GENERATION OF MAGNETIC FIELD ON THE ACCRETION DISK AROUND A PROTO-FIRST-STAR

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ABSTRACT

The generation process of a magnetic field around a proto-first-star is studied. Utilizing the recent numerical results of proto-first-star formation based on radiation hydrodynamics simulations, we assess the magnetic field strength generated by the radiative force and the Biermann battery effect. We find that a magnetic field of \( \sim 10^{-9} \) G is generated on the surface of the accretion disk around the proto-first-star. The field strength on the accretion disk is smaller by two orders of magnitude than the critical value, above which the gravitational fragmentation of the disk is suppressed. Thus, the generated seed magnetic field hardly affect the dynamics of on-site first star formation directly, unless an efficient amplification process is taken into consideration. We also find that the generated magnetic field is continuously blown out from the disk on the outflows to the poles, that are driven by the thermal pressure of photoheated gas. The strength of the diffused magnetic field in low-density regions is \( \sim 10^{-14} - 10^{-13} \) G at \( n_H = 10^3 \) cm\(^{-3}\), which could play an important role in the next generation star formation, as well as the seeds of the magnetic field in the present-day universe.

Key words: early universe – H\( \alpha \) regions – magnetic fields – radiative transfer

Online-only material: color figures

1. INTRODUCTION

The energy density of a magnetic field in local interstellar gas is not negligible, which plays significant roles on the formation of stars in our Galaxy. This magnetic field is generally regarded as a consequence of dynamo amplification of an initial seed magnetic field generated in the early universe. Various generation mechanisms of this seed field have been proposed: magnetic field generation in the very early universe due to the coupling of gravity and the electromagnetic field (e.g., Turner & Widrow 1988), non-zero \( \nabla \times E \) term due to the inhomogeneity of the radiation field at the recombination of the universe (e.g., Ichiki et al. 2006), and the Biermann battery effect (Biermann 1950) at the shock front in forming galaxies (e.g., Kulsrud et al. 1997; Xu et al. 2008)/at the ionization fronts in the reionizing universe (Gnedin et al. 2000). It has also been proposed that the radiation force and the Biermann battery effect in the vicinity of luminous sources can generate seed fields (Langer et al. 2005; Ando et al. 2010; Doi & Susa 2011). Interestingly, all of these models suggest a seed field strength of \( 10^{-20} - 10^{-18} \) G at intergalactic medium (IGM) densities, which is well below the observational constraint (Durrer & Neronov 2013 and the references therein).

The generated seed magnetic field could potentially affect the star formation process in the early universe as seen in our Galaxy, e.g., through launching jets, transferring angular momentum, and suppressing the gravitational fragmentation of disks. It has been pointed out that the resistivity of primordial gas should be relatively low throughout the collapse of a cloud (e.g., Maki & Susa 2004, 2007; Schleicher et al. 2009). As a result, magnetic fields do not dissipate from the cloud at the Jeans scale. Thus, given the same strength of seed magnetic fields at the onset of the collapse, magnetic fields should have a larger impact on star formation in primordial gas than that in the present-day molecular cloud in which magnetic fields dissipate within a certain range of densities (e.g., Nakano & Umebayashi 1986).

