

Research on the Critical Mass of Planetary Embryos Forming Earth-like Planets and Gas Giants in Protoplanetary Disks

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Abstract:

In the nuclear accretion model of planet formation, critical mass is an important factor determining the formation of Earth-like planets or gas giants from planetary embryos. However, the critical mass is complexly influenced by various variables, and existing research still has idealized assumptions. In this paper, the method of large-scale planetary sample evolution is adopted to study the influence of photoinduced evaporation on the critical mass under the traditional nuclear accretion model and the pebble accretion model, as well as the changes in the critical mass after considering the convective mixing length theory. After considering the convective mixing length theory, the critical mass increases, and it is found that the smaller the mixing length parameter, the greater the impact on the increase of the critical mass. After taking into account the influence of photoinduced evaporation, the lifetime of the protoplanetary disk decreased, and the snow line experienced severe shaking, resulting in an increase in the critical mass. Taking all factors into account, the critical mass may be larger than the previous theoretical calculation value, and since planets will migrate towards orbits closer to their stars after formation, a larger critical mass is possible.

Keywords:

Planet Formation, Critical Mass, Protoplanetary Disk, Photoinduced Evaporation

1. Introduction

Exploring the origin of planets is an objective and realistic advancement in physics for seeking ultimate philosophical questions, such as the origin of humanity and the origin of the world. Studying the specific process of planet formation is a way to help humans understand the origin of their own planet, providing the possibility and scientific basis for solving ultimate philosophical questions such as the origin of the universe and the origin of life.

The protoplanetary disk is the cradle of planet formation. Studying clearly the evolution of gas and dust from protoplanetary disks and the processes of different types of planets is an indispensable step for humans to understand the formation of planets. To study the influence of different initial and boundary conditions in the

protoplanetary disk on the formation of two types of planets, providing a foundation for the research on planet formation. Due to the limitations of scientific and technological development, humans still do not have sufficient observational data for protoplanetary disks. The number of protoplanetary disks observable by humans in the universe is relatively small compared to other types of celestial bodies. Therefore, it is a better choice to use a model of large-scale planetary evolution to study the influence of different initial and boundary conditions in the protoplanetary disk on the critical mass of Earth-like planets and gas giant planets. Li Sinan et al. found through a model of large-scale planetary evolution that the mass function of planets was in good agreement with the observational data, further improving the nuclear accretion model [1].

There are currently two types of model hypotheses for planet formation: the disk instability model and the nuclear accretion model. Among them, the nuclear accretion model is more widely accepted. Under the nuclear accretion model, protoplanets gradually accrete gas and dust in their protoplanetary disks. During the lifespan of the protoplanetary disk, if the planetary embryo accretes enough gas, it will form a Jovian planet, that is, a gas giant. If sufficient gas is not accreted, an Earth-like planet will form. The critical mass is the key to determining whether the planetary embryo begins uncontrolled accretion, and is used to judge whether the planetary embryo has accreted enough gas. Another relatively newly discovered mechanism - the pebble accretion model - can significantly increase the accretion rate of solid matter in the core accretion scenario and can better explain some problems existing in the nuclear accretion model, such as the meter-level obstacle and the formation time of gas giant planets in the nuclear accretion model [2].

This paper will comprehensively discuss the influence of the critical mass change and photoinduced evaporation effect on the critical mass after considering the convective mixing length theory. It aims to provide readers with the theoretical basis of critical mass and its influencing factors.

2. Theoretical Basis

A protoplanetary disk refers to a disc-shaped structure formed by dense gas and dust around a young star, featuring spiral arms and annular gaps. A protoplanetary disk is a molecular cloud composed of a large amount of gas and a small amount of dust around a young star. The size of the molecular cloud core differs from that of the star by approximately six orders of magnitude. Therefore, small disturbances in the molecular cloud will promote the formation of the disk structure around the protostar under the constraint of conservation of angular momentum, and subsequently, planets will form in the disk. At this time, this kind of circumstellar disk is called a protoplanetary disk. The mass of a protoplanetary disk is approximately one percent of that of the central star, and its lifespan is no more than 10^7 years [3].

The formation of planets under the nuclear accretion model is roughly as follows. Firstly, in the gas drag of the protoplanetary disk, dust and small solid particles condense into planetesimals on a scale of approximately kilometers, which takes about 10^2 to 10^4 years [1]. The main stage of particle condensation occurs in dense and long-lived protoplanetary disks, which typically range in size from 100 to 1000 astronomical units [3]. Then, it takes approximately 10^5 to 10^6 years for the planetesimals to collide and aggregate with each other to form planetary embryos on a scale of a thousand kilometers [1]. Secondly, the interaction between the planetary

