Recurrent Planet Formation and Intermittent Protostellar Outflows

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Since 1995, over 550 exo-planets have been discovered. It is considered that a large fraction of exo-planets are the gas giant planet. Recently, some planets were observed by SUBARU telescope with direct image. They orbit at >10 AU far from the central star. However, the classical planet formation theory cannot explain the formation of such planets. To understand the formation of such planets, we need to consider the formation of the circumstellar disk, in which planet forms. In this study, we investigated the formation of the circumstellar disk from the prestellar cloud stage. As the initial state, we adopted the spherical cloud. Then, we added the rotation and magnetic field comparable to the observation to this cloud.

As a result of calculation, we found that dissipation of the magnetic field is closely related to the formation of the gas giant planet[1]. Our previous studies showed that the first core that is formed before the protostar formation is directly transformed into the circumstellar disk after the protostar formation[2,3]. At the moment of the birth of the protostar, the circumstellar disk is more massive than the protostar and is gravitationally unstable. However, when the initial cloud is very weakly (or no) magnetized, a spiral structure develops in the circumstellar disk, and it effectively transfers the angular momentum outward. Then, the gas in the circumstellar disk falls onto the central star and the surface density gradually decreases. Therefore, the circumstellar disk becomes stable against gravity and suppresses fragmentation or the gas giant planet formation.

On the other hand, when the magnetic field dissipates in the circumstellar disk, fragmentation occurs and the gas giant planet appears. The circumstellar disk has a lower surface density in the outer disk region where the ionization degree is relatively high and magnetic field is well coupled with neutral gas. Thus, the angular momentum in such region effectively transfers by the magnetic braking, and the gas can flow into the inner disk region. In addition, the magnetic field drives the protostellar outflow as shown in Figure 1. The magnetic field is decoupled from the neutral gas in the inner disk region, because higher surface density lowers the ionization degree. In such a region, the magnetic field dissipates by the Ohmic dissipation. As a result, the angular momentum transfer due to the magnetic field is not effective. Thus, the gas accumulates and the disk surface density continues to increase because the gas flows from the outer region. Finally, the disk becomes highly unstable against the gravity and fragmentation occurs to form the gas giant planet. However, after fragmentation, the protoplanet falls onto the protostar because the massive disk gravitationally interacts with protoplanet. After the falling, fragmentation occurs and protoplanet appears again. The planet formation and its falling onto the protostar last until the infalling gas is depleted. It is considered that the planet appeared just before the infalling envelope is depleted evolves into the gas giant planet orbiting the region far from the central star. In addition, protoplanet's motion disturbs the protostellar outflow. The protostellar outflow synchronizes with the orbital motion of the protoplanet. We may confirm the existence of the protoplanet and its orbital motion from the intermittent outflow.

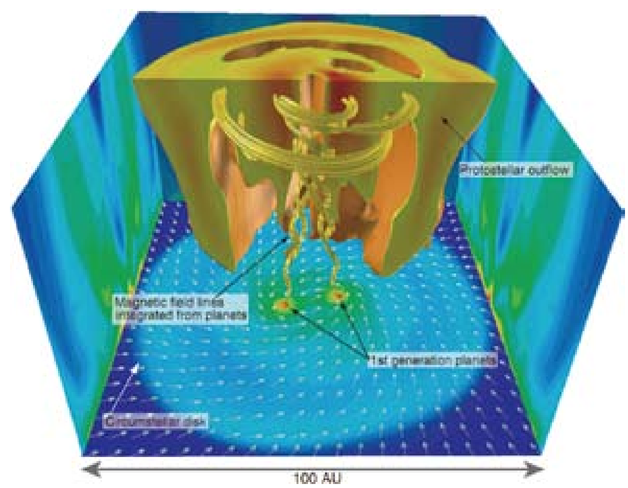

Figure 1: Gas giant planet formation due to the gravitational instability in the protoplanetary disk. Color and lines represent the gas density and magnetic field line, respectively. The yellow structure above the disk indicates the protostellar outflow.

References

[1] Machida, M. N., Inutsuka, S., Matsumoto, T.: 2011a, *ApJ*, **729**, 42.
[2] Machida, M. N., Matsumoto, T.: 2011b, *MNRAS*, **413**, 2767.
[3] Machida, M. N., Inutsuka, S., Matsumoto, T.: 2010, *ApJ*, **724**, 1006.