The origin and formation of the circumstellar disc

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ABSTRACT

The formation and evolution of the circumstellar disc in the collapsing molecular cloud with and without magnetic field is investigated from the pre-stellar stage resolving both the molecular cloud core and the protostar itself. In the collapsing cloud core, the first (adiabatic) core appears prior to the protostar formation. Reflecting the thermodynamics of the collapsing gas, the first core is much more massive than the protostar. When the molecular cloud has no angular momentum, the first core falls on to the protostar and disappears a few years after the protostar formation. On the other hand, when the molecular cloud has an angular momentum, the first core does not disappear even after the protostar formation, and directly evolves into the circumstellar disc with a Keplerian rotation. There are two paths for the formation of the circumstellar disc. When the initial cloud has a considerably small rotational energy, two nested discs appear just after the protostar formation. During the early main accretion phase, the inner disc increases its size and merges with the outer disc (i.e. first core) to form a single circumstellar disc with a Keplerian rotation. On the other hand, when the molecular cloud has a rotational energy comparable to observations, a single centrifugally supported disc that corresponds to the first core already exists prior to the protostar formation. In such a cloud, the first core density gradually increases, maintaining the Keplerian rotation and forms the protostar inside it. The magnetic field rarely affects the early formation of the circumstellar disc because the magnetic field dissipates in the high-density gas region where the circumstellar disc forms. As a result, in any case, the protostar at its formation is already surrounded by a massive circumstellar disc. The circumstellar disc is about 10–100 times more massive than the protostar in the main accretion phase. Such discs are favourable sites for the formation of binary companions and gas-giant planets.

Key words: accretion, accretion discs – stars: formation – stars: low-mass, brown dwarfs – planetary systems: protoplanetary discs – ISM: clouds.

1 INTRODUCTION

A star is born with a circumstellar disc in the molecular cloud core. Molecular clouds have an angular momentum (Arquilla & Goldsmith 1986; Goodman et al. 1993; Caselli et al. 2002) that can form a disc in the star formation process. Thus, disc formation is a natural consequence of the conservation of angular momentum in the collapsing cloud core. Observations have also supported the existence of a circumstellar disc around young stellar objects. The circumstellar discs have been identified by spectral energy distributions, and are resolved in their scattered light (see review of Watson et al. 2007). Thus, there is no room for doubt about the emergence and presence of circumstellar discs in the star formation process.

The circumstellar disc plays important roles in star and planet formation. The planets are formed in the circumstellar (or protoplanetary) discs. Recent theoretical studies state that planets are formed according to the gravitational instability scenario with massive discs and according to the core accretion scenario with less massive discs (Durisen et al. 2007). Thus, the mass of the circumstellar disc determines the planet formation mode and properties of planets. In addition, the protostellar outflows are driven by the circumstellar disc (Pudritz et al. 2007). It is considered that these flows are closely related to the angular momentum transfer, and they determine the star formation efficiency (Matzner & McKee 2000). Therefore, it is necessary to investigate the formation and properties of the circumstellar disc to understand both star and planet formation. Nevertheless, so far, the formation process of the circumstellar disc in the collapsing cloud core has rarely been investigated.

In a classical star formation scenario, it is envisaged that the circumstellar disc begins to form after the protostar formation and...
increases its size with time. This picture is evoked by the idea that a small part of the natal cloud having the lowest angular momentum first collapses and forms the protostar, while the remainder of the cloud, which has larger angular momentum, collapses later and forms the circumstellar disc. However, in this picture, the thermal evolution of collapsing (or infalling) gas is not taken into account. Recent star formation scenarios including thermal evolution have shown that the transient object that is called the first core appears prior to the protostar formation (Masunaga & Inutsuka 2000). In the collapsing cloud core, the gas collapses isothermally for \( n \lesssim 10^{10} \text{ cm}^{-3} \), while it collapses adiabatically for \( n \gtrsim 10^{10} \text{ cm}^{-3} \) and forms the first (adiabatic) core at \( n \gtrsim 10^9-10^{12} \text{ cm}^{-3} \). Although the first core is in a nearly hydrostatic equilibrium state, its central density gradually increases because the first core increases its mass by the gas accretion (Masunaga, Miyama & Inutsuka 1998). When the central density exceeds \( n \gtrsim 10^6 \text{ cm}^{-3} \) (or temperature \( T \gtrsim 2000 \text{ K} \)), the molecular hydrogen begins to dissociate and the central region rapidly collapses again (the so-called second collapse). Finally, the collapsing gas becomes adiabatic again and the protostar forms at \( n \gtrsim 10^{20} \text{ cm}^{-3} \) (Larson 1969; Masunaga & Inutsuka 2000). Because the second collapse occurs only in a small part of the first core, the first core does not disappear just after the protostar formation. In a spherically symmetric calculation, the first core falls on to the central protostar and disappears several years after the protostar formation (Masunaga & Inutsuka 2000). However, the rotational effect is not included in the spherically symmetric calculation. In reality, because the first core is supported by not only the thermal pressure but also the rotation, it does not disappear in such a short duration without effective angular momentum transfer (Saigo & Tomisaka 2006).

Recently, Machida, Inutsuka & Matsumoto (2010a) and Bate (2010) pointed out that the first core is the origin of the circumstellar disc (see also Bate 1998), indicating that the disc appears before the protostar formation (see also Banerjee, Pudritz & Holmes 2004; Saigo, Tomisaka & Matsumoto 2008) and is more massive than the protostar at the protostar formation epoch (Inutsuka, Machida & Matsumoto 2010). Such massive discs tend to exhibit the gravitational instability that contributes to the angular momentum transfer through the non-axisymmetric gravitational torque, and binary or planet formation through fragmentation. To investigate the formation and evolution of the circumstellar disc in the collapsing cloud core, we need a three-dimensional simulation that covers both the circumstellar disc and its natal cloud with adequate spatial resolution. However, because such a calculation requires a considerably higher spatial resolution, only a few studies have investigated the formation of the circumstellar disc from the pre-stellar stage. In many other calculations, the evolution of circumstellar discs after the main accretion phase was investigated with artificial settings in which the disc properties are artificially modelled (see review of Durisen et al. 2007). However, the evolution of the circumstellar disc even after the main accretion phase should be investigated from the pre-stellar stage to give adequate initial condition. Otherwise, artificial initial settings may determine the final fate of the circumstellar disc.

Walch et al. (2009, 2010) and Machida et al. (2010a) calculated the formation of the circumstellar disc from the pre-stellar stage (i.e. from the starless molecular cloud core stage) up to the main accretion stage in an unmagnetized cloud. However, they did not resolve the protostar itself to perform a long-term calculation of the circumstellar disc. Bate (1998, 2010) and Saigo et al. (2008) investigated the evolution of the collapsing cloud before and after the protostar formation with a sufficient spatial resolution. However, they did not include the effect of the magnetic field. Although Banerjee & Pudritz (2006) and Machida, Inutsuka & Matsumoto (2006b, 2008b) calculated the cloud evolution with magnetic field resolving the protostellar radius, they did not investigate the formation and evolution of the circumstellar disc after the protostar formation.

In summary, so far, the evolution of the circumstellar disc in the proximity of the protostar just after the protostar formation has rarely been investigated with a multidimensional simulation resolving the protostar itself. If the first core that is formed before the protostar formation falls on to the protostar and disappears for a short duration, the circumstellar disc gradually forms after the protostar formation, as envisaged in the classical picture. Instead, as pointed out by Bate (2010) and Machida et al. (2010a), if the first core remains longer, it becomes the circumstellar disc that is considerably more massive than the protostar. In this study, we calculate the cloud evolution with and without magnetic field from the pre-stellar stage up to the period after the protostar formation resolving the protostellar radius of 0.01 au and investigate the formation process of the circumstellar disc in the proximity of the protostar. The structure of this paper is as follows. The framework of our models and the numerical method are given in Section 2. The numerical results are presented in Section 3. We discuss the further evolution of the disc in Section 4, and summarize our results in Section 5.

