THE EVOLUTIONAL MODEL OF CHROMIUM ISOTOPIC HETEROGENEITIES IN THE PROTOPLANETARY DISK. R. Fukai[1] and S. Arakawa[2], [1]Institute of Space and Astronautical Science, Astromaterials Science Research Group, [2]National Astronomical Observatory of Japan.

1. Introduction: The C-complex asteroids located in the main asteroid belt are considered to have formed in lower-temperature environments compared to rocky planets. These types of small bodies should possess the vital records of several types of volatiles, such as ice and organic volatiles, in the early Solar System. These volatiles were possibly delivered to the rocky planets by early or late accretion [e.g., 1]. Thus, deciphering the formation processes of C-complex asteroids is essential for establishing a comprehensive evolutionary scenario of the asteroid belt. However, spatial information on the asteroid formation process in the protoplanetary disk has not been clearly identified because the initial orbits of asteroids were likely disturbed by interaction with gas, the other small bodies and planets [e.g., 2].

In contrast, the original information on the formation region of C-complex asteroids was possibly recorded in carbonaceous chondrites (CCs). CCs are undifferentiated meteorites considered to have originated from C-complex (partly D-, K-, and X-type) asteroids based on the similarity in reflectance spectroscopy. The isotopic compositions of bulk CCs vary with the spatial and/or temporal heterogeneities of “presolar grains” that possess extremely anomalous isotopic compositions compared to bulk CCs (reviewed in [3]).

The physicochemical processes inducing nucleosynthetic isotopic variation have been extensively discussed in several previous studies [e.g., 4]. One plausible model of isotopic heterogeneity is nebular thermal processing, which assumes the thermal gradient with the disk radius in the protoplanetary disk [5–6]. In the inner Solar System, micrometer-scale grains are effectively vaporized to the gas phase compared to those in the outer Solar System, which causes spatial heterogeneities of presolar grains. However, these processes cannot explain the isotopic heterogeneities within lower-temperature environments like the CC formation regions. Alternatively, the injection of presolar dusts to the protoplanetary disk possibly explains the observed isotopic variation. A previous study explained the Cr isotopic variation among bulk-scale chondrites and achondrites by the inward-drift of injected grains [4]. This model was based on the correlation between the Cr isotopic compositions and the accretional ages. In addition to the temporal changes of dusts, the spatial heterogeneities of the presolar dusts could be key to assessing the cause of isotopic variations in CCs.

In this study, we conduct numerical calculations for the evolution of isotopically different (solar and presolar) dusts in the protoplanetary disk [7]. We explain the Cr isotope variations by temporal and spatial heterogeneities and determine the formation regions of meteorite-related D- and K-type asteroids and two types of C-complex asteroids (i.e., B and Ch types). Finally, we construct the evolutionary scenario of these asteroids, explaining their initial and present locations.

2. Methods: We calculated the viscous evolution of a protoplanetary disk, then we obtained the radial distribution of gas and dust particles with the disk conditions modified from previous studies [e.g., 8–9]. The initial distribution of the gas surface density, $\Sigma_{g,0}$, is given by a self-similar profile, $\Sigma_{g,0} = [(2-\gamma)M_d/(2\pi R_d^2)] (r/R_d)^{-\gamma} \exp[-(r/R_d)^{2-\gamma}]$, where r is the distance from the Sun. We set the disk exponent of $\gamma = 15/14$, the initial disk radius of R_d = 5 au. and the total disk mass of M_d = 0.01 solar mass. The turbulent viscosity of the disk, ν, is described by $\nu = \alpha\ c_s\ h_g$, where α is the dimensionless parameter, c_s is the sound speed, and h_g is the gas scale height. The α is the key parameter to understand the viscous evolution of the gas disk and the diffusion of dust particles. We also adopted the temperature profile using the passively heated disk model [10].

In this study, we consider three processes, i.e., advection, diffusion, and drift, along with the formulation of Desch et al. [9]. We introduce two populations of the dust particles in this study: solar and presolar components. The initial distribution of the surface density of solar dust, Σ_{SD}, is assumed as $\Sigma_{SD,0} = 0.01\ \Sigma_{g,0}$, and $\Sigma_{SD,0}$ decreases with increasing the distance from the Sun. On the other hand, we assumed that the presolar component is injected from a nearby supernova at the initial stage of disk evolution. Then we set the surface density of presolar dust is $\Sigma_{PSD,0} = \Sigma_{inj} \exp[-(r/R_d)^{2-\gamma}]$, and $\Sigma_{PSD,0}$ is the approximately constant within the disk radius. We parameterized Σ_{inj} in this study. The particle radius of solar and pre-solar dust was set to grains observed in meteorites [11] without size distribution, and we do not consider the dust growth.

