EXPOSED LONG-LIFETIME FIRST CORE: A NEW MODEL OF FIRST CORES BASED ON RADIATION HYDRODYNAMICS

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ABSTRACT

A first adiabatic core is a transient object formed in the early phase of star formation. The observation of a first core is believed to be difficult because of its short lifetime and low luminosity. On the basis of radiation hydrodynamic simulations, we propose a novel theoretical model of first cores, the Exposed Long-lifetime First core (ELF). In the very low-mass molecular core, the first core evolves slowly and lives longer than 10,000 years because the accretion rate is considerably low. The evolution of ELFs is different from that of ordinary first cores because radiation cooling has a significant effect there. We also carry out a radiation-transfer calculation of dust-continuum emission from ELFs to predict their observational properties. ELFs have slightly fainter but similar spectral energy distributions to ordinary first cores in radio wavelengths, therefore they can be observed. Although the probabilities that such low-mass cores become gravitationally unstable and start to collapse are low, we still can expect that a considerable number of ELFs can be formed because there are many low-mass molecular cloud cores in star-forming regions that could be progenitors of ELFs.

Key words: hydrodynamics – ISM: clouds – radiative transfer – stars: formation

Online-only material: color figures

1. INTRODUCTION

Larson (1969) studied star formation processes in low-mass molecular cloud cores using one-dimensional (1D) spherically symmetric hydrodynamic simulations. In his work, a transient, quasi-hydrostatic object is formed in the early phase of the protostellar collapse, a so-called first (adiabatic) core. The first core evolves via accretion from the natal core and it collapses again when it attains a temperature high enough to dissociate hydrogen molecules. Although first cores are transient, they are essential to understand star formation processes because they assume a crucial role in the two major problems in the star formation process, the angular momentum and the magnetic flux problem. The first cores are interesting sites of diverse phenomena related to these problems, such as driving molecular outflow (Tomisaka 2002; Matsumoto & Tomisaka 2004; Machida et al. 2006; Duffin & Pudritz 2009; Tomida et al. 2010; Ciardi & Hennebelle 2010), binary formation (Machida et al. 2008; Commerçon et al. 2010), planet formation (Inutsuka et al. 2010), circumstellar disk formation (Hennebelle & Ciardi 2009; Machida et al. 2010; Machida & Matsumoto 2010; Bate 2010; Dapp & Basu 2010), and so on. More than 40 years have passed since Larson’s theoretical prediction, but it has not been robustly confirmed yet by observations due to its observational difficulties. The lifetime of a first core is so short, on the order of 100–1000 years, compared to the dynamical timescale of its natal cloud, which can be about $10^2$–$10^4$ years depending on its initial density, that the detection probability of the first core is considered to be small. The first core is also deeply obscured in the infalling envelope with very large column density; hence, it is believed to be difficult to observe with current instruments. However, if we could observe first cores directly, they will significantly contribute to our understanding of star formation processes.

The evolution of cloud cores with masses around $1M_\odot$ has been well studied using three-dimensional (3D) numerical simulations (Bate 1998; Whitehouse & Bate 2006; Saigo et al. 2008; Commerçon et al. 2010; Tomida et al. 2010; Bate 2010). In those cases, the first cores evolve over very short dynamical timescales because accretion from their natal cores controls the evolution. Rotational support extends the lifetime of the first cores, but it is still brief compared to the dynamical timescales of the clouds (Saigo et al. 2008). However, we can expect that the first cores formed in very low mass cloud cores do not evolve into the second collapse stage over these short dynamical timescales because most of the gas in the envelope quickly falls into the first core and the accretion rate rapidly decreases. These first cores survive longer before the second collapse starts than do cores formed in more massive clouds. In the long-term evolution of these systems, radiation cooling plays an important role in disk stability and angular momentum transport (Gammie 2001). To handle the gas thermodynamics properly, radiation hydrodynamics (RHD) simulations are required.

