DISSIPATION OF MAGNETIC FIELDS IN VERY DENSE INTERSTELLAR CLOUDS AND THE MAGNETIC FLUX OF A NEWBORN STAR

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1. INTRODUCTION

The magnetic flux to mass ratio of an interstellar cloud is 10^4 to 10^5 times the ratio in a typical magnetic star with a surface field of 1kG, and is at least several hundred times the ratio in most strongly magnetic stars. This excess magnetic flux must be lost in some stage of star formation. The dominant process of magnetic flux loss in ordinary clouds is the drift of charged particles and magnetic fields in the sea of neutral particles (plasma drift, also called ambipolar diffusion). However, even this process is inefficient in a cloud of hydrogen number density $n_H \lesssim 10^{10}$ cm^{-3}.

At $n_H \gtrsim 10^{10}$ cm^{-3} the physical situations change drastically: (1) the ionization degree of the gas decreases as the density increases, and the grains with charge ±e soon become the main charged particles; (2) because of frequent collisions with neutral particles, even ions and electrons are hardly bound to the lines of magnetic force. In this paper we shall investigate the dissipation of magnetic field in such situations, and estimate the magnetic flux brought into a newborn star.

2. DISSIPATION OF MAGNETIC FIELDS

By solving the motion of many kinds of charged particles such as electrons, ions and grains, we obtain the velocity of magnetic fields $\mathbf{v}_B$ relative to the fluid (Nakano & Umebayashi 1986a). Any closed curve moving with v_B has a constant magnetic flux. The drift velocity $\mathbf{v}_B$ contains both the effects of the plasma drift and the Joule dissipation.

Comparing v_B with the free-fall velocity of the cloud u_f, we investigate the dissipation of magnetic fields and clarify at what situations the magnetic field decouples from the contracting gas.

For the cloud of mean density $n_H \lesssim 10^{10}$ cm^{-3}, where ions and electrons are the main charged particles, v_B is at least 20 times smaller than u_f. The dissipation of magnetic fields which is mainly due to the plasma drift is inefficient at such densities. Around $n_H \simeq 10^{11}$ cm^{-3}, v_B

begins to increase rapidly with the density, and it exceeds u_f at $n_H \simeq 5\times10^{11}$ cm^{-3}. Thus we can conclude that the magnetic field decouples from the gas at $n_H \gtrsim 5\times10^{11}$ cm^{-3} where charged grains are more abundant than ions and the magnetic field decays mainly through Joule dissipation. We have also investigated clouds of different configurations, and found that the magnetic field is decoupled from the gas in the region of $n_H \gtrsim 10^{12}$ cm^{-3} (Nakano & Umebayashi 1986a). Only nearly current-free fields can exist in this region.

After a cloud becomes opaque to thermal radiation, the temperature increases with contraction. Above several hundred kelvins the thermal ionization becomes efficient, and the interaction of the gas with magnetic fields increases with temperature. We investigate the decay time of magnetic fields due to the Joule dissipation, and find that the contracting gas recovers the coupling with magnetic fields at $T \gtrsim 10^3$K (Nakano & Umebayashi 1986b).

3. THE MAGNETIC FLUX OF A NEWBORN STAR

Using the results obtained in Section 2, we shall investigate the behavior of magnetic fields in each phase of the contraction of a protostar.

In the isothermal contraction phase, a core of radius $r \lesssim 8\times10^{13}$ cm and mass $10^{-2}M_\odot$ decouples from the magnetic field when the central density comes up to 10^{12} cm^{-3}. The current-free field in the core is nearly equal to the surrounding frozen-in field at $n_H \simeq 10^{12}$ cm^{-3} which is 0.8G or less.

The subsequent evolution is rather complicated. An opaque core of $10^{-2}M_\odot$ nearly in hydrostatic equilibrium appears, and the temperature of the core gradually rises nearly adiabatically. When the central temperature reaches 2000K, hydrogen molecules begin to dissociate and the core begins to collapse again. The region of $T \gtrsim 10^3$K at this epoch collapses by grasping the magnetic field prevailing there. The magnetic flux brought into the initial stellar core in this way is at most of the order of the flux of a magnetic star (Nakano & Umebayashi 1986b).

The behavior of magnetic fields in the later accretion phase depends on the magnetic configuration around the stellar core (Nakano & Umebayashi 1986b). If the field B_* in the core is not much stronger than the surrounding field B_d of the envelope, the accreted matter may bring in some magnetic flux. If $B_* \gg B_d$, the field around the core would be dipolar superposed with a uniform field B_d. In this case the matter finally flows in along the field line pentrating the core, and little additional flux is brought in. When the stellar core has acquired a flux of a magnetic star, the latter configuration ($B_* \gg B_d$) is realized, and the increase of the flux ceases. Therefore, the flux of a newborn star hardly exceeds the flux of the most strongly magnetic star with a mean surface field of 20kG.

References

Nakano, T. & Umebayashi, T. 1986a. Mon. Not. R. astr. Soc., in press.

Nakano, T. & Umebayashi, T. 1986b. Mon. Not. R. astr. Soc., in press.