Saas Fee Winter School 2013

Hands-on session for lecture by Ralf Klessen
Exercise designed by Cornelis Dullemond

Radiation Transfer in Spherical Cloud with Embedded Star

In this exercise we model a spherical gas cloud with an embedded main-sequence star in the center. We perform radiative transfer calculations using the Monte Carlo RT code `RADMC-3D` developed by Cornelis Dullemond in Heidelberg. We begin by performing dust continuum transfer calculations in the optically thick regime. Then we compute the equilibrium dust temperature and calculate the spectral energy distribution. Finally, we add gas to the problem and study the line transfer for the $J = 1 \rightarrow 0$ rotational transition of CO.

A. Optically thick dusty envelope around main-sequence star

1. Download version 0.31 or higher of the `RADMC-3D` code from the code website[1]. Compile the code (using the command "make" in the `src` directory), and have a quick look at the manual.

   Note: To make optimal use of `RADMC-3D`, it is best to have IDL installed. However, the hands-on exercises have been designed to work without IDL. The only thing you need is the ability to read and plot ASCII tables.

2. Download the files `problem_setup_1.f90` and `dustkappa_silicate_1.inp` from the hands-on page. Put these into a new directory.

3. Study the file `dustkappa_silicate_1.inp`. It contains the opacity table. Make a log-log plot of the absorption opacity versus wavelength.

4. Look at the program `problem_setup_1.f90`.
   (a) How is the spatial grid defined?
   (b) What is the density structure of the dusty envelope, and which parameters determine this structure and how?
   (c) How are the stellar properties defined?
   (d) What is the meaning of the files it is writing? Please read the RADMC-3D manual (in the directory `manual/`) to figure this out.

5. Now compile `problem_setup_1.f90` with e.g. `gfortran problem_setup_1.f90`, and then execute the program e.g. with `a.out`.

6. Type `radmc3d mctherm` and see that RADMC-3D is performing the thermal Monte Carlo iteration. Once the temperature structure is written into the file `dust_temperature.dat`,

[1] `http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/`

make a plot of the resulting temperature as a function of radius (in a log-log fashion). You will need to use the data from the `dust_temperature.dat` as well as from the `amr_grid.inp` file.

7. *Voluntary:* Repeat the last two steps, but now for 10x smaller density and 10x larger density.
   (a) Explain the differences in behavior (in particular the speed) of the code for the three cases.
   (b) Explain the differences in the temperature profiles for the three cases.

B. Spectral energy distribution (SED)

1. Use `RADMC-3D` to create the SED of this envelope covering all wavelength of interest (from the UV to the millimeter) and make a plot of this. Assume the observer is at a distance of 100 parsec. *Note:* Since RADMC-3D is optimized for 3-D transfer, it is not particularly fast for 1-D problems, so you may need to wait a few minutes before it is finished. *Tip:* Find in the manual of RADMC-3D how to make an SED. The file `spectrum.out` that RADMC-3D produces contains some header lines and then two columns. The first one is the wavelength, the second one is the flux (in erg/cm^2/s/Hz) of the object when the observer is at a distance of 1 parsec.

2. Do the same, but now for an envelope with $\rho_{\rm dust,0} = 10^{-21}$ gram/cm^3 (i.e. a 1000x lower optical depth). Explain the difference to the previous result.

C. 2-dimensional envelope model with conical polar cavity

Now we add polar cavity to the model discussed above, e.g. as created by an outflow.

1. Download the new `problem_setup_2.f90` code. Compare it to the previous one, and try to understand the differences.

2. Also download the new `dustkappa_silicate_2.inp` opacity. What is the difference with the previous one?

3. Run the `problem_setup_2.f90` program (using the new opacity) and calculate the dust temperatures with RADMC-3D in the usual way.

4. Compute the SED for face-on inclination ($i = 0$), for edge-on inclination ($i = 89$[2]) and for an inclination in between ($i = 35$). Plot all three SEDs in a single plot and explain the differences.

