ZT Protostellar Model Grid. I. SED Fitting

Sept. 29, 2017

Contents

1 Overview

1.1 Model Grid

In the model, the evolution of the protostar and its surrounding structures are self-consistently calculated from two initial/environmental conditions of the core, the initial core mass (M_c) and the mean mass surface density of the clump that the core is embedded in ($\Sigma_{\rm cl}$). The latter sets the pressure on the boundary of the core, which further determines the size of the core. We refer to the evolutionary history of the protostar and its surround structures from a given set of initial conditions as an *evolutionary track*, and a particular moment on such a track as an *evolutionary stage*, which is specified by a third parameter, the protostellar mass m_*. We refer to the entire set of tracks as the *model grid*. Therefore, the physical model grid is of three dimensions ($M_c - \Sigma_{\rm cl} - m_*$).

In the current model grid, M_c is sampled at 10, 20, 30, 40, 50, 60, 80, 100, 120, 160, 200, 240, 320, 400, 480 $M_\odot$ ($n_{M_c} = 15$), $\Sigma_{\rm cl}$ is sampled at 0.1, 0.32, 1, 3.2 $\mathrm{g\,cm^{-2}}$ ($n_{\Sigma_{\rm cl}} = 4$), forming $n_{M_c} \times n_{\Sigma_{\rm cl}} = 60$ evolutionary tracks. m_* is sampled at 0.5, 1, 2, 4, 8, 12, 16, 24, 32, 48, 64, 96, 128, 160 $M_\odot$ ($n_{m_*} = 14$; but for each track, not all of these m_* are sampled). As a result, there are totally 432 different physical models defined by different sets of (M_c, $\Sigma_{\rm cl}$, m_*).

For each model, the SEDs at 20 viewing inclinations ($n_{\rm view} = 20$) are produced. The inclination is sampled at $\mu_{\rm view} \equiv \cos\theta_{\rm view} = 0.975$, 0.925, ..., 0.025, i.e. equally sampled between 1 (face-on) and 0 (edge-on). Therefore there are totally 8640 SEDs in the current SED model grid with a 4 independent parameters M_c, $\Sigma_{\rm cl}$, m_*, $\mu_{\rm view}$.

1.2 Fitting Method

In order to compare with the observation, the model SEDs need first to be scaled by the distance, and then adjusted by additional foreground extinction described by the parameter A_V,

$$F_{\nu,\rm mod,ext}(\lambda) = F_{\nu,\rm mod}(\lambda) \times 10^{-0.4 A_V \kappa(\lambda)/\kappa_V}, \tag{1}$$

where $\kappa(\lambda)$ and κ_V, the dust opacities at the wavelengths λ and in the V-band, are from the extinction law of the dust model, and $F_{\nu,\rm mod}$ are the distance-scaled model fluxes. The model SEDs are further convolved with the transmission profiles of instrument filters to simulate the fluxes detected in observational bands of various instruments.

We use χ^2 minimization to find the best model to fit the observations. Assuming that we have observed flux densities $F_{\nu,\mathrm{obs}}$ with upper and lower uncertainties of $\sigma_u(F_{\nu,\mathrm{obs}})$ and $\sigma_l(F_{\nu,\mathrm{obs}})$ at wavelengths $\lambda_1, ..., \lambda_N$, and for each model (i.e., each set of M_c, Σ_{cl}, m_*, μ_{view}, d, A_V) we have model flux densities $F_{\nu,\mathrm{mod,ext}}$ at these wavelengths, the reduced χ^2 is defined as

$$\begin{aligned}\chi^2 \quad = \quad & \frac{1}{N_{\mathrm{total}}}\left\{\sum_{F_{\nu,\mathrm{mod,ext}}>F_{\nu,\mathrm{fit}}}\left[\frac{\log F_{\nu,\mathrm{mod,ext}}-\log F_{\nu,\mathrm{fit}}}{\sigma_u(\log F_{\nu,\mathrm{fit}})}\right]^2\right.\\ & \left. + \sum_{F_{\nu,\mathrm{mod,ext}}<F_{\nu,\mathrm{fit}}}\left[\frac{\log F_{\nu,\mathrm{mod,ext}}-\log F_{\nu,\mathrm{fit}}}{\sigma_l(\log F_{\nu,\mathrm{fit}})}\right]^2\right\}, \end{aligned} \tag{2}$$

