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Radial transport of hot minerals in the primordial nebula

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Abstract

A grid of protoplanetary disk models is used to study the outward transport of hot minerals in the form of aggregates from the warm inner regions of the solar nebula under the influence of photophoresis. We compute the distance range at which these aggregates migrate and we show that this mechanism can lead to an influx of hot minerals in the formation regions of the main cometary reservoirs. Moreover, our calculations of the evolution of the dust size distribution within disks strongly suggest that it depends on their mass and lifetime. Future measurements of the size distribution of dust could then place important constraints on the physical properties of disks.

1. Introduction

Hot temperature minerals (crystalline silicates, CAIs) have been detected in several comets and also identified in the samples returned by the Stardust mission [1]. Because these minerals are expected to be formed at high temperatures in the inner regions of the Solar Nebula, a mechanism of transport towards the outer parts of the disk is required to explain their presence in cometary bodies. Here we use a time-dependent model of the solar nebula using the alpha prescription [2, 3] to explore the photophoretic transport of aggregates formed in the inner part of the disk towards its outer regions.

2. Model

The solid particles embedded in the gas are heated heterogeneously by light. Gas molecules adsorbed and rejected at their surface will carry different momentum and a net force on the particle results (photophoresis effect), which is strongly pressure dependent and can be stronger than radiation pressure and Sun's gravity. The dust particles migrate in the nebula under the combined action of three forces: the residual gravity force, the radiation pressure and the photophoretic force. The dust particles are pushed away via photophoresis and at the same time, being dragged back towards the Sun by the infalling nebula flow [4, 5]. An inner gap is also postulated, corresponding to a dust-free zone due to material clearing by the young star radiative forces. Aggregates considered in our simulations have sizes ranging between 10^{-5} and 10^{-1}m and are assumed to be spherical and composed of olivine, with a variable porosity. We also consider a density of aggregates of 500 kg.m^{-3}, value holding within the range of densities measured by the Stardust mission in the Wild 2 cometary samples. All the disks used in our calculations extend up to 50 AU and their viscosity parameter is fixed to 7x10^{-3}. The mass of the disks is varied between 1 and 10 times that of the Minimum Mass Solar Nebula (MMSN) and their considered lifetimes range between 1 and 6 Myr.

3. Results

In all cases, the trajectories of 10^{-2} and 10^{-1} m aggregates are almost similar within the disk. These aggregates migrate faster than the smaller ones at the beginning of the disk evolution and are pushed far away in the nebula, at distances that can exceed 30 AU when an inner gap of 2 AU is postulated. Note that all our calculations are based on the assumption that the disk opacity is dominated by the Rayleigh scattering and not by that of dust. Moreover, 10^{-3}–10^{-1} m aggregates reach an equilibrium where the outward drift just balances the accretion flow, and hence rebound slightly toward the Sun during the late stages of evolution of the disk. Interestingly enough, smaller aggregates (10^{-5}–10^{-4} m) migrate at higher heliocentric distances than the bigger ones (10^{-3}–10^{-1} m) within disks with longer lifetimes. This is due to the progressive decrease of the gas density and opacity that enable the radiation pressure to push the particles beyond the outer edge of our disk models (50 AU).

Figure 1 establishes the relation between the settling distances of aggregates and the disk's initial mass and lifetime. It suggests that the measurement of the dust size and its radial distribution within ring-like structures observed as remnant of protoplanetary disks around stars may provide constraints on their lifetime and evolution.

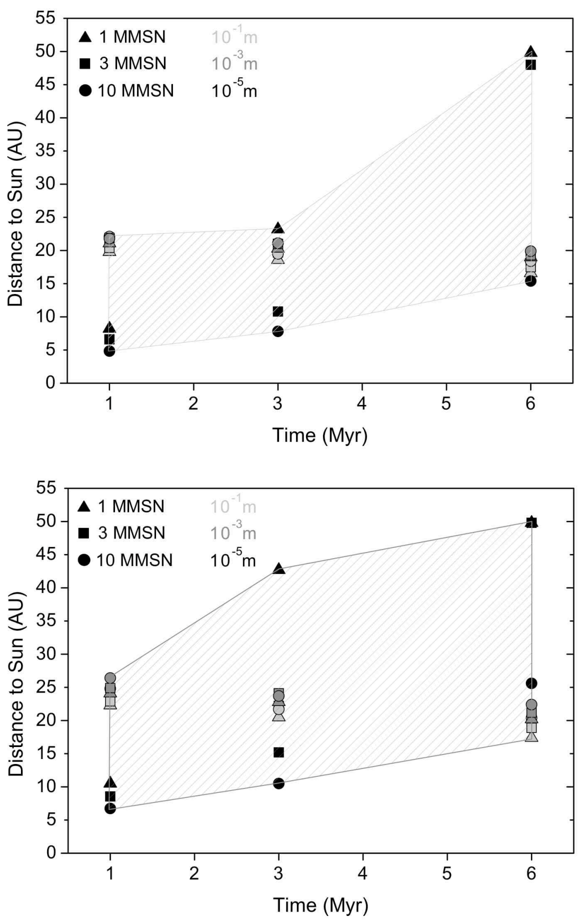

Figure 1: The migration distances reached by particles of different sizes and owning density of 500 kg.m^{-3} at the end of the evolution of protoplanetary disks.

4. Discussion

Photophoresis is a ballistic transport mechanism that explains the presence of hot temperature particles in the outer part of the Solar Nebula. This process is consistent with the hypothesis that CAIs and crystalline silicates may have been accreted by comets in the outer part of the Solar Nebula. The comparison between the migration locations of particles at the end of the disks evolution determined via our model and the observed ones may give constraints on their lifetime. In particular, our simulations show that the location of small particles in low-mass disks with long lifetimes is clearly distinct from that of bigger particles. For example, in the 1 MMSN disk with a lifetime of 6 Myr, 10^{-5} and 10^{-4} m particles are pushed at more than 50 AU from the star while 10^{-3}–10^{-1} m particles settle at about 20 AU.

References

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