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MULTI-WAVELENGTH MODELING OF PROTOPLANETARY DISKS

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Abstract. The on-going revolution of high angular resolution observations and increasing wavelength coverage promises to unlock tightly-kept secrets of circumstellar disks. Thanks to these advances, many issues have already been addressed : large scale geometry of disks, evidence of grain growth, of dust settling, ... Most of these results are based on models that emphasize on fitting either SEDs or scattered light images or, more recently, interferometric visibilities. In this contribution, we present a global approach which aims at interpreting the increasing amount of observational data coherently, in the framework of a single model, in order to get a more global picture and to better characterize both the dust population and the disk properties. Results of such a modeling approach, applied to a few disks for which large observational data-sets are available, are presented.

1 Numerical modeling

1.1 Radiative transfer code

Synthetic images and spectral energy distributions (SEDs) 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 polarisation, passive dust heating assuming radiative equilibrium and continuum thermal re-emission. Dust properties may vary with location within the disk, allowing us to model vertical dust settling (e.g. IM Lupi) or increase of ice mantles from the inner, hot regions to the outer, cold edge of the disk (e.g. IRAS 04158+2805).

1.2 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 the Mie theory. The grain sizes are distributed according to the power-law $n(a) \propto a^{-3.7}$, with $a_{\rm min}$ and $a_{\rm max}$ the minimum and maximum sizes of grains.

2 IRAS 04158+2805

IRAS 04158+2805 is an M5 star, near the stellar/substellar boundary. It presents evidence of circumstellar dust up to large radius ($\approx 1\,100$ AU). We interpret optical and near-IR images, (VLT-FORS1, CFHT-IR), I band polarization map (VLT-FORS1), archive mid-infrared spectrum (SPITZER-IRS) and 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, Glauser et al. 2006).

All the observables are well reproduced by our model with a single disk and both the disk geometry and dust properties are narrowly constrained : the total disk mass is 1.0-1.75 $10^{-4}\,\mathrm{M}_\odot$, the inclination 62-63°. The maximum grainsize required to fit all available data is of the order of $1.6 - 2.8\,\mu$m although the upper end of this range is only loosely constrained.

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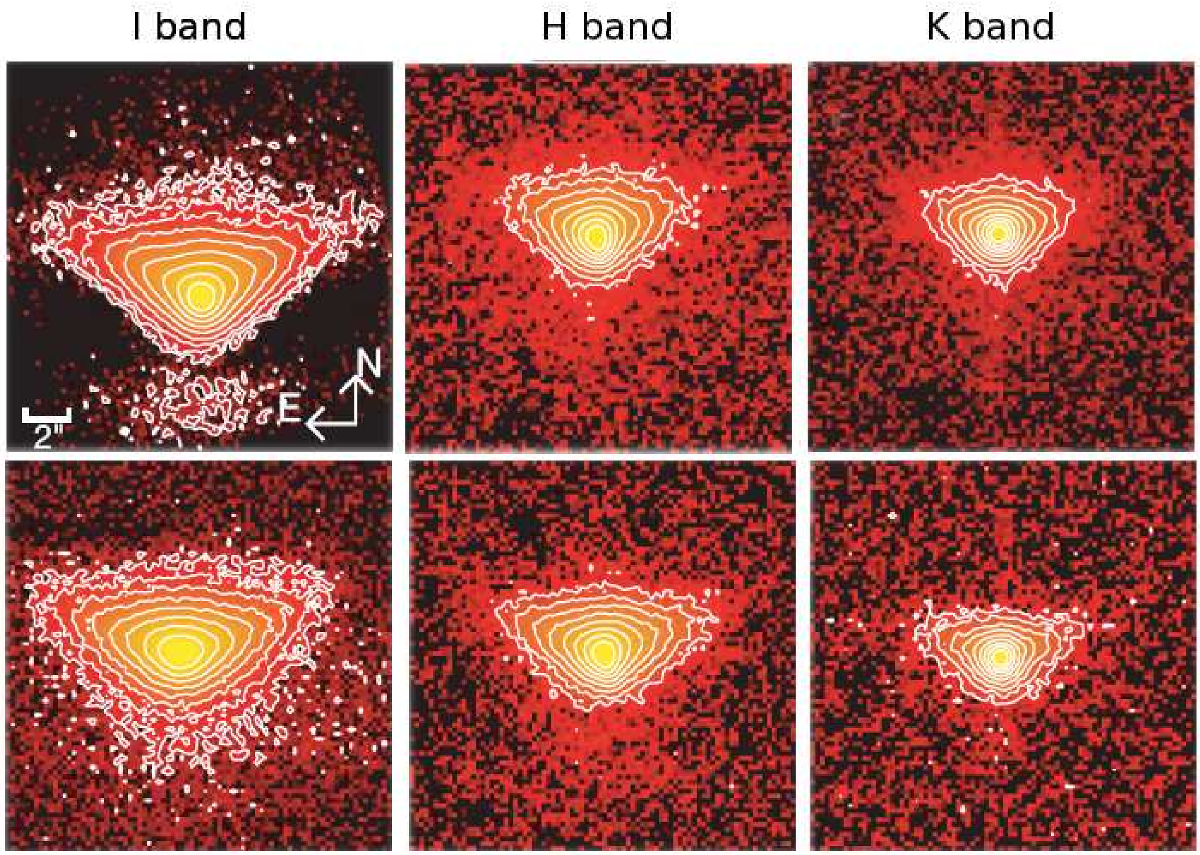

