Radiative Transfer Simulations of Infrared Dark Clouds

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Abstract. The determination of prestellar core structure is often based on observations of (sub)millimeter dust continuum. However, recently the Spitzer Space Telescope provided us with IR images of many objects not only in emission but also in absorption. We developed a technique to reconstruct the density and temperature distributions of protostellar objects based on radiation transfer (RT) simulations both in mm and IR wavelengths. Best-fit model parameters are obtained with the genetic algorithm. We apply the method to two cores of Infrared Dark Clouds and show that their observations are better reproduced by a model with an embedded heating source despite the lack of 70 μm emission in one of these cores. Thus, the starless nature of massive cores can only be established with the careful case-by-case RT modeling.

Keywords. radiative transfer; ISM: clouds, dust, extinction; methods: data analysis, numerical;

1. Objectives

Parameters of prestellar and protostellar molecular cores are usually derived from millimeter and sub-millimeter observations of their thermal dust emission. However, the interpretation of these observations is ambiguous as the same spectrum can be produced by different density and temperature distributions. In some cases, millimeter continuum data are supplemented by molecular line observations to derive the temperature. But the interpretation of molecular line observations is also not trivial because of the non-LTE conditions of line formation and complex chemical structure of the cores. The Spitzer Space Telescope provided us with infrared images of many dense cores, seen not only in emission but also in absorption. These data can be used to derive the core density and temperature distributions by fitting absorption and emission simultaneously.

We present a framework to reconstruct the density and temperature distributions of protostellar objects based on detailed RT simulations and on the comparison of model intensity distributions with observations both in emission and absorption at mm and IR wavelengths. We apply the method to two Infrared Dark Cloud cores IRDC-320.27+029 (subcore P2) and IRDC-321.73+005 (subcore P2) which are believed to represent the initial stage for the massive star formation (Fig. 1). For brevity, they are further referred to as IRDC 320 and IRDC 321.

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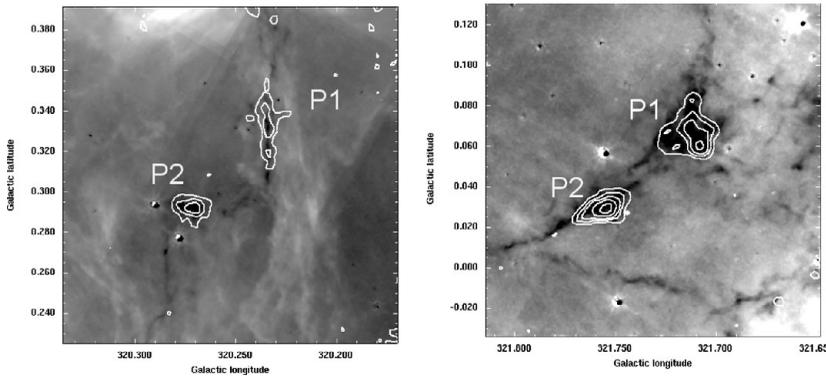
Figure 1. Composite images of dark cores IRDC-320.27+029 and IRDC-321.73+005. The grey map is for 8 μm emission provided by the Spitzer Space Telescope while contours show 1.2 mm emission from the SEST Telescope.
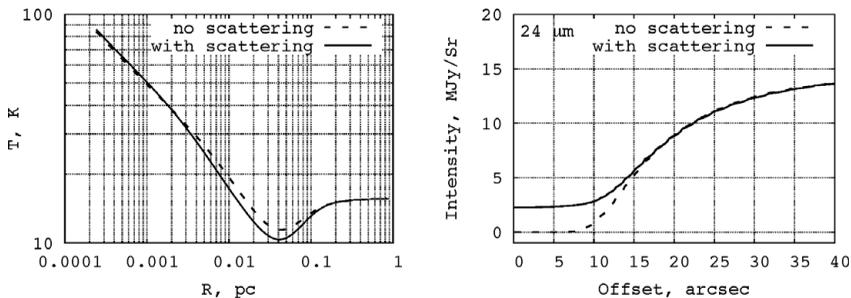
Figure 2. Temperature and intensity distributions for a representative model of a protostellar core. The central heating source is responsible for the inner temperature gradient while the external radiation field heats the envelope. The solid and dashed lines correspond to the models with and without scattering, correspondingly.

