Multi-technique observations and modeling of protoplanetary disks

C. Pinte[1], F. Ménard[2], G. Duchêne[2], J. Patience[1], C. Ceccarelli[2], G. Duvert[2]

([1] University of Exeter, UK, [2] Laboratoire d'astrophysique de Grenoble, France)

ABSTRACT. *Most of the studies on circumstellar disks are based on models that put an emphasis on fitting either SEDs or scattered light images or molecular emission maps. In this contribution, we present a more general approach which aims at interpreting the increasing amount of observational data in the framework of a single model, in order to obtain a more global picture and to better characterize both the dust population and the gas disk properties. The main objective of this general method is to couple the constraints from the gas- and dust-oriented studies to shed light on aspects of the disk structure that are cannot otherwise be studied in a coherent manner. Results of such a modeling approach, applied to the disk surrounding IRAS 04158+2805 for which a large observational data-set is available, are presented.*

Numerical modeling

Radiative transfer code

Synthetic images, spectral energy distributions and molecular emission maps are computed using MCFOST, a 3D continuum radiative transfer code based on the Monte-Carlo method (Pinte et al, 2006). It includes multiple scattering with a complete treatment of polarization, passive dust heating assuming radiative equilibrium and continuum thermal re-emission. NLTE radiative transfer in molecular lines has recently been implemented in MCFOST. Calculations are performed using a long-characteristic Monte Carlo method similar to the one presented Hogerheijde & van der Tak, 2000.

Model definition

We assume a simple disk geometry, with a gaussian vertical profile: $\rho(r,z) = \rho_0(r)\,\exp(-z^2/2\,h(r)^2)$ valid for a vertically isothermal, hydrostatic, non self-gravitating disk. We use power-law distributions for the surface density $\Sigma(r) = \Sigma_0\,(r/r_0)^\alpha$ and the scale height $h(r) = h_0\,(r/r_0)^\beta$, where r is the radial coordinate in the equatorial plane, h_0 the scale height at the radius $r_0 = 100$ AU. We consider homogeneous spherical grains and calculate optical properties with Mie theory. The grain sizes are distributed according to the power-law $\mathrm{d}n(a) \propto a^{-3.5}\,\mathrm{d}a$, with a_{min} and a_{max} the min and max sizes of grains.

Results

Modeling of the dust phase

IRAS 04158+2805 is an M5 star, near the substellar boundary. It presents evidence of circumstellar dust up to a large radius (≈ 1 100 AU). We interpret optical and near-IR images, (VLT-FORS1, CFHT-IR), I band polarization map (VLT-FORS1), mid-infrared spectrum (SPITZER-IRS) and the SED in terms of a central star surrounded by an axisymmetric circumstellar disk, but without an envelope, to test the validity of this simple geometry (Fig. 1, 2 and 3, Glauser et al. 2008).

