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Enrichment of Heavy Elements in Gas Giant Planets during the Supply-Limited Accretion Phase

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Abstract

Recent studies of internal structure of gas giants suggest that their envelope is enriched with heavier elements than hydrogen and helium, relative to their central star composition. Previous studies examined the possibility of additional increase of heavy elements through the capture of planetesimals in the vicinity of a growing protoplanet in constant protoplanetary disk. However, it is well known that sufficiently massive protoplanet opens a gap in the protoplanetary disk(PPD) and circumplanetary disk(CPD) is formed around it. Gap structure would change the growth rate of protoplanet and accretion rate of planetesimals, and CPD also change the accretion rate. In this study, we investigated the effects of opening of gap in PPD and formation of CPD on the accretion rate of planetesimals. We find that both of the opening of gap structure in PPD and formation of CPD enhance the accretion rate.

1. Introduction

Recent studies suggest that gas giants' envelope is enriched with heavier elements. It is considered that these enrichment in heavy elements are caused by the capture of planetesimals during the late formation stage of gas giant. Zhou & Lin 2007 and Shiraishi & Ida 2008 performed orbital integration of planetesimals around growing protoplanet in constant protoplanetary disk, and Shiraishi & Ida estimated the total captured mass of planetesimals for Jupiter and Saturn. However, their simplified constant disk model might be incorrect, because it is well known that sufficiently massive protoplanet opens a gap in the protoplanetary disk(PPD) and circumplanetary disk(CPD) is formed around it. Gap structure would change the growth rate of protoplanet and accretion rate of planetesimals, and CPD would also change the accretion rate. In order to estimate the total captured mass of planetesimals through protoplanet growth, these effects have to be evaluated correctly.

2. Aims of Study

A system composed with a central star, a massive protoplanet and negligibly small planetesimals can be treated as a restricted three body problem. In this system, planetesimals conserve Jacobi energies $E_{\rm Jacobi}$ which is written as

$$E_{\rm Jacobi} \equiv \frac{1}{2}{v'}^2 + U_{\rm Jacobi}, \tag{1}$$

where v' is a velocity of planetesimals on the co-rotating flame and $U_{\rm Jacobi}$ is Jacobi potential written as

$$U_{\rm Jacobi} = -\mathbf{h}\cdot\mathbf{n}_{\rm p} - G\frac{M_{\rm s}}{r_{\rm pl,s}} - G\frac{M_{\rm p}}{r_{\rm pl,p}}, \tag{2}$$

where $\mathbf{h}$, $\mathbf{n}_{\rm p}$ are angular momentum of planetesimal and mean motion of protoplanet. $M_{\rm s}$ and $M_{\rm p}$ are mass of central star and protoplanet, and $r_{\rm pl,s}$ and $r_{\rm pl,p}$ are relative distance between planetesimal and central star, and between planetesimal and protoplanet, respectively.

The capture process of planetesimals is divided into two stages. First stage is the entering into the feeding zone. In order to enter the Hill Sphere of protoplanet, planetesimals have to flow over the potential barrier surrounding the protoplanet. The area which meets this requirement condition is called as feeding zone, and defined as

$$E_{\rm Jacobi} > 0. \tag{3}$$

Thus, planetesimals' Jacobi energy have to be increased in this stage. Second stage is the capture by the Hill Sphere. In order to be captured by the protoplanet gravitaionally, planetesimals have to lose their escape energy in the Hill Sphere.

The change of the Jacobi energy occurs due to the increase of protoplanet mass and the drag of disk gas. Thus, we expect that the capture process of planetesimals is closely tied to the disk gas structure. In this study, we construct the gap opened disk model and CPD formed disk model. Performing the orbital integration of planetesimals around growing protoplanet in these models, we get the total captured mass of planetesimals in each models. Comparing the results with those performed in the constant disk model, we evaluate the enhancement rate of captured mass due to the gap opening and circumplanetary disk formation, respectively.

3. Results

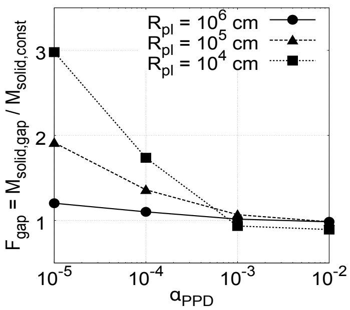

Figure 1: The change of the enhancement rate due to the gap opening with the viscosity of protoplanetary disk. The enhancement rate is defined in eq. 4. The solid, dashed and dotted lines show the case of $R_{\rm pl}{}^6{\rm cm}$, $R_{\rm pl}{}^5{\rm cm}$ and $R_{\rm pl}{}^4{\rm cm}$, respectively. The enhancement factor increases with the size of planetesimals and the width and depth of gap (gap is wider and deeper for small disk viscosity). These results suggests that the opening of gap changes the inflow flux of planetesimals into the feeding zone.

We define the enhancement rate of captured mass due to the gap opening in PPD as

$$f_{\rm gap} \equiv \frac{M_{\rm solid,gap}}{M_{\rm solid,const}}, \tag{4}$$

where $M_{\rm solid,gap}$ and $M_{\rm solid,const}$ are total captured mass of planetesimals in the gap opened disk model and constant disk model, respectively. Investigating the detailed effects of the gap opening, we performed the parameter study for the size of planetesimals $R_{\rm pl}$ and the disk viscosity $\alpha_{\rm PPD}$. Fig 1 shows the result of numerical calculations. Gap is wider and deeper for small disk viscosity, so the enhancement factor increases with the size of planetesimals and the width

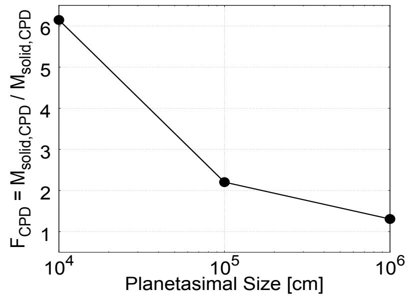

Figure 2: The change of the enhancement rate due to the formation of CPD with the size of planetesimals. The enhancement rate is defined in eq. 5. The enhancement factor is larger for smaller planetesimals, and this is because strong gas drag in Hill Sphere increases the capture probability.

and depth of gap. These results suggest that gap opening change the inflow flux of planetesimals into the feeding zone, namely first stage of planetesimal capture process.

We also define the enhancement rate of captured mass due to the formation of CPD as

$$f_{\rm CPD} \equiv \frac{M_{\rm solid,CPD}}{M_{\rm solid,const}}, \tag{5}$$

where $M_{\rm solid,CPD}$ is total captured mass of planetesimals in the CPD formed disk model. Investigating the detailed effects of the formation of CPD, we performed the parameter study for the size of planetesimals $R_{\rm pl}$. Fig 2 shows the result of numerical calculation. The enhancement factor is larger for smaller planetesimals. The formation of CPD changes the gas structure in the Hill Sphere, so it increases the losing rate of Jacobi energy in Hill Sphere and affect the second stage of planetesimal capture process. The losing rate of Jacobi energy is larger for smaller planetesimals, which consistent with our results.

References

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[2] Shiraishi M., Ida S., 2008, apj, 684, 1416