where $F_{\nu,\mathrm{fit}}$, $\sigma_u(\log F_{\nu,\mathrm{fit}})$ and $\sigma_l(\log F_{\nu,\mathrm{fit}})$ are derived from $F_{\nu,\mathrm{obs}}$, $\sigma_u(F_{\nu,\mathrm{obs}})$, and $\sigma_l(F_{\nu,\mathrm{obs}})$ (see below). For $F_{\nu,\mathrm{obs}}$ used as upper limits, $\sigma_l = \infty$, i.e., no contribution to the χ^2 if $F_{\nu,\mathrm{mod,ext}} < F_{\nu,\mathrm{fit}}$, and for $F_{\nu,\mathrm{obs}}$ used as lower limits, $\sigma_u = \infty$, i.e., no contribution to the χ^2 if $F_{\nu,\mathrm{mod,ext}} > F_{\nu,\mathrm{fit}}$. The total number of data points N_{total} contains both normal data points and upper/lower limits.

During each fitting, the code first searches for a minimum χ^2 by varying the foreground extinction A_V for each set of (M_c, Σ_{cl}, $m_*, \mu_{\mathrm{view}}, d$). The code then compares these minimum χ^2 values to find the best models in the 5 dimensional parameter space formed by different (M_c, Σ_{cl}, m_*, μ_{view}, d) (4 dimensions if an exact source distance d is provided). The code also selects another group of best models. For each set of ($M_c, \Sigma_{\mathrm{cl}}, m_*$), the code searches a minimum χ^2 by varying A_V, d, and μ_{view}, and then compare these minimum χ^2 values to find the best models in the 3 dimensional parameter space formed by different ($M_c, \Sigma_{\mathrm{cl}}, m_*$). Therefore, each member in the second group of best models is a different physical model. Both groups of results are output and users can choose which to use according to their need.

While the χ^2 defined in Equation 2 is used in the ranking and selection of the best fitted models, we also define

$$\chi^2_{\mathrm{nonlimit}} \equiv \chi^2 \frac{N_{\mathrm{total}}}{N_{\mathrm{nonlimit}}} \tag{3}$$

where $N_{\rm nonlimit}$ is the number of data points which have non-zero contributions to χ^2. Note that for the same observed SED, $N_{\rm nonlimit}$ is dependent on the model SEDs. For example, for a data point used as an upper limit, if the model SED is higher than that data point, it is counted in $N_{\rm nonlimit}$. Therefore $\chi^2_{\rm nonlimit}$ tells about the average deviation of the model SED from the observed values.

1.2.1 Treatment of the Errors

The fitting is performed in logarithm space since the fluxes are nonlinear with wavelength and most of the errors are best described as certain percentages of the fluxes. The expectation and variance of the fluxes in logarithmic space are related to the observed fluxes and errors in linear space with following equations

$$\log F_{\nu,\rm fit} = \log F_{\nu,\rm obs} - \frac{1}{2\ln 10}\left[\frac{\sigma(F_{\nu,\rm obs})}{F_{\nu,\rm obs}}\right]^2, \tag{4}$$

$$\sigma_l(\log F_{\nu,\rm fit}) = \sigma_u(\log F_{\nu,\rm fit}) = \frac{1}{\ln 10}\frac{\sigma(F_{\nu,\rm obs})}{F_{\nu,\rm obs}}. \tag{5}$$

