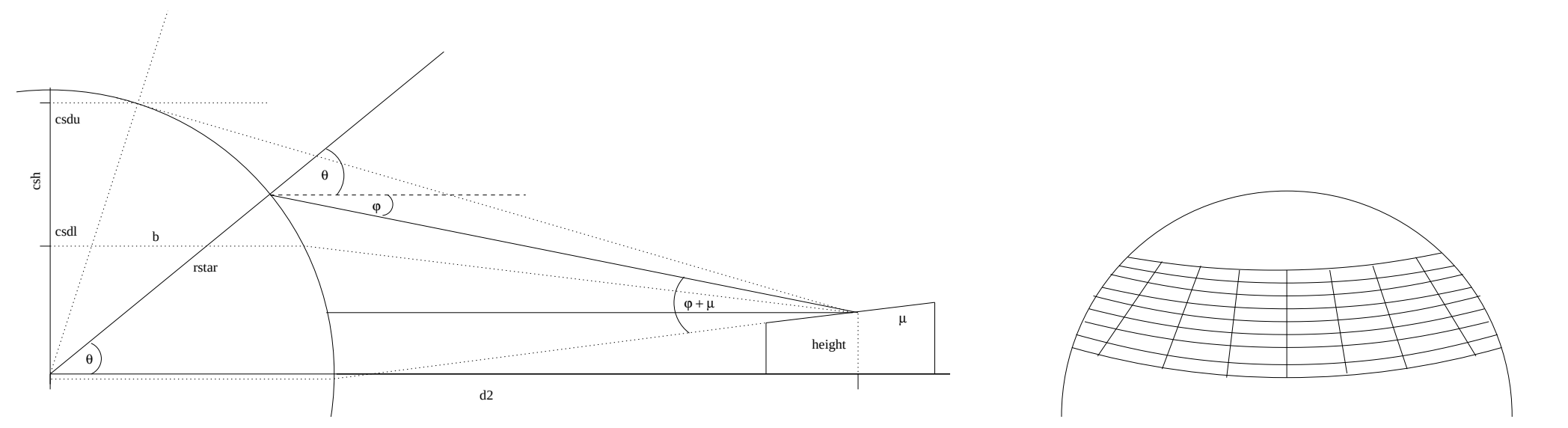

Figure 2: Star – disk irradiation geometry (*left*). The star's surface fraction is subdivided in sections and the irradiation flux is calculated for each ray considering limb darkening (*right*).

Results

We have considered the irradiation of the central star onto the disk surface. As a consequence, a temperature inversion in the upper layers of the atmosphere occurs. The effect is shown in the following temperature contour plots:

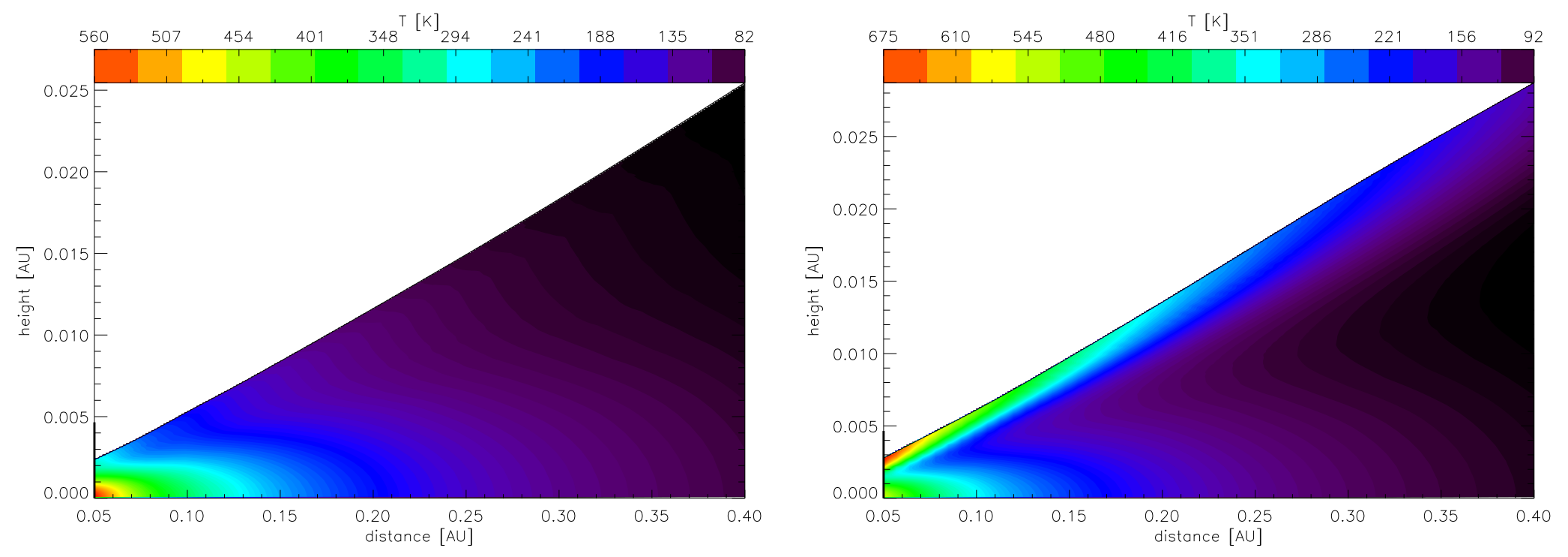

Figure 3: Temperature stratifications in a disk without (*left*) and with irradiation (*right*) from the central star. $M_\star = 0.6\ M_\odot$, $R_\star = 1\ R_\odot$, $T_{\mathrm{eff}}^\star = 4150$ K, and $\dot{M} = 2 \cdot 10^{-9}\ M_\odot/yr$.

