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On the validity of grey radiation transfer in dusty envelopes

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Abstract. Radiative transfer calculations in dusty protostellar envelopes have been performed to test the validity of the grey approximation which is often used in radiation hydrodynamic calculations. In the spherical symmetric (1D) case we compare grey calculations with the frequency dependent exact solution of radiation transport. In the 2D case we use the flux-limited diffusion approximation to solve the radiation transport equation in grey and frequency dependent form. In all cases the dust temperature distributions are determined self-consistently.

Model envelopes are considered with a density peaked structure $\rho \propto r^{-\alpha}$ and with different total optical depths in the 1D case. In the 2D case we use the density distributions of various disk models. A dust model consisting of amorphous carbon and silicate grains, partially coated with "dirty ice", is assumed. We find that the dust temperatures are generally underestimated in the grey approximation (by factors up to three) and that the radiative acceleration can be underestimated by orders of magnitude. The importance of efficient but more accurate algorithms than the usual grey approximation is stressed.

Key words: radiation transfer – stars: circumstellar matter – stars: formation of

1. Introduction

Multiple-dimensional simulations of the collapse and subsequent evolution of molecular clumps are performed in order to understand the sequence of events leading to the formation of stars. In these calculations the hydrodynamic equations have to be solved simultaneously with radiation transfer (see e.g. Shu et al. 1993; Tscharnuter & Boss 1993 for recent reviews). At present radiation-hydrodynamic calculations are only possible with drastical simplifications of the radiation transfer.

Grey radiation transfer is an approximation widely used in radiation-hydrodynamics (e.g. Morfill et al. 1985; Tscharnuter & Boss 1993; Boss 1993; Yorke et al. 1993). This approximation is valid as long as the optical depths are very large. Since every protostellar cloud or envelope has regions (at least the outer parts) which are optically thin, serious errors could be introduced when using the grey approximation.

In this paper we wish to test the validity of the grey approximation for dusty envelopes. We thus compare two quantities necessary for the hydrodynamic evolution of molecular clumps, the dust temperature and the radiative acceleration obtained in grey calculations to those found in frequency dependent calculations.

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2. The numerical problem

We consider the transfer of radiation in a dusty circumstellar envelope that is heated internally by a central source and at the same time is embedded in an external radiation field. A more general treatment can be found e.g. in Mihalas (1978).

The intensity $I_\nu(\boldsymbol{x}, \hat{\mathbf{s}})\,\mathrm{d}\nu$ is the flux of radiation energy at the point $\boldsymbol{x}$ in the frequency interval $[\nu,\ \nu + \mathrm{d}\nu]$ into the direction $\hat{\mathbf{s}}$. In the time-independent case the intensity is a function of 6 variables,

$$I_\nu(\boldsymbol{x}, \hat{\mathbf{s}}) = I_\nu(r, \theta, \phi, \theta', \phi')$$

given here in spherical coordinates. The radiation field can also be described by its moments. The zeroth moment J_ν and the first moment $\mathbf{H}_\nu$ of the radiation field are defined as

$$J_\nu := \frac{1}{4\pi} \int_{4\pi} I_\nu \,\mathrm{d}\Omega \quad \text{and} \quad \mathbf{H}_\nu := \frac{1}{4\pi} \int_{4\pi} I_\nu \,\hat{\mathbf{s}}\,\mathrm{d}\Omega$$

The zeroth moment is proportional to the energy density of the radiation field $u_\nu = 4\pi\, J_\nu / c$ and the first moment is proportional to the energy flux $\mathbf{F}_\nu = 4\pi \mathbf{H}_\nu$.

