STAR FORMATION: 3D COLLAPSE OF TURBULENT CLOUD CORES

Michael A. Reid, Ralph E. Pudritz & James Wadsley

Department of Physics and Astronomy, McMaster University, Hamilton, ON, Canada L8S 4R8

Abstract

We have performed fully 3-D simulations of the collapse of molecular cloud cores which obey the logatropic equation of state. By following the collapse of these cores from states of near hydrodynamic equilibrium, we are able to produce accretion histories which closely resemble those of observed cores. The accretion proceeds in four distinct stages: an initial period of very slow accretion; a period of vigorous accretion following the development of a central density singularity, with $M \propto t^3$, as predicted by self-similar models; a period of relatively stable, vigorous accretion; and finally a gradual decrease in the accretion rate once about 50% of the available mass of the molecular cloud core has been accreted. These results may explain the accretion histories of cores as they pass through the pre-protostellar, Class 0, and Class I stages.

Key words: stars:formation – equation of state – methods: numerical

1. Introduction

Mounting evidence indicates that massive molecular cloud cores possess properties which are not adequately explained by models employing an isothermal equation of state. For example, surveys of prestellar cores in a variety of star-forming complexes show that intermediate and high mass cores have nonthermal line widths which are significantly greater than their thermal line widths (Caselli & Myers 1995). Models of the collapse of isothermal molecular cloud cores exhibit a number of features which are not borne out by observations, such as a time-invariant rate of accretion onto the central object (Shu 1977) and highly supersonic infall (Foster & Chevalier 1993).

To address some of the shortcomings of isothermal models, McLaughlin & Pudritz (1996) advanced a model for molecular cloud core collapse which accounts for some degree of turbulent support via a phenomenological equation of state. This logatropic equation of state reads $P/P_c = 1 + A \ln(\rho/\rho_c)$ where the subscript “c” denotes “central” values. The constant $A$ is an adjustable parameter whose value for a range of molecular cloud core masses was determined empirically by McLaughlin & Pudritz (1996) to be $A = 0.2 \pm 0.02$.

The logatropic equation of state admits two equilibrium solutions. The features of each solution are developed in McLaughlin & Pudritz (1996). The “singular” equilibrium solution is analogous to the singular isothermal sphere (SIS) of Shu (1977), except that its density profile is $\rho \propto r^{-1}$. The “nonsingular” solution is analogous to the Bonnor-Ebert sphere, in that it is a pressure-truncated equilibrium solution with a finite central density and density profile in its outer regions which matches that of the singular solution.

The nonsingular logatrope has the potential to be as useful a model for massive star-forming cores as the Bonnor-Ebert sphere is for low mass star-forming cores (see, for example, Alves, Lada, & Lada (2001) who showed that a Bonnor-Ebert sphere is an excellent fit to the structure of dark cloud B68). Hence, we undertook a numerical study of the collapse of a nonsingular logatropic sphere from an initially near-equilibrium state until most of its mass had been accreted onto the central condensation.

2. Numerical Methods and Tests

Our fully 3D simulations were conducted using the ZEUS-MP parallelized hydrodynamics code. We used a 256³ Cartesian grid with a “sink cell” at its centre. Mass falling into the sink cell was presumed to have accreted onto the central protostar and was represented thereafter by a point mass at the grid centre. The initial configuration for each of our simulations was a spherical molecular cloud core in near hydrodynamic equilibrium, surrounded by an external medium of low and constant pressure. We conducted extensive tests of our numerical method using the collapse of the singular logatrope (McLaughlin & Pudritz 1996).
1997) as our test case. Excellent agreement between the analytic and numerical solutions was found. (see Reid, Pudritz, & Wadsley (2002) for a full description of our numerical method).

3. Results

The most interesting of our results from the collapse of the nonsingular logatrobe are presented in Figures 1-3. Figures 1 and 2 show the evolution of the density and infall speed profiles of a collapsing nonsingular logatrobe prior to the formation of a singular density profile. The model has been scaled such that the total mass of the core is 1 $M_\odot$. The total core mass is determined by the choice of central temperature and external pressure—our choices of $T_c = 10$ K and $P_s = 1.3 \times 10^5$ k$_B$ result in a core of total mass 1 $M_\odot$, but the results can be rescaled and applied to models of higher mass (for example, by assuming a higher confining pressure). Indeed, observational evidence has emerged which indicates that the confining pressures on molecular cloud cores are one or two orders of magnitude higher than we assumed (Johnstone et al. 2000).

Perhaps one of the most notable features of Figure 1 is the behaviour of the density profile at late times. At the moment when the density becomes singular (labeled $t=0$), the density in the inner parts of the core scales as $r^{-3/2}$. This is the density profile expected for a collapsing singular logatropic sphere, as well as for a collapsing SIS. This implies that, whereas observations of $r^{-3/2}$ density profiles in molecular cloud cores have traditionally been interpreted as evidence for isothermal collapse, this should no longer be the case. Even models which incorporate turbulent support will show such a density profile.