embryo and the protoplanetary disk and the accretion of gas result in the formation of Jovian-like planets within the lifespan of the protoplanetary disk, which is 107 years. If sufficient gas is not accreted, an Earth-like planet will form [1]. Finally, the gas in the protoplanetary disk gradually dissipated, and the interaction between stars, planets, and other solid residues evolved to the current observed state [1]. When a planetary embryo grows to a certain extent, it will accrete gas to form an atmospheric envelope. The pressure gradient established in the atmosphere and the gravitational contraction are balanced, preventing a large amount of gas accretion [4]. Afterwards, the atmosphere enters a quasi-static contraction stage marked by long evolution. During this long period of time, the mass of the atmosphere and the core increased slowly until the mass orders of magnitude of the two were the same, and the core of the protoplanet reached the critical mass. Protoplanets began uncontrolled accretion and eventually formed Jovian planets. If the core of a protoplanetary planet fails to reach the critical mass before the protoplanetary disk dissipates and thus cannot undergo uncontrolled accretion, an Earth-like planet will form. However, there are some unsolved problems with the nuclear accretion model. For instance, the lifespan of a protoplanetary disk is typically only about 3 to 10 million years, but it takes more than 10 million years to form a planetary core that reaches a critical mass [3].

The pebble accretion model is a type of nuclear accretion model, which was proposed to address the meter-level obstacles and formation time issues of traditional nuclear accretion models. The pebble accretion model holds that the core of a planet is formed by the accretion of the planet's embryo to capture pebbles. Pebbles refer to solid particles that have already formed in the protoplanetary disk and are on the scale of centimeters to decimeters in size. The pebble accretion model has solved the problem of formation time and can explain the planetary composition gradient.

3. Factors Influencing Critical Mass

3.1. Photoinduced evaporation and snow line jitter

The critical mass is the key to initiating uncontrolled accretion in planetary embryos. Studying the critical mass clearly has a strong promoting effect on the specific process of planet formation.

Pollack et al. Presented the growth rate of planetary embryos [5] :

$$\frac{dM_e}{dt} = \pi R_c^2 \Sigma_p \Omega F_g \quad (1)$$

Among them, M_e is the mass of the planetary embryo. R_c is the effective capture radius. Σ_p is the surface density of a stellar particle. $F_g = (R_{eff}/R)^2$ is the gravitational enhancement factor, which is given by the ratio of the effective cross-section to the geometric cross-section of the accretion particle. For Kepler motion, $\Omega \propto r^{-3/2}$. The time scale of the protoplanet's growth increases rapidly with the increase of the semi-major diameter r . Because the angular velocity Ω decreases with the increase of the semi-major diameter r , and the particle density Σ_p also decreases with the increase of the semi-major diameter r . If the collective gravitational force of other planetesimals and the gravitational force of the star are ignored, the collision of planetesimals can be described by the framework of two-body motion. Therefore, the gravitational enhancement factor satisfies:

$$F_g = 1 + \frac{v_{eac}^2}{v_{rel}^2} \quad (2)$$

Here, $v_{\text{esc}} = \sqrt{2GM_e/R}$ represents the escape velocity. When the relative velocity is large enough, $v_{\text{rel}} \gg v_{\text{esc}}$, $F_g \approx 1$. In regions with relatively high speeds, when planetary embryos increase in size, the growth rate will decrease. In regions with relatively low growth rates, when planetary embryos increase in size, the growth rate also increases. This process is called runaway growth [1]. The formula for critical mass can be derived from this formula [1].

Planetary large-scale sample evolution is a research method based on planetary formation models, mainly nuclear accretion models. By setting different initial and boundary conditions, a large number of planets are evolved using the same planetary formation model. Then, the statistical characteristics of the obtained planetary samples are directly compared with the observational results. Thus, the influence of different initial and boundary conditions in the protoplanetary disk on the formation of Earth-like planets and gas giants was discovered, and the critical conditions for the formation of Earth-like planets and gas giants, namely the critical mass, were obtained [1]. By analyzing the results of the large-scale evolution of planets, it is found that in the small-mass planets close to the central star, their material composition is mainly Earth-like. They form within the snow line and do not accrete volatile icy substances. Gas giant planets are relatively easy to form outside the snow line and reach their final stable orbits through inward migration [6]. However, the position of the snow line is not constant. It will first expand outward over time to reach a maximum value. Then, it contracts inward. During the evolution of the snow line, the snow line will experience severe shaking, and the phenomenon of snow line shaking will be affected by photoinduced evaporation and other factors [6].

