BINARY FORMATION IN STAR-FORMING CLOUDS WITH VARIOUS METALLICITIES

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ABSTRACT

Cloud evolution for various metallicities is investigated by three-dimensional nested grid simulations, in which the initial ratio of rotational to gravitational energy of the host cloud \( \beta_0 = (10^{-3} \text{ to } 10^{-1}) \) and cloud metallicity \( Z = (0 \text{ to } Z_{\odot}) \) are parameters. Starting from a central number density of \( n_c = 10^4 \text{ cm}^{-3} \), cloud evolution for 48 models is calculated until the protostar is formed \( (n_s \simeq 10^{23} \text{ cm}^{-3}) \) or fragmentation occurs. The fragmentation condition depends on both the initial rotational energy and the cloud metallicity. Cloud rotation promotes fragmentation, while fragmentation tends to be suppressed in clouds with higher metallicity. Fragmentation occurs when \( \beta_0 > 10^{-3} \) in clouds with solar metallicity \( (Z = Z_{\odot}) \), while fragmentation occurs when \( \beta_0 > 10^{-3} \) in the primordial gas cloud \( (Z = 0) \). Clouds with lower metallicity have larger probability of fragmentation, indicating that the binary frequency is a decreasing function of cloud metallicity. Thus, the binary frequency at the early universe (or lower metallicity environment) is higher than at the present day (or higher metallicity environment). In addition, binary stars born from low-metallicity clouds have shorter orbital periods than those from high-metallicity clouds. These trends are explained in terms of the thermal history of the collapsing cloud.

Subject headings: binaries: general — cosmology: theory — early universe — stars: formation

1. INTRODUCTION

Observations have shown that about 60%–80% of field stars are members of binary or multiple systems (e.g., Duquennoy Mayor 1991). Hence, a majority of main-sequence stars belong to binary or multiple systems. These stars have a metallicity equivalent to that of the Sun (i.e., solar metallicity). On the other hand, Lucatello et al. (2005) investigated radial velocities of binary or multiple systems. These stars have a metallicity from the formation of dense cores \( (n \approx 10^4 \text{ cm}^{-3}) \) up to stellar core formation \( (n \approx 10^{25} \text{ cm}^{-3}) \). The calculations indicate that the binary frequency increases as cloud metallicity lowers, and binary separation in lower metallicity clouds is narrower than in higher metallicity clouds.

For the present-day star formation process, detailed numerical simulations studies of fragmentation and the binary formation process have been performed by many authors (see Goodwin et al. 2007). In these studies, the cloud evolution has been calculated from \( n_c = 10^4 \text{ cm}^{-3} \) to \( \approx 10^{23} \text{ cm}^{-3} \), where \( n_c \) is the number density at the cloud center. The studies have shown that fragmentation occurs only for \( 10^5 \text{ cm}^{-3} \leq n_c \leq 10^9 \text{ cm}^{-3} \) (see also Bate 1998).

On the other hand, in the collapsing primordial cloud \( (Z = 0) \), fragmentation rarely occurs for \( 10^9 \text{ cm}^{-3} \leq n_c \leq 10^{16} \text{ cm}^{-3} \) (e.g., Yoshida et al. 2006; Bromm et al. 2002; Abel et al. 2002) and frequently occurs for \( n \approx 10^{16} \text{ cm}^{-3} \) (Saigo et al. 2004; Machida et al. 2008a). Machida et al. (2008a) also showed that binary separation in the early universe is narrower than that at the present day. Recently, star formation in a collapsing low-metallicity \( (Z \leq 10^{-4} Z_{\odot}) \) gas cloud has been studied by Tsuribe & Omukai (2006, 2008), Smith & Sigurdsson (2007), and Clark et al. (2008). Clark et al. (2008) found that binary or multiple stellar systems can form even in a low-metallicity cloud. However, in their studies, since they adopted a sink cell, they calculated the cloud evolution only up to \( n_s \approx 10^{16} \text{ cm}^{-3} \). Fragmentation may occur in a later collapsing phase \( (n_s \approx 10^{16} \text{ cm}^{-3}) \), as shown in Machida et al. (2008a).

In this Letter, we adopt a barotropic equation of state and calculate the evolutions of collapsing clouds with various metallicities \( (Z = 0 \text{ to } Z_{\odot}) \), from the formation of dense cores \( (n \approx 10^4 \text{ cm}^{-3}) \) up to stellar core formation \( (n \approx 10^{23} \text{ cm}^{-3}) \). The calculations indicate that the binary frequency increases as cloud metallicity lowers, and binary separation in lower metallicity clouds is narrower than in higher metallicity clouds.