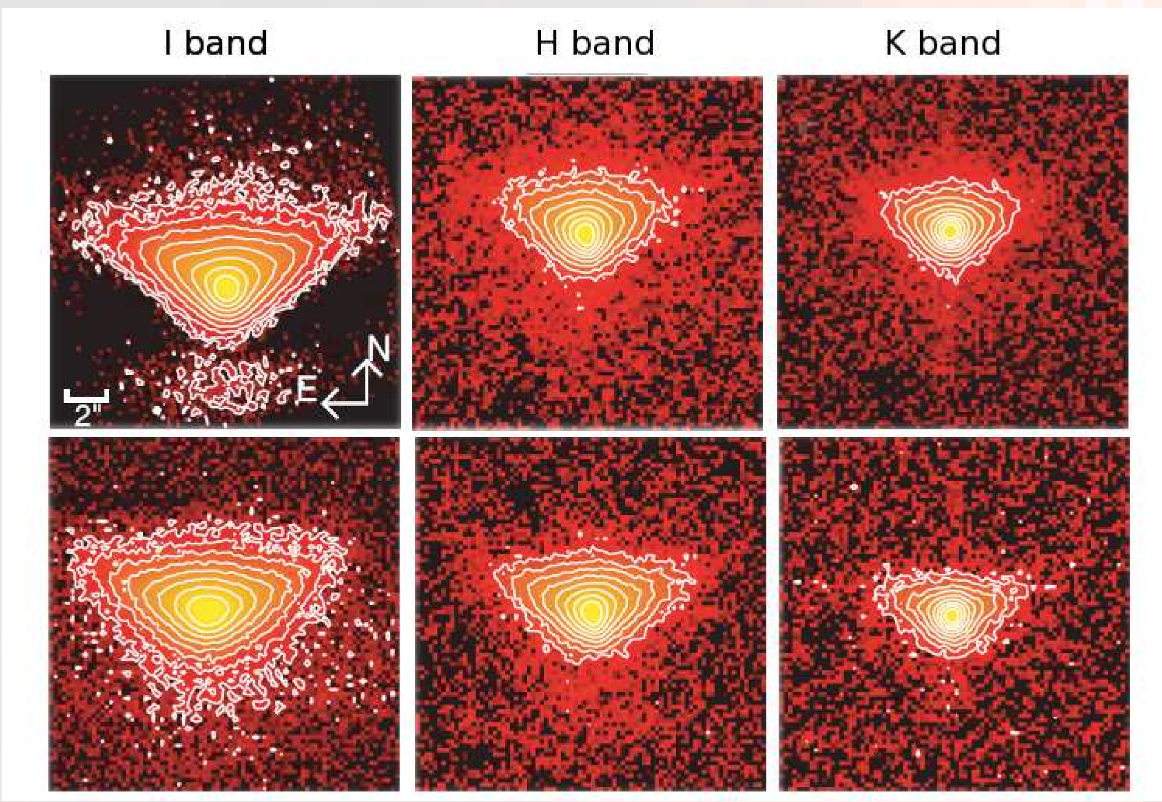

Fig. 1: *Comparison of observed (top) and synthetic (bottom) images in I band (left), H band (center), and K band (left) of IRAS 04158+2805. Contour levels are* $I = I_{\mathrm{max}}\,2^{-n}$ *with* $n = 1 \ldots 8$.

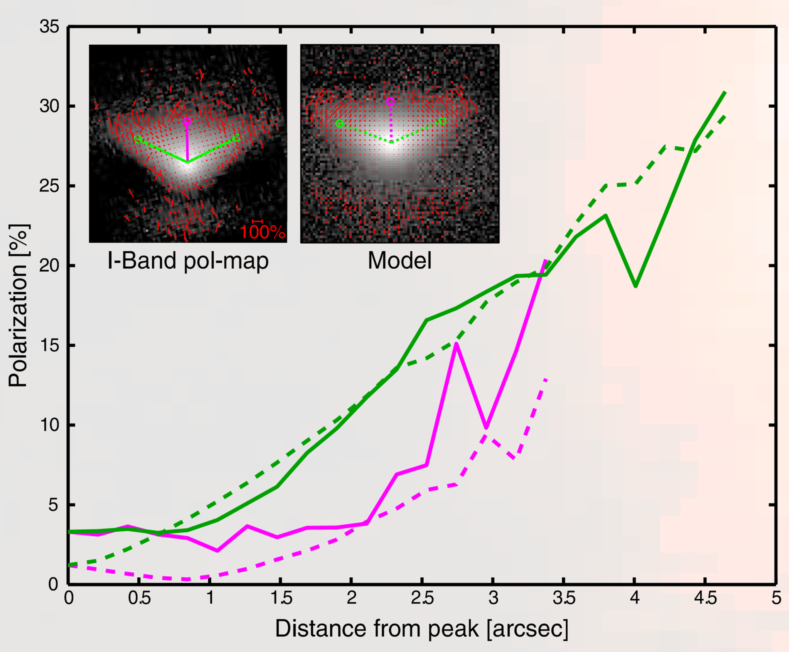

Fig. 2: *Comparison of the polarization level as a function of the position in the observed (solid) and modeled (dashed) nebula. Polarization (red vectors in the two small pictures) is compared along the ridge (green) and symetry axis (pink) of the nebula.*