3. Results and discussions: Using the surface density distribution of the solar and presolar components at 3 Myr (which is the typical accretion age of carbonaceous chondrite parent bodies), we obtain the spatial distribution of Cr isotope anomalies. The Cr isotope anomalies are described in ε notation, which represents parts per 10^4 deviations from the mean values of terrestrial rocks ($\mu^iM = (R_{meteorites} / R_{terrestrial\ rocks} - 1) \times 10^4$, $R = {}^iM / {}^jM$). The $\varepsilon^{54}Cr$ at each location was calculated from the mass balance equation, $\varepsilon^{54}Cr = [(\varepsilon^{54}Cr)_{SD}\ \Sigma_{SD} + (\varepsilon^{54}Cr)_{PSD}\ \Sigma_{PSD}] / (\Sigma_{SD} + \Sigma_{PSD})$. We assumed $(\varepsilon^{54}Cr)_{SD} = -1$ based on the lowest values among bulk-scale meteorites. We assumed $(\varepsilon^{54}Cr)_{PSD}$ = 25,000 or 500,000 from the measurement of chromium isotope anomalies in presolar Cr-rich spinel grains [11].

Cr-rich spinel grains are considered to be formed in supernovae environments. We can estimate the relative formation regions of four types of asteroids (i.e., B-, Ch-, D-, and K-types by CI, CM, Tagish Lake, and CV meteorites, respectively) from the numerical results of the ε^{54}Cr evolution with the disk radius. In our results, a plausible formation region of four types of CCs can be obtained with the supernova from approximately 2 pc and $(\varepsilon^{54}\mathrm{Cr})_{\mathrm{PSD}}$ = 25,000 (Fig. 1).

This study first determined the formation region of asteroids using the nucleosynthetic isotopic anomalies recorded in the CCs. Desch et al. [9] previously calculated the formation region of CC parent bodies based on the abundances of refractory materials (e.g., calcium–aluminum-rich inclusions) in individual CCs. The relative formation radius of the CC parent bodies obtained by Desch et al. [9] was consistent with our model.

We proposed the comprehensive evolutionary scenario of volatile-rich asteroid's orbits using the initial and present asteroid locations. A comparison of the initial location of asteroids obtained from the numerical calculation and the present location discussed earlier showed that their orbits are disturbed during the evolutionary history of the Solar System. In particular, most of the D-type asteroids are located in the Jupiter Trojan region beyond the heliocentric distance of most C-complex asteroids [12]. This observation is in contrast to the initial location between the D- and B-type asteroids obtained in this study. Primarily, the process scattering the asteroids is the gas-drag migration of giant planets. We explain the scattering of volatile-rich asteroids by the multiple migration of giant planets.

Importantly, the formation regions of Jupiter and Saturn have not been constrained. To explain the observed discrepancy in B- and D-type asteroids, Saturn may have been located between these types of asteroids. In this case, the orbits of the parent bodies for each asteroid type (i.e., B, Ch, D, and K types) were disturbed when the migration of giant planets started. First, Jupiter migrated inward, which did not significantly affect the orbits of the four asteroid types but caused the scatter of inclination and orbits of S-type asteroids. A subsequent inward migration of Saturn induced scattering of the K-, Ch-, and D-type asteroids both inwardly and outwardly. Remarkably, a part of the D-type asteroids may be transported beyond the formation region of the B-type asteroids. Finally, the outward migration of Jupiter and Saturn mainly transported K-, Ch-, and B-type asteroids to the main belt. The formation regions of the K-, Ch-, and B-type asteroids were reflected in the compositional zoning of the main belt. D-type asteroids were possibly delivered to the Trojan regions at approximately 3.6–3.8 Gyr by late heavy bombardment from trans-Neptune [e.g., 13]. This scenario does not include the dynamic properties of asteroids, such as inclinations and eccentricities, instead, we emphasized the significance of the scenario proposed herein as the first case of linking the isotopic records of meteorites and the population of asteroids.

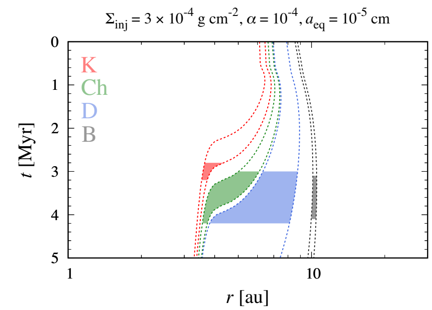

Fig. 1: Estimated relative formation region with accretional ages. Dotted lines show the analytical uncertainties of ε^{54}Cr.

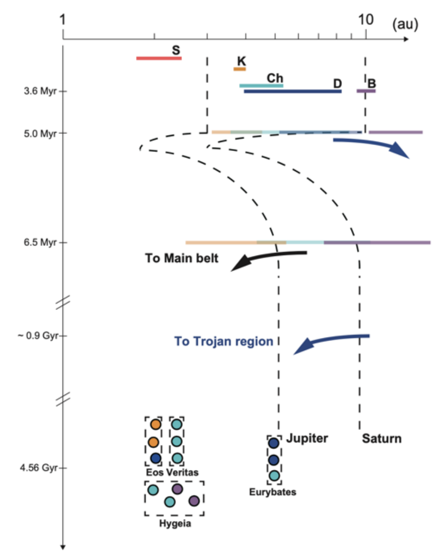

Fig. 2: Schematic image of the asteroid's evolution with the migration of giant planets.

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