Machida et al. (2008) have addressed the dynamical effects of magnetic fields on star formation in primordial gas, assuming ideal MHD, which is correct as long as we consider larger scales than the Jeans length. They found that the magnetic field does have a dynamical impact on collapsing gas, including the formation of jets if \( B \gtrsim 10^{-5} \) G at \( 10^5 \) cm\(^{-3}\). Machida & Doi (2013) addressed the later evolution of the system (the gas accretion phase) by resistive MHD calculations. They found that the fragmentation of the disk is significantly suppressed by the magnetic field when \( B \gtrsim 10^{-10} (n_H / 10^3 \text{ cm}^{-3})^{-2/3} \) G. However, if we convert this field strength to the IGM density at \( z = 20 \), assuming flux freezing, we obtain \( B \gtrsim 10^{-14} \) G, which is much larger than the seed field strength predicted by various models as mentioned above. Hence, magnetic fields seem unlikely to affect the dynamics of the formation of primordial stars. To put it another way, if a seed field of \( B \gtrsim 10^{-14} \) G is generated by some mechanism, the magnetic field is a vital part of star formation in the early universe. It has been suggested that small-scale turbulence can amplify the seed magnetic field with a dynamical timescale, and it can inversely cascade into larger scales to affect the dynamics of star-forming clouds at the Jeans scale (Schleicher et al. 2010; Schober et al. 2012; Sur et al. 2012), although sufficient amplification that would affect the dynamics of the gas has not yet been shown to start from a very weak seed field of \( 10^{-18} - 10^{-20} \) G by ab initio numerical simulations (Sur et al. 2010; Federrath et al. 2011; Turk et al. 2012; Latif et al. 2013). In any case, the amplitude of a seed magnetic field is an important key parameter to understanding primordial star formation.

In this paper, we discuss the seed magnetic field generation mechanism regarding the anisotropic radiation field and complex density/temperature structures in the vicinity of forming first stars, which was originally discussed in our previous studies at 100 pc–10 kpc scales (Ando et al. 2010; Doi & Susa 2011). We focus on magnetic field generation, particularly in the vicinity of proto-first-stars at the 100–1000 AU scale, where accreting/outflowing gas create intricate structures. Since the
generated field strength depends on the radiation flux from the source star, a stronger magnetic field is expected.

Such complicated structures have already been calculated by Hosokawa et al. (2011). They investigated the gas accretion process onto a proto-first-star by two-dimensional (2D) radiation hydrodynamics (RHD) simulations, although the generation process of the magnetic field was not taken into account. In this paper, we evaluate the growth of the magnetic field by a post-processing scheme utilizing their simulation as a background. Then, we discuss the impact of the magnetic field generated through this process on the evolution of the proto-first-stars and the formation of second generation stars.

This paper is organized as follows. We describe the fundamental processes of seed field generation in Section 2. In Section 3, we show our numerical model, and the results are shown in Section 4. Section 5 is devoted to discussion and the conclusion.

2. GENERATION OF THE MAGNETIC FIELD

In this section, we briefly describe the basic equations of magnetic field generation; however, a more detailed description can be found in Ando et al. (2010). The growth of the magnetic field is described by the following induction equation with two source terms:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{c}{en_e^2} \nabla n_e \times \nabla p_e - \frac{c}{e} \nabla \times \mathbf{f}_{\text{rad}}. $$

(1)

This equation is obtained by combining the equation of the force balance on a single electron with the Maxwell’s equations. Here, we omitted the Hall current term, which is proportional to $j \times \mathbf{B}$, since this is the higher-order term than the others, in case we consider the generation of a weak magnetic field.

The first term in the right-hand side denotes the advection of magnetic field lines which stick to the gas. If the second and third terms are neglected, the frozen-in condition is satisfied. Thus, the first term is not the source of the magnetic field generation. The second term is the Biermann battery term (Biermann 1950), which is non-zero in case the gradient of electron density and pressure are not perfectly parallel with each other. The third term is the radiation term, which is proportional to the rotation of the radiation force field on a single electron ($\mathbf{f}_{\text{rad}}$).