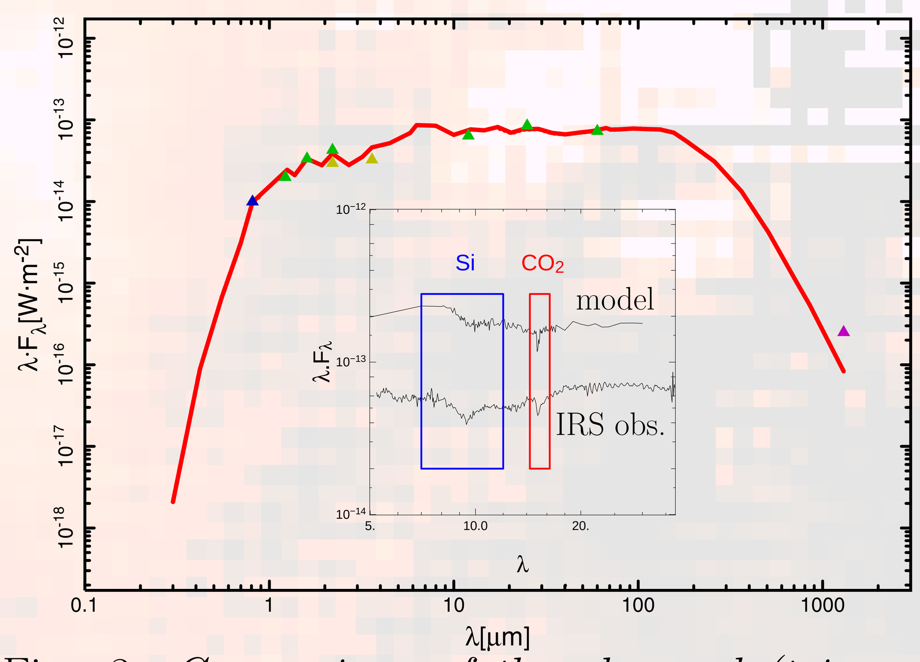

Fig. 3: *Comparison of the observed (triangles) and modeled (red line) SEDs. The SED, reminiscent of a class I is reproduced by a close to edge-on disk. The IRS spectrum (small subfigure) presents silicate and* CO_2 *absorption features (flux level is arbitrarily shifted), also seen in the model (*CO_2 *was added in disk regions where* $T_{\mathrm{dust}} < 50$ *K).*

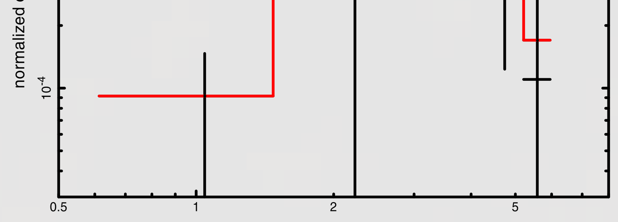

Fig. 4: *Chandra ACIS-S spectrum and spectral fit (red)*

Glauser et al. 2008 extracted the gas column density $N_H = 7.2^{+4.8}_{-3.0}\,10^{-2}$ g.cm^{-2} by fitting the X-ray spectrum (Fig. 4) in XSPEC. Together with the dust column column density $N_{\mathrm{dust}} = 3.3^{+1.8}_{-1.2}\,10^{-4}$ g.cm^{-2} obtained from the best fitting model, it provides a direct estimate of the gas-to-dust ratio along the line of sight: $N_H/N_{\mathrm{dust}} = 220^{+170}_{-150}$

All the observables are well reproduced by our model with a single disk (*i.e.* no envelope) and both the disk geometry and dust properties are constrained.

Modeling of the gas phase

The density, temperature profiles and UV flux density derived from dust modeling are used to calculate the CO abundance throughout the disk (Fig. 5), by considering that CO molecules freeze-out onto the dust grains in the midplane and are photo-dissociated by the FUV in the upper layers (Ceccarelli & Dominik, 2005).