Very recently, several groups reported possible detection of first core candidates. Chen et al. (2010) found a very faint and compact core and claimed that it was a good first core candidate. Their object must be very young, but it seems to be more evolved than a first core because it is associated with a well-collimated and high-velocity outflow, which is thought to be driven from a protostar after the second collapse. Chen & Arce (2010) reported another candidates in the R Corona Australis cloud. Enoch et al. (2010) found a good candidate for a first core whose spectral energy distribution (SED) is consistent with a theoretical model. A Japanese group (R. Kawabe et al. 2011, in preparation) also reported a peculiar dense core which is a good first core candidate. These objects need to be confirmed by more precise observations, but these observations imply that first cores are more common than expected. The observed candidates commonly have faint SEDs and some of them seem to have small masses. Considering the observed core mass function, there are so many low-mass cores whose masses
are less than $1 M_{\odot}$ (Motte et al. 1998; Enoch et al. 2007; Rathborne et al. 2009; André et al. 2010). In the initial mass function, there are still many low-mass stars and brown dwarfs (Chabrier 2003), although the relationship between the two mass functions is still unclear. Therefore, it seems reasonable and interesting to study the evolution of low-mass cores which have masses less than $1 M_{\odot}$.

The observational properties of first cores such as their SEDs were predicted on the basis of 1D RHD simulations (Masunaga & Inutsuka 2000) and post-processing radiation-transfer calculations by using the results of 3D hydrodynamic simulations with barotropic approximation (Saigo & Tomisaka 2010). First cores have faint, low-temperature black-body-like SEDs in wide wavelengths from mid-infrared to centimeter-length radio wave. First cores are faint but detectable with modern facilities such as the Herschel Space Observatory, the Submillimeter Array (SMA), the Expanded Very Large Array, and the Atacama Large Millimetre/Submillimetre Array (ALMA). With ALMA in full operation, it is expected that we will be able to resolve the structure of first cores such as spiral arms formed via gravitational instability in the disk and driving region of the molecular outflow driven by magnetic fields predicted with magnetohydrodynamics (MHD) simulations.

In this paper, we propose a new scenario for the evolution of first cores formed in very low mass cloud cores. We prove that first cores in the very low mass molecular cloud cores have significantly long lifetimes. We also calculated SEDs and visibility amplitude distributions of our model, and compared them with the models of both a typical first core and a starless core. The plan of this paper is as follows. In Section 2, we briefly describe our method of RHD simulations and models used in the simulations. We show the results of the numerical simulations in Section 3 and the observational properties of those simulated first cores in Section 4. Section 5 is devoted to conclusions and discussions.

2. METHOD AND MODELS

We perform 3D nested-grid self-gravitational RHD simulations. Radiation transfer is treated with gray flux limited diffusion approximation (Levermore & Pomraning 1981). The details of our simulation code are described in our previous work (Tomida et al. 2010), but we neglect magnetic fields in this work because initially we just intend to prove the concept. We use an idealized equation of state (EOS) with adiabatic index $\gamma = 5/3$, which is different from that used in our previous work, $\gamma = 7/5$, to make the calculations easier. We use the compiled tables of Rosseland and Planck mean opacities of Semenov et al. (2003) and Ferguson et al. (2005), as in our previous paper. The number of grid points in each level of the nested grids is 64$^3$, and the finer grid is generated around the center of the computational domain to resolve the local Jeans length with at least 16 grid cells to prevent artificial fragmentations (Truelove et al. 1997).

We calculated three models for comparison: $SI$ is a non-rotating $1 M_{\odot}$ model, $R1$ is a rotating $1 M_{\odot}$ model, and $R01$ is a rotating very low mass model whose mass is $0.1 M_{\odot}$. As the initial conditions, we take critical Bonnor–Ebert-like spheres with uniform rotation, and increase the density by a factor of 1.6 to make them unstable. The initial gas densities at the center and the radii of the clouds are $(\rho_c, R_c) = (3.2 \times 10^{-18} \text{ g cm}^{-3}, 6300 \text{ AU})$ in $SI$ and $R1$, and $(\rho_c, R_c) = (3.2 \times 10^{-16} \text{ g cm}^{-3}, 630 \text{ AU})$ in $R01$. It is not trivial how we should scale the angular velocity between models with different masses, but here, we assume that both $R1$ and $R01$ initially have the same amount of rotational energy, $T \equiv \alpha M R^2 \Omega^2$ ($\alpha$ is a constant of order unity). The initial angular velocities are $4.3 \times 10^{-14} \text{ s}^{-1}$ and $1.4 \times 10^{-12} \text{ s}^{-1}$ in $R1$ and $R01$, respectively. We adopt the boundary conditions that all the cells outside the sphere of the cloud radius maintain their initial values. The initial gas temperature and boundary conditions for radiation transfer are set to 10 K. Here, we note that our boundary conditions allow the gas to inflow into the computational domain through the boundaries, and at the end of the simulations about 30% of the initial mass increased in the low-mass case and less than 10% increased in the $1 M_{\odot}$ cases.

