Cooling rate of chondrules from diffusion profiles in relict olivine grains

Conference or Workshop Item

COOLING RATES OF CHONDRULES FROM DIFFUSION PROFILES IN RELICT OLIVINE GRAINS

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Introduction: The cooling rates of chondrules are one of the important constraints on chondrule formation and can be used to distinguish between competing chondrule formation mechanisms. Proposed mechanisms range from shockwaves in the solar nebula [1] to impacts between planetesimals [2]. Dynamic crystallisation experiments are the most widely cited methods of determining chondrule cooling rates and this indirect method has provided cooling rates from 1 to 3000 Kh^{-1} [3, 4]. In order to assess whether this is a true representation of chondrule cooling rates, it should be validated or better constrained by using a more direct method. Modelling of diffusion profiles observed across the boundary between forsteritic-olivine relict grains and more fayalitic overgrowth provides a more direct approach to determining chondrule cooling rates.

Methods: Forsteritic-olivine relict grains have been identified in a thin-section of ALHA 77307 CO3.0. They were characterised using Back Scattered Electron (BSE) imaging, Energy Dispersive X-ray Spectroscopy (EDS) mapping and EDS point analyses, using the FEI Quanta 3D FIB-SEM at The Open University. Chondrule liquidus temperatures were calculated from chondrule bulk compositions using geochemical modelling software Petrolog3 [5]. Bulk compositions were calculated using a modal recombination analysis, combining the density, proportion and composition of each phase identified in the studied thin section [6]. The composition of each phase was determined by electron microprobe analyses using the Cameca SX-100 electron microprobe at The Open University. Diffusion profiles have been measured using BSE greyscale images, calibrated to electron microprobe analyses and extracted using open-source software ImageJ [7]. As diffusion in olivine is highly anisotropic, the crystal orientations have been determined with Electron Back Scatter Diffraction (EBSD) using the Zeiss SUPRA™ 55VP FEG-SEM equipped with an Aztec HKL EBSD system and HKL Nordlys Nano high-sensitivity camera at The Open University.

Modelling: Fe-Mg diffusivity in olivine is well constrained [8], and Fe-Mg diffusion profiles were modelled using a one-dimensional, finite-difference method incorporating shifting boundary conditions and the effects of olivine composition, crystal orientation, oxygen fugacity and chondrule liquidus temperature.

Results: Fe-Mg diffusion profiles from 8 relict grains in 6 chondrules have been modelled. Good diffusion model fits to the observed diffusion profiles are generally produced with non-linear cooling rates over the modelled temperature range. Initial cooling rates range from 5 to 500 Kh^{-1} and increase to final cooling rates of 50 to 2000 Kh^{-1}. The change in cooling rate varies from a near-constant cooling rate to an increase in cooling rate of an order of magnitude.

Discussion: These cooling rates of 5 to 2000 Kh^{-1} are broadly consistent with experimental constraints on chondrule formation [4]. They are also consistent with cooling rates determined from modelling olivine zoning profiles in chondrules [9] and previous work determining chondrule cooling rates from diffusive exchange between forsteritic relict grains and the fayalitic overgrowth [10]. However, the results here indicate that chondrule cooling was more complex than has previously been considered, requiring up to a tenfold increase in cooling rate at high temperatures when diffusion is most efficient (~1900 to ~1785 K). This new detail offers additional scope for constraining the origin of chondrules. One possible situation where this could occur is during a planetary embryo bow shock. Immediately after passing through the bow-shock, chondrules cool relatively slowly. As chondrules pass through the post shock region, adiabatic expansion of gas causes more rapid cooling of the region [11]. However, some of the measured cooling rates may be lower than have so far been modelled for planetary embryo bow shocks. We will therefore consider the detailed implications of our results for a range of bow-shock models as well as other chondrule formation scenarios.

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