THREE-DIMENSIONAL CONTINUUM RADIATIVE TRANSFER IMAGES OF A MOLECULAR CLOUD CORE EVOLUTION

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ABSTRACT

We analyze a three-dimensional smoothed particle hydrodynamics simulation of an evolving and later collapsing prestellar core. Using a three-dimensional continuum radiative transfer program, we generate images at 7 μm, 15 μm, 175 μm, and 1.3 mm for different evolutionary times and viewing angles. We discuss the observability of the properties of prestellar cores for the different wavelengths. For examples of nonsymmetric fragments, it is shown that, misleadingly, the density profiles derived from a one-dimensional analysis of the corresponding images are consistent with one-dimensional core evolution models. We conclude that one-dimensional modeling based on column density interpretation of images does not produce reliable structural information and that multidimensional modeling is required.

Subject headings: dust, extinction — infrared radiation — ISM: clouds — stars: formation — submillimeter

Online material: color figures

1. INTRODUCTION

Molecular cloud cores are thought to be the direct progenitors of stars. However, their initial properties and early evolution are still poorly understood. Current observations therefore aim to find and study these cores in more detail. Density structure, velocity field, and temperature distribution of the gas and dust are key parameters for the physical interpretation of the long lifetimes of these objects. The continuum radiation spectra of deeply embedded sources contain only ambiguous information about the density and temperature distribution of the dust. Column densities can be inferred from the analysis of continuum images in the millimeter range (e.g., Ward-Thompson et al. 1994) and the mid-infrared (MIR; e.g., Bacmann et al. 2000). The emission of molecules within the core contains information about the structure, the velocity field (Tafalla et al. 2004 and references therein), and the turbulence (Ossenkopf et al. 2001 and references therein). The currently discussed supporting mechanisms against gravitational collapse are magnetic fields and turbulence. There are a number of simulations treating the full three-dimensional structure of collapsing prestellar cores (e.g., Bate et al. 2003; Ballesteros-Paredes et al. 2003; Burkert & Bodenheimer 1993, 2000; Krumholz et al. 2003; Klessen et al. 2000; Heitsch et al. 2001). In some of these papers, the resulting column density along a line of sight was compared with observationally obtained column densities. The question of which structures of the distribution can be seen at which wavelength, however, can only be answered by producing images of the core for given dust properties. In turn, the majority of models that have been applied to observational data are mostly based on spherical symmetry (e.g., André et al. 1996). They rely on spherically symmetric models of isolated star formation, which describe core formation, gravitational collapse, and protostellar accretion. Commonly, averaged radial density profiles are derived and compared with power-law density distributions (e.g., André et al. 1996) or Bonnor-Ebert spheres (e.g., Alves 2004). The major difficulties using three-dimensional models in observations are (1) the information loss due to the projection effect, (2) the complex and unique structure of each individual prestellar core, and (3) the numerical effort of multidimensional radiative transfer.

In this Letter, we investigate how an evolving cloud core simulated by a three-dimensional smoothed particle hydrodynamics (SPH) code would appear at different wavelengths, which structures are visible, and which density distributions would be inferred using common one-dimensional models. The results from the SPH simulation are described in § 2, along with a discussion of underlying assumptions. We present the images from the three-dimensional continuum radiative transfer (CRT) modeling and discuss the observability of different structures and physical effects. The comparison to density structures obtained from applying one-dimensional models to the images is given in § 3, and the findings are summarized and discussed in § 4.

2. CLOUD CORE EVOLUTION MODEL AND RADIATIVE TRANSFER MODELING

2.1. Three-dimensional SPH Simulation of the Evolution of a Cloud Core

We have calculated the evolution of a cloud core using a three-dimensional SPH code (version described in Bate et al. 1995), originally developed by Benz et al. (1990). The smoothing lengths of particles are variable in time and space, following the constraint that the number of neighbors for each particle has to be approximately constant with N_{mean} = 50. The SPH equations are integrated using a second-order Runge-Kutta-
Fehlberg integrator with individual time steps for each particle (Bate et al. 1995).

The simulation was initiated with a mass of \( M = 3 M_{\odot} \), where we adopted a spherically symmetric nonrotating homogeneous cloud with a temperature of \( T = 10 \, \text{K} \), a diameter of \( d = 0.12 \, \text{pc} \) (corresponding to a density of \( 2 \times 10^{-16} \, \text{kg m}^{-3} \)), and a mean molecular weight \( \mu = 2.36 \times 10^{-2} \, \text{kg mol}^{-1} \). This configuration is Jeans unstable. A turbulent velocity field is added only at the beginning of the simulation with a Mach number of \( M = 2 \) and following an approximate Kolmogorov law \( P(k)dk \sim k^{-2} \) for the different modes. The turbulence supports the cloud core against collapse for the first \( 10^5 \, \text{yr} \). This enables the formation of a prestellar corelike structure, self-consistently as a result of turbulent energy dissipation. A variable equation of state is used: isothermal for densities less than \( 10^{16} \, \text{molecules m}^{-3} \) and adiabatic for larger densities.