The radiation transfer equation describes the change of the intensity along direction $\hat{\mathbf{s}}$,

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\,\sigma_\nu^{\mathrm{ext}} \left[I_\nu(\boldsymbol{x}, \hat{\mathbf{s}}) - S_\nu(\boldsymbol{x}, \hat{\mathbf{s}}) \right] \tag{1}$$

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where the source function in a multi-component medium is given by

$$S_\nu = \frac{\sigma_\nu^{\rm sca} J_\nu + \sum_i \sigma_{\nu,i}^{\rm abs} B_\nu(T_i)}{\sigma_\nu^{\rm ext}} \tag{2}$$

Here $\sigma_{\nu,i}^{\rm ext}$, $\sigma_{\nu,i}^{\rm abs}$ and $\sigma_{\nu,i}^{\rm sca}$ are the extinction, absorption and scattering coefficients, respectively, for the component i at temperature T_i. We have assumed isotropic scattering and emission of thermal radiation. Note that

$$\sigma_{\nu,i}^{\rm ext} = \sigma_{\nu,i}^{\rm abs} + \sigma_{\nu,i}^{\rm sca}$$

and

$$\sigma_\nu^{\rm sca} = \sum_i \sigma_{\nu,i}^{\rm sca} \quad , \qquad \sigma_\nu^{\rm ext} = \sum_i \sigma_{\nu,i}^{\rm ext}$$

In the optical and infrared continuum the opacity of the dusty envelope is dominated by the dust. Neglecting the effects of ionizing radiation on the gas, the temperature of a dust grain can be calculated by equating the power absorbed by the grain from the radiation field and the power emitted by the grain as thermal radiation:

$$\int_0^\infty \sigma_{\nu,i}^{\rm abs} J_\nu \, {\rm d}\nu = \int_0^\infty \sigma_{\nu,i}^{\rm abs} B_\nu(T_i) \, {\rm d}\nu \tag{3}$$

Integrating the radiation transfer equation (1) over the full solid angle one gets the zeroth momentum equation

$$\nabla \cdot \mathbf{H}_\nu + \sigma_\nu^{\rm abs} J_\nu - \sum_i \sigma_{\nu,i}^{\rm abs} B_\nu(T_i) = 0 \tag{4}$$

Note that by integrating equation (4) over all frequencies and using relation (3) we obtain $\nabla \cdot \mathbf{H} = 0$, i.e. we have no sources or sinks of radiative energy within the inner and outer boundary of the envelope.

As boundary conditions we specify I_ν at an inner (outer) sphere of radius $R_{\rm star}$ ($r_{\rm out}$) for all outward (inner) directed lines of sight

$$I_\nu(R_{\rm star}, \theta, \phi, \mathbf{s}^+) = B_\nu(T_{\rm eff})$$

$$I_\nu(r_{\rm out}, \theta, \phi, \mathbf{s}^-) = W \; B_\nu(T_{\rm out})$$

where $T_{\rm eff}$ and $R_{\rm star}$ describe the temperature and radius of the embedded black-body source, and $T_{\rm out}$ and W the radiation temperature and dilution factor of the isotropic external radiation field, respectively. $\mathbf{s}^+$ denotes the outward directed lines of sight with $\cos\theta' \geq 0$, $\mathbf{s}^-$ the inward directed lines of sight with $\cos\theta' \leq 0$ (a detailed description can be found in Yorke 1980b).

3. Solution of the radiation transfer problem

The numerical solution of radiation transfer is generally a major computational effort. Since the time-independent intensity is a function of 6 independent variables, one would have to compute about 10^{12} intensity values, assuming a numerical resolution of 100 grid points for each variable. Obviously simplifications have to be made, especially when time-dependent calculations are made. For example, axially or spherically symmetric geometries are usually considered, an approximation to the radiation transfer equation is used, and/or the equations in their frequency independent (grey) form are considered.

3.1. Exact solutions

To get an exact solution the frequency dependent radiation transfer equation has to be solved simultaneously with a self-consistent determination of the dust temperatures. Up to now, an exact solution of the radiation transfer problem is only practical in spherical symmetry, where the number of variables is reduced to 3: $I_\nu(\boldsymbol{x}, \hat{\mathbf{s}}) = I_\nu(r, \theta')$. Efstathiou & Rowan-Robinson (1990) describe an exact code for solving the radiation transfer problem in axial symmetry, but their numerical resolution is extremely low and the computational effort seems to be huge, since only a few calculations with this code have been published. Steiner et al. (1994) solve the exact grey 2D radiation transfer problem simultaneously with MHD. Their low angular resolution makes the application of their code to dusty envelopes, where optical depths are not extremely large, impractical. In any case the validity of the grey approximation needs to be tested.