Fig. 1. Comparison of observed (top) and synthetic (bottom) images in I band (left), H band (center), and K band (left) of IRAS 04158+2805. Contour levels are $I = I_{\max} 2^{-n}$ with $n = 1 \ldots 8$.

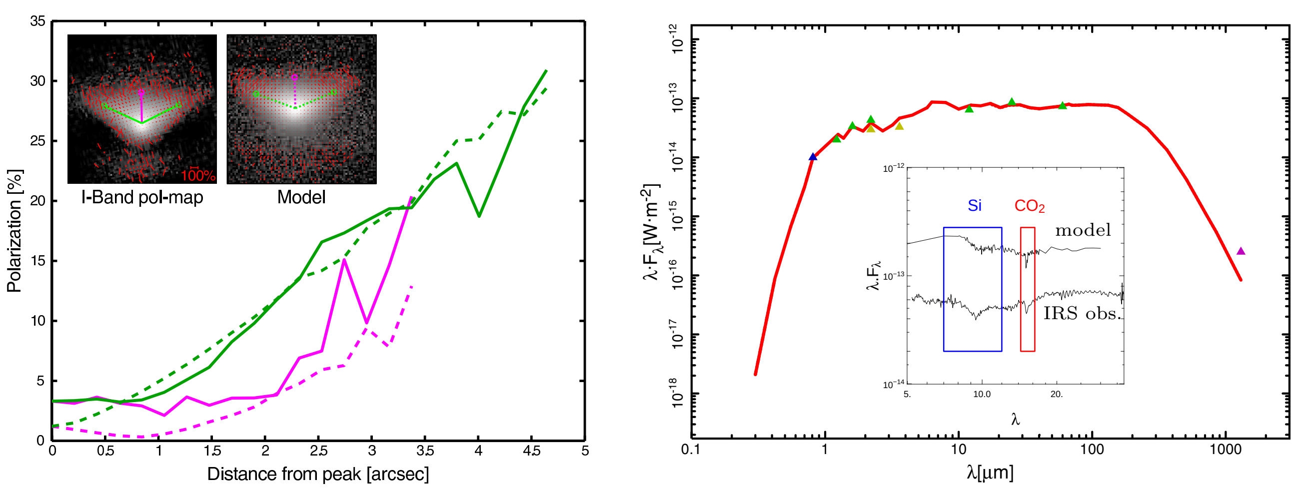

Fig. 2. Comparison of the polarization level as a function of the position in the observed (solid) and modeled (dashed) nebula. Polarization (red vectors in the two small pictures) is compared along the ridge (green) and symmetry axis (pink) of the nebula. Comparison of the observed (triangles) and modeled (red line) SEDs. The SED, reminiscent of a class I is reproduced by a near edge-on disk, without envelope. IRS spectrum (small subfigure) presents silicate and CO_2 absorption features (flux level is arbitrarily shifted), also seen in model (CO_2 was added in disk regions where the calculated $T_{\rm dust} < 50$ K).

