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The evolution of the protoplanetary disk with mass influx from a molecular cloud core and the photoevaporation winds

Chunjian Liu[a,*], Zhen Yao[b], Hongna Li[c], Haosen Wang[d]

[a] College of Mathematics and Physics, Bohai University, Jinzhou, Liaoning, 121013, PR China
[b] College of Science, Liaoning University of Technology, Jinzhou, Liaoning, 121001, PR China
[c] School of Science, University of Science and Technology, Anshan, Liaoning, 114051, PR China
[d] Department of Mathematics and Physics, Hebei Institute of Architecture and Civil Engineering, Zhangjiakou, Hebei, 075000, PR China

HIGHLIGHTS

- Our disk model includes both mass influx from a molecular cloud core and the photoevaporation winds.
- The photoevaporation winds produce an inner hole in the protoplanetary disk.
- The formation time of the inner hole is determined by the properties of the molecular cloud core.

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ABSTRACT

We investigate the formation, evolution, and dispersal processes of protoplanetary disks with mass influx from the gravitational collapse of a molecular cloud core and the photoevaporation winds. Due to the initial angular momentum of the molecular cloud core, the gravitational collapse of the molecular cloud core forms a protostar+protoplanetary disk system. We calculate the evolution of the protoplanetary disk from the gravitational collapse of the molecular cloud core to the dispersal stage. In our calculation, we include the mass influx from a molecular cloud core, the irradiation from the central star, the viscosity due to the magnetohydrodynamic (MHD) turbulence driven by the magnetorotational instability (MRI) and the gravitational instability, and the effect of photoevaporation. We find that the protoplanetary disk has some interesting properties, which are different from the previous studies. Firstly, with particular values of parameters of the molecular cloud core, the gravitational instability does not occur during the whole evolution of the resultant protoplanetary disk. With some other parameters of the molecular cloud core, the gravitational instability occurs all the time of the lifetime of the resultant protoplanetary disk. Secondly, the radial distribution of the α parameter exhibits a nearly ladder-like shape, which is different from the three regions' shape in previous studies. Thirdly, the value of the surface density is increased significantly (about a factor of 8.0) compared with that in the Minimum Mass Solar Nebula (MMSN) model. We suggest that this increased surface density can provide enough material for the formation of giant planets within the lifetime of the protoplanetary disk, and may provide a routine for reducing the timescale of the formation of giant planets. We also discuss the influence of the photoevaporation winds on the evolution of the protoplanetary disk.

1. Introduction

The state of our present solar system indicates that our solar system is formed from a protostar+protoplanetary disk system. Observations have found that many young stellar objects such as protostars and T Tauri stars are surrounded by disks with the outer radii expanded to about 1000 AU (Beckwith et al., 1990; Williams and Cieza, 2011). The protoplanetary disk provides the environment for planet formation, thus investigating the formation, evolution, and dispersal processes of the protoplanetary disk is essential to under planet formation process and the origin of the solar system.

Ruden and Lin (1986) extensively presented time-dependent results of the physical quantities of the primordial solar nebula during the viscous diffusion stage. They developed a one-zone model of the primordial solar nebula by assuming the initial surface density of the nebula being in a form of the step-function. In the

* Corresponding author.
E-mail addresses: chunjianjlu@163.com (C. Liu), yaozhenjlu@163.com (Z. Yao), lihongna1240@163.com (H. Li), wanghaosenwanghs@163.com (H. Wang).

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one-zone model of the nebula, all nebular physical quantities can be expressed as functions of the radius and the surface density of the nebula. They found that the evolution of the solar nebula can be divided into three stages: infall, viscous diffusion, and clearing. The structure of the disk in each stage is determined by different physical processes. However, they adopted an artificial initial surface density distribution to study the viscous diffusion stage of the solar nebula, rather than adopted the realistic mass influx processes from the gravitational collapse from the molecular cloud core to investigate the whole evolution of the solar nebula. Boss (1989) used a three-dimensional hydrodynamic code to model the gravitational collapse process of the molecular cloud core and the early evolution of the solar nebula. He found that the gravitational instability indeed occurs in the protoplanetary disk and the angular momentum transport through gravitational torques was efficient enough to make the evolution of the protoplanetary disk on timescales of 10^6–10^7 year.

Cassen and Moosman (1981) and Cassen and Summers (1983) investigated the formation of the protoplanetary disk using a semianalytic model and a viscous accretion disk. They found that the angular momentum of the infalling material from the parent molecular cloud core is redistributed by the action of turbulent viscosity on a shear layer near the surface of the disk and on the radial shear across cylindrical surfaces. Nakamoto and Nakagawa (1994) studied the formation, viscous diffusion and gravitational instability of the protoplanetary disk by considering both the mass influx process from the gravitational collapse of the molecular cloud core and the viscous diffusion process. In constructing their model, they adopted the results of Cassen and Moosman (1981) and Shu (1977) to derive an expression of the mass influx rate onto the protoplanetary disk from the gravitational collapse of the molecular cloud core. They found that in the early formation stage of the disk, the viscous torque operates. After that, when the gravitational instability occurs, the gravitational torque is dominant. Jin and Sui (2010) studied the formation, evolution of the protoplanetary disk by considering the mass influx from the gravitational collapse of the molecular cloud core. They adopted the mass influx expression in Nakamoto and Nakagawa (1994) to derive a diffusion equation of the surface density of the protoplanetary disk. However, they adopted some artificial assumptions (e.g., the 800 K criterion of the viscosity induced by the thermal ionization) and did not consider the photoevaporation winds. Kimura et al. (2016) investigated formation, evolution, and dispersal processes of the protoplanetary disk and estimated the disk lifetime. They found that the irradiation from the central star generates thermal winds, and this winds lead to the dispersal of the protoplanetary disk. The typical lifetime of the protoplanetary disk from a molecular cloud core is $2–4 \times 10^6$ year. In this work, we adopt the typical lifetime of the protoplanetary disk to be 4×10^6 year, which is consistent with Kimura et al. (2016) and Haisch et al. (2001).

