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Material mixing in a protoplanetary disk formed by the collapse of a molecular cloud core

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Almost all the rocky samples taken from meteorites and comets have the isotopic compositions of refractory elements nearly identical to those of the terrestrial rocks in spite of the difference in the original locations of their formation. In the parent molecular cloud core, on the other hand, the isotopic composition may be significantly heterogeneous because the traces of short-lived radio nuclides found in primitive meteorites support the external injection of super nova ejecta or gas wind from AGB star just prior to the core collapse. These facts imply that the isotopic homogenization had occurred in the early protoplanetary disk from which the solar system was formed. Furthermore, the observations of cometary dust and extra-solar protoplanetary disks indicate that crystalline silicate dusts are contained in them with significant proportions, implying radial mixing of dust from the inner disk region to the outer one. Such mixing might be induced by the same disk mechanism which causes the homogenization of isotopic abundance.

This study therefore explores the possible mixing processes in an accreting protoplanetary disk including the stage of the collapse of parent molecular cloud by using a disk model with the 1D axial symmetry and the alpha parameterization of turbulent viscosity. Mixing of disk gas is formulated by the advection and turbulent diffusion of gas components discriminated by their infall age and maximum temperature in the disk. Because the difference in the infall age corresponds to that of original position in the core, the mixing of different gas components may represent the isotopic homogenization.

According to the parameter study, the isotopic homogenization is found to occur within the timescale of 10^6 yr when the viscosity parameter alpha is larger than 10^{-2}. On the other hand, mixing of high temperature gas toward the outer disk region becomes ineffective with increasing the angular momentum of the parent molecular cloud core. Given the angular momentum consistent with the observations and single star formation, the calculated mean crystallinity of silicate dust is in the range of 1-30 % among disks at the stage of 99% completion of isotopic homogenization. The correlation between disk mass and crystallinity is basically consistent with the observation of protoplanetary disks. These results contain examples which are consistent with the properties of the solar system, that is, the total disk mass required for making the all planets, the observed isotopic homogeneity among solid materials, and the crystallinity in the cometary dust. The calculated timing of homogenization also implies that the oldest refractory inclusions in primitive meteorites are formed about 1 My after the beginning of the collapse of the parent molecular cloud core.

Keywords: protoplanetary disk, molecular cloud core, material mixing, primitive meteorite, isotopic anomaly, crystallinity