2. Model of a protostellar core

We assume that a core is spherically symmetric and its density distribution can be represented by following law, see Tafalla *et al.* (2002):

$$n(\mathrm{H}_2) = \frac{n_0}{1 + (r/r_0)^\beta}, \tag{2.1}$$

where n_0 is the central density, r_0 is the radius of inner plateau, β describes the density decrease in the envelope. We also set the inner core radius of 50 AU and the outer radius of 1 pc. To take into account the possible spread in evolutionary stages, e.g. the presence of a (proto)star, we assume that there is a blackbody source in the core center with the temperature of T_* and radius of 5 $R_\odot$. The core is illuminated by the diffuse interstellar field with the color temperature 10000 K and dilution D_{bg}. This field controls the temperature in the envelope. We also postulate the isotropic infrared background emission for those wavelengths where the comparison with observations has to be made. The intensity of infrared background field is equal to the observed intensity at the edge of the core. Note that it is much stronger than the diluted interstellar field.

Temperature distribution and emergent intensity distribution are found as a result of RT simulation with the NATA(LY) code by Pavlyuchenkov *et al.* (2010) for the given set of parameters. Dust emission, absorption and isotropic scattering are taken into account. The accelerated Λ-iteration method is used where the mean intensity is calculated using
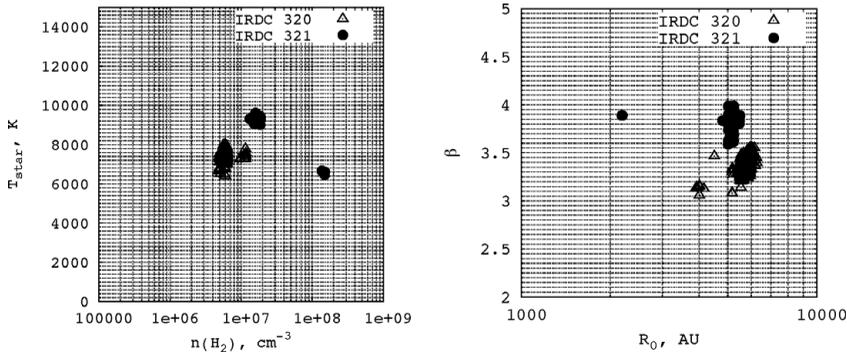
Figure 3. Localization of IRDC 320 and IRDC 321 model parameters with $\chi^2 < 11$ found by PIKAIA code. In the case of IRDC 320 the parameters are well localized while for IRDC 321 there are two groups of parameters with nearly the same χ^2.

the set of selected rays. The frequency dependent dust opacities are calculated from the Mie theory. Temperature and intensity distributions for a representative core model are shown in Fig. 2. Note that scattering does not significantly affect the thermal structure but can strongly affect the emergent intensity distribution.

3. Search for best-fit parameters

For each set of free parameters we perform RT simulations and calculate the model intensity distributions for 1.2 mm, 70 μm, 24 μm, and 8 μm. Then we calculate the χ^2-criterion which characterizes the agreement between the model and observed intensity distributions. Millimeter data are taken from Vasyunina *et al.* (2009). Infrared data are downloaded from NASA/IPAC Infrared Science Archive (http://irsa.ipac.caltech.edu/).

The search for best-fit parameters i.e. the minimization of χ^2 is performed using the genetic code PIKAIA, see Charbonneau (1995). This algorithm allows not only to identify the global minimum of χ^2 in the multi-dimensional parameter space but also to study the degeneracy of the solution. The localization of the optimal parameters (with $\chi^2 < 11$) for IRDC 320 and IRDC 321 in two parameter subspaces is shown in Fig. 3. In Table 1 the best-fit, derived and fixed parameters for the studied cores are shown.

