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The role of initial protostellar disk size on the chemical evolution of the disk

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Abstract. Chemical evolution of protoplanetary disk was investigated with a newly developed physico-chemical model with special interest on the initial size of the disk. The results shows that chemical diversity of protoplanets recorded in chondrite chemical compositions is not explained if the initial disk size is as large as 50 A.U. and the initial disk mass should be 0.1 to 0.2 solar mass.

1. Introduction

Protoplanetary disks evolve from dense molecular cloud cores through the stages of prestellar core and protostellar core and disks where gas and dust particles interact to finally planetary systems by loosing gas. Recent astronomical observation on protoplanetary disks with ALMA has revealed many interesting structures (e.g., Cieza et al., 2016; Perez et al., 2016; Andrews et al., 20160), however, all the observation are snapshots of systems that continuously change. Despite numerous work on the evolution of protoplanetary disks, the role of initial conditions has not been studied yet. Thus, the role of the initial disk conditions are investigated in the present work specifically focusing on the initial conditions of our solar system. The model calculation results are compared with chemical composition of chondrites, which is thought to be the remnants of protoplanets that are formed in the protosolar disk.

2. Model

A new model combining physics and chemistry of disk evolution was developed. The basics of physical evolution of the disk follows Ciesla (2011, 2009), which is a 1D radial disk model with viscous heating. The radial advection-diffusion equation is written with the Lagrangian expression, which enables us to trace the movement of individual grains in the disk, where density and temperature change with time and space. Chemical composition of dust grains is obtained with the chemical equilibrium calculation for the initial conditions. At first, density and temperature profile of the disk is calculated and chemical equilibrium calculation is performed corresponding to the conditions. Then, physical evolution of the disk is calculated. Next, advection-diffusion calculation for particles is made, where most of the grains are transported inward by advection and a small fraction of grains are transported outward by diffusion. The chemical composition of a certain location of the disk at a certain evolutionary stage is obtained by summing all the dust grains with various chemical compositions. Dust particles are assumed to be 1 micron in size, which follow the movement of gas all through the calculation time. The viscosity parameter, alpha, is 0.001. The initial spatial

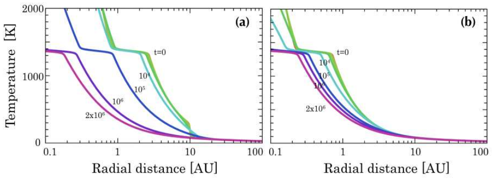

Fig. 1. Temperature evolution of protoplanetary disks. (a) Initial disk mass=0.1 solar mass and radial extension of 10 AU. (b) 100AU.

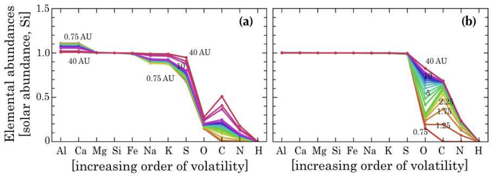

Fig. 2. Chemical composition of protoplanetary disks for 0.75 to 40 AU after 1 million years. (a) Initial disk mass=0.1 solar mass and radial extension of 10 AU. (b) 100AU.

extension and mass of the disk are free parameters, which varied from 10 to 100AU and 0.05 to 0.5 solar mass.

3. Results

Figure 1 compares temperature profile evolution of disks with different initial spatial extension with the same mass : (a) is for 10 AU and 0.1 solar mass and (b) is for 100 AU and 0.1 solar mass. A high temperature region extends beyond several AU in the compact disk (a) at the early stage, where T≥~1400K means evaporation of silicates and metal, whereas within ~1AU in the spatially extended disk (b). The disk cools with time, the high temperature region shrinks, and the temperature profiles after a million years are nearly the same in both cases. The difference in distribution of high temperature region at the early stage results in difference in mixing of refractory-rich and volatile-rich dust grains that are initially located at different region of the disk. The chemical composition of the disk after a million years as a function of the distance from the sun is compared for initially compact and extended disks in Fig. 2. The disk is chemically slightly heterogeneous for the compact disk (Fig. 2a), but homogeneous for the extended disk except for highly volatile elements (Fig. 2b). The initially compact disk is fractionated with refractory-enriched and volatile-depleted composition. On the contrary, initially extended disk is unfractionated with the solar abundance elemental ratios for solid planet forming elements.

4. Discussion

The results show two important implications for our understanding of protoplanetary disks. One is that the initial size of our solar system was not large, which enlarged with time. The elemental abundance pattern in Fig. 2a is similar to that of carbonaceous chondrites except for CI chondrite, suggesting that the initial conditions applied for Fig. 2a is within the range of suitable conditions. By calculating with various initial disk parameters, we conclude that the chemical fractionation recorded in carbonaceous chondrites are reproduced with the initial disk size of 10~20AU and the disk mass of 0.1 to 0.2 solar mass. The disk should have been flattened to at least the present size conserving the angular momentum. The second importance is that the initial condition of the disk significantly affects the formation location of rocky planets and the location of the snow line, which is specifically important for the understanding of exoplanetary systems. Although chemical variation of protoplanets in protoplanetary systems is not directly observed, the location of the snow line is one of possible observational targets. The present work suggests that observed locations of rocky planets and snow line are results of various parameters that can not be uniquely defined.

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