2. MODEL AND NUMERICAL METHOD

To study the evolution of star-forming cores in a large dynamic range of density and spatial scale, a three-dimensional nested grid method is used and the equations of hydrodynamics including self-gravity are solved (see eqs. [1]–[3] of Machida et al. 2008a). For gas pressures in collapsing clouds with different metallicities, barotropic relations that approximate the dynamic range of density and spatial scale, a three-dimensional approach is taken.

For the case of spherical symmetry, the initial central density is taken as \( n_{\odot} = 1.4 \times 10^4 \text{ cm}^{-3} \). Each cloud rotates rigidly around the z-axis. The initial temperatures, which are derived from Omukai et al. (2005), are different in clouds with different metallicities (see dotted lines

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of Fig. 1). For example, a cloud with $Z = 0$ (primordial composition) has an initial temperature of 230 K, while a cloud with $Z = Z_{\odot}$ (solar composition) has 7 K as the initial temperature. Since critical Bonnor-Ebert spheres are assumed as the initial state, the radii of the initial spheres are different depending on the initial temperature (or assumed metallicity): the radius of a $Z = 0$ cloud is $5.5 \times 10^4$ AU, while that of a $Z = Z_{\odot}$ cloud is $1.2 \times 10^3$ AU. We have confirmed that these initial differences of radius do not greatly affect the subsequent cloud evolution in calculations.

The models are characterized by two parameters: the initial rotational energy $\beta_0$ of whole cloud and the cloud metallicity $Z$. The values used for these parameters are $\beta_0 = 10^{-3}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}$ and $Z = 0, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1$ $Z_{\odot}$. Combining these two ranges of values, cloud evolution for 48 models is investigated. To induce fragmentation, 1% of the nonaxisymmetric density perturbation of the $m = 2$ mode (i.e., bar mode) is added to the initial cloud (for details, see Machida et al. 2008a).

To calculate a large spatial scale, the nested grid method is adopted (for details, see Machida et al. 2005a, 2005b). Each level of a rectangular grid has the same number of cells $(128 \times 128 \times 8)$, although the cell width $h(l)$ depends on the grid level $l$. The cell width is reduced by a factor of 2 for every upper level. The calculation is first performed with three grid levels $(l = 1, 2, 3)$. The box size of the coarsest grid $l = 1$ is chosen to be $2R_e$, where $R_e$ is the radius of the critical Bonnor-Ebert sphere. A new finer grid is generated whenever the minimum local Jeans length becomes smaller than $8h(l_{\text{max}})$, where $h$ is the cell width. The maximum level of grids is restricted to $l_{\text{max}} \leq 30$.

3. RESULTS

In each model, starting from a nearly hydrostatic core with central density $n_c = 10^4 \text{ cm}^{-3}$, the evolution of the collapsing cloud is calculated. When fragmentation does not occur, the cloud evolution is calculated until the protostar is formed at $n_c = 10^{22} \text{ cm}^{-3}$. When fragmentation does occur, the calculation is often stopped after fragmentation (i.e., before the protostar formation), because fragments escape from the finest grid.

Figure 2 shows the final state for each model against the metallicity $Z$ (x-axis) and initial rotation energy $\beta_0$ (y-axis). In the figure, the cloud evolutions are classified into four types: fragmentation (red panel border), merger (violet), nonfragmentation (blue), and stable core (gray) models. Fragmentation occurs and two or more fragments appear in fragmentation and merger models. After fragmentation, fragments survive without merger until the end of the calculation in fragmentation models, while fragments merge to form a single core in merger models. In nonfragmentation and stable core models, fragmentation does not occur. A single protostar is formed in nonfragmentation models, while a long-lived core is formed before protostar formation in stable core models.