## 2 Model Settings

To study the formation and evolution of a circumstellar disc in a magnetized molecular cloud core, we solve the three-dimensional resistive magnetohydrodynamics (MHD) equations including self-gravity:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla P - \frac{1}{4\pi} \mathbf{B} \times (\nabla \times \mathbf{B}) - \rho \nabla \phi, \tag{2}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \tag{3}
\]

\[
\nabla^2 \phi = 4\pi G \rho, \tag{4}
\]

where \( \rho, \mathbf{v}, P, \mathbf{B}, \eta \) and \( \phi \) denote density, velocity, pressure, magnetic flux density, resistivity and gravitational potential, respectively. To mimic the temperature evolution calculated by Masunaga & Inutsuka (2000), we adopt the piece-wise polytropic equation (see equation 5 of Machida, Inutsuka & Matsumoto 2007). In this study, we investigate the cloud evolution with the barotropic equation of state up to the epoch just after the protostar formation. Note that we discuss the effect of the radiation and barotropic approximation in Section 4.4. We think that, in this period, the cloud evolution and formation of the circumstellar disc can be safely investigated by using the barotropic approximation. This treatment reduces CPU time and makes it possible to study cloud evolution with sufficiently high spatial resolution. For a realistic evolution of the magnetic field in the circumstellar disc, we adopt the resistivity \( \eta \) as the fiducial value in Machida et al. (2007) in equation (3), in which the Ohmic dissipation becomes effective for \( 10^{11} \text{ cm}^{-3} \lesssim n \lesssim 10^{15} \text{ cm}^{-3} \) (for details, see equations 9 and 10, and fig. 1 of Machida et al. 2007).

As the initial state, we take a spherical cloud with critical Bonnor–Ebert (BE) density profile, in which a uniform density is adopted.
outside the sphere ($r > R_\text{c}$). For the BE density profile, we adopt the central density of $n_\text{c} = 10^6$ cm$^{-3}$ and isothermal temperature of $T = 10$ K. For these parameters, the critical BE radius is $R_\text{c} = 4.8 \times 10^3$ au. To promote the contraction, we increase the density by a factor of $f = 1.68$, where $f$ is the density enhancement factor that represents the stability of the initial cloud. With $f = 1.68$, the initial cloud has (negative) gravitational energy twice that of thermal energy. The mass within $r < R_\text{c}$ is $M = 0.8 M_\odot$. Initially, the cloud rotates rigidly with an angular velocity $\Omega_0$ around the $z$-axis. We parametrized the ratio of the rotational to the gravitational energy ($\beta_0 = E_\text{r}/E_\text{g}$, hereafter the rotational energy) inside the initial cloud. We calculated the cloud evolution for four unmagnetized clouds with different $\beta_0$ and a single magnetized cloud with a uniform initial magnetic field strength of $B_0 = 34 \mu$G. The model with magnetic field has a ratio of the magnetic to the gravitational energy of $E_\text{m}/E_\text{g} = 0.06$, and mass-to-flux ratio of $(M/\Phi)/(M/\Phi)_\text{crit} = 6$ (for detailed description, see Machida, Inutsuka & Matsumoto 2010b). Model names, initial angular velocities $\Omega_0$, rotational $\beta_0$ and magnetic field strength ($B_0$) are summarized in Table 1.

The time-step for the calculation becomes increasingly short as the cloud collapses (or the central density increases). When the time-step becomes extremely short, we cannot calculate the evolution of the cloud and circumstellar disc for long durations. To avoid this, we adopt a sink at the centre of the cloud after the protostar formation. To model the protostar, we adopt a sink around the centre of the computational domain when the number density $n$ exceeds $> 3 \times 10^{11}$ cm$^{-3}$ at the cloud centre. In the region $r < r_{\text{sink}} = 2 R_\odot$, the gas having a number density of $n > 3 \times 10^{11}$ cm$^{-3}$ is removed from the computational domain and added to the protostar as gravity in each time-step (for details, see Machida, Inutsuka & Matsumoto 2009; Machida et al. 2010a). Masunaga & Inutsuka (2000) showed that the protostar forms at $n \sim 10^{20} - 10^{21}$ cm$^{-3}$ with a radius of $\sim 2 R_\odot$ in the collapsing cloud. This treatment of the sink makes it possible to calculate the evolution of the collapsing cloud and circumstellar disc for a longer duration. However, in our calculations, the central density never exceeds $n > 3 \times 10^{11}$ cm$^{-3}$ except for the model with $\beta_0 = 0$ (i.e. non-rotating model). Thus, we calculated the cloud evolution up to the end of the calculation without a sink for the model with $\beta_0 \neq 0$ (models 1, 2, 3 and 5), while with a sink for model with $\beta_0 = 0$ (model 4). In each model, we stopped the calculation about 4 yr after the protostar formation.

To calculate over a large spatial scale, the nested grid method is adopted (Machida et al. 2005a, 2006a). Each level of a rectangular grid has the same number of cells, $128 \times 128 \times 16$. The calculation is first performed with five grid levels ($l = 1$–5). The box size of the coarsest grid $l = 1$ is chosen to be $2^3 R_\odot$. Thus, a grid of $l = 1$ has a box size of $1.5 \times 10^4$ au. A new finer grid is generated before the Jeans condition is violated. The maximum level of grids is restricted to $l_{\text{max}} \leq 21$. The $l = 21$ grid has a box size of $0.14$ au and a cell width of $1.1 \times 10^3$ au. With this method, we cover eight orders of magnitude in spatial scale. In other words, we can spatially cover both the molecular cloud core and protostar itself.

### Table 1. Model parameters and calculation results.

| Model | $\beta_0$ | $\Omega_0$ (s$^{-1}$) | $B_0$ (\(\mu\)G) | $M_{\text{ps}}$ (\(M_\odot\)) | $M_{\text{disc}}$ (\(M_\odot\)) | $r_{\text{disc}}$ (au) |
|-------|----------|-----------------|----------------|-----------------|----------------|----------------|
| 1     | $10^{-3}$| $6.5 \times 10^{-14}$ | 0 | $2.4 \times 10^{-3}$ | 0.062 | 8.5 |
| 2     | $10^{-4}$| $2.1 \times 10^{-14}$ | 0 | $3.5 \times 10^{-3}$ | 0.025 | 1.1 |
| 3     | $10^{-5}$| $6.5 \times 10^{-15}$ | 0 | $4.2 \times 10^{-3}$ | 0.016 | 0.3 |
| 4     | 0        | 0               | 0 | $3.4 \times 10^{-3}$ | 0 | 0 |
| 5     | $10^{-3}$| $6.5 \times 10^{-14}$ | 32 | $3.5 \times 10^{-3}$ | 0.019 | 0.7 |

### 3 RESULTS

The disc formation process depends on the rotation rate of the initial cloud, because the cloud rotation makes the circumstellar disc in the star formation process. In this study, we calculated the formation of the protostar and circumstellar disc in the molecular cloud core for five different models in which the rotational energy of the initial cloud is parametrized in the range of $0 < \beta_0 < 10^{-3}$. The observations have shown that the molecular clouds have rotational energy in the range of $10^{-3} \leq \beta_0 \leq 0.07$ with an average of $\beta_0 = 0.02$ (Goodman et al. 1993; Caselli et al. 2002). Recent numerical studies showed that the cloud with rapid rotation $\beta_0 \sim 10^{-2}$ tends to show fragmentation or binary formation before the protostar formation (Matsumoto & Hanawa 2003). However, it is difficult to investigate the formation process of the circumstellar disc in a binary system. Thus, in this study, we limited the rotational parameter in the range of $\beta_0 \leq 10^{-3}$ to focus on the circumstellar disc around the single protostar. In this section, after we show the cloud evolution without magnetic field, we describe it with magnetic field.