5. Use RADMC-3D to make an image at $\lambda = 1\,\mu$m at $i = 30$, using the following command: `radmc3d image lambda 1.0 incl 30`. This will produce a file called `image.out`. The RADMC-3D manual can tell you the format of this file. However, this file is not yet directly viewable.

[2]RADMC-3D still doesn't like exact edge-on images and spectra; bug to be fixed.

6. Now let us make a directly viewable image, a `.bmp` file. Download the program `image_to_bmp.f90`. It will allow you to convert `image.out` into `image.bmp` which is a standard (Microsoft) image format. This program asks you questions such as the minimum and maximum intensity, and whether you wish to use a linear or log scale, and whether to use a greyscale or color table. For a color table, please also download the `ct.inp` file. Play a bit until you are satisfied with the image.

7. *Voluntary:* There is observational evidence that outflow cavities are not perfectly conical in shape. Let us try to make a somewhat more realistic model.

   (a) Let us assume that, at any given z above the equatorial plane, the cylindrical radius r_{cc} that defines the cavity walls is given by

   $$r_{cc} = r_0 \sqrt{z/r_0}$$

   for some r_0 to be set by you. Build this model cavity into the model (replacing the conical cavity).

   (b) Make SEDs and images to get a feeling for the result.

   (c) Show that the angle-dependency of the SED is less sharp than before.

D. Spherical circumstellar envelope model with CO lines

1. Find and download the molecular data file of CO from the Leiden LAMDA database[3]. Also download the files form the isotopologues ^{13}CO, C^{17}O and C^{18}O. Compute the wavelengths of the $J = 1-0$ line for all these, and determine the relative shifts. Why they are (slightly) different? Do you expect to observe them, for typical molecular clouds and protoplanetary disks, as separate lines or will they typically be blended together?

2. We assume a gas temperature of $T = 50$ K, and for simplicity take only thermal line broadening into account, and set the gas velocity to zero. We also assume that the CO abundance is 10^{-4} in number density with respect to the number of H_2 molecules in the gas, i.e. we ignore the presence of Helium. Compute the gas opacity $\alpha_\nu/\rho_{\rm gas}$ at line-center for the $J = 1 - 0$ transition of CO.

3. With the above abundance, add CO to the 1-dimensional spherical envelope model that you made before (take $\rho_{\rm dust,0} = 10^{-20}$ gram/cm^3). Please use the opacity without scattering (`dustkappa_silicate_1.inp`). You must make the following additions to your model:

   (a) Rename the `co.dat` file to `molecule_co.inp`, and likewise for the other isotopologue files.

   (b) Add the line `tgas_eq_tdust = 1` to the `radmc3d.inp` file, so that the gas temperature is going to be taken to be equal to the dust temperature.

[3] `http://home.strw.leidenuniv.nl/~moldata/`

(c) Create a `numberdens_co.inp` file (see manual) with the appropriate abundance of CO. *Note:* The gas-to-dust ratio should be taken to be 100 in terms of the mass.

(d) Create a `gas_velocity.inp` file (see manual), but assume that the velocity is everywhere 0 for now.

(e) Create a `lines.inp` file (see manual) where you specify the to-be-used molecular data file.

4. Make a CO $J = 1 - 0$ line spectrum (see manual). Find the appropriate width of the velocity channel. Use 20 frequency points.

5. *Voluntary:* Do the same for ^{13}CO and C^{18}O, with the appropriate abundances (50× lower for ^{13}CO, and 500× for C^{18}O) and the appropriate molecular files.

6. *Voluntary:* Let us introduce a radial velocity field according to the following formula:

$$v(r) = v_{\rm in}\sqrt{\frac{r_{\rm in}}{r}}$$

with $v_{\rm in} = -1$ km/s. Make a spectrum. Now try out higher and lower values of $\rho_{\rm dust,0}$ (i.e. increase and decrease the gas density and CO number density together). When do you get a nice inverse P-Cygni profile?