The radiation force, $\mathbf{f}_{\text{rad}}$, is composed of two micro processes that potentially could be important for the momentum transfer from photons to electrons. The first process is the Thomson scattering. We use a formal solution of the radiation transfer equation for $\mathbf{f}_{\text{rad,T}}$ as follows:

$$\mathbf{f}_{\text{rad,T}} = \frac{\sigma_T}{c} \int_{0}^{v_L} F_{0v} dv + \frac{\sigma_T}{c} \int_{v_L}^{\infty} F_{0v} \exp[-\tau_{\nu_L} a(v)] dv, $$

(2)

where $\mathbf{f}_{\text{rad,T}}$ denotes the radiation force per single electron due to Thomson scattering, $\sigma_T$ is the cross section, and $F_{0v}$ is the incident energy flux density. $v_L$ denotes the Lyman-limit frequency, $\tau_{\nu_L}$ is the optical depth at the Lyman limit regarding the photoionization, and $a(v)$ denotes the frequency dependence of the photoionization cross section, which is normalized at the Lyman limit, i.e., $a(v_L) = 1$ is satisfied.

The second process is the photoionization, whose contribution to $\mathbf{f}_{\text{rad}}$ is given as

$$\mathbf{f}_{\text{rad,I}} = \frac{1}{2} \frac{n_H}{n_e} \int_{v_L}^{\infty} \sigma_{\nu_L} a(v) F_{0v} \exp[-\tau_{\nu_L} a(v)] dv, $$

(3)

where $\sigma_{\nu_L}$ denotes the photoionization cross section at the Lyman Limit. We note that the factor 1/2 in the right-hand side of Equation (3) is due to the fact that the photon momentum is equally delivered to protons and electrons. Then, we can also safely assume that only electrons are accelerated by this momentum transfer process, since protons have much larger inertia than electrons.

3. MODEL DESCRIPTION

3.1. The Underlying Model of Proto-first-star Formation

We take the underlying model of the proto-first-star formation from Hosokawa et al. (2011). The initial condition of the model is taken from Yoshida et al. (2008), where the formation of the embryo protostar is simulated in a fully cosmological context. The subsequent evolution in the mass accretion stage is followed with 2D RHD simulations coupled with the protostellar evolution calculations (see Hosokawa et al. 2011 for full details). The stellar mass rapidly increases in this stage, as the gas accretes onto the star through a circumstellar disk. The stellar UV luminosity also sharply rises with increasing stellar mass, and a bipolar HII region emerges. The HII region then begins to expand dynamically in the accreting envelope, which blows away the gas in the envelope. The circumstellar disk is exposed to the stellar ionizing radiation, and gradually loses its mass as a result of photoevaporation. In the fiducial case, which is adopted here, a 43 $M_{\odot}$ star forms as the mass accretion is finally shut off by the stellar UV feedback effect.

3.2. Magnetic Field Generation by Post-processing

Now, we are able to simulate the generation of a magnetic field by integrating the Equation (1) by a post-processing method utilizing the results of the RHD simulation mentioned above, i.e., the snapshots of the spatial distributions of density, temperature, velocity, and chemical abundances in the accretion envelope. Then, we assess the Biermann battery term by a simple finite difference scheme. Because of axisymmetry, $\nabla n_e$ and $\nabla p_e$ are both perpendicular to $e_{\phi}$, the base vector of the azimuthal angle. Thus, the source term $\nabla n_e \times \nabla p_e$ is parallel to $e_{\phi}$ (Figure 1).

We can also calculate the radiation term by ray-tracing from the central protostar. This radiation term, $\nabla \times \mathbf{f}_{\text{rad}}$, is also directed to $e_{\phi}$, again because of the axisymmetry (Figure 1). We also remark that this term is expected to be significant on the ionization front, where the shear of $\mathbf{f}_{\text{rad}}$ is large.
Thus, the seed field generated by these source terms is parallel to \( \mathbf{e}_\phi \). In addition to these source terms, the dynamo term, \( \nabla \times (\mathbf{v} \times \mathbf{B}) \), is also parallel to \( \mathbf{e}_\phi \) as long as \( \mathbf{B} \propto \mathbf{e}_\phi \) is satisfied. Since we assume zero field strength at the initial state in the present simulations, the magnetic field is always parallel to \( \mathbf{e}_\phi \) throughout the simulation. It is also worth noting that the dynamo term reduces to a simple advection term under the assumed symmetry in the present simulation.