The rightmost column in Figure 2 shows the final states for models with solar metallicity $(Z = Z_{\odot})$. Including radiative effects, the evolution of clouds with solar metallicity has been investigated by many authors. Assuming spherical symmetry, the evolution from the molecular cloud to the stellar core has been calculated by many authors (e.g., Larson 1969; Masunaga & Inutsuka 2000). In three dimensions, Stamatellos et al. (2007) have calculated stellar core formation from the molecular cloud core. These studies have shown that the molecular gas obeys the isothermal equation of state with a temperature of $\sim 10 \text{ K}$ until $n_c = 10^{12} \text{ cm}^{-3}$, then the cloud collapses almost adiabatically $(10^4 \text{ cm}^{-3} \leq n_c \leq 10^{16} \text{ cm}^{-3})$ (adiabatic phase) and a quasi-static core (hereafter, first adiabatic core) forms during the adiabatic phase. Thermal evolution for a cloud with solar metallicity is also confirmed in Figure 1, in which the gas temperature increases adiabatically after the number density reaches $n_c = 10^{11} \text{ cm}^{-3}$. In models with solar metallicity, the first adiabatic core surrounded by a shock front is formed at $n_c = 10^{10}-10^{14} \text{ cm}^{-3}$.

The rightmost column of Figure 2 (models with $Z = Z_{\odot}$) indicates that fragmentation occurs when the initial cloud has $\beta_0 > 10^{-3}$. In these clouds, fragmentation occurs only after the first adiabatic core formation: fragmentation occurred at $n_c = 6.8 \times 10^{11} \text{ cm}^{-3}$ ($\beta_0 = 10^{-1}$), $n_c = 2.4 \times 10^{12} \text{ cm}^{-3}$ ($\beta_0 = 10^{-2}$), and $n_c = 1.7 \times 10^{13} \text{ cm}^{-3}$ ($\beta_0 = 10^{-3}$). In these fragmentation models, fragments survived without merger until the end of the calculation for models with $\beta_0 = 10^{-3}$ and $10^{-2}$, while a single stable adiabatic core was formed after merger in the model with $\beta_0 = 10^{-3}$. The fragmentation condition ($\beta_0 > 10^{-3}$) for a cloud with solar metallicity is consistent with that of Matsumoto & Hanawa (2003b). Matsumoto & Hanawa (2003b) calculated the evolution of a cloud with solar metallicity in a large parameter space and found that fragmentation occurs when the initial cloud has $\beta_0 > 2.2 \times 10^{-3}$. In addition, many studies have shown that fragmentation occurs only after the first adiabatic core formation (see Goodwin et al. 2007).

For clouds with $Z = Z_{\odot}$, fragmentation occurs in models with $\beta_0 \geq 10^{-3}$ after the first adiabatic core formation, while stable first adiabatic cores are formed in models with $\beta_0 < 10^{-4}$. In models with $\beta_0 < 10^{-4}$, although the cloud evolution was calculated for a sufficiently long time, the first adiabatic core did not collapse to reach the protostellar density $(n_c = 10^{22} \text{ cm}^{-3})$. When a nonrotating cloud is adopted as the initial state, the first adiabatic core increases its mass with time by gas accretion and can collapse again (the second collapse; see Masunaga & Inutsuka 2000) to form a protostar in a short time. On the other hand, a long-lived first adiabatic core is frequently formed in a rotating cloud, as shown in Saigo & Tomisaka (2006). This long-lived core can collapse further after the nonaxisymmetric perturbation grows sufficiently owing to the bar mode instability (Durisen et al. 1986), because the angular momentum of the core is transferred by the nonaxisymmetric structure (Bate 1998; Saigo & Tomisaka 2006). To investigate further the evolution for models with $\beta_0 < 10^{-4}$, in different
models of Figure 2, a large initial amplitude of the nonaxisymmetric perturbation is adopted. In these calculations, after the first adiabatic core formation, the nonaxisymmetric pattern grows and the cloud collapses (the second collapse) to reach the stellar density \( n_s \approx 10^{12} \text{ cm}^{-3} \). However, these models do not show fragmentation even in the later evolution phase \( (n_s \gtrsim 10^{14} \text{ cm}^{-3}) \), as shown in Bate (1998). Thus, it is expected that fragmentation does not occur in stable core models even after a calculation for an extended time period. This is because the central region transforms from a disklike to a spherical configuration due to the large thermal energy after the first adiabatic core formation; fragmentation can easily occur in a thin disklike configuration. In addition, the angular momentum is effectively transferred from the high-density region by the nonaxisymmetric pattern.

