Modelling of the continuum emission from Class 0 sources

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Abstract. Class 0 sources are objects representing the earliest phase of the protostellar evolution. Since they are highly obscured by an extended dusty envelope, these objects emit mainly in the far-infrared to millimetre wavelength range. The analysis of their spectral energy distributions with wide wavelength coverage allows to determine the bolometric temperature and luminosity. However, a more detailed physical interpretation of the internal physical structure of these objects requires radiative transfer modelling. We present modelling results of spectral energy distributions of a sample of nine Class 0 sources in the Perseus and Orion molecular clouds. The SEDs have been simulated using a radiative transfer code based on the Monte Carlo method. We find that a spherically symmetric model for the youngest Class 0 sources allows to reproduce the observed SEDs reasonably well. From our modelling we derive physical parameters of our sources, such as their mass, density distribution, size, etc. We find a density structure of $\rho \sim r^{-2}$ for the collapsing cores at young ages, evolving to $\rho \sim r^{-3/2}$ at later times.

Key words: Radiative transfer–Stars: formation–dust

1. Introduction

A Class 0 source is an object representing the earliest phase of the protostellar evolution (e.g. André et al. 1993). It consists of a central protostellar object surrounded by an infalling dusty envelope and a flattened accretion disk. Many (presumably all) Class 0 sources are associated with a bipolar molecular outflow. Because of their difficult detection (their photospheres are highly obscured and
the objects spend only a short time ($\sim 10^4$ yr) in this evolutionary phase), and the lack of knowledge in model protostellar parameters (distribution, composition, and size of dust, density, and temperature distribution, etc.), constraining physical properties to Class 0 objects is quite difficult. Continuum sub-mm observations of Class 0 sources, however, let us detect dust emission of the massive circumstellar envelope of these sources. Information from the dust emission, a physical model of the extended envelope as a pre-requisite, and the implementation of techniques like the blackbody and the envelope fitting procedures, open a way to interpret the structure of Class 0 sources.

2. An envelope model

How can we describe the protostellar emission from the envelope? We adopt the standard envelope model (Adams 1991) to keep the problem as simple as possible. The circular symmetry of the observed emission (Rengel et al. 2004a), and the lack of significant internal structure justifies the simplicity of a spherical model case. If the emission is optically thin, the observed intensity for a spherical symmetric protostellar envelope at an impact parameter $b$ is given by Eq. 1 assuming single power-laws of the opacity, the radial temperature and density distribution ($\beta$, $q$, and $p$, respectively).

$$I_{\nu}(b) = 2\kappa_{\nu} \int_{b}^{r_0} B_{\nu}[T_d(r)] \rho(r) \frac{r}{\sqrt{r^2 - b^2}} dr$$  \tag{1}$$

$r_0$ is the outer radius, $\rho$ is the density, $T_d$ the dust temperature, $\kappa_{\nu}$ the opacity of the dust grains, and $B_{\nu}[T_d(r)]$ the Planck function at dust temperature $T_d$. If the emission is in the Rayleigh-Jeans limit and if $r_0 \gg b$, Eq. 1 can be approximated to $I_{\nu}(b)/I_{\nu}(0) = (b/b_0)^{-m}$ (where $m$ is the power-law index of the observed intensity profile, and $b_0$ is the normalization factor to the peak emission).

Results from the standard theory provide the first direct insights into observable estimations. Nevertheless, the temperature profile will diverge from a single power-law $q$ as the envelope becomes optically thick at the primary wavelengths of energy transport (inner portion of the envelope) (e.g. Shirley, Evans & Rawlings 2002). Here it becomes necessary to calculate the temperature distribution self-consistently by implementation of a radiative transfer code. To calculate the observables (temperature and density distributions, and
3. Modeling continuum submillimetre emission

First constrains to physical properties (spectral indices, masses, radial profiles and sizes) of 15 objects are derived from continuum SCUBA imaging of six star formation regions in the Perseus and Orion molecular cloud complexes (Rengel et al. 2004a). Accurate SEDs are computed for nine sources combining existing multi-wavelength surveys with new sub-mm data (Rengel et al. 2004b), and fitting a modified blackbody curve to the fluxes (Froebrich et al. 2003). We derived the bolometric temperature and luminosity, size of the envelope and sub-mm slope for each source. Furthermore, dust temperature distribution, SED, and an intensity map are derived self-consistently by the MC3D code. Physical parameters of the sources (e.g. envelope masses, density distributions, sizes and sublimation radius) were derived by finding the consistency between observed and modelled SEDs.

