Radiative transfer models of protoplanetary disks: Theory vs. observations

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Appendices
3.A VISIR imaging

3.A.1 VISIR observations

During the night of March 26 2005, Q-band imaging was performed using the VLT Imager and Spectrometer for the mid-IR (VISIR, Lagage et al. 2004). For photometric calibration and PSF determination, the standard stars HD 50310 and HD 150798 were observed before and after the science observation respectively. Standard chopping and nodding was employed to remove the atmospheric background emission. The imaging was performed with the Q2 filter ($\lambda_c = 18.72 \mu m$) in the small field mode (pixel field of view = $0.075''$). The observing conditions were fair, airmass $\sim 1.4$, and the optical seeing $\sim 0.8''$. The achieved sensitivity was 80 before and $\sim 100$ mJy/10$\sigma$1h after the science observation. The full width at half maximum (FWHM) of the point spread function (PSF) was $\sim 0.5''$. The data reduction was performed with a dedicated pipeline, which corrects for various instrumental signatures (see Pantin et al. 2008, 2009; Pantin 2010). The reduced image is presented in figure 3.10.

3.A.2 Image analysis

The VISIR image (fig 3.10) shows a resolved disk that is almost completely spherical, consistent with previous imaging at this wavelength (Liu et al. 2003). Deviations from spherical symmetry are down to the 10 % level, which means that inclination...
must be small. Due to the relatively large size of the PSF at this wavelengths, it is difficult to get a direct constraint on the inclination out of the image. Comparison with a set of inclined, PSF-convolved model images show that it is consistent with an inclination less than \( \sim 40 \) degrees and a position angle along the South-East to North-West.

Due to the increased sensitivity with respect to previous observations, the image shows resolved emission up to \( \sim 1.4'' \), corresponding to a physical radius of 145 AU at 103 pc. To characterize this emission, we construct a surface brightness profile. Because the disk is not seen face-on, we construct the surface brightness profile from the image by averaging the surface brightness over an elliptical annulus – rather than a circular one. The shape of the annuli correspond to a disk inclination of 42° and a position angle of 145°. The semi-major axis of this ellipse corresponds to the distance from the star at which the radiation is emitted (radius). Annuli are 0.075'' wide, the size of one pixel on the VISIR chip. They are thus much smaller than the width of the VISIR PSF.

Comparing the measured radial intensity profiles to that of the VISIR PSF\(^8\) (Fig 3.11), we see that the disk is clearly resolved. The profile itself is not easily characterized by simple power-laws as is often the case for scattered light images, due to the different emission mechanism (thermal versus scattered light) as well the relatively large size of the PSF.

Instead, we recognize two components. The profile up to 0.5'' is well described by a Gaussian with a FWHM of 0.73''. After quadratic subtraction of the PSF, we derive a spatial scale of 0.33'' for this central component, corresponding to a physical scale of FWHM = 34 AU at a distance of 103 pc. This number agrees well with the value of 34 ± 2 found by Liu et al. (2003) with direct imaging at the same wavelength. This component therefore originates in a region just behind the disk wall, which has a spatial scale of \( \sim 26 \) AU.

The second component – outside of 0.5'' – comes from farther out in the disk, and has not been analysed before at this wavelength. Extended emission is seen up to 1.4'', corresponding to a physical radius of 145 AU at 103 pc. This emission probes the thermal continuum emission from the outer disk surface. The bump around 1.0'' corresponds to the first diffraction ring in the VISIR PSF, and does not represent a real structure in the disk. Because the radial profile traces the disk surface over almost an order of magnitude in radius, we can use it to put limits on the surface density of small grains, which we will do in the next section.

\(^8\)To be consistent, the plotted surface brightness profile of the PSF is also calculated using an elliptical annulus even though it is spherical, and its FWHM in the plot is larger than the 0.5'' previously quoted.
3.B Continuum subtraction

To measure feature strengths and compare continuum subtracted spectra, we have to fit and subtract the continuum from both our model spectra and data. An example for model R20 is shown in figure 3.12, for the Spitzer spectrum in figure 3.13.

3.A.3 Limits on the surface density distribution of small grains

To test if the assumed power law index of $p = 1$ for the surface density profile matches our VISIR image, we compare model images of varying SDP with the observed image, keeping the dust mass and outer radius fixed, as well as the inner disk surface density. Because the pixel size is much smaller than the VISIR PSF, we convolve it with our model images before constructing the radial intensity profiles, and take into account the errors on the width of PSF (FWHM = 0.509±0.008") in the fitting procedure.

