CLOSED SYSTEM BEHAVIOR OF CHONDRULES – NEW CONSTRAINTS FOR THE CHONDRULE FORMING PROCESS

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Introduction: Chondrules are typically 0.1 – 1 mm in diameter and consist of olivine, pyroxene, sulfide, metal and glass/feldspar. They are major constituents (up to 80 vol.%) of 96% of all meteorites (excluding lunar and martian meteorites) [1]. This implies that a major fraction of material of the asteroid belt has been processed in chondrules; making the chondrule formation process one of the most important processes of the early solar system.

Mainly based on their often spherical shape and characteristic barred olivine structure, chondrules were suggested to have formed by a brief but very intense heating event ($t_{max} \approx 1850°C$) in a solar nebular environment [2, 3].

Recently, solar nebular shock wave heating has been favoured as origin of the transient heat for chondrule melting [4]. Alternatively, planetary impacts [5] or nebular flash heating [6] have been proposed as heat sources for the melting of chondrules.

Bulk chondrules from one of the least altered chondrite Semarkona (LL3.0 [7]) contain up to 2.5 wt.% Na_2O [this study]. Evaporation experiments with chondrite-like material [8-11] have shown, however, that chondrules ($P_{total} < 10^{-3}$ bar, log $fO_2 < -8$, $t \approx 1200 – 1600°C$) would loose 50 wt.% of their Na within 15 minutes of melting (**Fig. 1**).

In our approach, we study Na in chondrule olivine in order to address the question of Na contents of molten chondrules.

Methods: Major and minor elements in olivine, pyroxene and mesostasis were determined by standard EPMA (JEOL 8900 RL). Na trace element analyses were conducted by high-current EPMA (I = 300 nA, 600 s on the peak and 2 x 300 s on the backgrounds, focussed beam). The detection limit was at 15 µg/g Na_2O. The modal compositions of chondrules were determined on base of Mg, Si, Ca and Fe element distribution maps.

Results: All chondrules have, within analytical error, a solar K/Na-ratio (**Fig. 2**). The Na_2O contents of bulk chondrules were calculated on base of the phase and modal compositions to <0.1 – 2.5 wt.%. The mesostasis glasses contain between <0.1 – 10 wt.%. The Na_2O concentrations in olivine vary between ≤15 µg/g and 250 µg/g.

Discussion: Unfractionated K/Na-ratios in Semarkona chondrules (**Fig. 2**) indicate the absence or only a negligible parent body alteration of alkalis [12]. This finding is in agreement to previous analyses of Semarkona chondrules [13].

The Na concentration of olivine is compared to the Na concentration of the coexisting liquid during olivine crystallization. The cores of the olivine grains are compared with the bulk Na concentration of the respective chondrules. In cases where chondrules contain olivine and mesostasis only, olivine rim Na concentrations are compared with the Na concentration in the mesostasis. For chondrules that contain olivine and pyroxene, Na concentrations in olivine rims are compared to a calculated melt composition. These melts were calculated by combining the modal abundances of mesostasis and low- and high-Ca pyroxene and the respective phase compositions.

Olivine is the liquidus phase for all studied chondrules, as indicated by petrography and thermodynamic calculations using MELTS [14]. The liquidus temperatures were calculated to range between 1535°C and 1800°C.

The data are displayed in **Fig. 3**. The correlation between Na in olivine and Na in the coexisting melts suggest that Na was present in the liquid chondrules at temperatures above 1500°C and during the entire olivine crystallization. The olivine/melt partitioning coefficient derived from our chondrule data is, within error, identical to the experimental $D_{Na} = 0.003$ by Borisov et al. [in preparation] **(Fig. 3)**.

We conclude that Na in chondrules is primordial. The conclusion that alkalis in chondrules are primordial fully explains the lack of K isotope fractionation, which seems inevitable when evaporation occurs [11, 15]. Complex models that explain the presence of Na in chondrules by means of recondensation (e.g. [16]) are not required.