#### 3.1 Circumstellar disc formation without magnetic field

In this section, first, we show the cloud evolution for the model with a relatively slow rotation rate ($\beta_0 \leq 10^{-4}$). Then, the evolution of a relatively rapidly rotating cloud ($\beta_0 = 10^{-3}$) is described. The evolution of the cloud with larger rotational energy ($\beta_0 > 10^{-3}$) is discussed in Section 4.2.

##### 3.1.1 Evolution of cloud with a relatively slow rotation

Figs 1 and 2 show the density distribution and velocity vectors on the $z = 0$ (Fig. 1) and $y = 0$ (Fig. 2) planes for a model with $\beta_0 = 10^{-4}$ (model 2) with different spatial scales $l_c = 1.2083$ yr after the protostar formation. In these figures, Figs 1(a) and 2(a) cover the entire region of the molecular cloud core with a box size of $\sim 10^4$ au, while Figs 1(f) and 2(f) cover the protostar and a part of the disc with a box size of $\sim 0.3$ au. For this model, the protostar forms in the collapsing cloud $t = 5.064 \times 10^4$ yr after the calculation begins (i.e. after the initial cloud begins to collapse). In this paper, we define $t_c$ as the elapsed time after the protostar formation where the protostar formation epoch ($t_c = 0$) is defined as the epoch when the central density reaches $n_c = 10^{20}$ cm$^{-3}$ in the collapsing cloud core. We also define $t$ as the elapsed time after the calculation begins (or the initial cloud begins to collapse). In addition, after the protostar formation, we integrate the gas exceeding $n > 10^{20}$ cm$^{-3}$ and define it as the protostellar mass $M_{\text{ps}}$.

Figs 1(a) and 2(a) show that a molecular cloud with a size of $\sim 10^4$ au maintains a spherical structure even after the protostar formation, because the gas begins to collapse in the small area of the centre of the cloud and the outer envelope maintains its nearly initial structure, as shown in Larson (1969). As seen in Figs 1(b)
and 2(b), the gas collapses spherically towards the centre of the cloud in a large scale of $\gg 1$ au, because the rotation hardly affects the dynamical evolution of the cloud at such a scale (Machida et al. 2005a). In the collapsing cloud, the gas becomes optically thick against the dust cooling and the first core surrounded by the shock appears when the number density exceeds $n \gtrsim 10^{10}$ cm$^{-3}$ (Masunaga & Inutsuka 2000). When the cloud has an angular momentum, the first core has a disc-like structure. The disc-like structure surrounded by the shock in Figs 1(c) and 2(c) corresponds to the first core. Figs 1(b–d) show that the gas falls radially towards the first core outside the first core, while the gas rotates rapidly inside the first core. This is because, inside the first core, the gas collapses very

Figure 1. The density distribution (colour and contours) and velocity vectors (arrows) on the equatorial plane at the epoch just after the protostar formation ($t = 5.064 \times 10^4$ yr, $t_c = 1.2083$ yr) for model 2 ($\beta_0 = 10^{-4}$) at various spatial scales. Each object (molecular cloud core, first core, circumstellar disc and protostar) is identified by an arrow.

Figure 2. Same as Fig. 1 but on the $y = 0$ plane.
slowly in the radial direction and the rotation dominates the radial motion after the gas becomes adiabatic (i.e. after the first core formation).

Inside the first core, there is another structure with a radius of ~0.4 au surrounded by the disc-like shock, as seen in panels d and e of Figs 1 and 2. This disc-like object is formed inside the first core after the protostar formation. In this paper, we call this object (i.e. the disc around the protostar) the inner disc. In addition, the protostar with a radius of ~0.02 au exists with a nearly spherical structure inside the disc, as seen in Figs 1(f) and 2(f). Thus, after the protostar formation, three different structures appear inside the collapsing molecular cloud core: two nested discs (a disc-like first core and an inner disc) and a protostar.

After the first core formation, further rapid collapse is induced in a small central part of the first core owing to the dissociation of molecule hydrogen when the number density exceeds $n \gtrsim 10^{16} \, \text{cm}^{-3}$ (Larson 1969; Masunaga & Inutsuka 2000). In such a collapsing region, the gas becomes adiabatic again after the dissociation of molecule hydrogen is completed and a protostar with a shock (or the second adiabatic core) appears in the region of $n \gtrsim 10^{20} \, \text{cm}^{-3}$. In this model, then, the inner disc appears around the protostar after the protostar formation, because the first core has an angular momentum and the rotation of the infalling gas from the first core cannot be neglected as it approaches the protostar. Therefore, the disc structure is formed inside the first core because of the rotation. Note that the first core appears in the collapsing cloud even without rotation, because the first core is supported by not only the rotation but also thermal pressure, while no inner disc appears without rotation. Figs 1 and 2 clearly show two nested discs inside the molecular cloud core outside the protostar.

The nested discs can also be seen in Fig. 3, in which the first core and inner disc are plotted by the orange and red iso-density surfaces, respectively. This figure clearly shows that the thin inner disc is surrounded by the thick torus-like disc (i.e. the first core). In the figure, the velocity vectors on the equatorial plane are projected on to the bottom wall surface. The direction of the velocity vector is suddenly changed at the surface of the first core; the gas falls vertically on to the protostar or the inner disc, because the vertical direction is mainly supported by the thermal pressure gradient force not by the centrifugal force. After the protostar formation, the inner disc increases its size, while the first core slightly decreases its size, as seen in Figs 4(b)–(c). This is because the region inside the first core gradually collapses to accrete on to the inner disc. In addition, the first core increases its mass by the gas accretion and shrinks its size (Saigo & Tomisaka 2006). Finally, two shocks (or two discs) composed of the shrinking first core and expanding inner disc form the circumstellar disc.

Figure 3. First core (orange iso-density surface) and inner disc (red iso-density surface) for model 2 ($\beta_0 = 10^{-4}$) at $t_* = 1.664 \, \text{yr}$ after the protostar formation are plotted in three dimensions. The density distribution on the $x = 0$, $y = 0$ and $z = 0$ plane is projected on to each wall surface. The velocity vectors on the $z = 0$ plane are also projected on to the bottom wall surface.
disc merge to form a single disc (or single shock) $t_c = 3.4$ yr after the protostar formation, as shown in Fig. 4(d). After the merger, the single disc acquires the accreting gas from the infalling envelope, and increases its size with time.

To confirm this merger, the radial distribution of the density (a), radial velocity (b), azimuthal and Keplerian velocities (c) and ratio of the radial velocity to the azimuthal velocity (d) are plotted in Fig. 5, in which each quantity is azimuthally averaged. At the protostar formation epoch ($t_c = 0$ yr; black line), the density profile shows only a single shock at $r \sim 1.7$ au (Fig. 5a). At the shock surface that corresponds to the surface of the first core, the radial velocity approaches nearly zero (Fig. 5b). Inside the first core ($r < 1.7$ au), the infall velocity ($-v_r$) gradually increases towards the centre in the range of $0.02$ au $\lesssim r \lesssim 1.7$ au, while it decreases in the range of $r \lesssim 0.02$ au. Because the protostar ($n \gtrsim 10^{20}$ cm$^{-3}$) has a size of $\sim 0.01$ au, the infall (or negative radial) velocity approaches zero near the protostellar surface. The azimuthal velocity suddenly increases at the surface of the first core (Fig. 5c). Fig. 5(d) shows that the radial velocity greatly dominates the azimuthal velocity outside the first core, while the azimuthal velocity dominates the radial velocity inside the first core. This indicates that the first core is rotating rapidly and collapses slowly.