This is only valid when the percentage errors are small, since it is a first-order approximation. In real observations, due to the uncertainties in brightness calibration, background subtraction, and selection of apertures to integrate the emission, the percentage uncertainties in the observed flux can easily be several $\times 10\%$ or higher, in which case the error becomes asymmetric around the observed flux in the logarithm space. Therefore we define the following fluxes and errors in logarithm space:

$$\log F_{\nu,\rm fit} = \log F_{\nu,\rm obs}, \tag{6}$$

$$\sigma_u(\log F_{\nu,\rm fit}) = \log\left[1 + \frac{\sigma_u(F_{\nu,\rm obs})}{F_{\nu,\rm obs}}\right], \tag{7}$$

$$\sigma_l(\log F_{\nu,\rm fit}) = -\log\left[1 - \frac{\sigma_l(F_{\nu,\rm obs})}{F_{\nu,\rm obs}}\right]. \tag{8}$$

The log space flux densities and errors in these two methods start to differ significantly when the percentage error becomes $\gtrsim 50\%$. Both types of conversion are available in the code. If the first method is used, the input upper and lower errors need to be same, while if the second method is used, the users can input different upper and lower errors for each flux.

In the second method, the data points with lower errors larger than 100% have log space σ_l that is infinite, and therefore act as upper limits and have no constraints on the models below the observed fluxes. Therefore we provide a third option so that certain constraints can still be applied to the models even in such a situation. If at some wavelength $\sigma_l(F_{\nu,\mathrm{obs}}) \geq 100\%\ F_{\nu,\mathrm{obs}}$, we set $\sigma_l(\log F_{\nu,\mathrm{fit}}) = \sigma_0 \equiv 2$. However, unlike the normal data points, the contribution of this data point to the total χ^2 is set to be $\mathrm{arcsinh}(x^2) = \ln(x^2 + \sqrt{x^4+1})$, where $x = (\log F_{\nu,\mathrm{mod,ext}} - \log F_{\nu,\mathrm{fit}})/\sigma_0$, instead of x^2. Since the function $\mathrm{arcsinh}(x^2) \simeq x^2$ when x is small and $\simeq \ln(2x^2)$ when x is large, this constraint tends to select the models with fluxes closer to $F_{\nu,\mathrm{fit}}$, while the constraint is not as strong as a normal data point. This method has the effect of preferring models that are close to the data points with $> 100\%$ lower uncertainties provided by these constraints.

2 Explanation of the Programs

2.1 Package Structure

The structure of the package is as follows:

```
sedfit
 ├── idlfit
 └── Model_SEDs
      ├── flux_filt
      ├── model_info
      ├── parfiles
      ├── sed
      ├── sed_plot
      └── sed_plot_filt
```

The IDL version of the program is in the directory `idlfit/`. Details are explained in following sections. The generated output files and figures will also be in this directory. The model data are stored in the directory `Model_SEDs/`.

Details about the model data stored in the `Model_SEDs/` directory are explained in Appendix A. Normally, the users do not need to inspect these data files. However, understanding the structure of the model data will be helpful, if you would like to fully understand the model grid, or use the model grid to perform your own fitting and analysis.

Table 1: List of the programs.

Main	`sedfit`	The main program. Prepare the input parameters and call the subroutines.
Subroutine	`chisq`	Calculate the χ^2 and output the results.
	`bestmodel` `plotsed`	Select the best models and plot their SEDs.

	`plotsed1`
	`plotchisq`
	`plotchisq1`
	`plotchisq2`
		Plot additional graphs for analysis.

Other	`filtflux`	Add new filters to the model data.