3 IM Lupi

IM Lupi (Schwartz 82) is an M0 T Tauri star, with a modest emission-line activity but surrounded by a large amount of dust (mm flux of 260 mJy, Nuernberger et al. 1997). An *analysis of the global SED, c2d Spitzer/IRS and MIPSSED spectra* seems to indicate the presence of *dust settling*, with small (< 1 μm) amorphous silicate grains close to the surface and large grains (≈ 1 mm) deeper in the disk.

HST Nicmos 1.6 μm and WFPC2 0.606 μm scattered light images confirm the presence of a disk. A *simultaneous fitting of the images and the SED* was performed over $\approx$ 200 000 models, by varying the disk geometry and degree of settling.

Both the SED, including the IRS spectrum, and scattered light images are well reproduced (Fig. 3) and give us strong constraints on model parameters.

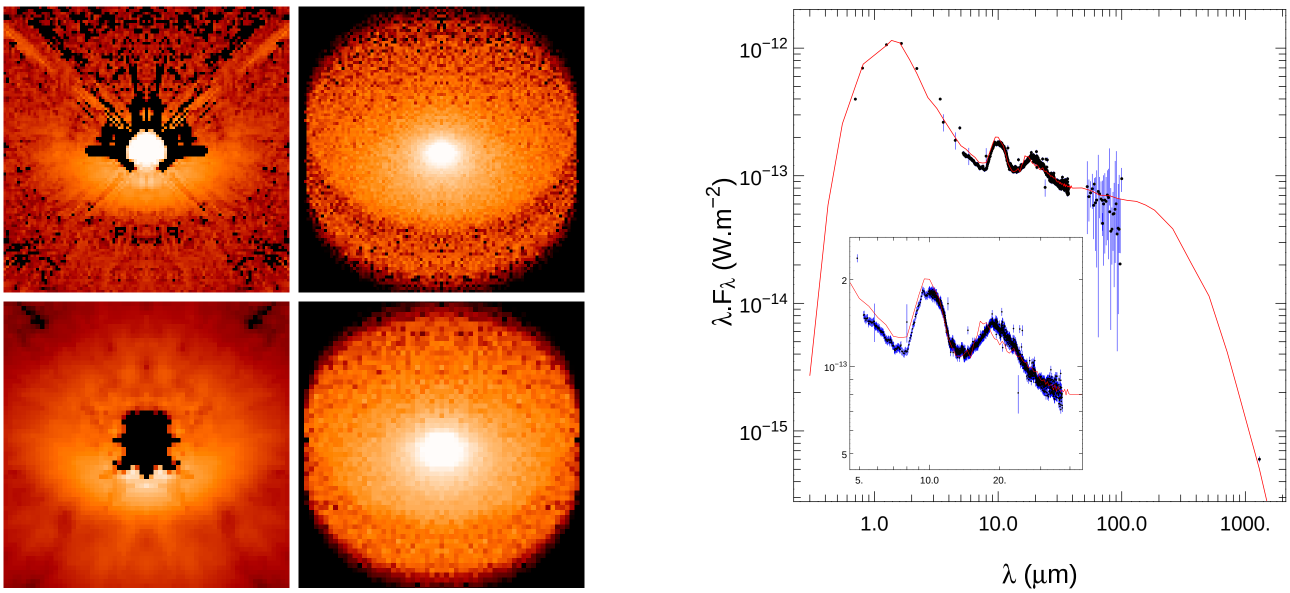

Fig. 3. Comparison of the best model with observations. Observed images were symmetrized to increase S/N and remove diffraction patterns. Synthetic images are presented without convolution. Amorphous olivine dust was used.

A Bayesian analysis was performed to determine the range of validity of each model parameter (Fig. 4). The method shows the complementarity between information extracted from SED and images and allows to quantitatively constrain model parameters and, in particular, to exclude models without dust settling.

4 Conclusion

We presented multi-wavelength studies of two circumstellar disks. In both cases, we reproduce most of the observables using a single model with simple assumptions : a disk described by power-laws from the inner rim to outer regions and spherical and homogeneous dust grains. Combining all these observations enables us to draw strong constraints on model parameters and to derive the first direct (*i.e.* using N_H rather than N_{CO}) measurement of the gas-to-dust ratio in a protoplanetary disk and new evidence of dust settling. Such a global approach is needed to fully exploit present observational data sets and to prepare observations with future instruments like VLT/SPHERE (former Planet Finder), Herschel and ALMA.