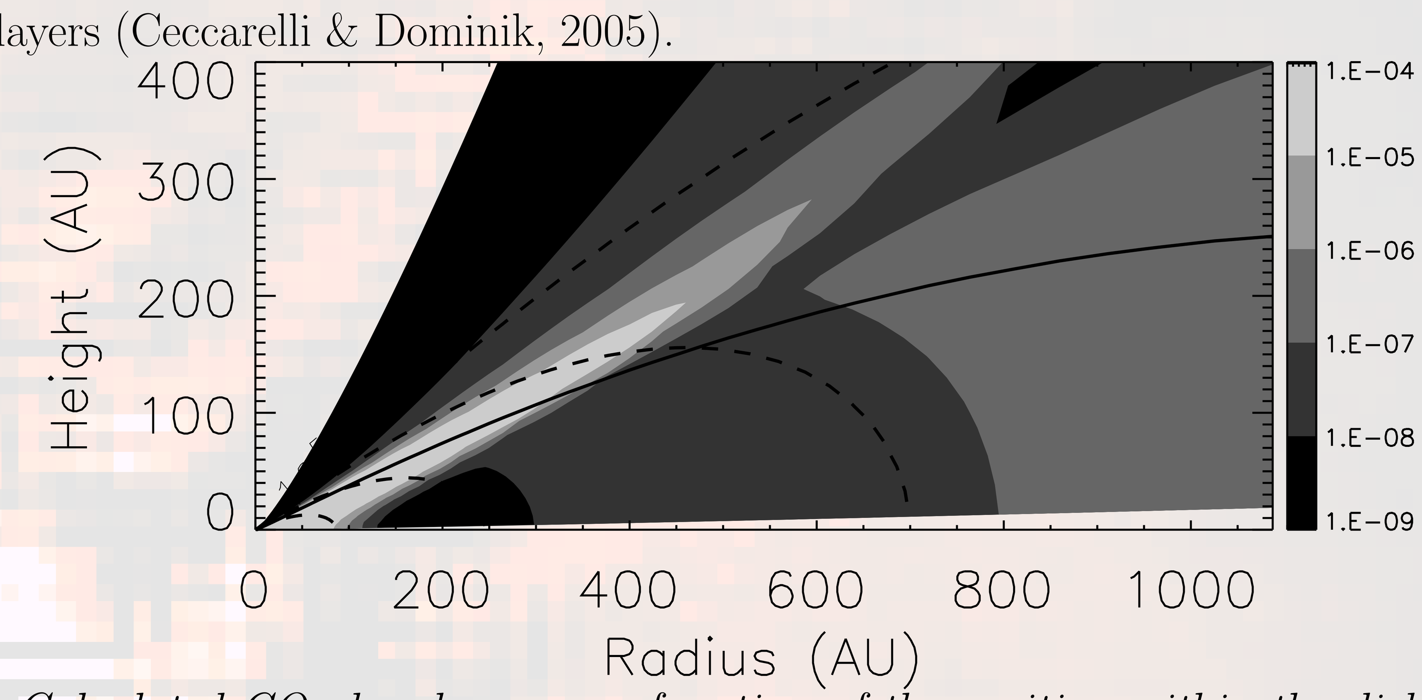

Fig. 5: *Calculated CO abundance as a function of the position within the disk.*

From these abundances, the level populations of the CO molecules and corresponding emission maps are calculated with MCFOST (Fig. 6, Pinte et al, in prep.).

