Disk Formation and Magnetic Interchange Instability in Weakly Ionized Star-Forming Clouds

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Stars are the most fundamental building blocks of the Universe, and understanding their formation process is therefore of critical importance. Since planets and planetary systems are born during the course of star formation, this process is also closely tied to the origin of life. Magnetic fields and rotation play essential roles in star formation. Because the natal molecular cloud cores are in weakly ionized plasma state, it is necessary to consider both the amplification of the magnetic field due to gravitational collapse and its dissipation through Ohmic dissipation and ambipolar diffusion. During the collapse, angular momentum is transported outward from the central region of the star-forming core via magnetically driven outflows. In addition, protoplanetary disks are formed in regions where the magnetic field dissipates.

One long-standing issue in star formation theory is the so-called "magnetic flux problem," which arises from the fact that the magnetic flux observed in newly formed protostars is more than five orders of magnitude smaller than that in their parent molecular cloud cores. Since magnetic flux is a conserved quantity under ideal MHD conditions, this discrepancy implies that a significant amount of flux must be removed from the central region during the star formation process. Traditionally, it has been thought that magnetic flux is gradually removed from the disk over long timescales (>100,000 years) via Ohmic dissipation and ambipolar diffusion.

In this study, we performed three-dimensional non-ideal magnetohydrodynamic simulations, following the gravitational collapse of a prestellar core. These simulations employ nested grid method to accurately capture both the small-scale disk structure and large-scale magnetic field evolution.

As shown in Figure 1, magnetic flux escapes from the outer edge of the disk, forming a low-density cavity structure in the surrounding region. Notably, similar cavity-like structures have recently been identified in high-resolution observations of young circumstellar disks using instruments such as ALMA.

Our results indicate that magnetic flux is expelled on short timescales not through gradual dissipation but via magnetic interchange instability, suggesting a fundamentally different mode of magnetic flux removal than previously considered. This process also helps to resolve the magnetic flux problem in a more dynamic and timely fashion than traditional diffusion-based models. These findings not only reveal a novel mechanism for magnetic flux evolution but also provide new insight into the formation and size regulation of circumstellar disks and planetary systems. Our study highlights the importance of interchange instability in shaping the early environment of star and planet formation.

References
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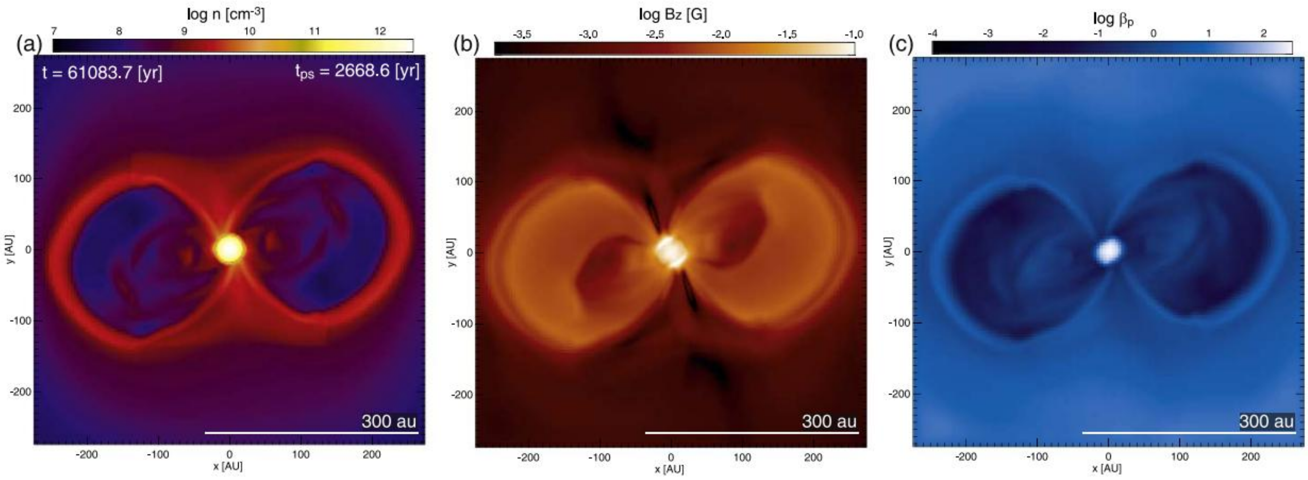

Figure 1. Density (left), z-component of the magnetic field (center), and plasma beta (right) distributions on the equatorial plane at t_{ps} = 2668.6 yr.