The blue and red lines in Fig. 5(a) show two nested shocks in the range of $0.1$ au $\lesssim r \lesssim 2$ au; the outer shock corresponding to the first core is located at $r \sim 1–2$ au, while the inner shock corresponding to the inner disc is located at $r \sim 0.1–0.5$ au. The figure indicates that the inner shock is outwardly expanding, while the outer shock is inwardly shrinking. In Fig. 5(b), we can clearly see two shocks for red and blue lines, in which the radial velocity is considerably small except for the very proximity of the protostar ($r < 0.01$ au) inside the inner shock (or the inner disc). Fig. 5(c) shows that, inside the first core, the azimuthal velocity gradually increases with time and has a nearly Keplerian velocity inside the inner disc. Here, the Keplerian velocity is derived from the gravity at each point and is azimuthally averaged. In addition, Fig. 5(d) shows that the azimuthal velocity is over 10 times larger than the radial velocity inside the first core. Thus, at these epochs, the gas orbits around the protostar with a nearly Keplerian velocity inside the first core.

Two nested structures (i.e. the first core and the inner disc) merge to form a single disc $t_c = 3.396$ yr after the protostar formation (the green line in Fig. 5a). The green lines in Fig. 5(c) indicate that the merged disc is supported by rotation and has a size of $\sim 1$ au. After the merger, the disc increases its mass and size with time. This disc corresponds to the circumstellar disc. At the end of the calculation ($t_c = 3.5$ yr), the circumstellar disc has a mass of $0.025 M_{\odot}$ with a size of $1.1$ au, while the protostar has a mass of $3.5 \times 10^{-3} M_{\odot}$ with a size of $0.01$ au. Thus, the circumstellar disc is approximately seven times more massive than the protostar.

### 3.1.2 Evolution of cloud with extremely slow rotation and no rotation

We also calculated the evolution of the circumstellar disc in the molecular cloud with a further lowering of the rotational energy...
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Figure 5. Radial distribution of (a) the density, (b) radial velocity, (c) azimuthal velocity and (d) the ratio of radial velocity to azimuthal velocity for model 2 (\(\beta_0 = 10^{-4}\)) with different epochs. The lower-left inset in panel (a) is a close-up view in the range of \(0.2 \text{ au} < r < 2 \text{ au}\). The dotted line in panel (c) is the Keplerian velocity at each epoch.

Of \(\beta_0 = 10^{-5}\) (model 3). However, the formation process of the circumstellar disc is almost the same as that of the model with \(\beta_0 = 10^{-4}\) (model 2). Also, in this model, two nested discs appear just after the protostar formation, and finally they merged to form a single circumstellar disc. The circumstellar disc has a mass of 0.016 M\(_\odot\) with a size of 0.3 au, while the protostar has a mass of \(4.2 \times 10^{-3} \text{ M}_\odot\) with a size of 0.01 au at the end of the calculation (\(t_c = 3.7\) yr).

On the other hand, when the initial cloud has no angular momentum, only a single core appears outside the protostar. The time sequence for evolution of the collapsing cloud after the protostar formation for the model without rotation (\(\beta_0 = 0\), model 4) is shown in Fig. 6. The azimuthally averaged distributions of the density and velocity for three different epochs corresponding to each panel in Fig. 6 are plotted in Fig. 7. Also, in this model, the first core appears in the collapsing cloud before the protostar formation. Fig. 6(a) indicates that the first core has a radius of \(\sim 8\) au and has already become sufficiently thin before the protostar formation. The velocity vectors in this figure indicate that the gas is rapidly rotating inside the first core. Fig. 9 shows the density and velocity distribution for model 1 \(t_c = 1.475\) yr after the protostar formation with various spatial scales. The entire region of the first core is covered in Fig. 9(a), while the protostar embedded in the first core is seen in Fig. 9(d). At this epoch \(t_c = 1.475\) yr, the first core and protostar have radii of \(\sim 8\) au and \(\sim 0.01\) au, respectively. The mass and density distributions in the infalling envelope are proportional to \(\rho \propto r^{-1.5}\) in the range of \(0.01 \text{ au} < r < 10\) au, while it is proportional to \(\rho \propto r^{-2}\) in the range of \(r > 10\) au. This distribution resembles the singular isothermal self-similar solution (Shu 1977).

3.1.3 Evolution of cloud with a relatively rapid rotation

As shown in Section 3.1.1, when the initial cloud has a considerably slow rotation (\(\beta_0 = 10^{-4}\)), two nested discs (the first core and the inner disc) co-exist for a short duration after the protostar formation, in which the inner disc is enclosed by the outer first core. On the other hand, when the cloud has a rapid rotation, we cannot distinguish the first core and the inner disc in the star formation process. In other words, only a single rotating disc (or rotating first core) appears before and after the protostar formation. To investigate the formation of the circumstellar disc for the cloud with a relatively rapid rotation, the cloud evolution for the model with \(\beta_0 = 10^{-3}\) (model 1) is presented here.

The density and velocity distributions 16.7 yr (i.e. \(t_c = -16.7\) yr) before the protostar formation for model 1 (\(\beta_0 = 10^{-3}\)) are shown in Fig. 8. The figure shows that the first core has a radius of \(\sim 8\) au and has already become sufficiently thin before the protostar formation. The velocity vectors in this figure indicate that the gas is rapidly rotating inside the first core. Fig. 9 shows the density and velocity distribution for model 1 \(t_c = 1.475\) yr after the protostar formation with various spatial scales. The entire region of the first core is covered in Fig. 9(a), while the protostar embedded in the first core is seen in Fig. 9(d). At this epoch \(t_c = 1.475\) yr, the first core and protostar have radii of \(\sim 8\) au and \(\sim 0.01\) au, respectively.
Figure 6. Time sequence for model 4 ($\beta_0 = 0$) after the protostar formation. The density distribution (colour and contours) and velocity vectors (arrows) on the equatorial plane are plotted in each panel. The elapsed time $t_c$ after the protostar formation is described in each panel.

Figure 7. Distribution of density (upper panel) and radial velocity (lower panel) for model 4 ($\beta_0 = 0$).

arrows in Figs 9(a)–(d) indicate that the gas is rapidly rotating inside the first core outside the protostar. Although the spiral structure appears inside the first core as seen in each upper panel of Figs 9(b) and (c), no clear shock corresponding to the inner disc as seen in Figs 1 and 2 appears in this figure. As shown in Fig. 9(d), the gas falls on to the protostar rapidly in the vertical direction and very slowly in the horizontal direction. In addition, the disc-like first core sags downwards in the proximity of the protostar, as seen in lower panels of Figs 9(c) and (d). In Fig. 10, the density and velocity distributions before (upper panel) and after (lower panel) the protostar formation are plotted in three dimensions. The figure shows that the first core has a sufficiently thin disc-like structure before the protostar formation. In addition, just after the protostar formation, the protostar is already enclosed by the thin disc. In the bottom wall, we can also see the spiral structure that is developed by relatively high angular momentum of the disc (or the first core).

In Fig. 11, the azimuthally averaged density (a), radial velocity (b), azimuthal and Keplerian velocities (c) and ratio of the radial to the azimuthal velocity (d) are plotted against the radius for three different epochs [the epoch before (black) and after (red) the protostar formation and just before the protostar formation epoch (blue)]. In Fig. 11(a), the shock at $\sim 8$ au corresponds to the surface of the first core and remains almost in the same position by the end of the calculation. Inside the first core ($\lesssim 8$ au), the gas density increases smoothly towards the centre of the cloud before the protostar formation, while it increases with waves after the protostar formation. This is because the spiral structure develops inside the first core after the protostar formation, as seen in Fig. 9. Fig. 11(b) shows that the radial velocity suddenly increases to approach zero at the surface of the first core ($\sim 8$ au) in each epoch. Just after the first core formation (black line), the radial velocity becomes $v_r \sim 0$ inside the first core, indicating that the gas collapses very slowly towards the centre of the cloud. As the central density increases, the second collapse is induced and the gas collapses rapidly again, as seen in the blue line of Fig. 11(b). After the protostar formation, the radial velocity inside the first core oscillates around $v_r = 0$, because the spiral structure appearing after the protostar formation contributes to the angular momentum transfer. Thus, inside the disc (or the first core), a fraction of gas can fall on to the protostar, while the remaining gas moves outwards with a relatively high angular momentum. However, as seen in Fig. 11(d), the radial motion is not much noticeable inside the first core, because the azimuthal velocity greatly dominates the radial velocity.