We ignore the contribution from the diffuse radiation emitted from the surface of the disk, since its contribution to the photoionization is smaller than the direct radiation from the surface of the disk, since its contribution to the UV flux is maximized at the border between the ionized region and the ionization front, since the shear field of the radiation force \( \propto \Delta Ra \) is larger than the required time step, we interpolate the data between the output time steps.

4. RESULTS

Figure 2 shows the evolution of electron number density and magnetic field around the protostar. The top three panels show the distribution of electron number density on the \( R-z \) plane of a cylindrical coordinate at \( 1.18 \times 10^4 \) yr, \( 2.02 \times 10^4 \) yr, and \( 7.54 \times 10^4 \) yr after the formation of the protostar. The middle panels show the spatial distribution of magnetic field strength at the corresponding epochs. The box is 1800 AU on each side. The protostars are located at the bottom left corners of the boxes, and their masses at the three epochs are \( 17.6 M_\odot \), \( 23.4 M_\odot \), and \( 39 M_\odot \), respectively. The bottom row shows the volume weighted probability distribution function on a \( \log n_H [\text{cm}^{-3}] - \log B [\text{G}] \) plane.

The left column corresponds to the time just after the breakout of the ionization front, when the magnetic field is generated in the very vicinity of the protostar. Roughly speaking, the ionized/photoheated small bubble (top) is magnetized (middle). On the other hand, the field strength is weak in the outer, less dense regions (bottom).

Another \( 10^4 \) yr later (middle column), an ionization front expands out of this box size to form an hourglass shaped ionized polar region (top). A magnetic field is generated at the ionization front, and the generated magnetic field is transferred to the outer, less dense regions, riding on the outflow into the polar direction roughly following the \( B \propto n_H^{2/3} \) law (bottom).

Finally, at \( 7.54 \times 10^4 \) yr (right column), the generated field strength is \( \sim 10^{-14} - 10^{-13} G (n_H/10^5 \text{ cm}^{-3})^{2/3} \) (bottom). This magnitude is still less than the critical field strength shown by a white solid line, above which the accretion disks around proto-first-stars are suppressed (Machida & Doi 2013).

Figure 3 shows color contour maps of the source terms regarding the magnetic field generation at \( 7.5 \times 10^4 \) yr after the formation of the protostar. This epoch corresponds to the final snapshot in Figure 2. The top left panel shows the Biermann battery term, the second term of the left-hand side in Equation (1), while the top right is the radiation term, i.e., the third term in Equation (1). The radiation term is prominent at the ionization front, since the shear field of the radiation force is maximized at the border between the ionized region and the shadowed neutral region. The Biermann battery term is also important at the ionization front, across which the temperature and the density changes dramatically. We also remark that the Biermann battery term dominates in more extended regions (see bottom left, total source term) since the temperature of the ionized region very weakly depends on the distance from the source star, while the radiation force \( f_{\text{rad}} \) is inversely proportional to the square of the distance from the source. Thus, the radiation term dominates in the vicinity of the protostar. We also mention that the generated magnetic field has a smoother structure than the source terms because the gas temperature/density changes with time, and the generated field is transferred to outer, less dense regions (bottom right).

Figure 4 shows the ratio of the radiation term to the Biermann battery term of each cell in the finest numerical box (the nested grid scheme is employed in the RHD simulation). The three colors of points correspond to the three epochs shown in Figure 2. It is clear that the Biermann term is more important than the radiation term just after the break out of the ionization front (blue stars), while the radiation term dominates in the later epochs (green and red symbols). This is because the gas is more dynamical in the phase of I-front break out, which leads to a larger gradient of density/pressure: so is the Biermann battery term. In the later phase, the density/pressure structure becomes smoother than that in the earlier phase, and the luminosity of ultraviolet radiation from the protostar becomes larger. Thus, the relative importance of the radiation source term becomes larger at later epochs.