3. RESULTS

We show the cross sections of the gas density and temperature of Model $R1$ and Model $R01$ at the epoch when they have the same first core masses, $1.06 \times 10^{-1} M_{\odot}$, in Figure 1. Here, the first core mass, $M_{FC}$ is defined as

$$M_{FC} = \sum_{\rho > \rho_{FC}} \rho \Delta V,$$

where $\Delta V$ is the volume of the cell and $\rho_{FC}$ is the critical density defined as the minimum density in the gas that experienced the shock, which we identified as the region where the radial velocity is less than the local sonic speed, $|V_r| < c_s$. The age of the first core at this epoch, $t_{FC}$, is 3100 yr in $R1$ and 10,600 yr in $R01$ from the core formation. Model $R01$ has a significantly larger (∼100 AU) first core disk because it is more evolved and the gas with a larger specific angular momentum from the outer region has accreted onto the core. Another outstanding difference between the models can be seen in the gas density and temperature in their envelopes. For the low-mass core model, almost all the materials in the natal core have already accreted onto the first core, and therefore, the gas density in the envelope is reduced drastically. Two factors cause the lower temperature in the envelope of $R01$: the smaller accretion rate in the very low mass core results in a weaker shock at the surface of the first core, and thus, less entropy is produced at the shock (in other words, the first core is intrinsically colder and fainter), and the smaller optical depth of the envelope contributes to the efficient radiation transport and cooling.

In Figure 2, we show the time evolution of physical quantities in each model such as central gas density (a), temperature (b), first core mass (c) and accretion rate onto the first core (d). It is obvious that $R01$ has a smaller accretion rate and its mass increases more slowly than it does in other models. As a result, the gas density and temperature at the center of the first core evolve significantly slower. The lifetime of the first core, from its formation to the second collapse, reaches more than $10^4$ years in $R01$. Both $1 M_{\odot}$ models achieved similar accretion rates because the initial structure of the cloud core determines the accretion rate (Saigo et al. 2008), although the non-rotating model evolves faster than the rotating model. These results clearly indicate that centrifugal force supports a considerable mass and prevents the first core from collapsing. We note that the lifetime of the non-rotating model is longer than previous predictions (Masunaga & Inutsuka 2000), by about a factor of two, because we assume a simple stiff EOS of $\gamma = 5/3$, and our model has a smaller accretion rate due to stable initial conditions. But in the rotating models, the difference of EOS affects the results less significantly because the centrifugal force dominates the structure of the first core disk.
We show the thermal evolution tracks of the gas elements at the center of the clouds in the $\rho$–$T$ plane in Figure 3. All the models show the effects of radiation cooling, but it appears most significantly in the low mass model. We also plot the evaporation temperatures of each dust component, which affect the thermal evolution of the gas. When the gas temperature reaches the evaporation temperature of iron and silicates, $T \sim 1400$ K, the opacity drops substantially and the core collapses violently, similar to the second collapse due to the endothermic reaction of hydrogen molecule dissociation. However, if we adopt a soft EOS with $\gamma = 7/5$, the impact of dust evaporation becomes less important because the gas density (and therefore the optical depth) at the same temperature is higher. Thus, the effect of radiation cooling is important in the low-mass core where dynamical accretion does not dominate the evolution. RHD simulations are required for these systems because the barotropic approximation fails to reproduce the realistic thermal evolution.

Our results show that the low-mass model has a longer lifetime compared with the dynamical timescale of its natal core. Therefore, we call this model an Exposed Long-lifetime First core (ELF). This suggests that a large fraction of low-mass cores can harbor the first core when we carry out an unbiased survey of collapsing starless cores. Although only a small fraction of the low-mass cloud cores is gravitationally bound and will collapse into stars, there are a lot of low-mass cores in star-forming regions, and we can, therefore, expect that a considerable number of ELFs can form.