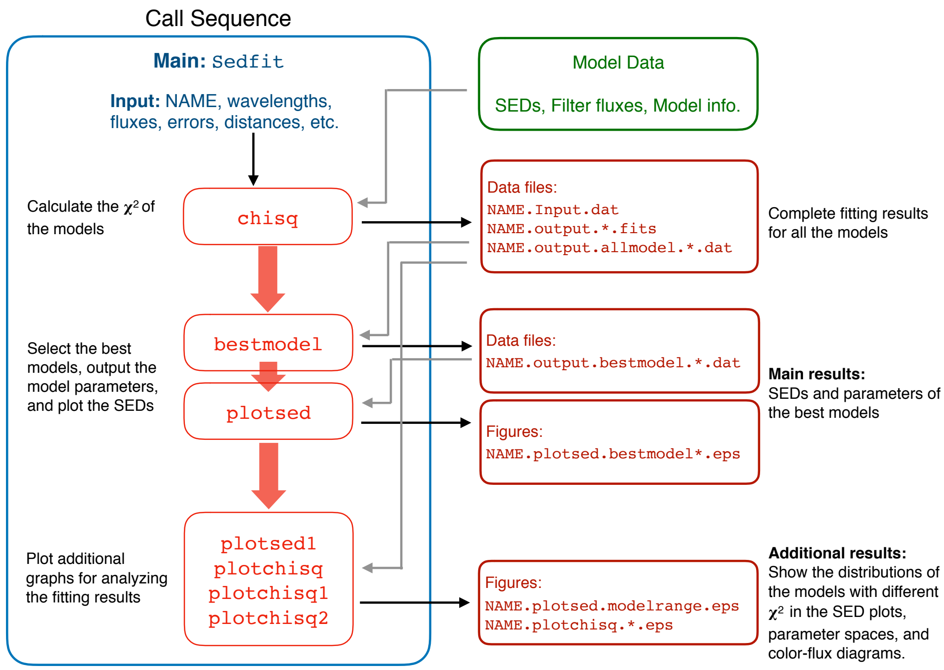

Figure 1: The basic workflow of the program

2.2 Basic Workflow

All the programs are listed in Table 1, and the basic workflow of the program is shown in Figure 1. The main program `sedfit` calls the subroutines to calculate the χ^2, select the best fitted models, and output the results. The users need to first edit the input section of `sedfit.pro`. The following parameters must be specified before calling `chisq` to fit.

NAME: string with no spaces, to specify the name of the output directory and files.

FILT_ARR: An array containing the names of the filters (observational bands). The names of the default filters are listed in `Model_SEDs/parfiles/filter_default.dat`. New filters can be added with the program `filtflux` (see §2.4).

FILT_WAV_ARR: The wavelengths of the filters specified in FILT_ARR (in μm).

FLUX_ARR: The observed fluxes at the filters specified in FILT_ARR (in Jy).

ERRUP: The relative upper errors for the fluxes.
ERRLO: The relative lower errors for the fluxes.

Currently only the IDL version of fitting code is available. The code has been tested on IDL 7 or higher version. The IDL Astronomy Library is needed to run the code. To run the program, start the IDL in a terminal from the `idlfit/` directory, and enter "`.run sedfit`". An output directory will be created inside `idlfit/`, and all the output files will be in that directory. If an directory with the same name already exists, the old files inside of it will be replaced by the new results.

The users do not need to run the whole program every time. For example, once `chisq` has been run and the result files are in the output directory, users can comment out the line calling `chisq` in the main program and start from `bestmodel` without rerun `chisq`. Users can also comment out the subroutines such as `plotchisq*` in the main program if the additional graphs are not needed.

2.3 Details of the Subroutines

The subroutines are called by the main program `sedfit` and should not be used independently. Their input parameters should be edited in the main program.

2.3.1 `chisq`

Calculate χ^2 for each model in the grid based on the input fluxes and errors, and output the results.

Input: NAME, FILT_ARR, FILT_WAV_ARR, FILT_FLUX_ARR, ERRUP, ERRLO. See §2.2 for explanations of these parameters. If ERRLO is not provided, it is assumed to be same as ERRUP.

Additional Input:
ERROPTION: (array or scalar, default 1) Set to 1 to convert the input fluxes and errores to the log space in a symmetric way. In this case, ERRLO is set to be same as ERRUP. Set to 2 to convert the upper and lower errors differently in the log space. ERROPTION=3 is similar to 2 but has a special treatment for the large lower errors. See §1.2.1 for more information.

LIMIT: (array or scalar, default 0) 0 for normal data points, 1 for upper limits and -1 for lower limits.