The leftmost column of Figure 2 shows final states for models with \( Z = 0 \) (primordial cloud). In the primordial cloud, fragmentation occurs in clouds with \( \beta_0 > 10^{-6} \), which is consistent with the results of Machida et al. (2008a). These panels also show that the fragmentation scale (i.e., distance between fragments) increases with \( \beta_0 \). As shown in Machida et al. (2008a, 2008b) the fragmentation scale is comparable to the Jeans length at the fragmentation epoch. Since fragmentation occurs in the earlier epoch (or lower density) for models with larger \( \beta_0 \), and the Jeans length shortens as the density increases, fragments have a larger separation in clouds with larger \( \beta_0 \).

The first adiabatic core is formed at \( n_s \approx 10^{11}-10^{14} \text{ cm}^{-3} \) in clouds with solar metallicity, while the protostar is formed directly without the first adiabatic core formation in the primordial cloud. As shown in Figure 1, since the temperature in the primordial cloud \( (Z = 0) \) gradually increases with \( \gamma \approx 1.1 \) of the polytropic index (Omukai & Nishi 1998) in a wide density range of \( 10^3 \text{ cm}^{-3} < n_s < 10^{18} \text{ cm}^{-3} \), the (first) adiabatic core is not formed before the protostar formation \( (n_s \approx 10^{21} \text{ cm}^{-3}) \). Thus, fragmentation can occur for \( n_s \approx 10^{21} \text{ cm}^{-3} \) in the primordial cloud in which the cloud collapses keeping a thin-disk structure, while fragmentation occurs only for \( n_s \approx 10^{14} \text{ cm}^{-3} \) in clouds with solar metallicity. In addition, in the primordial cloud, since the central region can spin up until the protostar is formed \( (n_s \approx 10^{21} \text{ cm}^{-3}) \) due to the absence of the first adiabatic core (see Machida et al. 2007), fragmentation occurs even in clouds with smaller \( \beta_0 \).

In Figure 2, the border between fragmentation and nonfragmentation models is shown by a gray-white line, which indicates that fragmentation tends to occur in clouds with lower metallicity. For example, fragmentation occurs in models with \( \beta_0 > 10^{-4} \) for...
clouds with $Z = 10^{-5} Z_\odot$ and $10^{-4} Z_\odot$, while fragmentation occurs for $\beta_0 > 10^{-3}$ for clouds with $Z = 10^{-3} Z_\odot$ and $10^{-2} Z_\odot$. The fragmentation epoch is closely related to the first adiabatic core formation epoch. The first adiabatic core is formed in clouds with $Z \geq 10^{-3} Z_\odot$, while the first adiabatic core is not formed in clouds with $Z < 10^{-5} Z_\odot$. As shown in Figure 1, the gas temperature increases keeping $\gamma = 1.1$ for clouds with $Z = 0$ and $10^{-6} Z_\odot$, while the gas temperature increases adiabatically ($\gamma = 1.4$) after the central density reaches $n_c = 10^{11}$--$10^{10} \text{cm}^{-3}$ in clouds with $Z \geq 10^{-3} Z_\odot$. In clouds with $Z \geq 10^{-2} Z_\odot$, the epoch when the cloud collapses adiabatically depends on the cloud metallicity. The first adiabatic core is formed at an earlier epoch (or lower density) in clouds with higher metallicity. For example, the first adiabatic core is formed at $n_c = 5 \times 10^{11} \text{cm}^{-3}$ in clouds with $(Z, \beta_0) = (10^{-1}, 10^{-6})$, while the first adiabatic core is formed at $n_c = 6 \times 10^{10} \text{cm}^{-3}$ in clouds with $(Z, \beta_0) = (10^{-3}, 10^{-6})$. When the first adiabatic core is formed at a later evolution phase (or higher density), the cloud is spinning up for a long time and forms a thin rotating disk even in clouds with small $\beta_0$. Then, fragmentation occurs in the thin disk.

4. DISCUSSION

Although we cannot observe the primordial gas cloud in the early universe, we have observed many molecular clouds in the solar neighborhood. Caselli et al. (2002) observed about 60 molecular cloud cores and found them to have rotational energies in the range $\beta_0 > 10^{-3}$, with a typical value $\beta_0 = 5 \times 10^{-4}$, while the first adiabatic core is formed at $n_c = 6 \times 10^{10} \text{cm}^{-3}$ in clouds with $(Z, \beta_0) = (10^{-3}, 10^{-6})$. When the first adiabatic core is formed at a later evolution phase (or higher density), the cloud is spinning up for a long time and forms a thin rotating disk even in clouds with small $\beta_0$. Then, fragmentation occurs in the thin disk.

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