3.2. The flux-limited diffusion approximation

In many multiple-dimension radiation-hydrodynamic calculations the flux-limited diffusion (FLD) approximation is used. It is based on a relation between the radiation flux and the radiation energy density:

$$\mathbf{H}_\nu = -\frac{1}{\omega_\nu \sigma_\nu^{\rm ext}} \lambda_\nu(R) \nabla J_\nu \tag{5}$$

λ_ν is the so called flux-limiter, ω_ν the effective albedo. They are defined as

$$\lambda_\nu(R) = \frac{1}{R}\left(\coth R - \frac{1}{R}\right), \qquad \mathbf{R} = -\frac{\nabla J_\nu}{\omega_\nu \sigma_\nu^{\rm ext} J_\nu}$$

$$\omega_\nu = \frac{\sigma_\nu^{\rm sca} J_\nu + \sum_i \sigma_{\nu,i}^{\rm abs} B_\nu(T_i)}{\sigma_\nu^{\rm ext} J}$$

Levermore & Pomraning (1981) could show that with this choice of λ_ν Eq. (5) is valid in the optical thin as well as in the optical thick limit and is a reasonable approximation between these limits.

Combining Eq. (5) with the zeroth momentum equation (4), we obtain

$$\nabla \frac{1}{\omega_\nu \sigma_\nu^{\rm ext}} \lambda_\nu(R) \nabla J_\nu = \sigma_\nu^{\rm abs} J_\nu - \sum_i \sigma_{\nu,i}^{\rm abs} B_\nu(T_i)$$

So one only has to solve for J_ν, a function of at most 4 variables.

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3.3. The grey approximation

The grey approximation is widely used in radiation transfer to reduce the computational effort. It uses the same equations as above, but now in frequency integrated form:

$$I_\nu \longrightarrow I := \int_0^\infty I_\nu \, \mathrm{d}\nu$$

and accordingly for J and $\mathbf{H}$. The Planck-mean

$$\sigma_B := \left(\int_0^\infty \sigma_\nu^{\mathrm{abs}} B_\nu \, \mathrm{d}\nu \right) \Big/ \left(\int_0^\infty B_\nu \, \mathrm{d}\nu \right) \quad (6)$$

is used instead of $\sigma_\nu^{\mathrm{abs}}$ and the Rosseland-mean

$$\frac{1}{\sigma_R} := \left(\int_0^\infty \frac{1}{\sigma_\nu^{\mathrm{ext}}} \frac{\mathrm{d}B_\nu}{\mathrm{d}T} \, \mathrm{d}\nu \right) \Big/ \left(\int_0^\infty \frac{\mathrm{d}B_\nu}{\mathrm{d}T} \, \mathrm{d}\nu \right) \quad (7)$$

instead of $\sigma_\nu^{\mathrm{ext}}$.

Substituting σ_B into Eq. (3) yields for each dust component i

$$T_i = T_{\mathrm{rad}} = \left(\frac{\pi}{\sigma_{SB}} J \right)^{1/4}$$

where T_{rad} is the radiation temperature and σ_{SB} is the Stefan-Boltzmann constant. This is a good approximation in the limit of high optical depth, because the energy density distribution approaches a blackbody spectrum in this limit: $J_\nu \longrightarrow B_\nu(T_{\mathrm{rad}})$. However, every dusty envelope has regions where it is optically thin, at least in the outer parts. This approximation consequently leads to considerable errors in the dust temperature, as will be shown below.

The computational effort is greatly reduced with this approximation: First, radiative transfer needs to calculated only once and not for each frequency, second, the dust temperature needs not to be computed from solving Eq. (3), but can be directly found from J.