AVOPTION: A_V is used as a free parameter to find best χ^2 for each set of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$. Set AVOPTION=0 to search A_V in the range from 0 to 1000, and set it to 1 to search A_V in the range from 0 to the value that corresponds to $5\Sigma_{\rm cl}$, i.e., the range of A_V is related to the mean surface density of the cloud where the core is embedded.

NDIS, DISTANCE and DISERR: used to set the distance range when searching for the best fit model. DISTANCE is the central value of the distance range, DISERR is the half width of that range, and NDIS is the number of distances to sample. If the exact distance is known, the user can set NDIS=1, and DISTANCE to the known value, in which case DISERR is not needed. If no distance information is provided, the program will search the best fit model by varying the distance from 0.1 kpc to 10 kpc with a 0.1 kpc interval. DISTANCE and DISERR are in pc.

The output files are `NAME.output.*.fits` and `NAME.output.allmodel.*.dat`.

2.3.2 `bestmodel`

From the files `NAME.output.allmodel.*.dat` generated by `chisq`, select the best several models and output the model parameters. There are two ways to define how the best models are selected. 1). With THRESOPTION=1, NMODEL is used to specify the number of the best models with different $(M_c, \Sigma_{\rm cl}, m_*)$ to be outputted, and NFULLMODEL is used to specify the number of the best models with different sets of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$ to be outputted. 2). With THRESOPTION set to 2, the program will output the models with $\chi^2 < \chi^2_{\rm min}$+CHISQ_THRES. The output files are `NAME.output.bestmodel.*.dat`.

Default: THRESOPTION=1, NMODEL=10, NFULLMODEL=20, CHISQ_THRES=3

2.3.3 `plotsed`

Plot the SEDs of the best models listed in the file `NAME.output.bestmodel.parameter.dat` and `NAME.output.bestmodel.full.parameter.dat` generated by `bestmodel`. The output files are `NAME.plotsed.bestmodel.eps` and `NAME.plotsed.bestmodel.full.eps`

2.3.4 `plotsed1`

Plot all the SEDs with χ^2 <CHISQ_MAX. The output file is `NAME.plotsed.modelrange.eps`

Default: CHISQ_MAX=50

2.3.5 `plotchisq`

Plot the distributions of χ^2 (<CHISQ_MAX) in the primary parameter $(M_c, \Sigma_{\rm cl}, m_*)$ space.

Default: CHISQ_MAX=50

2.3.6 `plotchisq1`

Plot the distribution of χ^2 (<CHISQ_MAX) with various secondary parameters, such as the current envelope mass $M_{\rm env}$, total luminosity $L_{\rm tot}$, half opening angle of the outflow cavity $\theta_{w,\rm esc}$.

Default: CHISQ_MAX=50

2.3.7 `plotchisq2`

Plot the distributions of models with χ^2 <CHISQ_MAX in the color-flux diagrams at wavelengths specified by users, to show how the models with different χ^2 deviate from the observed fluxes and SED slopes (colors). Users must specify the wavelengths (using the filter names) to plot the color-flux diagrams. For given filters X and Y, the x-axis of the figure will be $\log(F_X/F_Y)$ and the y-axis of the figure will be $\log F_Y$, where F_X and F_Y are the fluxes of the filters of X and Y. Users can also specify how the multi-panels are arranged with NXP and NYP.

Default: CHISQ_MAX=50, NXP=3

2.4 Add New Filters

There are 39 default filters in the model, including observational bands of common instruments such as *Spitzer*, *Herschel*, and *SOFIA*. The default filters are listed in the file `Model_SEDs/parfiles/filter_default.dat`.

`fluxfilt` allows the users to add new filters, either from a file containing the transmission profile of the filter or by defining a square profile with given central wavelength and width. To run this program, edit the input parameters in the file `filtflux.pro`, start the IDL in a terminal from the `idlfit` directory, and enter "`.run filtflux`". The generated file containing the fluxes of all the models in this band will be in the directory `Model_SEDs/flux_filt/` (see Appendix A) and ready to be used by the fitting program.