Because of their extra nonthermal support, nonsingular logatropic spheres collapse more “gently” than do their isothermal counterparts. As can be seen by comparing our Figure 1 with Figure 1a of Foster & Chevalier (1993), the logatropic collapse is more gentle than that of the Bonnor-Ebert sphere. Foster & Chevalier (1993) find that, at the time of singularity formation, 44% of the mass of a Bonnor-Ebert sphere is in supersonic infall. We find that less than 5.5% of a nonsingular logatrobe is in supersonic infall at the same point in its evolution.

Figure 3 shows the rate of accretion onto the central object in collapsing nonsingular logatropes of masses 1, 2.5, and 5 $M_\odot$. The reader should bear in mind that these are fiducial masses only—the models can be rescaled to produce much more massive cores and hence higher accretion rates by increasing the confining pressure. Each curve shows the evolution of the accretion rate from the near-equilibrium starting point and until 95%, 91%, and 29% of the total available mass has been accreted (for the 1, 2.5, and 5 $M_\odot$ cases respectively).

4. Discussion

The accretion profiles shown in Figure 3 bear several important similarities to what is known observationally about accretion in young stellar objects. A simple picture of the evolution of an accreting molecular cloud core suggests an accretion history of the following form: accretion proceeds slowly through the pre-protostellar (PPC) phase, increases markedly at the formation of a central source (to power the substantial outflows seen in Class O sources), and finally declines and dissipates as the core passes into the Class I stage. André, Ward-Thompson, & Barsony (2000) mark the transition between the Class O and Class I phase at the point where the mass accreted onto the central object is roughly equal to that remaining in the envelope. Our results show a similar transition at the same point. As indicated for the 1 $M_\odot$ curve in Figure
there is an initial period of slow accretion, which we liken to the PPC stage. As soon as the density profile of the core becomes singular \((t = 0)\), which can be thought of as the moment of protostar formation, the accretion rate increases markedly, launching a phase of vigorous accretion sufficient to power an outflow. We liken this to the Class 0 phase. Once half of the available mass has been accreted, the accretion rate declines steadily to near-zero.

We suggest that our simulations of the collapse of logatropic molecular cloud cores bear significant similarities to the observations. They offer an alternative method for modelling the structure of intermediate and higher mass molecular cloud cores. Cores which exhibit density power-law indices of between 1 and 1.5 (see, for example, van der Tak et al. (2000)) should be pursued as possible candidate nonsingular logatropes. Our results bolster the argument that models of collapsing protostellar cores must account for some degree of nonthermal support in order to reproduce the observations.

**Acknowledgements**

We are grateful to the organizers of SFCHEM 2002 for allowing us to present our work. The work of M. A. R. was supported in part by a scholarship from the Natural Sciences and Engineering Research Council of Canada (NSERC). The work of R. E. P. was supported by NSERC. J. W. is a SHARCNET Research Associate.

**References**

Alves, J. F., Lada, C. J., & Lada, E. A. 2001, Nature, 409, 159

Andrè, P., Ward-Thompson, D., & Barsony, M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 59

Caselli, P., & Myers, P. C. 1995, ApJ, 446, 665

Foster, P. N. & Chevalier, R. A. 1993, ApJ, 416, 303

Johnstone, D., et al. 2000, ApJ, 545, 327

McLaughlin, D. E. & Pudritz, R. E. 1996, ApJ, 469, 194

McLaughlin, D. E., & Pudritz, R. E. 1997, ApJ, 476, 750

Reid, M. A., Pudritz, R. E., & Wadsley, J. 2002, ApJ, 570, 231

Shu, F. H. 1977, ApJ, 214, 488

---

**Figure 2.** Evolution of the radial infall speed, \(|v_r|\), of a 1 \(M_\odot\) nonsingular logatropic preceding the development of the singular density profile. Adapted from Reid, Pudritz, & Wadsley (2002).

**Figure 3.** Time evolution of \(M_{\text{acc}}(t)\) and \(\dot{M}_{\text{acc}}(t)\) for the collapse of nonsingular logatropic spheres with dimensionless radii of \(R/r_o = 1.34\) (solid line), 2.21 (dashed line), and 3.26 (dotted line). The data are scaled such that each core has a central temperature of \(T_c = 10^4\) K and surface pressure of \(P_s = 1.3 \times 10^3\) kB, giving them total masses of 1, 2.5, and 5 \(M_\odot\). The vertical dotted lines indicate suggested transitions between the PPC, Class O, and Class I stages for the 1 \(M_\odot\) model. Time \(t = 0\) marks the moment at which the core’s density profile becomes singular. Adapted from Reid, Pudritz, & Wadsley (2002).
van der Tak, F. S. et al. 2000, ApJ, 537, 283