論文の内容の要旨

Irradiation processes in the early solar system: A multiple isotope study on early solar system solids

（太陽系初期の固体物質に対するマルチ同位体分析から読み解く初期太陽系における宇宙線照射過程）

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In the present work, I studied early solar system solids in primitive meteorites and discussed the earliest history of the solar system formation. Especially, my study focused on the origin and distribution of short-lived radionuclide ^{10}Be in the early solar system.

Berrylium-10 is a unique short-lived radionuclide because it cannot be produced by thermonuclear reactions in stars, but by energetic particle spallation reactions. The stable isotopes of Li, Be, and B are also made by spallation processes, and the isotopic compositions of these elements are strongly energy dependent. Therefore, Li-Be-B isotopic systematics of meteoritic components would provide important constraints on the spallation-related processes in the early solar system.

Up to now, however, the origin of ^{10}Be in the early solar system is not well understood. A plausible candidate for the origin of ^{10}Be is irradiation by cosmic rays from the early active Sun. This is because the available ^{10}Be abundances recorded in Calcium-Aluminum-rich Inclusions (CAIs), which are the oldest known solids in our solar system, appear to show some heterogeneity. The variation in ^{10}Be abundances in CAIs may reflect various irradiation conditions, such as irradiation target compositions, energetic particle fluxes, irradiation time, irradiation distance from the proto-Sun. However, an accurate measurement of ^{10}Be abundances by Secondary Ion Mass Spectrometry (SIMS) is difficult because it is impossible to determine Be/B ratios unless a suitable and matrix-matched standard materials are prepared. Previous studies used silica-rich glasses for the Be-B measurements of milliliter in CAIs, because suitable standards for milliliter are not available in natural terrestrial environments. This use would lead to systematic errors on $^{9}Be/^{11}B$ ratios of milliliter and their 10Be abundances. Thus, it is possible that variations in $^{10}Be/^{9}Be$ ratios of CAIs may come from analytical artifacts by SIMS measurements. Furthermore, most of Be-B data thus far have been from the CAIs in CV chondrites. This is because sizes of CV CAIs are relatively larger than those of other chondritic components. To discuss the origin and distribution of ^{10}Be, investigation of Be-B systematics in various types of meteoritic components are important.

Chondrites, are the dominant constituent of most primitive meteorites, which also formed at the earliest stage of the solar system formation. Because chondrules show different textual, chemical, and isotopic compositions from those of CAIs, they would have information about different time and/or location in the solar protoplanetary disk. Thus, investigations of ^{10}Be abundances in chondrules shed light on the distribution of ^{10}Be in the early solar system. At present, however, because sizes of composed minerals of chondrule are relatively small, it is impossible to conduct the Be-B isotope measurements.

To overcome this problem, I developed a high-spatial-resolution Be-B measurement technique using NanoSIMS 50. In addition, I produced synthetic melilite and anorthite glass-standards doped with Be and B, and investigate the effects on different matrix compositions for Be-Be measurements using SIMS. Using the high-spatial and high-accuracy SIMS technique, I have performed the ^{10}Be-^{11}B dating of CAIs in four carbonaceous chondrites, Y81020 (CO3.05), Y82094 (ungrouped C3.2), SaU290 (CH3) and Isheyevo (CH/CBb) with a NanoSIMS 50. The CAIs in various types of chondrites studied here show high and variable initial $^{10}Be/^{9}Be$ ratios than previously thought. This result strongly suggests that ^{10}Be was produced by protosolar cosmic ray irradiation. I also measured Li isotopic compositions of these CAIs. The Li isotopic compositions of CAIs are nearly chondritic independent of their $^{10}Be/^{9}Be$ ratios. The present results may be explained if the targets of cosmic ray irradiation are the chondritic composition: in other words, targets are most likely not CAI themselves, but their precursors of solar gases. Several astronomical observations of solar analogs demonstrated that X-ray emissions from protostars with the earliest evolutional stage are high and variable. The variable $^{10}Be/^{9}Be$ ratios observed in this study may reflect the variable and extreme irradiation by cosmic rays from the earliest evolutional stage of the protosun. Also, I have investigated Al-Mg systematics on CH CAIs with high and variable $^{10}Be/^{9}Be$ ratios. All CAIs studied here show no resolvable excesses in ^{26}Mg. Considering the degree of variations in $^{10}Be/^{9}Be$ between CV CAIs and CH CAIs, the incorporation of ^{26}Al in the early solar system would occur within ~1Myr at the birth of our solar system.

Then I have expanded the Be-B study to chondrules in the Y82094 carbonaceous chondrite. I found evidence for live ^{10}Be at the time of chondrule formation, strongly suggest the widespread distribution of ^{10}Be in the solar protoplanetary disk. The inferred initial $^{10}Be/^{9}Be$ ratio is $(1.92 \pm 0.45) \times 10^{-3}$ (2σ), which is higher than those of CAIs in CV chondrites ($< 1.2 \times 10^{-3}$). This result can be interpreted as further evidence that ^{10}Be was produced by solar cosmic ray irradiation. Initial $^{10}B/^{11}B$ ratio and Li isotopic ratios of the chondrules are similar to the chondritic compositions, suggesting that ^{10}Be was produced by irradiation of a solar nebular gas. The high $^{10}Be/^{9}Be$ ratio observed in chondrules indicates that Y82094 chondrules might have formed very early and possibly contemporaneous formation of CAIs.