4. OBSERVATIONAL PROPERTIES OF THE FIRST CORES

We calculated the SEDs of first cores in the RHD simulations by performing post-processing radiation transfer. We solve the following radiation-transfer equation in one direction to draw an intensity distribution map for various inclination angles and wavelengths:

$$\frac{dI_{\nu}}{ds} = \rho \kappa_{\nu}(B_{\nu}(T) - I_{\nu}),$$

where $B_{\nu}(T)$ is the Planck function of temperature $T$ and $\kappa_{\nu}$ is the monochromatic (absorption) opacity. Here, we assume that the temperature $T$ obtained in the RHD simulations is correct, and we ignore scattering, which is a valid assumption in mid-infrared or longer wavelengths. We adopt the monochromatic dust opacities provided by Semenov et al. (2003), using the homogeneous aggregates model of normal abundances.

In Figure 4, we show the SEDs of our RHD models in the face-on configurations. For comparison, we also plot the SED of 0.1 $M_\odot$ Bonnor–Ebert sphere, a model of a low-mass starless core, and observed SED of L1521F-IRS (Bourke et al. 2006), which is a very low luminosity object (VeLLO) in the Taurus molecular cloud. The distance toward the targets is set to 150 pc and the SEDs are measured with a (1000 AU)$^2$ aperture. The flux in the far-infrared wavelengths increases when the first core forms and it can be observed with Herschel. Compared to L1521F-IRS, Model $R1$ has similar brightness in the submillimeter region but it disagrees in the mid-infrared region. In contrast, Model $R01$ is fainter than L1521F-IRS in...
Figure 2. Time evolution of the physical quantities, central gas density (a), temperature (b), first core mass (c), and smoothed accretion rate (d). Model R01 shows prominently longer lifetime than 1 $M_\odot$ models, S1 and R1. (A color version of this figure is available in the online journal.)

Figure 3. Evolution tracks of the thermal properties of the central gas elements in the $\rho$–$T$ plane. The dust evaporation temperatures are overplotted with orange dash-dotted lines. All the models show the influence of radiation cooling but it is most significant in the low-mass model.

Figure 4. SEDs of the first core models at the same epoch as in Figure 1 in face-on configuration and a 0.1 $M_\odot$ starless core. The observed SED of L1521F-IRS (Bourke et al. 2006) is also plotted. The distance toward the targets is 150 pc and the aperture is (1000 AU)$^2$. First cores are more luminous than starless cores, especially in the far-infrared wavelengths. Model R1 is brighter than Model R01 in radio wavelengths. On the other hand, Model R01 exceeds Model R1 in the mid-infrared region.

(A color version of this figure is available in the online journal.)

first core candidates (Enoch et al. 2010). We will discuss the time evolution of observational properties of first cores in a subsequent paper.

First cores emit larger flux in the infrared region than starless cores, but it is still difficult to identify the existence of a first core only from the SED, because it is so faint in the infrared wavelengths and the differences in radio wavelengths between the first cores and the starless cores are not so prominent. Another good method to distinguish first cores from starless cores is high resolution observation measuring visibility amplitude (Fourier components of the intensity map) distributions with (sub)millimeter interferometers. We show simulated visibility amplitude profiles of Model R01 measured in 850 $\mu$m, obtained with the Common Astronomy Software Applications (CASA) in Figure 5. The visibility amplitude of the starless core decreases steeply in the small scale because it contains no fine structure. In contrast, the first core clearly
Very low mass cores will not collapse so often by self-gravity and the formation probability of ELFs may be low. However, ELFs are still worth considering because there are a number of low-mass cores both in observations (Motte et al. 1998; Enoch et al. 2007; Rathborne et al. 2009; André et al. 2010) and in theoretical predictions (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008). ELFs are longlived compared to the dynamical timescale of their natal cloud cores, so observation possibilities are higher than for usual first cores. Therefore, we can expect that a considerable number of ELFs exist in the star-forming regions. Other mechanisms such as external pressure, cloud–cloud collision, radiation driven implosion (Motoyama et al. 2007), and dynamical ejection (Bate 2009) may help the formation of ELFs. We will study the effects of magnetic fields and a realistic EOS in future works.