We created a bolometric luminosity-temperature diagram for
4. Results

In Fig. 1, the calculated temperature profile (left), and the observed and best simulated SEDs for L1448 C are shown as an example. Table 1 lists the characteristics of the best-fitting model parameters. The envelope emission is calculated as an image from the MC3D code, and convolved by the SCUBA beam. The simulated intensity profile is calculated at 850 $\mu$m and compared with the observed profile to test the symmetric model.

Is there a correlation of the power-law index p with time? We plot the estimated values of p as a function of t. Fig. 2 suggests a density structure of $\rho \propto r^{-2}$ at younger ages, evolving to $\rho \propto r^{-3/2}$ at later times. In order to investigate this with a larger spread, a Class 1 sample is mandatory.

5. Conclusions

Detailed physical interpretation of the internal structure of nine objects was carried out with intensive computer modeling. A simple spherically symmetric model envelope, and assumptions about den-
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Density and dust distributions following the standard envelope model reproduce reasonably well the observed SED and the radial profiles of the sources. $T \propto r^{-0.4}$ is a good approximation for the sample. The radial temperature distribution as function of distance, however, departs significantly from the optically-thin assumption, an observational derivation of a single-power law $q$ of 0.4 for radii $\lesssim 10$ AU. Modelling results indicate a density profile well described by a power-law between $p=1.5$ to 2, which is expected by all of the collapse models and numerical studies. A density structure of $\rho \propto r^{-2}$ at younger ages, evolving to $\rho \propto r^{-3/2}$ at later times was found.

SED and radial profile fits can constrain physical parameters of the sources such as envelope masses, density distributions, sizes and sublimation radii. Nevertheless, observations at 10-300 $\mu$m, and the inclusion of outflow and disk, and other geometries will decrease the differences.

Table 1: Best envelope fit results for the embedded sources. The temperature of the central object $T_*$ is set to 3500 K. $\chi^2$ quantifies the agreement between model and data. The age is estimated according to the model of Smith (2000) and given in $10^3$ yrs.

| Object          | $T_{bol}$ [K] | $L_*$ [$L_\odot$] | $R_{sub}$ [AU] | $p$ | $R_{out}$ [AU] | age | $M_{env}$ [$M_\odot$] | $\chi^2$ |
|-----------------|---------------|-------------------|----------------|-----|----------------|-----|-----------------------|--------|
| L1448 NW        | 27            | 6                 | 5              | 2.0 | 4000           | 13.8| 2.8                   | 6.4    |
| L1448 C         | 40            | 11                | 5              | 1.6 | 3000           | 19.5| 1.7                   | 2.6    |
| RNO15 FIR       | 45            | 8                 | 3              | 1.6 | 3500           | 20.7| 1.0                   | 1.8    |
| NGC 1333 iras 1 | 52            | 13                | 3              | 1.5 | 4500           | 21.9| 1.5                   | 8.6    |
| NGC 1333 iras 2 | 48            | 68                | 3              | 1.5 | 7000           | 26.1| 3.0                   | 0.1    |
| HH 211-mm       | 30            | 5                 | 3              | 1.9 | 6000           | 13.8| 4.1                   | 4.5    |
| L1634           | 42            | 19                | 3              | 1.6 | 6000           | 21.9| 2.8                   | 1.1    |
| L1641 N         | 45            | 85                | 3              | 1.5 | 8500           | 25.2| 7.0                   | 1.0    |
| L1641 sms III   | 50            | 80                | 3              | 1.5 | 10000          | 27.6| 6.3                   | 0.6    |

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