If a profile file is used, the user must put it in the directory `Model_SEDs/parfiles/` and specify the name. In such a case, the width is not needed. The profile file need to contain two columns including wavelengths (in μm) and the filter transmission. Normalization is not needed. A useful website to find filter files of various instruments is http://svo2.cab.inta-csic.es/svo/theory/fps3/. In the case of defining a square filter, a central wavelength and a width are needed (both in μm).

3 Explanation of the Output Files and Figures

Table 2: List of the output files and figures.

Input parameters (reorganized)	`NAME.input.dat`

Main results (information and SEDs of the best fitted models)	`NAME.output.bestmodel.parameter.dat`
	`NAME.output.bestmodel.parameter_range.dat`
	`NAME.output.bestmodel.full.parameter.dat`
	`NAME.output.bestmodel.full.parameter_range.dat`
	`NAME.plotsed.bestmodel.eps`
	`NAME.plotsed.bestmodel.full.eps`

Additional graphs	`NAME.plotsed.modelrange.eps`
	`NAME.plotchisq.primary.eps`
	`NAME.plotchisq.primary.simplified.eps`
	`NAME.plotchisq.secondary.eps`
	`NAME.plotchisq.color.eps`

Complete results (Fitting results of all the models, used for analysis)	`NAME.output.chisqarr.fits`
	`NAME.output.avchisqarr.fits`
	`NAME.output.Ichisqarr.fits`
	`NAME.output.allmodel.parameter.dat`
	`NAME.output.allmodel.full.parameter.dat`

An output directory with the name specified in the main program `sedfit` will be created in `idlfit/`. Table 2 lists the output files that will be created by the fitting program in this output directory. Generally speaking, the main results contain informations of the best fitted models, and the additional graphs show the distribution of the models in the parameter spaces for users to better understand the constraints and degeneracies of the various parameters. The details of these files are discussed below. The fitting results of all the models are also recorded, which are mostly for the convenience of analyzing results and drawing figures, and normally can be ignored by the users. Their details are discussed in Appendix B.

NAME.input.dat

Records the input parameters, including the filter name, wavelengths, fluxes, errors (upper and lower), distance range, error options, limit options, and extinction options.

NAME.output.bestmodel.parameter.dat

Records the parameters of the best fitted models, in the order of increasing χ^2. The models listed here are all with different $(M_c, \Sigma_{\rm cl}, m_*)$, i.e. different physical models (see §1.2). Besides the SED number, χ^2, M_c, $\Sigma_{\rm cl}$, and m_*, other output parameters include: $\chi^2_{\rm nonlimit}$, $\mu_{\rm view}$, source distance d, A_V, core radius R_c, current envelope mass ($M_{\rm env}$; note that it is different from the initial core mass), half opening angle of the outflow cavity ($\theta_{w,\rm esc}$), protostellar radius (r_*), protostellar luminosity (L_*, not including any accretion luminosity), protostellar temperature (T_*, not including the accretion hotspot), mass of the disk (m_d), radius of the disk (r_d), accretion rate from the disk to the protostar ($\dot{m}_*$), true total luminosity ($L_{\rm tot}$), luminosity integrated from the unextincted model SEDs assuming isotropic radiation (i.e. without correction for the inclination, $L_{\rm inc}$), the inclination-uncorrected luminosities after A_V extinction ($L_{{\rm inc},A_V}$, which should be close to that integrated from observed SEDs assuming isotropic radiation if the model fit is good), and the age since the start of star formation.

NAME.output.bestmodel.parameter_range.dat

Records the ranges of the parameters listed in the file `NAME.output.bestmodel.parameter.dat`.

NAME.output.bestmodel.full.parameter.dat

Records the parameters of the best models, in the order of increasing χ^2. The models listed here are with different $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$, i.e. same physical models but viewd at different inclinations and distances are treated as different models here. The listed parameters are same as those in the file `NAME.output.bestmodel.parameter.dat`.