Fig. 11(c) shows that, in each epoch, the azimuthal velocity traces a near-Keplerian velocity inside the first core. Thus, the first core already has the Keplerian rotation inside the first core. In summary, the first core is mainly supported by a centrifugal force from its formation. Then, the first core gradually increases its central density maintaining the Keplerian rotation, and the protostar appears in the Keplerian rotating disc (or the Keplerian rotating first core). Therefore, as seen in the red line of Fig. 11(c), the protostar already has a Keplerian rotating disc at its formation. In other words, the...
protostar is born in the Keplerian rotating disc that formed long before the protostar formation. As described in Section 3.1.1, also in model 2 ($\beta_0 = 10^{-4}$), the protostar is formed inside the disc-like structure (or the disc-like first core). However, for model 2, the first core does not reach the Keplerian rotation before the protostar formation (see, Fig. 5c). Thus, the Keplerian rotating disc (i.e. the inner disc) appears inside the first core after the protostar formation and merges with the first core to form a single Keplerian rotating disc several years after the protostar formation. This difference between models 1 and 2 is caused by the initial rotation rate of the molecular cloud core. Because model 1 has a larger rotational energy than model 2, the first core has a Keplerian rotation from its formation and becomes the circumstellar disc directly after the protostar formation.

At the end of the calculation ($t_c = 1.5\ yr$), for model 1, the circumstellar disc has a mass of $0.062\ M_\odot$ with a size of 8.5 au, while the protostar has a mass of $2.4 \times 10^{-3}\ M_\odot$ with a size of 0.01 au. Thus, the circumstellar disc is about 26 times more massive than the protostar. The larger ratio of the mass of circumstellar disc to that of the protostar for this model is also attributed to the larger initial rotation rate.

### 3.2 Circumstellar disc formation with magnetic field

The early formation of the circumstellar disc in unmagnetized clouds was described in Section 3.1. In this section, we show the cloud evolution for an initially magnetized cloud (model 5) that has a magnetic field of $B_{z0} = 32\ \mu G$ and angular velocity of $\Omega_0 = 6.5 \times 10^{-14}\ s^{-1}$ ($\beta_0 = 10^{-3}$) at the initial state. The initial angular velocity for model 5 is the same as that for model 1 (see Table 1).

Figs 12(a) and (b) show the density distribution for model 5 just after the protostar formation ($t_c = 1.77\ yr$). As seen in unmagnetized models, the disc-like structure appears around the protostar also in this model. For this model, the first core appears at $t = 5.56 \times 10^4\ yr$ after the initial cloud begins to collapse. Then, the protostar forms inside the first core at $t = 5.60 \times 10^4\ yr$. Since model 5 also has an angular momentum at the initial state, the first core has a disc-like structure at its formation and becomes the circumstellar disc after the protostar formation as seen in unmagnetized models. However, the size of the first core and resulting circumstellar disc for model 5 is about 10 times smaller than that for model 1 at their formation epoch (compare Fig. 8 with Fig. 12), although both models have the same angular momentum at the initial state. In the magnetized...
cloud, the angular momentum can be transferred by the magnetic braking and protostellar outflow (Machida et al. 2007). Thus, the size difference of them is caused by the magnetic effects. Note that although the protostellar outflow is driven by the first core (or the circumstellar disc) for model 5, we do not comment on it in more detail because we mainly focus on the formation of the circumstellar disc in this paper.

The magnetic field effectively transfers the angular momentum outside the circumstellar disc. On the other hand, the angular momentum transfer by the magnetic effects is not so effective inside...
The origin of circumstellar disc

The density distribution (isodensity surface) around the centre of the cloud before (upper panel) and after (lower panel) the protostar formation. The density distribution on the \( x = 0, y = 0 \) and \( z = 0 \) plane is projected on to each wall surface. The velocity vectors on the \( z = 0 \) plane are also projected on to the bottom wall surface.

The circumstellar disc because the magnetic field largely dissipates by the Ohmic dissipation in the high-density gas region. Fig. 12 (right-hand panels) shows the plasma beta that is defined as

\[
\beta_p \equiv \frac{8\pi c_s^2 \rho}{B^2},
\]

where \( c_s \) is the sound speed. The plasma beta is \( \beta_p \lesssim 10^{-100} \) just outside the circumstellar disc, while the circumstellar disc that is directly evolved from the first core has \( \beta_p \gg 10 \) as a whole except for the proximity of the protostar \( (r \lesssim 0.1 \text{ au}) \). Thus, it is considered that the magnetic field rarely affects the evolution of the circumstellar disc in its early formation phase. On the equatorial plane (Fig. 12c), the plasma beta has a peak of \( \beta_p \sim 10^2 \) at \( r \sim 0.2 \text{ au} \) and shows a ring-like structure. As shown in Nakano, Nishi & Umebayashi (2002) and Machida et al. (2007), the magnetic field begins to dissipate at \( n \simeq 10^{12} \text{ cm}^{-3} \) by the Ohmic dissipation. After the number density exceeds \( n \gtrsim 10^{16} \text{ cm}^{-3} \) (or \( T \gtrsim 2000 \text{ K} \)), the ionization degree recovers due to the thermal ionization of alkali metals and the resistivity rapidly decreases. Thus, the magnetic dissipation mainly occurs in the range of \( 10^{12} \text{ cm}^{-3} \lesssim n \lesssim 10^{16} \text{ cm}^{-3} \) and magnetic diffusivity peak at \( n \simeq 10^{15} \text{ cm}^{-3} \) as shown in fig. 1 of Machida et al. (2007). Note that, in this paper, we only consider the Ohmic dissipation, while the ambipolar diffusion may contribute to the magnetic dissipation in the narrow density range of \( 10^{11} \text{ cm}^{-3} \lesssim n \lesssim 10^{12} \text{ cm}^{-3} \) (Nakano et al. 2002; Tassis & Mouschovias 2007; Kunz & Mouschovias 2010). However, we expect that our result is not qualitatively changed even if the ambipolar diffusion is taken into account because the disc has a weaker magnetic field (or higher value of plasma beta) with ambipolar diffusion and tracks the similar evolutionary path to that for unmagnetized cloud.
In summary, as seen in Fig. 12 (right-hand panels), the magnetic field is relatively strong outside the circumstellar disc, while a very weak magnetic field is realized inside the circumstellar disc. It is considered that angular momentum is effectively transferred by the magnetic field outside the circumstellar disc (or the first core). Thus, the infalling gas that makes the circumstellar disc has a smaller angular momentum and forms a smaller first core (or the circumstellar disc). On the other hand, inside the circumstellar disc, since a weak magnetic field cannot effectively transfer the angular momentum, a centrifugally supported disc can be formed as seen in unmagnetized models. Note that the magnetic field can be amplified and affects the disc structure in the very proximity of the protostar because the magnetic field is coupled with neutral gas again in such region with a smaller magnetic diffusivity (Machida et al. 2007).