4. The dust model

We use the dust model of Preibisch et al. (1993). This model was constructed to match the dust properties in dense molecular clouds. It consists of small amorphous carbon (aC) grains and large silicate grains, and it assumes that the silicate grains are coated with a mantle of dirty ice if their temperature is below 125 K. For the radii a_i of the grains a power law distribution of the form

$$n(a) \propto a^{-3.5} \quad \text{for} \quad a_{i,min} \leq a \leq a_{i,max}$$

is assumed. This is similar to the distribution used by Mathis et al. (1977), but we used different limits: For the aC grains the size distribution extends from 7 nm to 30 nm, for the silicate grains from 40 nm to 1 μm. The silicate grains are coated with "dirty ice", if their temperature is below 125 K. These coated grains will be denoted *core-mantle-particles* (CMP). We do not assume ice coatings on the aC grains since they are so small that temperature spikes produced by single photon absorption or cosmic rays can prevent the formation of ice mantles (Yorke 1985).

Our dirty ice model assumes a mixture of H_2O- and NH_3-ice with a volume ratio of 3:1 that is polluted with amorphous carbon. All mantles sublimate at CMP temperatures above 125 K, transforming the CMP particle to a bare silicate core and a number of aC grains which conserves the total number of C atoms. Here we use the model for which the mantle thickness is 1.145 times the core radius, giving an ice to silicate volume ratio of 0.5. The ice is polluted with 10 Vol-% amorphous carbon.

As sublimation temperatures of the individual dust components we used the values $T_{\mathrm{sub}}^{\mathrm{aC}} = 2000$ K, $T_{\mathrm{sub}}^{\mathrm{Sil}} = 1500$ K and $T_{\mathrm{sub}}^{\mathrm{CMP}} = 125$ K. A detailed description of the dust model and plots of the opacity of the dust components and Rosseland and Planck means can be found in Preibisch et al. (1993).

5. Radiation transfer calculations

5.1. Spherical symmetric calculations

For the spherical symmetric calculations we used an exact program and a program that solves the grey radiation transport equation.

5.1.1. Exact solution

For the exact solution the radiation transfer calculations were carried out with a modified version of the code (without hydrodynamics) described in Yorke (1980a,b). One has to specify the luminosity and the effective temperature of the central source, the density distribution including the outer radius of the shell, the total mass of the envelope and the temperature and frequency dependent absorption and scattering gram opacity of the dust.

Because of the large variation of the scales, we used a logarithmically equidistant distribution of 120 radial grid points. The temperature dependence of the opacity is given by the sublimation temperatures of the grains. The destruction of the grains through sublimation is simulated by setting the number density of the grains to zero, if the temperature of a particular grain component calculated simultaneously with the radiation field is above the sublimation temperature. So the inner boundary radius of the dust shell is given by the smallest sublimation radius of the dust components.

The density of the envelope can be characterized by the total optical depth at a certain wavelength. Here we choose the value at 200 μm, τ_{200}. We assume a protostar with a luminosity of 5 $L_\odot$ and an effective temperature of 4800 K. This protostar is embedded in a dusty envelope with a density distribution given by $\rho \propto r^{-\alpha}$ that extends to $10^{16.5}$ cm = 2122 AU. The inner boundary radius of the dust shell is equal to the sublimation radius of the aC grains at $\approx 10^{12.2}$ cm. To calculate the values of the flux density, a distance of the source of 150 pc is assumed, typical for the nearest molecular clouds.