Because we solve for the hydrostatic disk structure, the shape of the radial profile depends only on the surface density distribution (Figure 3.11). The model is best fit for a surface density power law with index $p = 1.1^{+0.4}_{-0.5}$.

3.B Continuum subtraction

Figure 3.11: Radial emission profiles in the Q band at 18.7 µm, calculated assuming elliptic annuli (see text for details). Displayed are: VISIR image (diamonds) and reference PSF (grey line). The errors on the PSF are displayed as horizontal error bars, those on the noise as vertical ones. Overplotted are PSF-convolved disk models with a varying surface density power law of $p = 0.0$, 1.0 and 2.0 (dotted, solid and dashed respectively). NOTE: radius refers to the semi-major axis of the ellipse, which reflects the physical radius where the radiation is emitted.
Figure 3.12: Example of continuum subtraction, for model R20. The top panel shows the model spectra (black line) and calculated continuum (grey line). The bottom panel shows the continuum subtracted spectra, with the same color-coding.

We are interested in the narrow emission features of forsterite (a crystalline silicate) which are superimposed on much broader features from amorphous silicates, that occupy the same wavelength region – except for the 69 µm feature. The continuum – that includes these broad features – is therefore not easily described by a low-order polynomial.

The continuum is better fit using a spline function, which is essentially a piecewise polynomial between (arbitrary) continuum points – or knots. At every knot, the polynomials are connected such that they have a continuous derivative. The best result is obtained when knots are placed just outside the features, and the knots (‘continuum points’) between features are spaced by a distance roughly equal to the feature width.

The fitted spline follows the shape of the continuum outside the features very well. Inside the features, the continuum is smooth, but has more structure than to be expected from the opacities of amorphous silicates only. Especially the bumps at 12, 27 and 32 µm are artifacts from the continuum subtraction, and not from the underlying amorphous silicate features. They arise because the opacity of forsterite between features is not always zero, especially between the big features and the little ‘wings’ at 11, 24/28 and 33 µm. These wings are much weaker or not seen in the Spitzer observations (Fig. 3.4), and do appear much weaker in other forsterite opacities (Servoin & Piriou 1973).

When comparing the model to the data, we therefore want to exclude these wings,
and choose our knots between feature and wings. Although the resulting continuum is not completely smooth – which systematically underestimates the integrated flux – we apply the same continuum subtraction to the observations. This cancels out the systematic error, allowing for a comparison of the shape of the feature, without a systematic error from the wings – which is not in the data. For the 33 µm feature, there is the additional complication that the Spitzer spectrum runs only up to 36.9 µm, and it is not possible to choose a continuum point outside the little wing. We therefore force the tangent at this point to zero to get a reasonable continuum, although this makes the 33 µm flux appear a little stronger than it really is.

3.C Implementation of temperature-dependent opacities

When we implement temperature-dependent opacities into the radiative transfer code, we have to take into account that the opacities that set the temperature depend on that same temperature\(^9\). We therefore recalculate the opacities at every iteration of the hydrostatic vertical structure loop, to keep the solution selfconsistent.

Optical constants for forsterite have been measured at temperatures of \(T_i = 50\),

\(^9\) Although in the case of forsterite, the changes in the opacities are too small to have a major influence on the disk structure
Temperature dependent forsterite opacity around 69 µm, calculated for the dust grains used in this paper. 

100, 150, 200 and 295 K (Suto et al. 2006) for iron free forsterite (Mg$_2$SiO$_4$), but no published measurements exist for crystalline olivines with small iron contaminations (Fe$_x$Mg$_{2-x}$SiO$_4$). For temperatures between 50 and 295 K, we calculate the opacity from the optical constants for every temperature component separately, and combine them using a linear interpolation. The opacity at temperature $T$ is calculated as:

$$
\kappa(T) = \left( \frac{T_{i+1} - T}{T_{i+1} - T_i} \right) \kappa_i + \left( \frac{T - T_i}{T_{i+1} - T_i} \right) \kappa_{i+1} \tag{3.1}
$$

where $\kappa_i$ is the opacity at temperature $T_i$, and $T$ is between $T_i$ and $T_{i+1}$. Below $T = 50$ K, we use the opacities of 50 K forsterite, and we use the 295 K opacity above a temperature of 295 K. This approach does not take into account the shift in wavelength that might occur outside the 50-295 K range. However the peak shift becomes smaller at lower temperatures (Suto et al. 2006) and is not so important below 50 K. Temperatures above 295 K are not present in the SED due to the disk gap, except in the inner disk which is does not contribute significantly at 69 µm because it is much hotter.