Figs 13(a)–(d) indicate that the density and velocity distributions for model 5 are qualitatively the same as those for model 1 (see Figs 11). However, there are some interesting differences. The size of the first core (or the circumstellar disc) for model 5 is about 10 times smaller than that for model 1. The outer shock surface appears at \( r \simeq 1–2 \) au for model 5, while it appears at \( r \simeq 10 \) au for model 1. Another difference is seen in the velocity and density distribution inside the disc. After the protostar formation (see the red line of Figs 11b and 13b), inside the shock surface, the radial velocity oscillates around \( v_r = 0 \) for model 1, while there is no oscillation for model 5. Such oscillations are also seen in the density and azimuth velocity (Fig. 11c) for model 1. For the unmagnetized model with a relatively higher rotation (model 1), the excess angular momentum forms spiral structure in the circumstellar disc as shown in Figs 9 and 10. Thus, the velocity and density oscillation inside the disc are caused by the spiral structure. Inside the disc, angular momentum is transferred by the non-axisymmetric structure for the unmagnetized model. On the other hand, the magnetic field can contribute to the angular momentum transfer inside the disc, although the disc has large \( \beta_s \) as a whole. Note that the magnetic field is relatively strong in the inner \( (r \lesssim 0.1 \) au) and outer \( (r \lesssim 1 \) au) disc region. Thus, it is considered that the magnetic field can transfer the excess angular momentum and suppresses the formation of the spiral structure. Regardless of the different mechanism of the angular momentum transfer, the circumstellar disc in both models shows a Keplerian rotation after the protostar formation. The red lines in Fig. 13(c) indicate that the circumstellar disc with a size of \( 0.6 \) au rotates with a Keplerian velocity.

The radial distribution of the magnetic field strength is plotted in Fig. 13(e). This figure shows that the magnetic field temporally decreases at \( r \sim 0.1–1 \) au where the number density exceeds \( n \sim 10^{12} \) cm\(^{-3}\) and Ohmic dissipation becomes effective. Fig. 13(f) shows the radial distribution of \( B_z/\rho^{1/2} \) normalized by its initial value \( B_{z,0}/\rho_{0}^{1/2} \) (hereafter the normalized magnetic field). The normalized magnetic field increases in proportion to \( \propto \rho^{1/6} \) when the cloud collapses spherically and keeps a constant value after the disc-like structure appears (Machida et al. 2005a). In Fig. 13(f), rapid decrease of normalized magnetic field at \( r \sim 1 \) au indicates that the magnetic dissipation becomes effective. After the protostar formation (the red line of Fig. 13e), the normalized magnetic field turns to increase at \( r \sim 0.03 \) au and is sufficiently amplified because the magnetic field is coupled with neutral gas again and amplified due to the protostellar rotation in the region of \( r \lesssim 0.03 \) au. The red line of Fig. 13(e) indicates that the magnetic dissipation is effective in the range of \( 0.03 \) au \( \lesssim r \lesssim 3 \) au that almost corresponds to the whole region of the circumstellar disc. We stopped calculation just after the protostar formation, and did not observe a jet driven near the protostar. With further calculation, a high-velocity jet may be
driven near the protostar and can transfer the angular momentum in the very proximity of the protostar (Machida et al. 2008a).

At the end of the calculation ($t_c = 3.7$ yr), for model 5, the circumstellar disc has a mass of $0.019 \, M_\odot$ with a size of 0.7 au, while the protostar has a mass of $3.5 \times 10^{-3} \, M_\odot$ with a size of 0.01 au. Thus, the circumstellar disc is about five times more massive than the protostar.

As seen in Figs 12 and 13, the magnetic field hardly changes the properties of the circumstellar disc in the early evolution phase. The magnetic field only decreases the initial size of the circumstellar disc. In addition, as described in unmagnetized models, the circumstellar disc originates from the first core and thus is massive than the protostar at its formation even when the initial cloud is magnetized.

### 3.3 Early evolution of circumstellar disc with and without magnetic field

To compare discs for models with and without magnetic field, the surface densities at the end of the calculation for models 1, 2, 4 and 5 are plotted in Fig. 14. The surface density is estimated as

$$\sigma(r, \theta) = \int_{z < z_{ic}} \rho(r, \theta, z) \, dz,$$

where $z_{ic} = 1$ au is adopted, and azimuthally averaged. Note that the surface density depends only a little on $z_{ic}$ when $z_{ic} > 0.5$ au (and/or $z_{ic} < 10$ au), because the disc mass is concentrated on the equatorial plane. As seen in Fig. 14, at the end of the calculation, the circumstellar disc for model 5 (magnetized model) is almost of the same size of $\sim 1$ au as that for model 2 (unmagnetized model). Both discs have a Keplerian velocity at this epoch as shown in Section 3.1.1 and 3.2. The thick and thin solid lines in Fig. 14 indicate that both models have almost the same surface density profile. This is because, for model 5, the magnetic dissipation is effective and a very weak magnetic field is realized in the disc-forming region (or high-density gas region) as shown in Section 3.2. Note that although those models have initially different $\beta_0$, they have almost the same size by coincidence. This is because the angular momentum, for model 5, is transferred by the magnetic field outside the circumstellar disc. The surface density for magnetized model (model 5) is slightly smaller than that for unmagnetized model (model 2) especially in the range of $r < 0.1$ au. In high-density gas region ($n > 10^{15}$ cm$^{-3}$ or $r < 0.1$ au), the magnetic field is coupled with the neutral gas again, and the magnetic field can affect the disc structure. Thus, it is expected that the difference of the surface density in the range of $r < 0.1$ au between models 2 and 5 is due to the magnetic effects. Since the magnetic field can effectively transfer the angular momentum, the gas in the magnetically active region can effectively fall on to the central protostar and the surface density decreases. Although there exist a slight difference between magnetized and unmagnetized model, the disc has almost the same surface density. Thus, the magnetic field rarely contributes to the disc formation, at least, in the very early formation phase of the circumstellar disc.
Figure 13. Radial distribution of (a) density, (b) radial velocity, (c) azimuthal and Kepler Velocities, (d) the ratio of radial velocity to azimuthal velocity, (e) magnetic field strength and (f) $B_z/\rho^{1/2}$ normalized by its initial value for model 5 with different epochs.

The dotted line in Fig. 14 shows the disc surface density for unmagnetized model (model 1) that has the largest initial rotation energy. The surface density for model 1 decreases approximately proportional to $r^{-2}$. Banerjee et al. (2004) also calculated the cloud evolution just before the protostar formation ($n \lesssim 10^{19} \text{ cm}^{-3}$) and investigated the disc formation. The surface density profile for model 1 well corresponds to that derived in Banerjee et al. (2004). They also showed that the surface density falls off roughly as $r^{-2}$. Note that the disc size in Banerjee et al. (2004) is different from ours because they calculated the disc formation for a longer duration not resolving the protostar itself. Thus, although we calculated the disc formation for a short duration from its formation, we can expect that the disc grows with the surface density profile of $\sigma \propto r^{-2}$ as seen in Banerjee et al. (2004).

The surface density profile for models 2 and 5 is different from model 1. Since models 2 and 5 have smaller rotational energy at the first core formation epoch, a single Keplerian disc appears just at the end of the calculation. Thus, for these models, Fig. 14 plots the surface density profile at the moment of formation of the Keplerian rotation disc. Note that the Keplerian rotation disc appears long before the end of the calculation for model 1. Thus, it might be expected that, even for models 2 and 5, the circumstellar disc grows with $\sigma \propto r^{-2}$ in further evolution phase.

4 DISCUSSION

4.1 Further evolution of the circumstellar disc

When the molecular cloud core has no angular momentum, the gas inside the first core gradually accretes on to the protostar and the first core disappears in several years after the protostar formation (e.g., Masunaga & Inutsuka 2000). On the other hand, the first core does not disappear and evolves into the circumstellar disc after the protostar formation when the molecular cloud core has an angular momentum.
The protostellar mass, $M_{\text{ps}}$, mass of the circumstellar disc, $M_{\text{disc}}$, and circumstellar disc radius $r_{\text{disc}}$ at the end of the calculation for each model are listed in Table 1. As noted in the table, the mass of the circumstellar disc is much more massive than that of the protostar by the end of the calculation (or several years after the protostar formation). The first core that is the origin of the circumstellar disc has a mass of $\sim 0.02$–0.06 $M_\odot$ at its formation, while the protostar has a mass of $\sim 10^{-3}$ $M_\odot$ at its formation. The mass of each object (the first core and protostar) is determined by the Jeans mass at its formation. The Jeans mass continues to decrease as the cloud collapses (see fig. 2 of Inutsuka et al. 2010), and the first core forms at earlier epoch than the protostar. Thus, the first core is about 10–100 times more massive than the protostar at the protostar formation epoch. Then, even in the early main accretion phase after the protostar formation, the mass of the circumstellar disc that is directly evolved from the first core is much more massive than that of the protostar. The existence of the initial magnetic field does not change this picture qualitatively.