We have calculated models with $\alpha = 1$ and $\alpha = 2$, each for four total optical depths, $\tau_{200} = 0.001$, $\tau_{200} = 0.01$, $\tau_{200} = 0.1$

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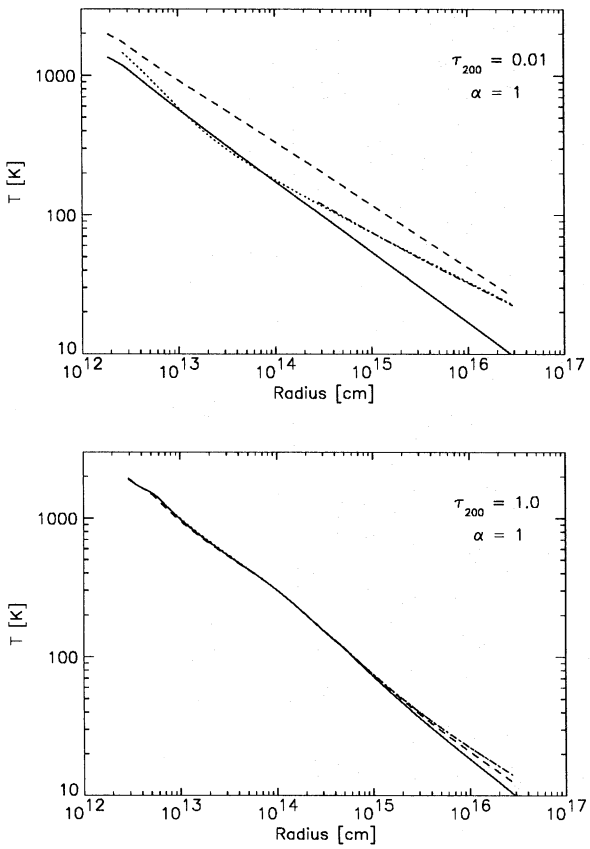

Fig. 1. Temperature distributions for the individual dust components (aC: dashed line, Silicate: dotted line, CMP: dashed-dotted line) and the radiation temperature (solid line) obtained from the exact solution

and $\tau_{200} = 1.0$. The corresponding optical depths in the visible region (0.55 μm) range from 2.5 to 2520. In Fig. 1 we show the temperature distribution for all three dust components for $\alpha = 1$ models with $\tau_{200} = 0.01$ and $\tau_{200} = 1.0$. Note that here and in the following figures we only show the average temperature for the grain size distribution of each dust component. Preibisch (1992) could show that the differences in the temperatures of grains with different radii are very small and do not affect the results of our calculations. We have also plotted the radiation temperature (solid line in Fig. 1). In the $\tau_{200} = 0.01$ envelope the temperatures of the individual dust components are considerably different and higher than the radiation temperature. In the $\tau_{200} = 1.0$ envelope there are nearly no differences between the temperatures.

5.1.2. Grey solution

Now we want to see what errors are introduced, if one uses grey radiation transport in comparison to the frequency dependent calculation. From the exact code of Yorke a program was developed, which solves the grey radiation transport equation. With this program we calculated the same envelope models as with the exact program. We will compare the temperature and radiative acceleration of the aC grains obtained from the exact and the grey program. Instead of the radiative acceleration itself, we use the quantity

$$\kappa_{H,aC} := \frac{1}{\rho H} \int_0^\infty \sigma^{\rm ext}_{\nu,aC} H_\nu \, {\rm d}\nu$$

which is proportional to the radiative acceleration of aC grains (Yorke 1985).

Table 1. Deviations in the spherical symmetric calculations

τ_{200}	α	$< F_T >$	$< F_\kappa >$	α	$< F_T >$	$< F_\kappa >$
0.001	1	0.32	0.0017	2	0.36	0.0024
0.01	1	0.48	0.019	2	0.54	0.021
0.1	1	0.76	0.20	2	0.69	0.082
1.0	1	0.87	0.36	2	0.83	0.20

The results of this comparison are shown in Fig. 2 for selected models. The dust temperatures and κ_H determined in the grey calculation are considerably too low in comparison with those obtained in the exact calculation. The dust temperatures are similar to the radiation temperature found in the exact calculations. To have a quantitative estimate of the deviations, we have calculated the mean values of $F_T = T_{aC,\rm grey}/T_{aC,\rm exact}$ and $F_\kappa = \kappa_{H,aC,\rm grey}/\kappa_{H,aC,\rm exact}$ over all grid points. In Table 1 these values are give for all models considered. One can see that the grey temperatures are too low by a factor up to 3. Even in the densest envelope the error is not below $\approx 15\%$.