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REFERENCES

André, P., et al. 2010, A&A, 518, L102
Bate, M. R. 1998, ApJ, 508, L95
Bate, M. R. 2009, MNRAS, 392, 590
Bate, M. R. 2010, MNRAS, 404, L79
Bourke, T. L., et al. 2006, ApJ, 649, L37
Chabrier, G. 2003, PASP, 115, 763
Chen, X., & Arce, H. G. 2010, ApJ, 720, L169
Chen, X., Arce, H. G., Zhang, Q., Bourke, T. L., Launhardt, R., Schmalzl, M., & Henning, T. 2010, ApJ, 715, 1344
Ciardi, A., & Hennebelle, P. 2010, MNRAS, 409, L39
Commerçon, B., Hennebelle, P., Audit, E., Chabrier, G., & Teyssier, R. 2010, A&A, 510, L3
Dapp, W. B., & Basu, S. 2010, A&A, 521, L56
Duffin, D. F., & Podriz, R. E. 2009, ApJ, 706, L46
Enoch, M. L., Glenn, J., Evans, N. J., II, Sargent, A. I., Young, K. E., & Huard, T. L. 2007, ApJ, 666, 982
Enoch, M. L., Lee, J., Harvey, P., Dunham, M. M., & Schnee, S. 2010, ApJ, 722, L33
Ferguson, J. W., Alexander, D. R., Allard, F., Barman, T., Bodnarik, J. G., Hauschildt, P. H., Hoffner-Wong, A., & Tamanai, A. 2005, ApJ, 623, 585
Gamme, C. F. 2001, ApJ, 553, 174
Hennebelle, P., & Chabrier, G. 2008, ApJ, 684, 395
Hennebelle, P., & Ciardi, A. 2009, A&A, 506, L29
Inutsuka, S., Machida, M. N., & Matsumoto, T. 2010, ApJ, 718, L58
Larson, R. B. 1969, MNRAS, 145, 271
Levermore, C. D., & Pomraning, G. C. 1981, ApJ, 248, 321
Machida, M. N., Inutsuka, S.-i., & Matsumoto, T. 2006, ApJ, 647, L151
Machida, M. N., Inutsuka, S.-i., & Matsumoto, T. 2010, ApJ, 724, 1006
Machida, M. N., & Matsumoto, T. 2010, arXiv:1008.0920
Machida, M. N., Tomisaka, K., Matsumoto, T., & Inutsuka, S.-i. 2008, ApJ, 677, 327
Masunaga, H., & Inutsuka, S.-i. 2000, ApJ, 531, 350
Matsumoto, T., & Tomisaka, K. 2004, ApJ, 616, 266
Motoyama, K., Unemoto, T., & Shang, H. 2007, A&A, 467, 657
Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150
Padoan, P., & Nordlund, Á. 2002, ApJ, 576, 870

Figure 5. Visibility amplitude distributions of the 0.1 $M_\odot$ first core model and a 0.1 $M_\odot$ Bonnor–Ebert sphere as a model of a starless core. The first core model shows clearly shallower distribution compared to the starless core. The edge-on configuration shows more widely scattered visibility amplitude corresponding to its oblate morphology.

(A color version of this figure is available in the online journal.)
Rathborne, J. M., Lada, C. J., Muench, A. A., Alves, J. F., Kainulainen, J., & Lombardi, M. 2009, ApJ, 699, 742
Saigo, K., & Tomisaka, K. 2010, ApJ, in press
Saigo, K., Tomisaka, K., & Matsumoto, T. 2008, ApJ, 674, 997
Semenov, D., Henning, T., Helling, C., Ilgner, M., & Sedlmayr, E. 2003, A&A, 410, 611
Tomida, K., Tomisaka, K., Matsumoto, T., Ohsuga, K., Machida, M. N., & Saigo, K. 2010, ApJ, 714, L58
Tomisaka, K. 2002, ApJ, 575, 306
Truelove, J. K., Klein, R. I., McKee, C. F., Holliman, J. H., II, Howell, L. H., & Greenough, J. A. 1997, ApJ, 489, L179
Whitehouse, S. C., & Bate, M. R. 2006, MNRAS, 367, 32
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The physical unit of the vertical axis in Figure 4 should not be (mJy) but (Jy). All the results and discussions are not affected by this correction.