As shown in Section 3.1.1, the first core evolves into the circumstellar disc in the main accretion phase even when the molecular cloud core has a considerably smaller angular momentum of $\beta_0 \simeq 10^{-4}$ to $10^{-5}$ whose value is comparable or smaller than the lower limit of observations $\beta_0 \sim 10^{-4}$ (Goodman et al. 1993; Caselli et al. 2002). This indicates that, in general, a massive Keplerian disc rapidly (or suddenly) appears just after (or before) the protostar formation. In the main accretion phase subsequent to the gas-collapsing phase, both the circumstellar disc and the protostar increase their mass by gas accretion. In this study, we could not investigate further evolution of the circumstellar disc in the main accretion phase, because we calculated its formation and evolution with a sufficiently high spatial resolution that requires a very small time-step. On the other hand, Machida et al. (2010a) calculated the formation and evolution of the circumstellar disc with a relatively coarser spatial resolution at the expense of the structure in the proximity of the protostar, and showed that the circumstellar disc is more massive or comparable to the protostar until the end of the main accretion phase. It is expected that such a massive disc tends to show fragmentation and subsequent formation of the binary companions or planet-size objects in the circumstellar disc. Even when no fragmentation occurs in the main accretion phase, such a massive disc is a favourable site for planet formation after the main accretion phase, because gas-giant planets can be formed by gravitational instability (Durisen et al. 2007). However, we require a huge amount of CPU time to investigate the further evolution of the disc after the main accretion phase from the molecular cloud core stage.

The circumstellar disc increases its size and mass until the end of the main accretion phase as shown in Machida et al. (2010a), in which the evolution of the circumstellar disc in the unmagnetized cloud was investigated. In this study, we confirmed that the magnetic field rarely affects the formation and early evolution of the circumstellar disc. However, the magnetic field may suppress further growth of the circumstellar disc. Recently, Mellon & Li (2009) and Duffin & Pudritz (2009) claimed that the formation of a larger size disc exceeding $\sim 10$ au may be suppressed in a strongly magnetized cloud, because the angular momentum is effectively transferred by magnetic braking. In our calculation, the circumstellar disc with the Keplerian rotation appears in the high-density gas region ($n \gtrsim 10^{15}$ cm$^{-3}$) where the magnetic field is decoupled from neutral gas. However, as the circumstellar disc grows by gas accretion, the low-density gas region ($n \ll 10^{15}$ cm$^{-3}$) appears, where the magnetic field can be coupled with neutral gas and the angular momentum is transferred by magnetic braking. In addition, in the magnetized collapsing cloud, the circumstellar disc (or first core) can drive the protostellar outflow that also outwardly transfers the angular momentum from the parent cloud (Tomisaka 2002; Machida, Tomisaka & Matsumoto 2004; Machida et al. 2006b, 2009).

However, in the later gas-accretion phase, the gas with larger specific angular momentum falls on to the circumstellar disc, because the outer envelope has a larger angular momentum and the gas of the outer envelope falls on to the centre of the cloud later. Such infalling gas with larger specific angular momentum can be able to contribute to the larger size disc formation, over the magnetic braking catastrophe. In addition, the magnetic braking becomes less effective as the mass of infalling envelope decreases (Machida et al. 2010b). Thus, circumstellar disc with a size comparable to observations is expected to be formed even in a magnetized cloud.

### 4.2 Fragmentation in the early collapsing phase

In this study, to suppress fragmentation and binary formation, we adopted a relatively small initial rotational energy ($\beta_0 \leq 10^{-3}$) that...
is smaller than the average of the observations $\beta_0 \sim 0.02$ (Goodman et al. 1993; Caselli et al. 2002). Recent numerical simulations have shown that fragmentation or binary formation occurs just after the first core formation when the initial cloud has a relatively larger rotational energy of $\beta_0 > 10^{-3}$ (Matsumoto & Hanawa 2003, see also Bodenheimer et al. 2000; Goodwin et al. 2007). The magnetic field tends to suppress fragmentation (Hennebelle & Teyssier 2008; Machida et al. 2008a), while fragmentation can occur in a magnetized cloud depending on initial configuration of the molecular cloud (Boss 2009). The mass and size of the fragments are comparable to those of the first core ($r \sim 1$--10 au, $M \sim 0.1$--0.01 $M_\odot$), because the first core fragments to form a few clumps. In addition, although the angular momentum is redistributed into the orbital and spin angular momentum after fragmentation, each fragment still has sufficient angular momentum to form the Keplerian-rotating disc inside it, as shown in Machida et al. (2005b). Therefore, it is expected that the circumstellar disc forms in each fragment passing through the same evolutionary path as the non-fragmentation model, and the circumstellar disc in each fragment has a similar size and mass to the non-fragmentation models. Note that the disc formation process may differ from non-fragmentation models when fragmentation occurs inside the first core (or in the higher-density region), because the properties of the fragment are different from those of the first core. However, Bate (1998) showed that fragmentation rarely occurs in such a high-density region ($n \gg 10^{10}$ cm$^{-3}$) in the collapsing cloud core.

We can expect that, in each fragment, the circumstellar disc with Keplerian rotation appears after the protostar formation, and such a disc is more massive than (or comparable to) the protostar in the early main accretion phase, as shown in Section 3. However, as the circumstellar discs grow, the discs in each fragment may interact. Thus, we do not know whether the circumstellar disc in each fragment traces the same evolutionary path for non-fragmentation model in the main accretion and subsequent phases. To investigate the evolution of the circumstellar disc in the binary or multiple systems, further long-term calculations that cover binary or multiple systems are necessary.

### 4.3 Comparison with previous studies

Using three-dimensional calculations with a sufficient spatial resolution, very few studies investigated the formation of the protostar and circumstellar disc from the pre-stellar core stage (or molecular cloud core). Without magnetic field, resolving the protostellar radius ($\sim 0.01$ au), Bate (1998) and Saigo et al. (2008) investigated the cloud evolution before and just after the protostar formation. In our calculation, with smaller $\beta_0$, two nested discs appear just after the protostar formation. As shown in Section 3.1.1, the inner disc corresponds to the centrifugally supported disc, while the outer disc is the remnant of the first core. These two discs merge into a single circumstellar disc with a Keplerian rotation a few years after the protostar formation. The appearance of the inner and outer disc in a cloud with a smaller angular momentum is also seen in Bate (1998) and Saigo et al. (2008). With larger $\beta_0$, we showed that a massive first core formed before the protostar formation is already supported by the centrifugal force and directly evolves into the circumstellar disc after the protostar formation (see Section 3.1.3). Saigo et al. (2008) also showed that the first core directly becomes the circumstellar disc in a cloud with initially larger angular momentum. Thus, the formation process of the circumstellar disc in the very early phase of the star formation derived in this study agrees with that derived in the previous studies.

Saigo et al. (2008) classified the formation of the circumstellar disc into two types: the circumstellar disc appears after the remnant of the first core falls on to the protostar in clouds with slow rotation, while the first core becomes a centrifugally supported disc after the protostar formation in clouds with a moderate rotation. Their result is not qualitatively contradicted with ours. Although Saigo et al. (2008) only expected the appearance of the centrifugally supported disc after the protostar formation, we confirmed that the circumstellar disc that originates from the first core really has a Keplerian rotation with our longer-term calculations after the protostar formation. To understand the subsequent evolution of the circumstellar disc, it is essential to determine whether the disc has a Keplerian rotation or not. The disc size appeared in our calculations is much smaller than that in observations. However, when the disc has a Keplerian velocity and is supported by the centrifugal force, the disc size increases with time and becomes comparable to observations without disappearing in a short duration.

