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Grand design spiral arms in a young forming circumstellar disk

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Abstract. We study formation and long-term evolution of a circumstellar disk using a resistive magnetohydrodynamic simulation. While the formed circumstellar disk is initially small, it grows as accretion continues and its radius becomes as large as 200 AUs toward the end of the Class-I phase. A pair of grand-design spiral arms form due to gravitational instability in the disk, and they transfer angular momentum. Although the spiral arms disappear in a few rotations, new spiral arms form recurrently throughout the Class-0 and I phases as the disk soon becomes unstable again by gas accretion. Using synthetic observation, we compare our model with a recent high-resolution observation of Elias 2-27, whose circumstellar disk has grand design spiral arms, and find good agreement. Our model suggests that the grand design spiral arms around Elias 2-27 are consistent with material arms formed by gravitational instability. If such spiral arms commonly exist in young circumstellar disks, it implies that young circumstellar disks are considerably massive and gravitational instability is the key process of angular momentum transport.

1. Introduction

Accretion and transport of angular momentum are the key processes to understand disk formation and evolution. We need to compare realistic numerical simulations with observations to quantify the effects of different physical processes and understand disk formation and evolution. We perform a long-term resistive MHD simulation of star and disk formation, and compare it with Elias 2-27 whose circumstellar disk has grand-design spiral arms (Pérez et al. 2016).

2. Disk formation and evolution

We perform a long-term MHD simulation until the end of the Class-I phase using a 3-dimensional nested-grid code (for details, see Machida & Hosokawa 2013). This code solves the MHD equations with self-gravity and Ohmic dissipation, and the barotropic approximation is adopted. In the earliest phase, the disk remains small because magnetic fields transport angular momentum efficiently. However, as the disk evolves, the magnetic angular momentum transport becomes less dominant because magnetic fields dissipate. Then the disk becomes gravitationally unstable, and grand-design m=2 spiral arms form spontaneously. These material spiral arms wind up tightly and disappear in several orbits by the shearing rotation. However, the disk becomes

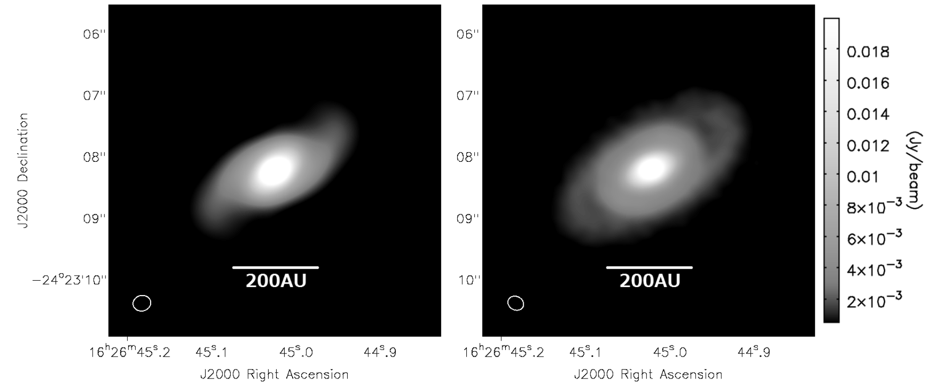

Fig. 1. Left: the result of the ALMA imaging simulation. The ellipse at the lower-left corner indicates the beam size of 0.29 arcsec × 0.26 arcsec. Right: the actual ALMA observation of Elias 2-27 (Pérez et al. 2016, https://safe.nrao.edu/evla/disks/elias2-27/).

gravitationally unstable again by gas accretion and spiral arms form recurrently.

Since the occurrence probability of the spiral arms is about 50%, it is likely that we can observe such grand-design material spiral arms if the disk is massive. The disk-to-star mass ratio remains almost constant and is about 30-40% throughout the Class-0 and I phases.

3. Synthetic observation

We calculate evolution of the central protostar using the STELLAR stellar evolution code (Yorke & Bodenheimer 2008), perform radiation transfer simulation of 1.3mm dust continuum using RADMC-3D (Dullemond et al. 2012), and produce synthetic observation images using the *simobserve* and *simanalyze* tasks of the Common Astronomy Software Applications package (McMullin et al. 2007) using the same observation parameters as Pérez et al. (2016). We find good agreement between our model and the observation (Figure 1) including many properties such as the protostar age, mass, spectral type, disk radius and so on. We conclude that the observed spiral arms can be well explained by gravitational instability, indicating that the disk around Elias 2-27 is young and massive. If such spiral arms commonly exist in young circumstellar disks, it implies that young circumstellar disks are massive and gravitational instability is the key process of angular momentum transport.

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