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DENSITY AND VELOCITY PROFILES IN COLLAPSING CLOUD L694-2

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ABSTRACT

From the HCN observations of dense molecular cloud L694-2, Lee *et al.*(2007) determined internal distributions of density and velocity for the cloud. The density profile collaborates roughly with the Bonnor-Ebert gas sphere, but the velocity field departs significantly from the result of numerical simulations that are started from the BE sphere. Taking L694-2 as an example of collapsing clouds, we have performed a series of collapse simulations and determined initial configurations for the cloud in such a way that the resulting density and velocity profiles both match with the empirically deduced ones. Among many trial configurations the cloud which is initially uniform in density and bound by an expanding envelop depicts most closely the empirically obtained profiles of both density and velocity.

Key words : ISM: Dark molecular clouds; Spherical collapse

I. INTRODUCTION

The gravitational collapse of dark molecular clouds has remained an interesting problem over the at least last half century, because stars are known to form through the collapse. Analytically the collapse dynamics was studied by similarity solutions(Penston 1969; Hunter 1977; Shu 1977), and numerically by model simulations(Larson 1969; Foster & Chevalier 1993; Ogino *et al.* 1999; Hennebelle *et al.* 2003; Gómez *et al.* 2007). The similarity solutions show that through the collapse the density attains a flat-top distribution in the central region and varies with radial distance r as $1/r^2$ in the cloud outskirts, which are well-known characteristics of the Bonnor-Ebert(BE) isothermal gas sphere (Ebert 1955; Bonnor 1956). Observed maps of the dust extinction in the near infrared (Alves *et al.* 2001), the dust thermal emission in the infrared and millimeter wavelengths (Ward-Thompson *et al.* 1994; Bacmann *et al.* 2000; Tafalla *et al.* 2002), and the column density of CO molecules (Kim & Hong 2002 and references therein; Tafalla *et al.* 2002) seem to suggest that the radial density profile of dense molecular clouds follows roughly an $1/r^2$ relation in the cloud outskirts, which is often interpreted as indicating the BE characteristics. In details, however, there remain many meaningful discrepancies in the density profile between the observed clouds and the BE sphere(Kim & Hong 2002).

When we come to the internal kinematics, confront us puzzling discrepancies between the profile deduced from radio line observations and the one from the numerical simulations that are started from the BE sphere. Utilizing recent observations of HCN hyperfine transition lines, Lee *et al.* (2007) probed the density and velocity fields in L694-2, which is a dense molecular cloud of almost spherical shape. They demonstrated existence of strong in-fall motion in the cloud. Imposing isothermal condition and using Monte Carlo technique, they solved one dimensional radiative transfer equation for the F(0-1), F(2-1) and F(1-1) lines of HCN(J= 1-0) transition, and deduced both density and velocity fields for L694-2. This cloud undergoes a supersonic collapse with velocity reaching as high as 0.28 $km\,s^{-1}$, and the in-fall prevails in the region extending from 0.025 pc to 0.125 pc from the cloud center. However, most of the previous simulations started from the BE configuration show in-falling velocity and region much slower and wider than in L694-2, respectively.

In their numerical simulations of cloud collapse Hennebelle *et al.* (2003) explicitly took into account the hot inter-cloud medium surrounding the cold dense cloud. Very recently Gómez *et al.* (2007) assigned a shock generating velocity field to the medium of initially uniform density and let the uniform cloud undergo gravitational collapse. Both sets of the simulations have recovered the $1/r^2$-type density distribution nicely, but the resulting velocity fields are quite different from each other. In the case of Gómez *et al.* the shock makes the in-fall layer sharply bound. On the other hand, simulations started from the BE sphere demonstrate the in-fall motion everywhere in the cloud with a broad and smooth U-type velocity profile in the V_r versus $\log r$ plane. This left us a question about the proper initial conditions for the collapse simulation. In recent years we began to witness an increasing number of clouds showing in-fall signatures(Sohn *et al.* 2004). Therefore, empirically determined profiles of the in-fall velocity would serve a powerful observational constraint for modeling the cloud collapse.

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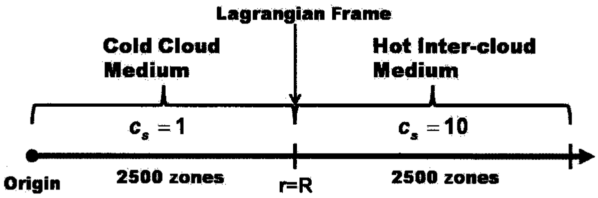

Fig. 1.— Schematic of the cloud model. The hot inter-cloud medium is superposed onto the cold cloud of radius R. The interface between the cloud and inter-cloud medium is treated as a contact discontinuity and tracked in the Lagrangian frame.

To understand the collapse dynamics in detail, we take L694-2 as a prototype of collapsing clouds and perform collapse simulation of model clouds having various initial configurations. By comparing the resulting profiles of density and velocity with those deduced from the radio line observations of L694-2, we may infer the initial configuration of the cloud. For this purpose we have developed one-dimensional hydrodynamics code, in which arbitrary Lagrangian-Eulerian frame is adopted to follow the cloud boundary freely.