Deviating from earlier work, we arranged the initial conditions in a way that the core reaches a dynamical equilibrium of density structures and velocity field before it evolves into a runaway collapse. The resulting structure is visualized by isodensity surfaces shown in the left panels of Figure 1. The top left panel shows the early stage of core formation \( 5.6 \times 10^4 \, \text{yr} \) after the initialization (isodensity of \( 4 \times 10^{-16} \, \text{kg m}^{-3} \)). Turbulence dominates the structure formation and creates several filamentary low-mass density maxima. The duration of this period before the onset of the collapse and thus the total "age" of the prestellar core stage depends on how turbulence is injected initially and its dissipation. In the course of time, the local density enhancements merge. After some additional \( 8.5 \times 10^4 \, \text{yr} \) just at the edge of gravitational instability, a single core has formed (second left panel, \( 5 \times 10^{-17} \, \text{kg m}^{-3} \)). The kinetic pressure support breaks down owing to rapid dissipation of turbulent energy inside the overdense region, and the core starts to collapse (\( t = 1.69 \times 10^5 \, \text{yr} \), third left panel, \( 5 \times 10^{-17} \, \text{kg m}^{-3} \)). A new single hydrostatic core forms when the gas becomes optically thick and the cooling time exceeds the dynamical time. Later on, the central part of the core is replaced by a sink particle. In the bottom left panel, the structure has flattened substantially, 20% percent of the total mass is already accreted onto the sink particle, and a massive disk has formed through an instability. It contains additional low-mass condensations and independently, a second fragment has started to form with a hydrostatic core (\( 5 \times 10^{-17} \, \text{kg m}^{-3} \)). The right panels give the isodensities for 0.16, 0.5, 1.6, and \( 5.2 \times 10^{-18} \, \text{kg m}^{-3} \) for a time of \( 2.4 \times 10^5 \, \text{yr} \), respectively. With increasing density, the second condensation becomes visible.1

2.2. Three-dimensional CRT Modeling of the Cores

The SPH density distributions of the gas were discretized on a three-dimensional grid and scaled to dust particle distributions assuming a dust-gas mass ratio of 1/100 and an efficient gas-dust mixing. The dust number densities were processed with a three-dimensional CRT code (Steinacker et al. 2003, 2002a, 2002b; Pascucci et al. 2004), producing 640 images of the cloud core at different wavelengths, times, and viewing angles, respectively. The temperatures were calculated from the radiative heating. Heating by compression is irrelevant during the prestellar core phase as a result of the fact that the cooling timescale is much faster than the dynamical timescale. For the illustrative purpose of this Letter, we used standard dust opacity data (Drain & Lee 1984) and a standard interstellar radiation field (Black 1994). Some of the images are shown in Figure 2 for the wavelengths 7, 15, 175, and 1300 \( \mu \text{m} \) (from top to bottom) and evolutionary times of 5.6 and 14.1 \( \times 10^4 \, \text{yr} \), respectively (left to right). The wavelengths are chosen to cover common observational windows (e.g., ISOCAM, ISOPHOT, IRAM, JCMT, CSO, Spitzer, Herschel). All images are scaled to have maximal contrast. A 10% random background noise representing a mean background variation was added for illustrative purpose only. In the MIR, as expected, the core is visible in absorption and the images reveal much of the outer thin structure, especially for the early stages. Detection of the inner, at later stages flattened struc-

1 See also animation at http://www.mpia-hd.mpg.de/homes/stein/Ani/animcf.htm.

Fig. 1.—Isodensity surfaces of the averaged SPH density distributions of a cloud core fragment. The left panels show densities of 40, 5, and \( 5 \times 10^{-17} \, \text{kg m}^{-3} \) at the times 5.6, 14.1, 16.9, and 27.2 \( \times 10^4 \, \text{yr} \) after the start of the simulation, respectively. The right panels give isodensity surfaces at the time 24.4 \( \times 10^4 \, \text{yr} \) and densities of 0.16, 0.5, 1.6, and \( 5.2 \times 10^{-18} \, \text{kg m}^{-3} \), respectively. [See the electronic edition of the Journal for a color version of this figure.]
structure is difficult and requires a careful background analysis. For wavelengths larger than 90 \( \mu m \), the cold dust can be seen in emission, revealing more of the inner structure at high densities, as the core also starts to get optically thin. This emission is dominating the millimeter images.

Animations showing the images for all viewing angles at different times of the evolution, as well as visualizations of the three-dimensional density data cube, can be found at the Web site given in footnote 1.

