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Importance of the early accretion stage of a protoplanetary disk on the chemical evolution of planetesimals and comets

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Abstract

Chemical evolution of a protoplanetary disk has been studied with a model combining dust transportation and chemical equilibrium of condensed matters. The results show that the initial size and mass of a disk strongly control the temperature evolution, thus chemical evolution of the disk. Assuming that chondrites are derived from planetesimals formed at a few to several a.u. and comets were formed at tens of a.u., the initial size of our solar system was less than 0.1 solar mass and spread to ~tens of a.u. in order to explain chemical variations of chondrites and recent observation of comprehensive inclusion of high-temperature condensates in comets.

1. Introduction

Recent ALMA observation has shown various features of protoplanetary disks, such as a ringed structure [1], gaps suggestive of formation of large planets [2], spiral arms [3], dust/gas/star mass relationships [e.g. 4, 5], a change of gas chemistry in the envelope [6], or possibility of the location of the snow-line [7], all of which suggest active and evolving protoplanetary disks. A few studies that reveal the age and sizes of central stars and surrounding disks show clear negative relationships between age and disk mass regardless of the size of the central stars.

However, more detailed information cannot be obtained with ALMA, and the information on our solar system is still critical in order to understand the evolution of protoplanetary disks. Because the critical information is taken from exploration and sample analysis of meteorites and comets, chemistry and mineralogical information are the critical ones, and therefore, physical and chemical evolution of protoplanetary disks should be considered consistently with meteorite and cometary material information including Rosetta and Stardust missions.

2. Model

We have developed a model that describes the chemical evolution of protoplanetary disks, which is basically a radial advection-diffusion equation written in the Cartesian coordinate originally developed by Ciesla [8,9]. The key of the model is that the equation is written in the Lagrangian expression, which enables us to trace movement of individual dust particles that experience different thermal histories in the protoplanetary disk due to advection and turbulent flows. We call the method “particle tracking method”. Chemical information is shown by equilibrium chemistry for individual grains according to the initial density and temperature conditions of the disk, which varies depending on the initial disk size discussing below.

The model contains two free parameters: initial disk mass and initial disk size, both of which control the temperature profile of the disk and time scale of dust transportation and temperature evolution.

The disk is a viscous disk with the parameter, alpha, and the initial disk mass and size determine the density and temperature distribution. Dust particles are assumed to be 1 micron in size, and we neither consider accretion to the disk nor dust coagulation. The dusts are chemically in equilibrium with ambient gas at the initial conditions. Silicate and metal-sulfide grains are assumed to keep the initial chemical compositions and organics and ice are assumed to evaporate according to the disk conditions.

Ten thousands of grains are set in more than 20 separated bins of the disk and the movement of the grains are traced for a million years. Chemical composition of a certain area and certain time of the disk is calculated by summing up all the grains with different histories that are present in the region at the time. Particular attention has been paid for high-temperature condensates and organics and ice grains.

3. Results

Temporal and spatial distribution of chemical composition of protoplanetary disks with various initial disk parameters was obtained. The important results are: (1) the initial temperature profile is strongly dependent on the initial disk size, the silicate evaporating region extends to ~1 au if the disk mass is 0.1 solar mass, but ~10au for 1 solar mass, (2) considerable amounts of dust particles initially located in the inner region are transported to the outer region, which continues for more than a million years although the absolute amount of such grains decreases significantly, and the outer edge where the grains from the inner region reach strongly depends on the initial disk mass and size, (3) chemical composition of a certain region varies significantly with time due to mixing of chemically highly fractionated materials from the inner region and unfractionated materials from the outer region, (4) chemical composition of chondrites, specifically those of carbonaceous chondrites, are reproduced with a limited range of initial disk conditions if they were formed at the asteroid belt as they are now, which is possible when the initial disk size is smaller than several au, (5) a protoplanetary disk becomes chemically highly homogeneous with unfractionated chemical composition, that is, the solar abundance elemental ratios, which is the case for smaller and/or lighter initial disk, and (6) mixing ratio of H2O ice and silicates originated at the inner region is strongly dependent on the initial disk mass and size. Figure 1 shows the fraction of solid materials along the midplane of a protoplanetary disk for initially small (10au) disk (a and b) and largely extended (100au) disk with the same mass(c and d), where the disk initial mass is the same for all the cases (0.05 solar mass). The initially small disk (a and b) results in highly depleted in H2O ice in the outer region, and silicates are much more abundant than H2O ice after a million year (Fig. 1b). On the other hand, largely extended disk results in H2O-ice enriched materials after ten thousand years (Fig. 1c) or later (Fig. 1d).

4. Discussions and conclusions

Comprehensive presence of high-temperature condensates in comets requires mixing of outward transported grains with a considerable amount of H2O ice beyond tens of au, which is possible for a disk with the initial mass of ~0.1 solar mass and the initial spread to tens of au. On the other hand, this condition results in almost homogeneous chemical composition in the asteroid belt region. The chemically fractionated compositions of chondrites in terms of volatile element depletion can be achieved at the early stage (earlier than 10^5 yrs). The present study predicts the importance of the initial conditions of the protoplanetary disk for its chemical evolution; in other words, planetary system chemistry is highly related to the star formation.

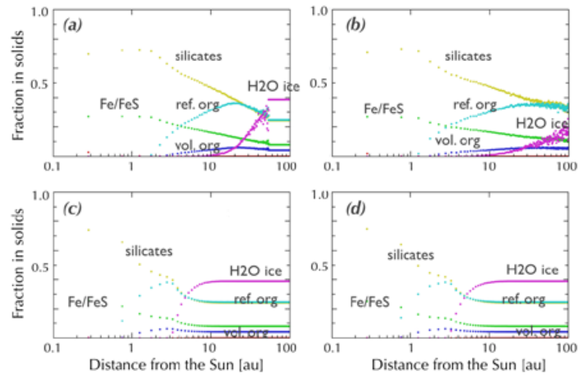

Figure 1: Temporal and spatial distribution of silicates and Fe-FeS transported from the inner region outward and H2O ice and organics transported from the outer region inward. (a) Initial disk mass= 0.05 solar mass and the initial disk radius=10 au after 10^5 yrs, (b) 10^6 yrs, (c) initial disk mass=0.05 solar mass and initial disk radius=100 au after 10^5 yrs, and (d) 10^6 yrs.

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