II. SIMULATION METHOD

(a) Basic Cloud Model

It is hard to imagine clouds that are completely isolated from the ambient medium. Cloud of cold dense gas is usually surrounded by hot rarefied inter-cloud medium, and the latter is then to influence internal dynamics of the former(Hong *et al.* 1992; Kim 1997; Kim & Hong 2002). Schematic of the cloud model is given in figure 1. To avoid complications arising from possible mixing of the cloud and the inter-cloud media, we treat the cloud boundary as a contact discontinuity. Both media are assumed to be in the isothermal condition but at two different temperatures. The cloud medium is taken to be one hundred times colder and denser than the inter-cloud medium.

(b) Numerical Code

The existence of hot inter-cloud medium requires the code to have capabilities of handling multi-fluid medium and following the two fluid interface freely. For this very reason we have written a 1D multi-fluid hydrodynamics code. (Details of the code will be given in Seo *et al.* [2008]). With the code one can simulate the dynamics of isothermal gases at different temperatures or of gases with different specific heat ratios. In actual simulations we normalize variables of density ρ and flow velocity V_r to its central value ρ_0 and sound speed c_c, respectively. Introducing scale factor $\alpha = c_c\,[4\pi G\rho_0]^{-1/2}$, we denote the dimensionless distance by ξ ($= r/\alpha$). Here, c_c represents the *rms* speed in the cloud medium, which may include both thermal and non-thermal components. We assign a mesh to the interface, and let that particular mesh always follow the interface. The number of meshes drawn in each medium is fixed to be 2500 and adaptively adjusted to maintain the same number of zones. Since simulation results are found to converge, when the total number of meshes is over 3000, we fixed the total number at 5000 in all the simulations. Width of the inter-cloud medium is adjusted in such a way that the sound wave may not travel the whole extent of the medium in the elapsed time of each simulation. In this way the errors propagating from the computational boundary are kept not to disrupt the cloud.

III. COLLAPSE SIMULATIONS

As an initial configuration of collapsing clouds the BE gas sphere has been a popular choice, since its stability criterion is known analytically. If the cloud initial size, ξ_c, is larger than a critical value, $\xi_{crt} = 6.47$, the cloud is thought to be gravitationally unstable. For comparison purpose, we simulate collapse of the BE spheres first, and the results are compared with the ones from the collapse simulation of uniform cloud. For the initial size of the cloud, we took two cases $\xi_c = 8$ and 3 in the dimensionless unit, and increased density at every points by 1% relative to the equilibrium value. The resulting density and velocity fields are compared with those of L694-2 in figure 2, where the dashed and dash-dotted lines represent the simulation results of the BE cases with $\xi_c = 8$ and 3, respectively. The solid line in the figure is for the model of uniform cloud. Large open circles are for the collapsing cloud L694-2.

As can be seen from the left frame of figure 2, the density fields of the BE sphere deviate somewhat from the corresponding field of L694-2, particularly in the cloud outskirts. Lee *et al.* (2007) approximated the density field of L694-2 to a trial function of the form, $\rho(r) = \rho_0/[1 + (r/r_0)^{\beta}]$, and determined $\beta = 2.5$ as the best choice for the cloud. However, the collapse simulation of the BE spheres results in a logarithmic slope of -2. In contrast to the density, the simulated velocity field, in the right frame of the figure, differs markedly from that of L694-2.

Since the BE sphere may not describe the initial configuration of L694-2 adequately, we took uniform density cloud of size $\xi_c = 2.5$ for it and performed the collapse simulation. The resulting density and velocity fields are shown in the same figure by solid line with mark *Uni.* $\xi_c = 2.5$. The density field shows good agreement with that of L694-2 and those of the collapsing BE spheres as well. Apart from initial conditions, the collapse seems to proceed in a fashion of the quasi hydrostatic equilibrium, which can be achieved if $\rho(r) \propto r^{-2}$ in the outskirts of isothermal cloud.

Among the three simulations shown in the figure the case *Uni.* $\xi_c = 2.5$ best fits to the velocity field of L694-2. The in-fall layer and peak velocity of the initially uniform cloud are generally narrower and higher than