5. DISCUSSION AND CONCLUSION

The magnetic field is generated by two source terms: the radiation term and the Biermann battery term. The order of magnitude of magnetic field strength generated via these processes in the vicinity of the central protostar can be assessed as follows:

\[
B_{\text{rad}} \approx \frac{L \sigma_b}{8 \pi e \Delta r R^2} \Delta t \quad (4)
\]

\[
B_{\text{Bier}} \approx \frac{c k_B T_e \sin \theta}{e \Delta r^2} \Delta t. \quad (5)
\]

Here, \( L \) is the luminosity of the source protostar, \( \Delta r \) denotes the length scale across which \( f_{\text{rad}} \) or the temperature/density changes, \( R \) is the distance from the star, \( \Delta t \) is the duration of field generation, and \( \theta \) represents the typical angle between \( \nabla T_e \) and \( \nabla n_e \).

The duration, \( \Delta t \), can be assessed as the timescale that the gas is sent brazing out distance \( R \) by the outflow of typical velocity \( v \), as \( \Delta t \equiv R/v \). Substituting this expression and typical values, we have

\[
B_{\text{rad}} \approx 10^{-9} G \left( \frac{L}{10^{37} \text{ erg s}^{-1}} \right) \left( \frac{\Delta r}{10 \text{ AU}} \right)^{-1} \times \left( \frac{R}{100 \text{ AU}} \right)^{-1} \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1}. \quad (6)
\]

\[
B_{\text{Bier}} \approx 10^{-12} G \left( \frac{T_e}{10^4 \text{ K}} \right) \left( \frac{\sin \theta}{0.1} \right) \left( \frac{\Delta r}{10 \text{ AU}} \right)^{-2} \times \left( \frac{R}{100 \text{ AU}} \right) \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1}. \quad (7)
\]

Here, we assume \( \Delta r = 0.1 R \). These estimated orders of magnitude are consistent with the numerical results at the inner...
Figure 2. Time evolution of magnetic field is presented. Top: electron density $n_e$ is shown by the color contour. In each panel, the protostar is located at the bottom left corner of the box. The three panels correspond to three snapshots. The box is 1800 AU on each side. The three panels correspond to the snapshots of $1.18 \times 10^4$ yr, $2.02 \times 10^4$ yr, and $7.54 \times 10^4$ yr after the formation of the protostar. Middle: magnetic field distribution in the vicinity of the protostar. Bottom: frequency distribution of computational cells on $\log n_H$ [cm$^{-3}$]–$\log B$ [G] plane.

(A color version of this figure is available in the online journal.)
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Figure 3. Color contour maps of source terms of magnetic field generation. The Biermann battery term (top left), radiation term (top right), total (bottom left), and the magnetic field itself (bottom right) at 7.5 × 10^4 yr after the formation of protostar.

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

high-density regions, \( n_H \gtrsim 10^8 \text{ cm}^{-3} \) (see the bottom three panels of Figure 2).

The generated field strength is \( \sim 10^{-13} \text{ G} (n_H/10^3 \text{ cm}^{-3}) \) at the final stage of the present simulation, which accounts for \( \sim 10^{-17} \text{ G} \), at IGM densities of \( z = 20 \). This magnitude is comparable to the value obtained by previous estimates at 100 pc–1 kpc scales (Doi & Susa 2011). The coherence length is also similar with each other, since the outflow will extend out to the host minihalos of \( \sim 100 \) pc. This obtained field strength is less than the critical value above which the fragmentation of the disk is suppressed by two orders of magnitude (Machida & Doi 2013). In addition, we also remark that such a relatively large magnetic field emerges after the central protostar grows up to \( \gtrsim 20 M_\odot \), since the protostar has to be massive enough to emit ultraviolet radiation. According to a three-dimensional (3D) RHD simulation, the gas disk is heated by the radiation from the protostar at such an epoch, and hence the disk is stabilized against gravitational instability (Susa 2013). Thus, the generated magnetic field in this context seems to hardly affect the on-site fragmentation of the disk directly.