It is also noted that the photoevaporation effect caused by the ultraviolet and X-ray radiation of stars may have an impact on the critical mass of planetary embryos. For a disk in a dense star cluster, the photoinduced evaporative wind can be jointly excited by EUV and FUV photons radiated by nearby massive stellar neighbors. FUV is generally regarded as dominant in setting the rate of mass loss. The following analyzes the possible impact of photoinduced evaporation on critical mass. Photoinduced evaporation drives hot air from the outside of the disk. Besides depleting the mass of the disk, if the material on the external disk is removed through photoinduced evaporation at a faster rate than it is replenished through viscous diffusion, then the disk can be cut off. The effect of intense photoinduced evaporation in inhibiting core growth is achieved by rapidly cutting off the outer edge of the disk and thereby rapidly cutting off the supply of pebble flow [7]. Photoinduced evaporation causes gas voids to form inside the protoplanetary disk, removing the gas from the disk from the inside out. The amount of gas that the planetary embryo can accrete decreases. It accelerates the dissipation process of the protoplanetary disk and reduces its lifespan. The time available for planetary embryos to accrete sufficient gas to reach critical mass has been shortened. Far ultraviolet light heats the gas in the protoplanetary disk by ionizing hydrogen, while extreme ultraviolet light generates hot air by dissociating molecules, causing the temperature in the heated area of the protoplanetary disk to rise. Moreover, the snow line will experience severe shaking due to the photoinduced evaporation effect, increasing the critical mass [8]. When a planetary embryo that has reached the original critical mass undergoes uncontrolled accretion, if the gas around the protoplanet is insufficient to be accreted due to photoinduced evaporation, an ice giant planet may form.

3.2. Convective Mixing Length Theory

Previous theoretical and simulation studies have confirmed the existence of a critical mass. In complex cases, the critical mass cannot be directly derived from the analytical formula and needs to be obtained through numerical simulation methods. From the above formula (2), it can be inferred that the critical mass is affected by the temperature of the protoplanetary disk, the nuclear accretion rate, the atmospheric opacity, the viscosity coefficient of the disk, and the radius of the planet's orbit. Given that the equations for calculating the changes in critical mass under the influence of different factors using complete hydrodynamic equations are extremely complex and involve a huge amount of calculation, it is unrealistic. It is concise and efficient to simulate the accretion process of protoplanetary gas in protoplanetary disks by using the most commonly used simplified model for describing convective motion in astronomy - the convective mixing length theory [5].

The critical mass after considering the convective mixing length is:

$$M_{cr} = \left[\frac{1}{12\pi} \frac{3\Gamma-1}{\Gamma} \left(\frac{k_B}{\mu m_H G \nabla_{ad}} \right)^3 \frac{T_0^3}{\rho_0} \right]^{1/2} = \frac{2}{3} M_p^{(cr)} \quad (3)$$

After applying the convective mixing length theory, the critical mass increases. However, the increase in the critical mass is basically only a few Earth masses. The proportion of relative increase varies with the differences in the semi-major diameter and the accretion rate, and it is found that the smaller the mixing length parameter, the greater the impact on the increase of the critical mass [5].

4. Discussion

In existing research, less consideration has been given to the various complex phenomena that occur during the evolution of protoplanetary disks. However, taking these factors into account would lead to an extremely large amount of computation, a highly complex system, and the observed data remains limited. Meanwhile, the traditional nuclear accretion model itself has problems, such as the excessively long formation time of protoplanets, which may exceed the lifespan of the protoplanetary disk itself, and the rapid loss of meter-scale celestial bodies, making it difficult for star clusters to form. The pebble accretion model also has problems, such as the specific process of pebble cloud formation being unclear and the explanation for the formation of the inner solar system phenomenon [9]. For the pebble accretion model, there are some problems with the mechanism of star formation. Flow instability requires a ratio of dust to gas slightly higher than the solar value. Therefore, the formation of stellar particles may be a local process, which is only triggered in regions where the gas density is low (due to photoevaporation) or the particle density is high (due to the particle packing effect). To establish a more precise model of stellar formation, it is necessary to have a deeper understanding of the interaction between fluid instability and vertical shear and oblique pressure instability - these instabilities are precisely the key factors driving turbulence in the planetary formation regions of protoplanetary disks [10].

In future research, AI data large models can be utilized to assist researchers in conducting some data simulations, fitting with more observational data, and proposing new models or hypotheses to better explain the existing data.

5. Conclusions

After applying the convective mixing length theory in this paper, it is found that the critical mass has increased compared to before, and the smaller the mixing length parameter, the greater the impact on the increase of the critical mass. The influence of photoinduced evaporation on critical mass is rather complex. Evaporation leads to a reduction in the amount of gas and dust that the planetary embryo can accrete, shortens the lifespan of the protoplanetary disk, raises the temperature in some local areas of the protoplanetary disk, and, at the same time, the snow line experiences severe shaking, increasing the critical mass. Taking all factors into account, on the basis of the original model, after considering more complex factors, the critical mass has increased.

After applying the convective mixing field theory and considering the influence of photoinduced evaporation in this paper, the critical mass increases, and the conditions for the formation of gaseous giant planets become more stringent. This article takes into account that the critical mass is the nuclear mass in the early stage of a planet's formation and evolution. After the formation of a gas giant planet, it may migrate from the orbit where it was originally formed to a orbit closer to the star, and during the migration process, there will be a certain loss of mass. Then, through subsequent complex evolution, it can reach the current observed form, and a relatively large initial value is possible.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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