BORON AND LITHIUM ISOTOPIC COMPOSITION IN CHONDRULES FROM THE MOKOIA METEORITE

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Introduction: Large Boron isotopic variations have been reported in individual chondrules from the Semarkona, Hedjaz and Allende meteorites [1, 2]. These variations were interpreted as resulting from the incomplete mixing of two isotopically distinct sources of Boron. Spallation is the only known nucleosynthetic process that can yield Boron in substantial amounts at the scale of the Universe. Therefore it has been proposed that the two sources observed in chondrules correspond to two different types of spallation reactions, namely at high and low energies. Indeed, in the case of Boron, the $^{11}B/^{10}B$ ratio is sensitive to the energy at which the spallation reaction takes place.

Since this report of large B isotopic variations in chondrules, two observations have allowed to identify the natural conditions under which at least one of such spallation reactions may have taken place in the early solar system. First, X-ray observations of T-Tauri stars have revealed daily outbursts which mimic the present day solar activity during the emission of flares [3]. Second, the decay product (i.e. ^{10}B) of the short lived radio-isotope ^{10}Be was discovered in Calcium-Aluminum-rich inclusions (CAIs) [4]. This is an indication that spallation did occurr in the solar system, shortly (i.e. less than a few million years) before the formation of the CAIs. In addition the possible occurrence of ^{7}Be in CAIs suggests that this duration can be as short as a few months [5].

The $\delta^{11}B$ variations in chondrules previously measured with the ion-microprobe Cameca 3f at the CRPG in Nancy were determined with a typical reproducibility of ±10‰ (2 sigma) for B concentrations around 1 ppm. In Semarkona the B concentrations were found to be highly variable from 2.6×10^{-6} to 9.9×10^{-5} (i.e. from 0.2 to 7.1 ppm) with different modes for the 3 chondrules studied in details of 0.36, 0.5 and 3.6 ppm [2]. The $\delta^{11}B$ values in Semarkona range from -42‰ to +44‰, 87% of the values being between -47‰ and +10‰ [2]. In Allende the $\delta^{11}B$ variations were found to lie between -50 and +20‰ for B/Si ranging from 2 to 7×10^{-5}. P. Hoppe et al. [6] have re-examined this problem and found $\delta^{11}B$ variations in 2 chondrules from the Allende meteorite ranging between -26±34‰ and +19±68‰ and between -26±38‰ and +6±14‰ (2 sigma error) for B/Si ranging from 0.5 to 7×10^{-6}.

Based on these data Hoppe et al., concluded that no isotopic heterogeneity is present in chondrules while we concluded the opposite from our data set. Obviously, these data illustrate the fact that the experimental reproducibility on the $\delta^{11}B$ values is the limiting factor to assess the Boron isotopic heterogeneity in chondrules. The only clear difference between the two data sets is in fact the generally lower B contents in the chondrules analysed by Hoppe et al. compared to ours, which may explain the difference in accuracy of the the two sets of $\delta^{11}B$ values.

In the present work we have used the ion microprobe Cameca IMS 1270 (i) to improve this reproducibility at low B contents and (ii) to better control the removal of surface contamination. As previously put into light from the ims 3f data on Semarkona, the present results data reveal significant intra-chondrule and chondrule-to-chondrule Boron isotopic heterogeneities in the case of the Mokoia meteorite.

Sampling and Results: In order to detect the possible matrix contamination in chondrules, we have chosen to study the Mokoia meteorite whose bulk $\delta^{11}B$ value is unusually elevated (+19.2±0.25‰; [7]). Since Boron is concentrated by a factor up to x100 in the matrix, such high $\delta^{11}B$ value allows us to trace the possible B contamination of the chondrules by their surrounding matrix. In order to get rid of possible contamination introduced during sample mounting in epoxy and polishing we have studied an unpolished fragment of Semarkona pressed into an indium foil. We have yet analyzed 8 chondrules from Mokoia and 1 from Semarkona.

In the 8 chondrules from Mokoia, the $\delta^{11}B$ values range between -39±6.8‰ and -0.6±7.8‰ (2 sigma). In one Boron depleted area of one chondrule, the $\delta^{11}B$ value was found to be as low as -68.5‰ and -61.5‰ (±29; 2 sigma). In one chondrule from Mokoia the $\delta^{11}B$ values range between -33.7±5.4 ‰ and -3.8±5.4 ‰. In one chondrule from Semarkona, the $\delta^{11}B$ variations are from 9.7±6.8 ‰ to -5.1±3.6 ‰.

In Mokoia, these data confirm with a resolution of ≈ ±6 ‰ the presence of a significant Boron isotopic heterogeneity, as previously observed in chondrules. Note that the presently observed range is consistent with our previous isotopic resolution of ±10 ‰ but marginally detectable with the resolution of ±35‰ reported by Hoppe et al. (poorer counting statistic due to the B contents lower by almost one order of magnitude). The B contents in Mokoia chondrules were determined directly from the count rate of $^{11}B^{+}$ ions calibrated on 2 standards : GB4 glass (980 ppm B) and BHV0 glass (2.3 ppm B) which gave count rates on ^{11}B of 42 counts / (sec × nA × ppm) and of 41 counts (sec × nA × ppm), respectively.

The $\delta^{7}Li$ were also measured along with the $\delta^{11}B$. They range from -53.7±2.4 and -0.15±1.6 ‰ (2 sigma) in the 8 chondrules of the Mokoia meteorite. Therefore the heterogeneity in B has its counterpart for Li. These data are reported in the Figure 1 ($\delta^{11}B = f(1/B)$) and in Figure 2 ($\delta^{11}B = f(\delta^{7}Li)$).