Considering κ_H, the errors are even larger: They are more than three orders of magnitude in the outer parts of the optically thin envelopes. The smallest deviation is found in the model with $\alpha = 1$ and $\tau_{200} = 1.0$, but even here the grey radiative acceleration is underestimated by a factor of ≈ 2.7.

5.2. Axial symmetric calculations

The 2D calculations were performed with a program described in Sonnhalter, Preibisch & Yorke (1995; hereafter SPY), which solves the zeroth moment equation in the approximation of the flux-limited diffusion (4) and an equivalent grey code. Here we consider a disk that is embedded in a spherical halo with cavities along the rotational axis z. We use four of the disk density distributions investigated by SPY, where a detailed description can be found:

- The density distribution of a self-gravitating disk.

  $\rho_{\rm disk} = \rho_0 \left(\frac{r_0}{r}\right)^\gamma \exp\left(-\frac{zr}{h}\right)$

  with $\gamma = 2$ (model d1 in SPY) and $\gamma = 0$ (model d3 in SPY).

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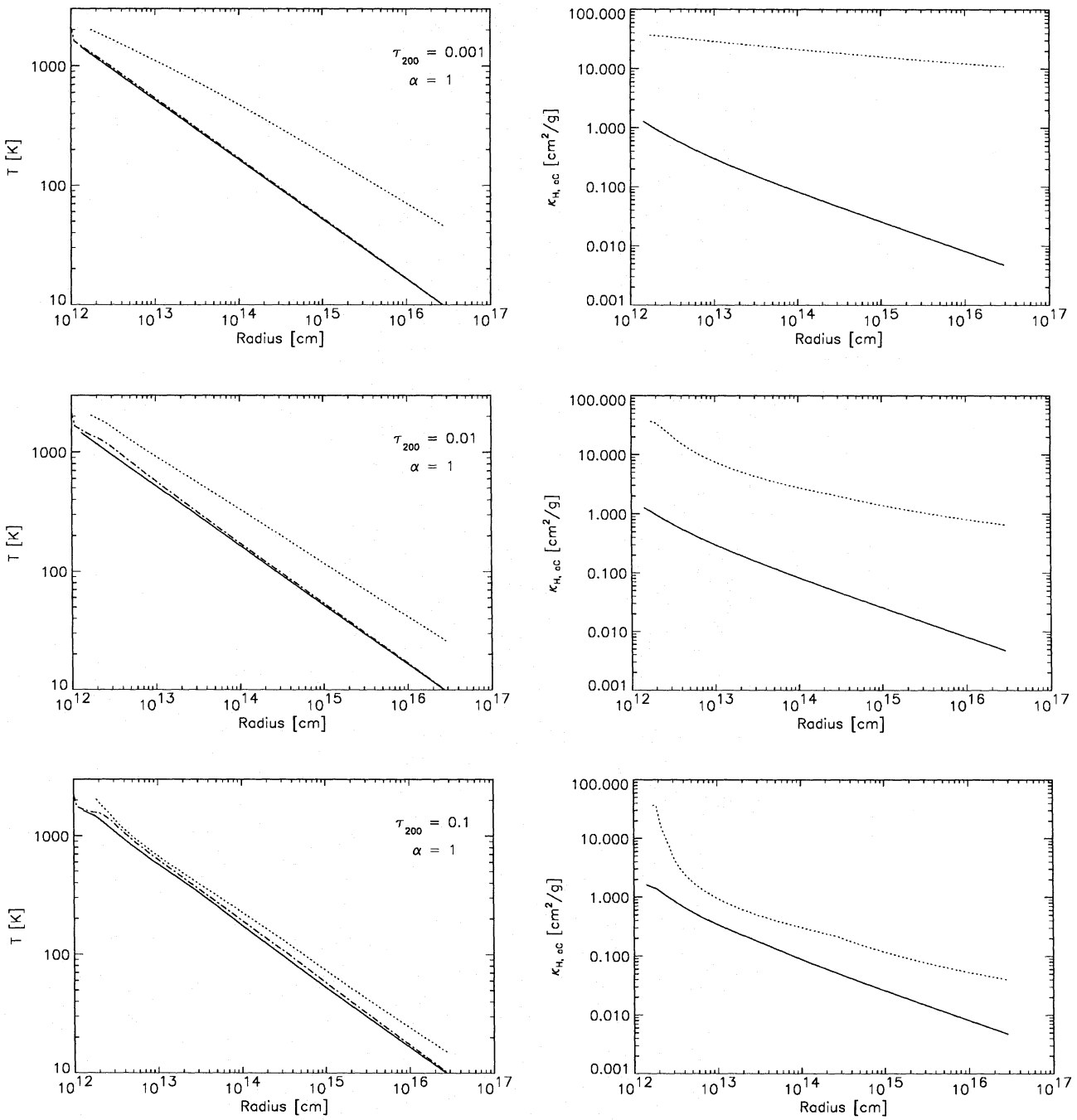