4. Main Results

In general, we achieved a good agreement between synthetic and observed intensity distributions both for IRDC 320 and IRDC 321 (Fig. 4). In the case of IRDC 320 we are able to fit 1.2 mm emission profile and to reproduce the flat intensity distribution at 70 μm and absorption profiles at 24 μm and 8 μm. In the model of IRDC 321 the emission appears not only at 1.2 mm but also at 70 μm in agreement with observations. That is a result of higher central density and higher temperature of the inner heating source.

In both cases our results are consistent with the presence of internal heating sources (proto-stars) in cores' interiors. While for IRDC 321 this assertion seems to be robust as it is seen in emission at 70 μm, for the particular case of IRDC 320 it should only be considered as tentative. In particular, we did not try to distinguish between the foreground and background radiation. Second, available molecular data do not show any typical hot core tracers in this object. So, this case deserves further study, in particular, with chemical models. The important conclusion of this study is that 70 μm band seems to be most promising to discriminate between starless and protostellar massive cores.

Table 1. Best-fit, derived and fixed parameters for template cores

Parameter	Name	IRDC 320	IRDC 321
Varied parameters			
H_2 central density, cm^{-3}	n_0	1.1×10^7	1.8×10^7
Radius of plateau, AU	r_0	4×10^3	5×10^3
Index for envelope	β	3.1	3.8
Star temperature, K	T_*	7300	9300
Dilution of background field	D_{bg}	1.3×10^{-13}	6.7×10^{-14}
Derived parameters			
Cloud mass, $M_\odot$	M	170	230
H_2 surface density, cm^{-2}	N	8.1×10^{23}	1.6×10^{24}
Star luminosity, $L_\odot$	L	60	160
Fixed parameters			
Radius of inner hole	R_{in}	50 AU	
Cloud radius	R_{out}	1 pc	
Star radius	R_*	5 $R_\odot$	
Temperature of background field	T_{bg}	10^4 K	
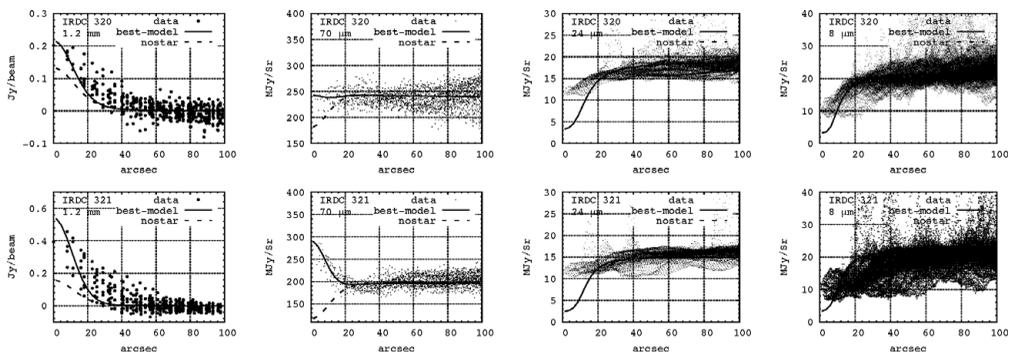
Figure 4. Observed (dots) and modeled (lines) intensity distributions at selected wavelengths for IRDC 320 (top row) and IRDC 321 (bottom row). The model distributions correspond to the model with lowest χ^2. With dashed lines, we show results for the same core model, but without the central heating source. It is noteworthy that not only 70 μm but also millimeter emission is sensitive to the presence of the heating source.

However, observations in this band should not be interpreted without careful modeling to avoid simplified conclusions. In particular, the mere absence of 70 μm emission is not a solid evidence that a core is starless.

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