With magnetic field, only Banerjee & Pudritz (2006) and Machida et al. (2008a) investigated the protostar formation from the pre-stellar core stage, resolving the protostellar radius. Banerjee & Pudritz (2006) showed the disc formation around the protostar, while they did not include the dissipation of the magnetic field. Machida et al. (2008a) showed a high-velocity jet driving around the protostar with magnetic dissipation, while they did not investigate the formation and evolution of the circumstellar disc. In this study, for the first time, we investigated the formation of the circumstellar disc in magnetized clouds including the magnetic dissipation with a sufficient spatial resolution, and showed that the first core directly becomes the circumstellar disc after the protostar formation as seen in unmagnetized cloud. Thus, as expected in Bate (1998) and Machida et al. (2010a), a massive circumstellar disc already exists at the moment of the birth of the protostar even with the magnetic field.

#### 4.4 Barotropic approximation and radiation hydrodynamics

In this study, we used a barotropic equation of state to reduce computational cost. In reality, the thermal evolution in the collapsing cloud may have to be investigated with radiation hydrodynamics code, while it needs a very high computational cost. With a sufficient spatial resolution, only Whitehouse & Bate (2006) and Bate (2010) calculated the protostar formation from the molecular core stage using smoothed particle hydrodynamics with radiative transfer, while they did not focus on the circumstellar disc formation. However, they commented that the cloud evolution with radiation hydrodynamics is almost identical to the evolution obtained from the calculation with the barotropic equation of state before the protostar formation (see also Tomida et al. 2010). Thus, we consider that the barotropic approximation is applicable to investigate the protostar formation and the evolution of the circumstellar disc just after the protostar formation. Note that the barotropic approximation may not be applicable (long) after the protostar formation, because the circumstellar disc is heated by the protostar and radiatively cools with time.

The cloud rotation makes the circumstellar disc in the star formation process. Thus, one may simply expect that a larger disc appears in a cloud having a larger initial angular momentum (or larger $\beta_0$). However, fragmentation can occur and binary or multiple stellar system appears in such a cloud (Bodenheimer et al. 2000; Goodwin et al. 2007). A large fraction of star is born as binary or multiple system (Mathieu 1994). Thus, we might have to investigate the disc formation in a binary system. The radiative effect may be crucial to
investigate fragmentation and binary formation. Boss et al. (2000) investigated the fragmentation process in the collapsing cloud using both barotropic equation of state and radiation hydrodynamics code with the Eddington approximation. For the fragmentation process, they showed a meaningful difference between calculations with barotropic and Eddington approximations. Thus, we may have to calculate the cloud evolution with radiation hydrodynamics code, at least, to investigate fragmentation and binary formation. In this study, however, to focus on the circumstellar disc around a single protostar (not binary system), we limited the initial rotational energy in the range of $\beta_0 \leq 10^{-3}$. With this parameter range, fragmentation is suppressed and a single protostar appears (e.g. Matsumoto & Hanawa 2003; Machida et al. 2008a).

With radiation magnetohydrodynamics (RMHD) simulations, Commerc¸on et al. (2010) and Tomida et al. (2010) showed that the cloud evolution for a single star formation with radiation hydrodynamics is not qualitatively different from that with barotropic equation of state (Commerc¸on et al. 2010; Tomida et al. 2010), in which, however, they could not calculate the cloud evolution until the stellar density. In this study, we calculated the cloud evolution until the protostar formation with a barotropic equation of state resolving the protostellar radius, and concluded that the circumstellar disc originates from the first core and is inevitably massive than the protostar in the early evolution phase. Thus, we expect that our main conclusion is not qualitatively changed even with radiation hydrodynamic simulations, while the disc properties such as size, mass and growth rate of the circumstellar disc derived in our calculation may be quantitatively changed in future RMHD simulations. To confirm detailed properties of the circumstellar disc, we need to calculate the cloud evolution for a long duration with a more developed radiation hydrodynamics code in the future.

5 SUMMARY

In this study, we calculated the evolution of the collapsing gas cloud from the molecular cloud core until the circumstellar disc with the Keplerian rotation appears resolving both molecular cloud core and protostar itself, and found that the circumstellar disc originates from the first core and is much more massive than the protostar in the early main accretion phase. The magnetic field slightly minifies the initial size of the first core (or the circumstellar disc), while it rarely affects the early evolution of the circumstellar disc because a very weak field is realized in the disc forming region due to the magnetic dissipation. Our results indicate that the massive Keplerian disc already exists just after the protostar formation. This result is different from the classical picture of the circumstellar disc formation, in which the circumstellar disc gradually grows in its size and mass after the protostar formation.

The formation of the circumstellar disc from the pre-stellar core stage is summarized in Fig. 15, in which three different epochs for first core formation, protostar formation and main accretion phases are schematically described for three different modes of the protostar and circumstellar disc formation (i.e. for the cloud with rapid [a], slow rotation [b] and no rotation [c]). The figure shows that the first core appears before the protostar formation. The first core shrinks and disappears in several years after the protostar formation when the molecular cloud has no angular momentum (Fig. 15c). On the other hand, when the molecular cloud has an angular momentum, the first core has a disc-like structure at its formation and remains without disappearing even after the protostar formation.

When the cloud has a relatively rapid rotation (Fig. 15a), the first core already has a Keplerian rotation from its formation. Then, the first core gradually increases its central density, and the protostar

![Figure 15. Schematic view of the circumstellar disc formation in the collapsing cloud core, showing three different evolutional sequences for the cloud with (a) rapid rotation, (b) slow rotation and (c) no rotation.](https://academic.oup.com/mnras/article-abstract/413/4/2767/964734)
appears when the number density exceeds \( n \gtrsim 10^{20} \text{ cm}^{-3} \). Thus, at the protostar formation epoch, the protostar is already surrounded by the Keplerian rotating disc, which is about 100 times more massive than the protostar. In summary, the Keplerian disc formation precedes the protostar formation. In other words, the protostar is born inside the Keplerian rotating disc.

When the molecular cloud has a relatively slow rotation rate (Fig. 15b), the first core is partially supported by the centrifugal force, and mainly by thermal-pressure-gradient force. Thus, at the first core formation epoch, although the first core has an oblate structure, it rotates slowly with a sub-Keplerian velocity. In this case, after the protostar (i.e. the first core) formation, two nested cores (two nested discs) appear as seen in Fig. 15(b). The outer disc corresponds to the remnant of the first core, while the inner disc corresponds to the Keplerian disc formed in the proximity of the protostar. In the main accretion phase, the gas of the first core gradually falls on to the protostar. Because the sizes of the first core (\( \sim 1 \text{ au} \)) and the protostar (\( \sim 0.1 \text{ au} \)) are considerably different, the infalling gas increases its rotational velocity as it shrinks in the radial direction according to the angular momentum conservation law. As a result, the Keplerian disc (i.e. the inner disc) appears around the protostar. Then, the inner disc increases its size, while the first core gradually shrinks. Finally, two nested discs merge to form a single disc that has a Keplerian velocity and corresponds to the circumstellar disc. At the epoch of the merger, the size and mass of the merged disc are almost the same as those of first core at its formation. Note that the first core shrinks before merger, while it still has a size of \( \sim 1 \text{ au} \) (Fig. 5). Thus, also in a cloud with considerably small rotational energy, the massive Keplerian disc already exists just after the protostar formation.

In this study, we showed that a massive disc already exists before the protostar formation, and the protostar is enclosed by the massive Keplerian circumstellar disc from the moment of its birth. In addition, our result indicates that the massive disc (>0.1–0.01 M⊙) with a size of >1 au already exists in the very early phase of the star formation (or before the star formation). We expect that such a disc can be detected using future instruments such as ALMA.

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