NAME.output.bestmodel.full.parameter_range.dat

Records the ranges of the parameters listed in the file `NAME.output.bestmodel.full.parameter.dat`.

NAME.plotsed.bestmodel.eps

Shows the SEDs of the models listed in the file `NAME.output.bestmodel.parameter.dat`. The thick line is for the best model.

NAME.plotsed.bestmodel.full.eps

Shows the SEDs of the models listed in the file `NAME.output.bestmodel.full.parameter.dat`. The thick line is for the best model.

NAME.plotsed.modelrange.eps

Shows how the model SEDs deviate from the data points as χ^2 increases. The model SEDs shown here are with different $(M_c, \Sigma_{\rm cl}, m_*, \mu, d)$. The thick black line is for the best model.

NAME.plotchisq.primary.eps

Shows the distribution of χ^2 in the parameter space of $(M_c, \Sigma_{\rm cl}, m_*)$. **Top row**: The first panel shows the best χ^2 for each set of $(M_c, \Sigma_{\rm cl})$, by searching through different m_*, $\mu_{\rm view}$ and A_V. The m_*, $\mu_{\rm view}$ and A_V that are used to achieve these best χ^2 are shown in the second to fourth panels of this row. **Middle row**: Similar to the top row, but shows the best χ^2 in the $M_c - m_*$ space, and the $\Sigma_{\rm cl}$, $\mu_{\rm view}$, A_V to achieve these best χ^2. **Bottom row**: Similar to the top and middle rows, but shows the best χ^2 in the $\Sigma_{\rm cl} - m_*$ space. The white crosses mark the locations of the five best models, and the large cross is the best model. The grey regions are not covered by the model grid, and the white regions are where the χ^2 is too large (larger than a value specified in the `sedfit` program. The red contours are at the level of $\chi^2 = \chi^2_{\rm min} + 5$. This figure shows the constraints applied to the primary parameter space by fitting the observational data, and the possible degeneracies among these parameters.

NAME.plotchisq.primary.simplified.eps

Is a simplified version of `NAME.plotchisq.primary.eps`, showing only the first panel of each row.

NAME.plotchisq.secondary.eps

Shows the distribution of χ^2 with varies secondary parameters. Although in our model, these secondary parameters are derived from the primary parameters (M_c, $\Sigma_{\rm cl}$ and m_*), they are more directly related to the properties of the observed massive protostellar objects. This figure shows the constraints put on these parameters by the fitting. Only the models with the χ^2 lower than a specified value (set in `sedfit`) are shown. Each model is different in the $(M_c, \Sigma_{\rm cl}, m_*)$ space. The crosses mark the location of the best five models, and the large cross is the best model

NAME.plotchisq.color.eps

The distribution of the χ^2 in the color-flux diagrams, showing how the models deviate from the observations at specified wavelengths or wavelength ranges. The center of each panel is the location of the observation, and the dark and light grey areas show the ranges of 1σ and 3σ. Only the models with the χ^2 lower than a specified value (set in `sedfit`) are shown. Each model is different in the $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$ space. The crosses mark the locations of the best five models, and the large cross is the best model.

A Details of the Model Data

The directory `Model_SEDs/` contains the model data used by the fitting program. The SED data are stored in the directory `sed/`. The numbers in the file names are i_{M_c} $(1, 2, ..., n_{M_c})$, $i_{\Sigma_{\rm cl}}$ $(1, 2, ..., n_{\Sigma_{\rm cl}})$, i_{m_*} $(1, 2, ..., n_{m_*})$ and $i_{\rm view}$ $(1, 2, ..., n_{\rm view})$, indicating the four parameters (M_c, $\Sigma_{\rm cl}$, m_*, $\mu_{\rm view}$) to define an SED. For example, the file `01_01_01_01.dat` records the SED of the model with $M_c = 10\ M_\odot$, $\Sigma_{\rm cl} = 0.1\ {\rm g\,cm^{-2}}$, $m_* = 0.5\ M_\odot$ viewed at an inclination of $\mu_{\rm view} = 0.975$ (nearly face-on) (see §1.1). The two columns of the SED files are wavelength (in μm) and flux (in $L_\odot$). The fluxes can be converted to νF_ν (in erg s^{-1}cm^{-2}) by multiplying $L_\odot/(4\pi d^2)$, where d is the source distance.