Fig. 2. Results from the grey calculations (solid lines) compared to those of the exact calculations (dotted lines) for selected 1D model envelopes. Left side: Temperatures of the aC grains; the radiation temperatures are shown in the dashed-dotted lines. Right side: $\kappa_{H,aC}$, a quantity proportional to the radiative acceleration of the aC grains (see text)

- The density of an infinite isothermal slab, which is often used in simple model calculations to approximate the disk around a young stellar object (model d4 in SPY).

$$\rho_{\rm disk} = \rho_0 \exp\left(-\frac{z}{z_0}\right)$$

- A model density for an Keplerian disk (model d5 in SPY).

$$\rho_{\rm disk} = \rho_o \left(\frac{r_0}{r}\right)^{15/8} \exp\left(-\frac{\pi}{4}\left(\frac{z}{z_0}\right)^2 \left(\frac{r_0}{r}\right)^{9/4}\right)$$

As an example of the temperature deviations which occur between the grey and frequency dependent cases we display the temperature distribution of the aC grains and the grey temperature in Fig. 3. In these plots a plane perpendicular to the disk plane is selected. The density distribution in this plane is shown in the grey scale background, the temperature distribution is shown as isothermal contour lines.

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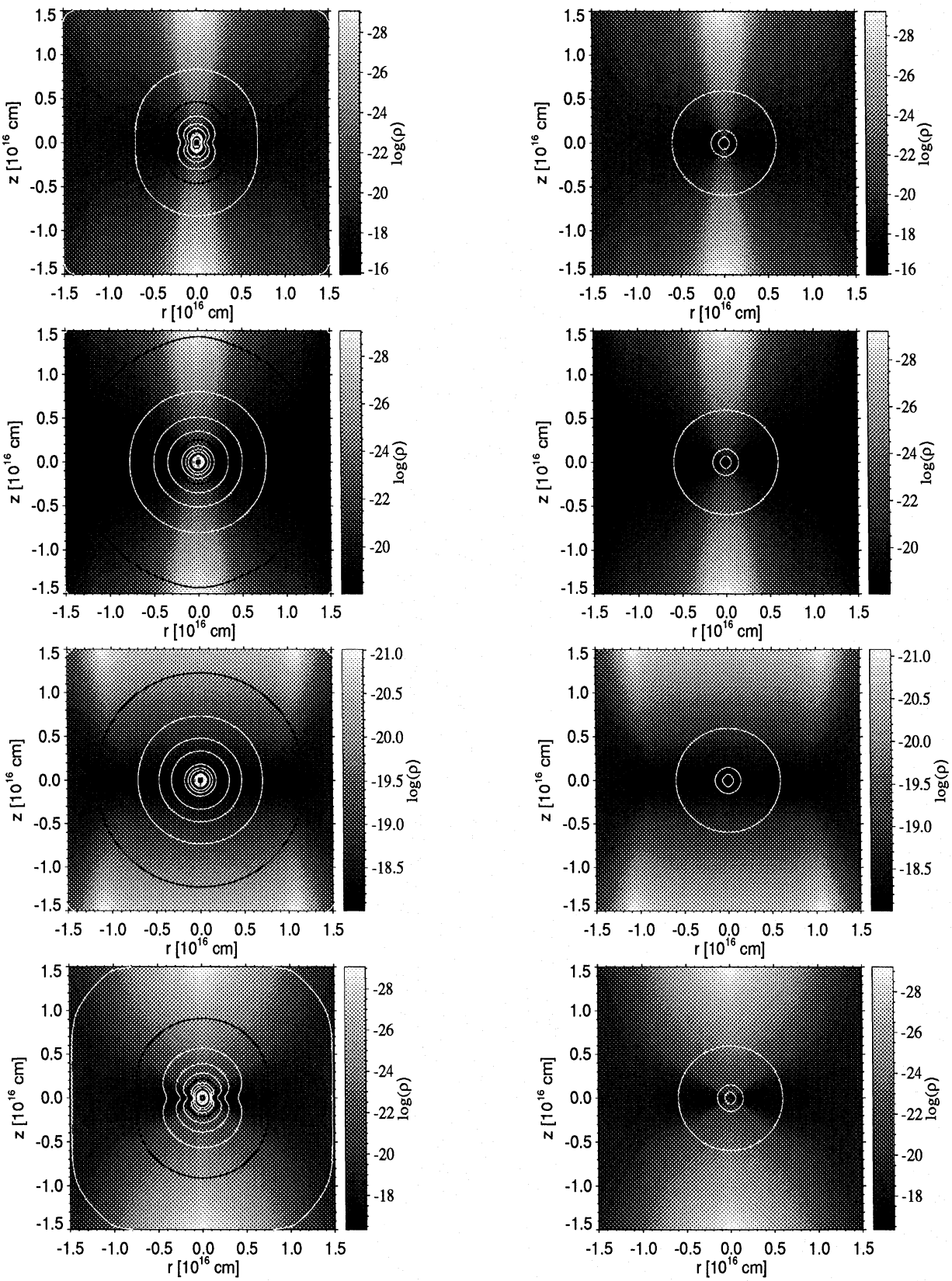

Fig. 3. Results from the frequency dependent FLD calculations (left side) compared to those of the grey FLD calculations (right side) for SPY's disks 1,3,4 and 5 (from top to bottom). The assumed density distribution is shown in the grey scale background and the temperature distribution as a series of contour line overlays. The outermost black contours correspond to 100 K (left) and 25 K (right). The distance between the temperature contours is 25 K