However, as for the second generation star formation, this field strength could play important roles. First, recent cosmological MHD simulations of first star formation revealed that the minihalos that host primordial star-forming gas clouds are very turbulent (e.g., Turk et al. 2012). According to the theoretical model, such turbulent motion at much less than the Jeans scale could amplify the seed magnetic field with a dynamical timescale, and it could inversely cascade into larger scales to affect the dynamics of star-forming clouds at the Jeans scale. If this mechanism also works in the collapsing gas clouds in the vicinity of first stars, the seed field formed in the present mechanism would be important for the formation of second generation stars.

Second, we might have underestimated the field strength. According to Equation (6), we have \( B_{\text{rad}} \propto R^{-2} \), assuming \( \Delta R \approx 0.1 R \). However, the neighbor around the central protostar is not spatially resolved in the underlying simulations. With the higher-resolution simulations resolving the innermost part of the disk, the magnetic fields generated there should be much stronger than the current estimates. At the disk surface of \( R \sim 10 R_\odot \), which is slightly larger than the radius of a 40 \( M_\odot \) star, the generated magnetic field could reach \( \sim 5 \times 10^{-3} \text{ G} \). We also can assess the density at the surface of the disk of \( R \sim 10 R_\odot \) by extrapolating the results of numerical simulation, where the gas density is approximately proportional to \( R^{-1} \). Consequently, we obtain \( n_H \sim 2 \times 10^{11} \text{ cm}^{-3} \). The generated magnetic field of \( \sim 5 \times 10^{-3} \text{ G} \) at \( n_H \sim 2 \times 10^{11} \text{ cm}^{-3} \) will be blown out to outer, less dense regions and result in \( B \sim 10^{-8} \text{ G} (n_H/10^3 \text{ cm}^{-3})^{2/3} \). This is obviously important for the dynamics of gravitationally collapsing gas clouds even without the amplification by small-scale dynamo action quoted in the previous paragraph. However,

3 It has been pointed out that there is an upper limit of the magnetic field strength generated by radiation drag effects such as the Compton drag (Balbus 1993; Chuzhoy 2004; Silk & Langer 2006). The estimated field strength here is much larger than the limit. However, there is no contradiction because the present radiation effect is not the drag effect.
Figure 4. Ratio between the radiation source term and the Biermann battery term is plotted as a function of distance from the protostar. Blue stars: $1.18 \times 10^4$ yr; green vertices: $2.02 \times 10^4$ yr; and $7.54 \times 10^4$ yr; red crosses. These three snapshots correspond to the three panels in Figure 1. Points above unity (dashed line) denote the grid cell where the radiation term is the dominant source for magnetic field generation. (A color version of this figure is available in the online journal.)

we remark that higher-resolution studies are necessary to find the actual field strength in the vicinity of the proto-first-star, since this is an estimate based upon the extrapolation of the present results.

We also point out that 3D effects can also enhance the magnetic field strength. As shown by recent 3D calculations (e.g., Susa 2013), the gas disk around the protostar is highly non-axisymmetric. Such 3D structures induce a poloidal component of the magnetic field, which will result in dynamo amplification in the disk.

In this paper, we assess the magnetic field generated in the neighbor of the proto-first-star due to the Biermann battery effect as well as radiation force. As a result, we find that a weak magnetic field is generated in the inner $\sim 100$–$1000$ AU region, and they are blown out to the outer, less dense regions riding on the outflows roughly following the $B \propto n_H^{2/3}$ law. The resultant field strength is $B \sim 10^{-14}$–$10^{-13}$ G ($n_H/10^3$ cm$^{-3}$)$^{2/3}$. This field strength can be the seed magnetic field of the universe and should be important for the next generation star formation, while it hardly affect the dynamics of the on-site first star formation unless a very efficient amplification process is taken into consideration.

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