Bae et al. (2013) performed calculations of one-dimensional, two-zone disk model to study the long-term evolution of the protoplanetary disk by including the initial angular momentum of the parent molecular cloud core and the photoevaporation effect. They found that the combination of the photoevaporative loss and a range of initial angular momentum of the molecular cloud core can adequately explain the observed disk frequencies, rather than varying the long-term X-ray luminosities as in Owen et al. (2012). However, they seemed to only investigate the influence of angular velocity of the molecular cloud core ω on the evolution of the protoplanetary disk. We think that the three parameters of molecular cloud cores (angular velocity ω, mass M_{core}, and temperature T_{core}) all have influences on the evolution of the protoplanetary disk. Kimura et al. (2016) also investigated the formation, evolution, and dispersal processes of protoplanetary disks by considering both the gravitational collapse of the molecular cloud core and the detailed photoevaporation effect (Owen et al., 2012). They obtained the disk fraction at a given stellar age and the mean lifetime of the disks by constructing the distribution functions of the angular velocity ω, the mass M_{core} and X-ray luminosities from observational data (Caselli et al., 2002; Konyves et al. 2010; Preibisch et al. 2005). Their results were in good agreement with the observational estimates. However, the gravitational collapse model of the molecular cloud core adopted by them seemed to be somewhat simple. Li and Sui (2017) also adopted both the mass influx from the gravitational collapse of the parent molecular cloud core and the effects of X-ray photoevaporation to investigate the evolution of the protoplanetary disk. They found that with the X-ray photoevaporation, a gap can form in the protoplanetary disk and the formation time and the initial location of the gap are functions of parameters of molecular cloud cores (angular velocity ω, mass M_{core}, and temperature T_{core}). They also found that in some circumstances, two gaps can be formed in the protoplanetary disk by the photoevaporation alone. This is a new find in the evolution model of the protoplanetary disk with the photoevaporation effect. The disk model of Li and Sui (2017) is most similar to our disk model, but still has many differences in details (see below). For example, we adopt the results of Alexander et al. (2006a) and Alexander et al. (2006b) to calculate the photoevaporation term, rather than the results from Owen et al. (2012) as in Li and Sui (2017). Additionally, besides of the pure local prescription of the viscosity induced by gravitational instability (Kratter et al., 2008), we also include the global model of the viscosity induced by gravitational instability (Laughlin and Bodenheimer, 1994; Laughlin and Rozyczka, 1996). Finally, we adopt the results of Zhu et al. (2012) to account for the irradiation onto the disk from the central star, rather than the results from Hueso and Guillot (2005) as in Li and Sui (2017). Thus the uniqueness of the present work is enough.

Here we constructed a more realistic and reasonable model of the evolution of the protoplanetary disk following the model of Jin and Sui (2010). We consider both the mass influx from the gravitational collapse of the molecular cloud core (Nakamoto and Nakagawa, 1994) and the photoevaporation winds (Alexander et al., 2006a, 2006b). And we adopt simulation results of the newest literatures about the physical effects in the calculation, such as the viscosity due to the gravitational instability (Kratter et al., 2008; Laughlin and Bodenheimer, 1994; Laughlin and Rozyczka, 1996), the thermal ionization results (Umebayashi, 1983), the irradiation from the central star (Zhu et al., 2012), and the photoevaporation winds (Alexander et al., 2006a, 2006b). Additionally, there is a flaw in the disk model of Jin and Sui (2010). With particular values of parameters of molecular cloud cores, the continuous timescale of gravitational collapse from the molecular cloud core t_{infall} is smaller than the timescale during which the centrifugal radius $R_d(t)$ expands from the center to the inner boundary of the protoplanetary disk 0.3 AU. This leads to an unphysical case that when the evolution of the disk surface density begins, the mass influx ceases. Then the protoplanetary disk cannot appear forever. We set a judging criterion in our disk model to eliminate this unphysical case.

We obtain some interesting results in our disk model, which are different from previous reports. Firstly, with particular values of parameters the molecular cloud core, the gravitational instability does not occur during the whole evolution of the disk. However, with some other values of parameters the molecular cloud core, the gravitational instability occurs all the time of the evolution of the disk. Additionally, the gravitational instability is local at the late stage of the evolution. Secondly, the radial distribution of the α parameter exhibits a nearly ladder-like shape, rather than the three regions' shape in Jin and Sui (2010). This ladder-like shape of the α parameter is due to different viscosity mechanisms in