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Again, the temperatures are considerably underestimated in the grey approximation. In addition, the shape of the distribution of the radiation temperature is different. Whereas the dust temperatures calculated by the frequency dependent code are influenced by the anisotropic density distribution, the temperature found in the grey calculation is nearly spherically distributed.

6. Conclusions

We have shown that the grey approximation for continuum radiation transfer in dusty circumstellar envelopes can result in considerable errors. The dust temperatures are systematically underestimated. The grey radiative acceleration of dust can be underestimated by up to several orders of magnitude. In 2D calculations the grey temperature distributions are hardly influenced by shape of the density distribution, whereas the true dust temperature distributions are. With the exception of the innermost parts of very dense regions, grey radiative transfer yields neither a good approximation for the temperature range nor for its spatial distribution.

In contrast, the grey radiation density agrees well with the exact values, as can be seen in Fig. 2 by comparing the grey temperature with the radiation temperature. The principal cause of the poor estimate of dust temperatures and radiative acceleration is the implicit assumption of a spectral distribution given locally by an *undiluted* Planck function at $T_{\rm rad}$. In actuality the spectral distribution is shifted significantly to shorter wavelengths and thus is better approximated by a *diluted* radiation field at a higher "color" temperature than $T_{\rm rad}$.

Extreme caution must be applied when using the grey approximation in radiation hydrodynamics, because both pressure effects (via an incorrect determination of temperature) and radiative acceleration are underestimated.

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