3. ONE-DIMENSIONAL ANALYSIS OF THE MAPS

Projection effects are a severe source of misinterpretation for structures seen in absorption or emission, as pointed out already, e.g., by Ballesteros-Paredes & Mac Low (2002). In Figure 3, we show as an example two structures seen at 7 \( \mu m \). The upper left panel depicts an elongated filament at an early stage of the evolution (5.6 \( \times 10^4 \) yr), while the upper right panel gives a flattened structure at a later stage (24.4 \( \times 10^4 \) yr). In the middle panels, the viewing angle was changed until we see the structures as a corelike feature. In the lower panel, they are zoomed and rebinned to an ISOCAM resolution typical for a core at 150 pc distance. We determined the one-dimensional number column density \( N(R) \) with the radius in the plane of the sky \( R \) by azimuthally averaging over annuli. As the absorption patterns have elliptical shape, we have used elliptical annuli. The resulting number column density was inverted to a one-dimensional number density distribution \( n(r) \) with the radius \( r \) using recursive integration. In Figure 4, we show the results for the early stage filament in the main panel and for the later stage disk in the inset. The range of profiles \( n(r) \) that have been transformed from \( N(R) \) profiles along individual directions is given by the solid thin lines, and the direction-averaged profile is plotted as a solid thick line. The dashed line indicates the slope of a density distribution following an \( r^{-2} \) power law as it was derived from one-dimensional core evolution models (Shu 1977). Although these absorption maxima are slightly less extended than commonly observed cores, the one-dimensional model seems to provide a reasonable description of the derived distributions. It could be inferred from this fit that the underlying density structure has an elliptical shape with a profile that—transformed to a spherical distribution—is in agreement with one-dimensional core evolution models. To compare with the true underlying three-dimensional density distribution, we calculated the number density \( n \) for a grid of equally sized cells from the SPH density distribution. For each cell, we determined the distance to the center of the “core” distribution defining a point in the \( n(r) \) diagram. This point distribution was rebinned to a gray-scale image for better clarity, where black refers to the maximum number of cells per bin. The advantage of this representation is that a one-dimensional core with a radial power law appears as a line in the \( n(r) \) diagram, with a gradient representing the power-law index.

The true density distributions overlaid as gray-scale images are far from being lines, as the filament is not one-dimensional spherically symmetric. The agreement with the one-dimensional evolution models would tend to validate static core formation.
The thick solid line. The dashed line indicates a dependency. The true maximum along elliptical tracks. The thin solid lines mark the range of profiles for individual directions, and the direction-averaged profile is represented by the thick solid line. The dashed line indicates an $r^{-2}$ dependency. The true three-dimensional density distribution $n_{gas}$ was discretized on a cell grid and transformed to a point distribution in the $n(r)$-plane. The number of points is shown as the gray-scale image, where black means the maximum number of grids with a certain density. The main picture corresponds to an elongated filament from the early stage, and the inset to a flattened structure from a later stage of the core evolution, respectively.

models, although the core formation mechanism modeled here is highly dynamical. This is in agreement with the findings of Ballesteros-Paredes et al. (2003). We also modeled the flattened structure at a later stage. The radial profile within the disk will be visible in our gray-scale representation as a line with the slope of the power-law exponent, and indeed the inset in Figure 4 shows a pronounced branch of the disklike structure. If the core-flattening is confirmed by an independent source of information, the column density profiles (and the resulting density profiles) can be used to determine the radial profile of the disklike structure.

4. CONCLUSIONS

We have presented three-dimensional simulations assuming that initially low-mass condensations pass through a stage of turbulence-dominated condensation where they accumulate mass and merge together to form extended prestellar corelike objects. The typical density structures in the cores are nonspherical throughout their evolution. The asymmetry is driven by the turbulent motion and causes complex structures from the very beginning. This complexity is partially seen in images that have been calculated from the densities obtained in the cloud core simulation. However, projection effects can lead to a severe misinterpretation of images. We showed that a one-dimensional analysis of the vicinity of the density maxima would suggest density profiles in agreement with one-dimensional core collapse models. The underlying density structure, however, is intrinsically three-dimensional and deviates strongly from the obtained one-dimensional model distribution.

As the column density also enters the optical thin emission in the millimeter range (aside from the Planck function), we expect the same projection ambiguities to occur when interpreting millimeter maps of dense molecular cloud regions. This aspect will be discussed in a forthcoming paper.

We conclude that one-dimensional modeling based on column density interpretation of images does not produce reliable structural information. For flattened structures appearing in later stages of the core evolution, a two-dimensional modeling might be applicable, but for the general case, multidimensional continuum and line radiative transfer modeling is required to derive consistent density and temperature distributions of the gas and dust in prestellar cores.

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