The temperature inversion in the outer layers of the disk leads to emission lines. CO molecules are very abundant in warm inner disks and the spectral lines of the fundamental rovibrational transitions are a suitable probe to study the structure and content of a disk. In Fig. 4 the influence of the different disk rings on the line intensities is shown.

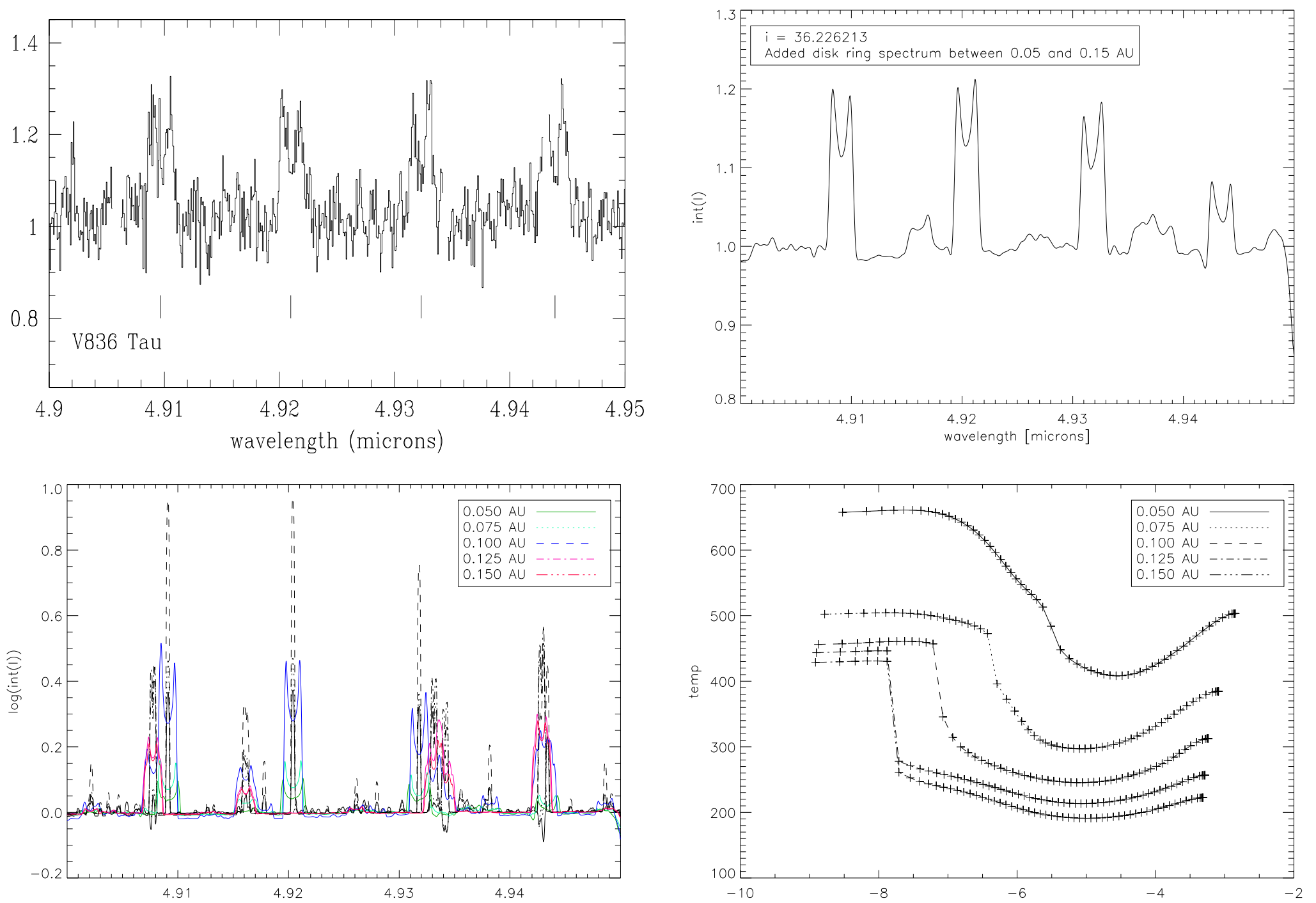

Figure 4: *Top left:* Spectrum showing CO fundamental emission from the disk system V836 Tau (from Najita et al. 2007). *Top right:* Combined synthetic spectrum of five disk rings with input parameters as in Figure 3. The inclination assumed is $i = 36.2°$. *Bottom left:* Contributions from the individual rings to the simulated lines. *Bottom right:* Temperature stratifications for the line forming rings.

The M-shape of the spectral lines is a result of the rotation profile induced by the Doppler effect. Each section of the ring emits radiation shifted corresponding to $\nu' = \nu\sqrt{(1 - v/c)/(1 + v/c)}$. The complete flux (integrated intensity) from a disk is calculated by:

$$\mathtt{int(I)} = F(\nu) = \cos(i)\int_{R_i}^{R_a}\int_0^{2\pi} I(\nu, \phi, r)\, r\, d\phi\, dr \tag{11}$$

The comparison of observations to our disk models (see Figures 4) shows the potential of future more detailed analyses.

Outlook

We plan to improve and extend our code by the following items:

- utilize and extend the molecular NLTE version of `PHOENIX` to get non-thermal CO and H_2 occupation numbers
- extend the irradiation by high energetic sources (e. g. X-rays coming from the active regions of the star)
- utilize the 3D radiative transfer soon to be included in `PHOENIX`

Furthermore, we plan to perform a detailed spectral analysis of high-resolution disk spectra to constrain the gas and dust content, the physical structure, and dynamical state of disks.

References

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