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Lithium isotope composition of ordinary and carbonaceous chondrites, and differentiated planetary bodies: Bulk solar system and solar reservoirs

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Abstract

In order to better constrain the Li isotope composition of the bulk solar system and Li isotope fractionation during accretion and parent body processes, Li isotope compositions and concentrations were determined on a number of meteorite falls and finds. This is the first comprehensive study that systematically investigates a representative set of samples from carbonaceous chondrites (CI, CM2, CO3, CV3, CK4 and one ungrouped member), enstatite chondrites (EH, EL), ordinary chondrites (H, L, LL), and achondrites (one eucrite, diogenites, one pallasite, and a silicate inclusion from a IAB iron).

Carbonaceous chondrites have an average isotope composition of $\delta^7\mathrm{Li}=+3.2‰\pm1.9$ (2σ) which agrees with the average composition of relatively pristine olivines (representative for the bulk composition) from the Earth primitive upper mantle (PUM). This is lighter than the average δ^7Li of the basaltic differentiates of the Earth, Moon and Mars and the achondrites. It is an important observation, however, that the lighter end of the isotopic range of the differentiates always coincides with the averages of the mantle olivines and the carbonaceous chondrites. From this we conclude that the bulk of the inner solar system consists mostly of material from carbonaceous chondrites and that the variation seen in the differentiates is due to planetary body processes. Ordinary chondrites are significantly lighter than carbonaceous chondrites. No significant differences in δ^7Li exist between enstatite chondrites ($n=3$) and carbonaceous or ordinary chondrites. The difference between carbonaceous and ordinary chondrites and the variability within the chondrites could indicate the existence of distinct Li isotope reservoirs in the early solar nebula.

Keywords: lithium isotopes; ordinary; carbonaceous and enstatite chondrites; HEDs; pallasite; IAB silicate inclusions; bulk silicate Earth BSE

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1. Introduction

Recent studies on lithium isotope composition of extraterrestrial material have furthered our knowledge of the isotopic composition of the solar system. Carbonaceous chondrite material displays a range in δ^7Li from

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−3.5 to +3.9‰ (James and Palmer, 2000; Chaussidon et al., 2001, 2002; McDonough et al., 2003; Sephton et al., 2004, 2006; Magna et al., 2006). Two nakhlites and their olivine and clinopyroxene separates give +5.1‰ and +3.7‰ (Bridges et al., 2005). SIMS data for pyroxenes and olivines from basaltic shergottite Northwest Africa (NWA) 480 and three nakhlites (NWA 817, MIL 03346, Nakhla) show large core to rim variations of up to 30‰ (Beck et al., 2004, 2006); a melt inclusion in lunar meteorite NWA 479, a low-Ti mare basalt, gave δ^7Li=+15‰ (Barrat et al., 2005). Magna et al. (2006) and Seitz et al. (2006) measured Li isotope composition of lunar samples and a number of Martian meteorites. The majority of these samples have an isotope signature close to +4‰, similar to a suggested bulk silicate Earth (BSE) value (Seitz et al., 2004). These authors concluded that this value represents the isotopic composition of the inner solar system which is identical to that of Orgueil (CI).

In contrast, McDonough et al. (2003) proposed a bulk solar system δ^7Li value of around 0‰ based on measurements of 6 carbonaceous chondrites of petrologic type 1 to 4, and one LL3.4 ordinary chondrite which range from +3.9‰ for Orgueil (CI) (James and Palmer, 2000) to about −3.5‰ for Felix (CO3). McDonough et al. (2003) opted for δ^7Li=0‰ reasoning that Li isotopes are altered on their parent bodies and become heavier due to interaction with isotopically heavier water. More recent data (Sephton et al., 2006; Magna et al., 2006; McDonough et al., 2006) further suggest that chondrites are isotopically lighter by about 2‰ than the value derived for planetary bodies of the inner solar system from their partial melting products.

In order to tighten constraints on the Li isotope composition of the bulk solar system and Li isotope fractionation during pre-accretionary and parent body processes, we determined Li isotope compositions and concentrations on a number of meteorite falls and finds comprising samples from various chondrite groups and selected achondrites.

2. Methods

2.1. Column chemistry and MC-ICP-MS

Rock digestion and column chemistry followed the procedure of (Seitz et al., 2004). Powdered rock samples (15–25 mg) were digested in a mixture of 1 ml conc. HNO_3 and 1 ml conc. HF on a hot plate (140 °C) for several days. Subsequently, samples were dissolved in 6 M HCl and reconstituted in 6 M HNO_3 followed by chromatographic Li purification (see Seitz et al., 2004 for more detail). For Li-chromatography clear sample solutions of 0.18 ml 5 M HNO_3 and 0.72 ml 100% methanol (analytical grade) were passed through single, small 1.4 ml exchange columns filled to height of 6 cm with BioRad AG50W-X8 (200–400 mesh) resin. With the collection of 10 ml of the eluate all lithium is recovered. To asses the accuracy and consistency of the dissolution and Li purification procedure, the JB-2 basalt standard and a blank were processed with each set of samples. To ensure 100% recovery we randomly checked pre and after cuts. Excess Li was never detected and was always within the concentration of the analytical blank. For measurement by MC-ICP-MS the samples were taken up in 2% HNO_3 (10 ng/g solution).

The MC-ICP-MS Neptune (ThermoFinnigan) allows simultaneous measurement of ^{6}Li and ^{7}Li. Measurements were performed at dry plasma conditions using a Cetac Aridus® nebuliser fitted with a PFA spray chamber and an ESI microconcentric-nebuliser with an uptake rate of 20 µl/s. The sample gas is dried at 160 °C before being introduced into the plasma. With the ThermoElectron standard cones (H-Cones) an intensity of 40–50 pA (i.e. a 4–5 V signal on the 10^{11} Ω resistor for ^{7}Li at a 10 ppb concentration level) is achieved. The analytical blank (chemistry blank minus background signal on double distilled 2% HNO3 was usually 30–20 pg, ~12–20 mV on ^{7}Li). Sample analysis is carried out sequentially by ‘bracketing’ the sample with the L-SVEC standard (Flesch et al., 1973). The total integration time for each Li isotope measurement was ≈4 min, following an electronic baseline measurement (at masses 5.9, 6.1 and 6.9, 7.1, respectively) of ≈1 min. Isotope compositions are expressed as per mil deviations from the NIST L-SVEC standard: $\delta^7\mathrm{Li}=[(^7\mathrm{Li}/^6\mathrm{Li})_{\mathrm{sample}}/(^7\mathrm{Li}/^6\mathrm{Li})_{\mathrm{L\text{-}SVEC\ standard}}-1]*1000$. Internal precision is typically between 0.2–0.6‰ (2 SE). The best measure for the external precision is the long term reproducibility, determined on replicate dissolutions of the geological standard JB-2, which is about 1.2‰ (2σ). Accuracy of the Li isotope measurements is documented by the analyses of rock standards (JB-2 and JGB-1) and meteorite samples which have been previously measured by other laboratories [e.g. our measurements of Orgueil yield a δ^7Li-value of 3.2‰± 0.7‰ (2σ) and 1.56 µg/g Li±0.25, (2σ), compared to +3.9‰±0.6‰ (2σ) and 1.49 µg/g (James and Palmer, 2000) (also see Table 1)]. The δ^7Li determined in this study for all of these samples agrees with literature values within uncertainties of 1.2‰.

Li concentrations of samples were determined along with the isotope measurements by comparing the ion beam intensities with those of the 10 µg/g NIST L-