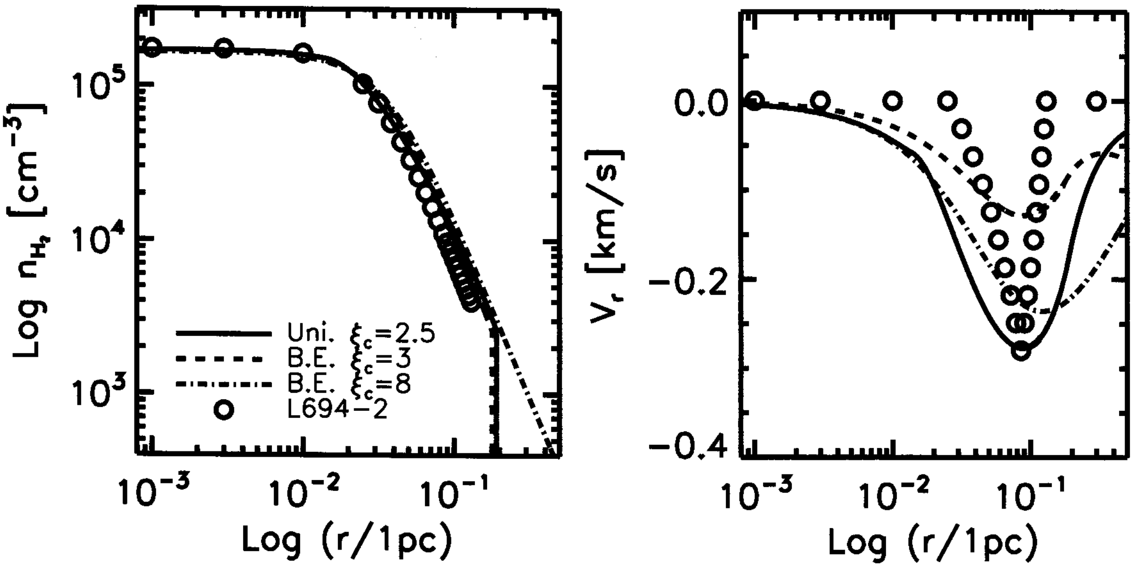

Fig. 2.— Density and velocity fields of collapsing model clouds are compared with the corresponding fields of L694-2. The model clouds started from the BE sphere are marked by *B.E.* ξ_c= 8 and *B.E.* ξ_c= 3, and the one from the uniform density cloud by *Uni.* ξ_c = 2.5. Although the initial conditions are different from model to model, the resulting density fields are all similar to each other. On the contrary, in the velocity field the initial cloud models distinguish themselves from each other. Internal kinematics may not be inferred from the density profile.

those of the BE spheres. Although the in-fall occurs in an area broader than the observation, the peak velocity position is consistent with the empirical determination of L694-2. We felt a need to have a means of narrowing the in-fall layer.

In order to reduce the in-falling region, we may impose an expansion motion near the cloud boundary. The expansion can be generated by tapering off the density of inter-cloud medium near the cloud boundary as

$$\rho(r) = \frac{P_0}{c_i^2} \exp[-(r - R)/\Delta],$$

where $r > R$, and P_0 and c_i represent the original pressure and the sound speed in the inter-cloud medium, respectively. By adjusting the width of the tapering region, Δ, we may control the expansion strength. If this type of expansion is imposed upon the initially uniform inter-cloud medium, the expansion motion first generated in the inter-cloud region is expected to gradually invade the cloud. In this way one may reduce the in-falling region of the cloud.

We have performed a number of simulations with varying strength of the imposed expansion. The resulting density field is still similar to the cases of the BE sphere: the dynamics of the inter-cloud medium doesn't seem to affect the quasi-equilibrium nature of the isothermal collapse. On the other hand, the velocity field turns out to depend much on the expansion strength. When the imposed expansion is strong (small Δ), the in-fall motion and region tend to get weak and narrow, respectively. In principle one may improve the comparison done in figure 2 better by imposing additional velocity field onto the initial cloud configuration. At the moment we are making this type of refinements.

IV. DISCUSSION AND CONCLUSION

As was pointed out by Shu (1977), development of the $1/r^2$-type density profile is a result of the balance between the pressure and the gravity forces. It is then understandable why the BE-like density profile is so robust a feature of the collapse simulations. Most of the observed clouds show a seemingly good agreement with the BE gas sphere(Alves *et al.* 2001; Kandori *et al.* 2005). Because of this agreement, Ebert's(1957) criterion $\xi_c \leq 6.47$ has been widely used in testing the cloud stability. However, the apparent agreement seen in density profile between the observation and the BE sphere doesn't necessarily mean that most of the interstellar clouds are in the BE stage. Even if a given cloud satisfies the criterion, we have no idea on what kind of the velocity field might be inside the cloud. For example, the cases of *B.E.* ξ_c = 3 and *Uni.* ξ_c =2.5 show density profiles hardly distinguishable from each other, but their velocity profiles are widely different in the peak in-fall velocity and the extent of in-fall region as well. Furthermore, the inter-cloud medium plays a considerable role in the internal dynamics of cloud.

From this study we may draw following conclusions: Once collapse starts, density field of the collapsing cloud quickly attains the $1/r^2$-type profile in the cloud outskirts. This doesn't mean the cloud is in the hydrostatic equilibrium of the Bonnor-Ebert isothermal gas sphere. The existence of inter-cloud medium makes the conventional stability criterion, $\xi_c \le \xi_{\rm crit}$, an insufficient one in predicting dynamical fate of clouds. It is suggestive that L694-2 currently experiences an expanding motion in its outskirts.

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