References

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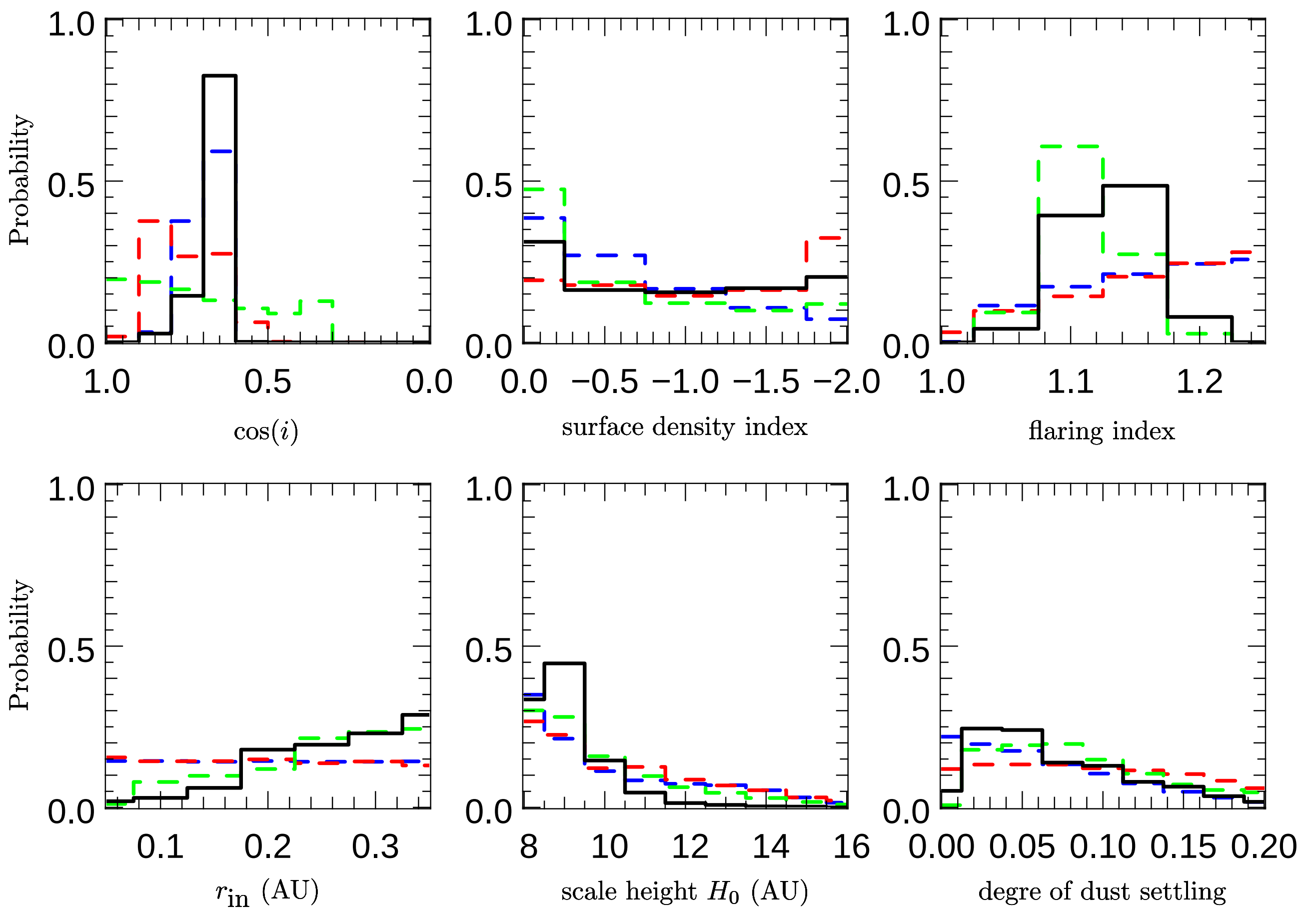

Fig. 4. Bayesian analysis. Probabilities that parameters take a certain value, for a fit of the SED only (green line), of the 0.606 μm image only (blue line), of the 1.6 μm image only (red line), of the SED and images simultaneously (black line).