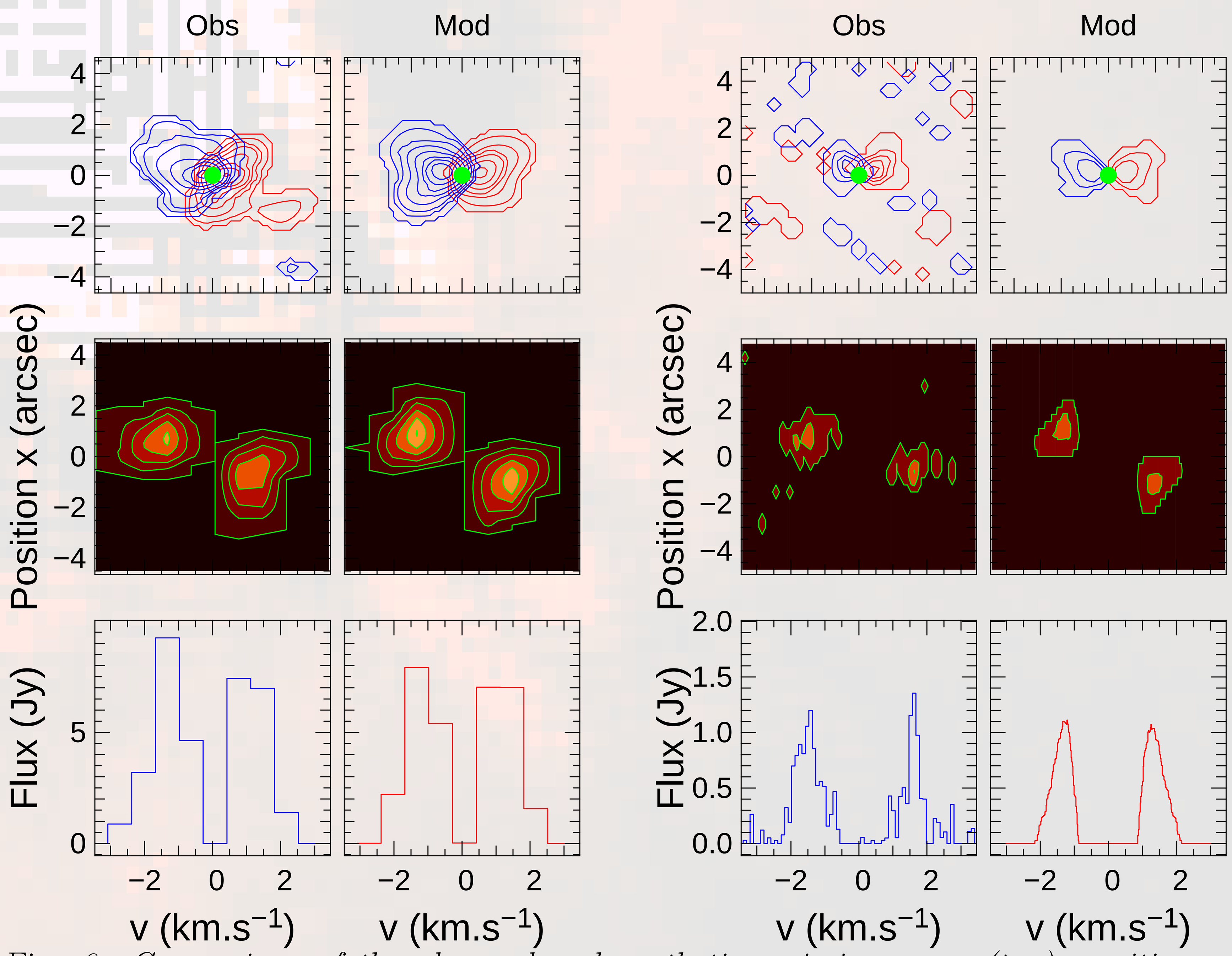

Fig. 6: *Comparison of the observed and synthetic emission maps (top), position-velocity diagrams (middle) and integrated spectra (bottom). Left panel is for the J=3-2 SMA observations and right panel is for the J=2-1 IRAM/PdB observations.*

The modelling allows us to constrain further the thermal and cinematic structures at large scale in the disk and additional information on the mass of the central object (in the range 0.3-0.5 $M_\odot$) and on the turbulence velocity (≈ 0.3 km.s^{-1}) is obtained.

Both the dust and gas observations of the disk can be modeled consistently within the framework of a single model.

Conclusions

The interest of the approach we present here is to combine coherently the disk density and temperature structure calculated using the *dust* disk geometry, as provided by continuum tracers to the different pieces of information provided by gas line tracers. The bulk of the disk mass is in the gas phase, but because most of the heating is provided by absorption of energy by dust, it is important (although difficult) to combine both approaches to improve curent modeling efforts of complex data sets. Such a global approach is needed to fully exploit present observational data sets and to prepare observations with future instruments like Herschel and ALMA.

References

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