

Efficient radiative transfer methods for continuum and line transfer in large three-dimensional models

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Abstract.

The relationship between physical conditions of an interstellar cloud and the observed radiation is defined by the radiative transfer problem. Radiative transfer calculations are needed if, e.g., one wants to disentangle abundance variations from excitation effects or wants to model variations of dust properties inside an interstellar cloud. New observational facilities (e.g., ALMA and Herschel) will bring improved accuracy both in terms of intensity and spatial resolution. This will enable detailed studies of the densest sub-structures of interstellar clouds and star forming regions. Such observations must be interpreted with accurate radiative transfer methods and realistic source models. In many cases this will mean modelling in three dimensions. High optical depths and observed wide range of linear scales are, however, challenging for radiative transfer modelling.

A large range of linear scales can be accessed only with hierarchical models. Figure 1 shows an example of the use of a hierarchical grid for radiative transfer calculations when the original model cloud ($L=10$ pc, $\langle n \rangle = 500$ cm⁻³) was based a MHD simulation carried out on a regular grid (Juvela & Padoan, 2005). For computed line intensities an accuracy of 10% was still reached when the number of individual cells (and the run time) was reduced by a factor of ten. This illustrates how, as long as cloud is not extremely optically thick, most of the emission comes from a small sub-volume. It is also worth noting that while errors are $\sim 10\%$ for any given point they are much smaller when compared with intensity variations. In particular, calculations on hierarchical grid recovered the spatial power spectrum of line emission with very good accuracy.

Monte Carlo codes are used widely in both continuum and line transfer calculations. Like any lambda iteration schemes these suffer from slow convergence when models are optically thick. In line transfer Accelerated Monte Carlo methods (AMC) present a partial solution to this problem (Juvela & Padoan, 2000; Hogerheijde & van der Tak, 2000). AMC methods can be used similarly in continuum calculations to speed up the computation of dust temperatures (Juvela, 2005). The sampling problems associated with high optical depths can be solved with weighted sampling and the handling of models with $\tau_V \sim 1000$ is perfectly feasible. Transiently heated small dust grains pose another problem because the calculation of their temperature distribution is very time consuming. However, a 3D model will contain thousands of cells at very similar conditions. If dust temperature distributions are calculated only once for such a set an approximate solution can be found in a much shorter time time. (Juvela & Padoan, 2003; see Fig. 2a).

MHD simulations with Automatic Mesh Refinement (AMR) techniques present an exciting development for the modelling of interstellar clouds. Cloud models consist of a hierarchy of grids with different grid steps and the ratio between the cloud size and the smallest resolution elements can be 10^6 or even larger. We are currently working on radiative transfer codes (line and continuum) that could be used efficiently on such grids (see Fig. 2b). The radiative transfer problem can be solved relatively independently on each of the sub-grids. This means that the use of convergence acceleration methods can be limited to those sub-grids where they are needed and, on the other hand, parallelization of the code is straightforward.

Keywords. radiative transfer, ISM: clouds, radio lines: ISM, infrared: ISM

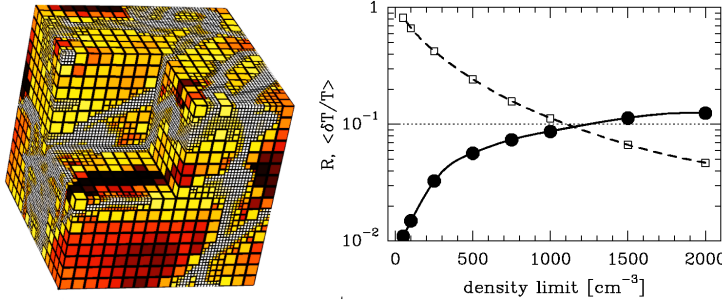


Figure 1. *Left:* A hierarchical discretization scheme used in line transfer calculations with 3D MHD models. Each cell can be recursively divided into eight sub-cells and fine discretization is limited to dense regions. The original grid corresponds to a situation where each cell would be divided twice. *Right:* Rms-error of computed ^{13}CO line intensities (*filled circles*) from a larger model when cells above given density threshold are sub-divided. The open squares show corresponding values of parameter R , the number of cells in relation to the full-resolution model. A rms-level of 10% is reached with $R \sim 0.1$ and the memory requirements and run times are only 10% of those required by the full-resolution model. The size of the model was 10 pc, mean density 500 cm^{-3} and temperature $T_{\text{kin}} = 10 \text{ K}$. (Juvela & Padoan, 2005)

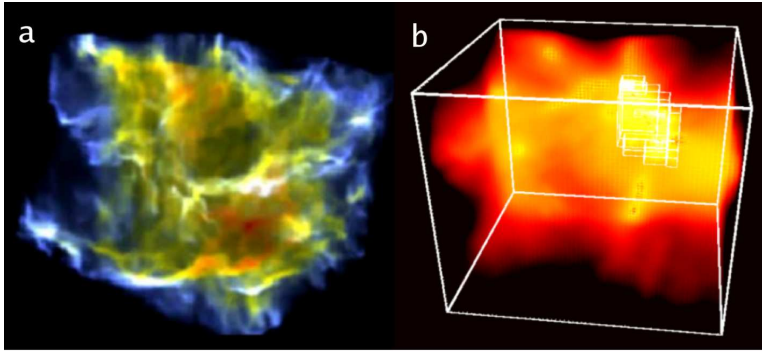


Figure 2. *a.* An example of infrared dust emission calculated for a three-dimensional MHD model of an interstellar cloud (size 6 pc, mean density $\sim 1000 \text{ cm}^{-3}$). Colours correspond to intensities at 25, 60 and $100 \mu\text{m}$ and indicate variations in dust colour temperature (Juvela & Padoan, 2003). *b.* First results from a program for continuum radiative transfer calculations on AMR grids. The colour plot shows distribution of absorbed energy. The white boxes denote boundaries of different sub-grids used in the hierarchical discretization of the model cloud.

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