The model fluxes that are really used to fit the observational data are after convolution of the SEDs with the filter responses of the instrument bands. These band fluxes are stored in the directory `flux_filt/` in fits format. The default filters are listed in the file `Model_SEDs/parfiles/filter_default.dat`. Users can freely add new filters or define square filters to generate similar files for fitting (see §2.4). Each fits file contains a four dimension array ($n_{M_c} \times n_{\Sigma_{\rm cl}} \times n_{m_*} \times n_{\rm view}$) to record the fluxes of all the models in this band. The fluxes are in $L_\odot$ and a factor of $L_\odot/(4\pi d^2)$ is needed to convert to νF_ν.

The SEDs and filter fluxes are plotted in `sed_plot/` and `sed_plot_filt/`. The numbers in the file names are i_{M_c}, $i_{\Sigma_{\rm cl}}$ and i_{m_*}, respectively. Different viewing inclinations are shown in different colors (pink: edge-on; green: face-on). These figures are for users to check the general behavior of the model SEDs. Note that these SEDs assume a source distance of 1 kpc and without any foreground extinction, while those used to fit the observations are scaled by the distance and adjusted by A_V (see §1.2).

The directory `model_info/` contains files recording the secondary parameters of each model, such as the current mass of the envelope $M_{\rm env}$, opening angle of the outflow cavity $\theta_{w,{\rm esc}}$, disk accretion rate $\dot{m}_*$, and luminosity $L_{\rm tot}$. They are derived from the three primary parameters (M_c, $\Sigma_{\rm cl}$, and m_*) based on the physical model. The numbers in the file names are i_{M_c}, $i_{\Sigma_{\rm cl}}$ and i_{m_*}, respectively.

The directory `parfiles/` contains additional files such as the filter transmission profiles and the dust extinction law (for foreground extinction).

B More Explanation of the Output Files

As mentioned in §3, the fitting results of all the models (not only the best ones) are recorded, which are mostly for the convenience of analysis or drawing figures. Normally the users do not need to inspect these files for result. Here we explain the formats of these files.

NAME.output.chisqarr.fits

Contains a 5 dimension array ($n_{M_c} \times n_{\Sigma_{\rm cl}} \times n_{m_*} \times n_{\rm view} \times n_{\rm dis}$) recording the minimum χ^2 for each set of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$ by adjusting A_V (see §1.2). $n_{\rm dis} = 1$ if an exact source distance is given.

NAME.output.avchisqarr.fits

Contains a 5 dimension array ($n_{M_c} \times n_{\Sigma_{\rm cl}} \times n_{m_*} \times n_{\rm view} \times n_{\rm dis}$) recording the A_V to achieve the minimum χ^2 for each set of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$. $n_{\rm dis} = 1$ if an exact source distance is given.

NAME.output.Ichisqarr.fits

Contains a 6 dimension array ($n_{M_c} \times n_{\Sigma_{\rm cl}} \times n_{m_*} \times n_{\rm view} \times n_{\rm dis} \times n_\lambda$) recording the extincted fluxes at each wavelength to achieve the minimum χ^2 for each set of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$. $n_{\rm dis} = 1$ if an exact source distance is given. The fluxes are in $\log$ Jy.

NAME.output.allmodel.parameter.dat

Similar to the file `NAME.output.bestmodel.parameter.dat`, but records the minimum χ^2 models with all sets of $(M_c, \Sigma_{\rm cl}, m_*)$, in the order of increasing χ^2.

NAME.output.allmodel.full.parameter.dat

Similar to the file `NAME.output.bestmodel.full.parameter.dat`, but records the minimum χ^2 models with all sets of $(M_c, \Sigma_{\rm cl}, m_*, \mu_{\rm view}, d)$, in the order of increasing χ^2.