Interpretation: In the Figure 1, the $\delta^{11}B$ values show a broad trend with B concentrations in the chondrules of Mokoia. First note that, because of the low Be/B and Be/Li ratios it is not possible to detect in these chondrules the possible occurrence of the two short life radiogenic isotopes ^{10}Be and ^{7}Be. As a consequence the observed variations in $\delta^{7}Li$ and $\delta^{11}B$ cannot be due to the in situ decay of ^{10}Be and ^{7}Be. Note also that the correlation in Fig.1 rules out an isotopic fractionation linked to an evaporation process.

Two end members can thus be defined : $\delta^{11}B \approx 0‰$ and $\delta^{11}B \leq -70‰$. The value of 0‰ is still significantly different from the matrix value reported by [6] (+19.2‰) and thus, this end member seems to be not caused by a simple contamination of the chondrules once in their parent body. This conclusion needs however to be experimentally checked because this value of +19.2‰ was determined on bulk samples at the mg scale. It is thus possible that an isotopic heterogeneity of the matrix will appear when these determinations will be repeated at the ion microprobe scale (10-30 µm). However, this possible contamination of the chondrule by their surrounding matrix does not modify the interpretation proposed on the basis of the Figure 2.

According to the Figure 2, the second end member should have $\delta^{11}B$ and $\delta^{7}Li$ values ≤-70‰ and ≤-50‰, respectively. For high energy spallation reactions (E ≥ 100 MeV/nucleon), the $\delta^{11}B$ and $\delta^{7}Li$ values should be close to -375 and -830 ‰, respectively. Assuming that these isotopic compositions stands for the second end member, mixing models were calculated and the predicted correlations are reported in Figure 2 as two solid lines : the upper and lower ones standing for B/Li ratios of 0.1 and 0.01, respectively.

As repeatedly discussed in the literature, it seems unlikely that the production of this high energy spallogenic boron could have taken place during the parent body exposure to the GCR and SCR. Therefore in chondrules, micrometer size regions have preserved a signature of the original isotopic compositions of their precursors. The fact that chondrules were not totally homogenized isotopically during their cooling, put constraints on their cooling rates. An order of magnitude of this duration can be empirically estimated.

The diffusion coefficient in a melted chondrule at 1500K is close to 3×10^{-9} $m^2.sec^{-1}$ and 4.8×10^{-12} $m^2.sec^{-1}$ for Li and B, respectively. Thus, in order to maintain a trace of the original isotopic heterogeneity of the precursors, the heating duration of the chondrules at 1500K cannot exceed 10 min.

Conclusions: In conclusion we repeat the point we wish to emphasize : a fraction of the range defined by the Boron and Lithium isotopic variations in the solar system material is due to the incomplete mixing of two different nucleosynthetic sources. This situation may illustrate the presence of a « protosolar »source mixed with products formed in-situ in the solar system during the intense activity of the early Sun in its T-Tauri phase.

References: [1] Chaussidon M., Robert F. (1995) *Nature* **374**, 337-339. [2] Chaussidon M. and Robert F. (1998) *Earth Planet Sci. Lett. 164,* 577-589. [3] Montmerle T. (1999) MPE Report : *Astronomy with Radioactivities*, 225-236. [4] McKeegan K., Chaussidon M., Robert F. (2000) *Science* **289**, 1334-1337. [5] Chaussidon M., Robert F. McKeegan K. (2002) Abst. 33th LPSC #1563 [6] Hoppe et al., (2001) *MAPS*, **36**, 1331-1343. [7] Zhai M et al., (1996) *Geochim. Cosmochim. Acta* **60**, 4877-4881.

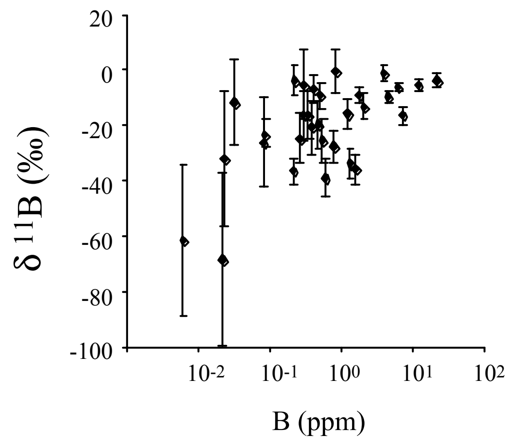

Figure 1 : Boron isotopic compositions in chondrules from Mokoia as a function of the B concentration (in arbitrary units).

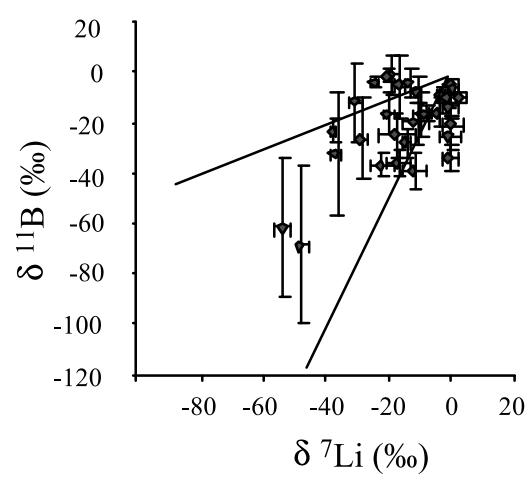

Figure 2 : Isotopic compositions of Boron and Lithium in chondrules from Mokoia. The two solid lines stands for the expected mixing correlations with a high energy spallogenic component having B/Li ratio lying between 0.1 and 0.01