If chondrules formed in the solar nebula at low pressure (≤10^{-3} bar) and low fO_2, heating and melting must have occurred within a time interval as short as ≤15 min to limit Na-loss to 50% (see **Fig. 1**). Most chondrules have liquidus temperatures (1535 – 1800°C) that are actually higher than the experimental temperatures shown in **Fig. 1** [8-11]. This limits the duration of chondrule melting to <10 min.

Alternatively, a high-pressure and/or high-fO_2 solar nebular gas would explain Na retention in the molten chondrules. In such a case (p = 1 bar), chondrule melting could have persisted for several tens of minutes (**Fig. 1**).

We suggest that the presence of Na during olivine crystallization has to be considered when studying phase relations in chondrules [17]. For example, Na_2O considerably extents the olivine stability field in CMAS systems towards very MgO-poor compositions.

Conclusions: Our measurements on Semarkona chondrules show that Na was present when they were molten. The absence of evaporative alkali loss explains the ubiquitous lack of K isotope fractionation in chondrules. Chondrule formation must have occurred on time scales in the range of 10 min. Alternatively, a high pressure/high fO_2 nebular environment is required.

Variations of alkali contents in different chondrules reflect the composition of the precursor material. Phase relation studies in chondrules must consider the effect of Na_2O, namely on the stability field of olivine.

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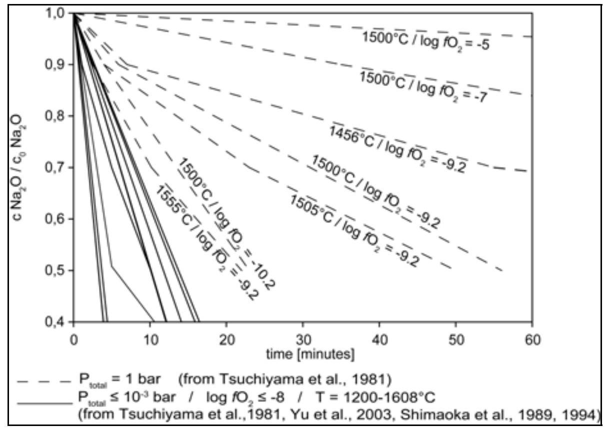

Fig. 1

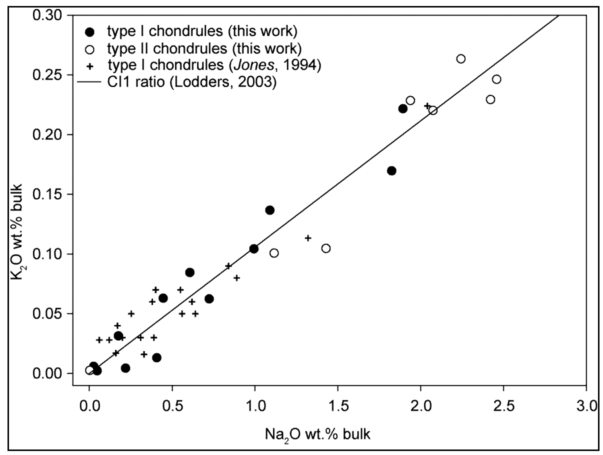

Fig. 2

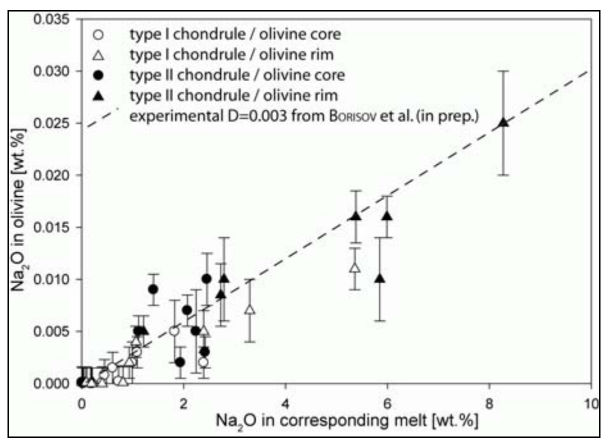

Fig. 3