Cooling rates of chondrules from diffusion profiles in relict olivine grains

Conference or Workshop Item

Cooling rates of chondrules from diffusion profiles in relict olivine grains

S. C. Stockdale (1), I. A. Franchi (1), D. J. Morgan (2), M. Anand (1), M. M. Grady (1)
(1) School of Physical Science, The Open University, Milton Keynes, MK7 6AA, UK (2) School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK (Shannon.Stockdale@open.ac.uk)

Abstract

Chondrule cooling rates are one of the important constraints on chondrule formation and can be used to distinguish between different chondrule formation mechanisms. Here we have modelled diffusion profiles observed across the boundary between forsteritic-olivine relict grains and more fayalitic overgrowth. We show that the cooling of chondrules is complex and good model fits are produced with non-linear cooling rates, offering additional scope for constraining the origin of chondrules.

1. Introduction

Chondrules are small, up to millimetre sized, spherical melt droplets composed of ferromagnesian minerals, olivine and pyroxene. They are one of the main components of chondritic meteorites, up to 80 vol % in some chondrites [1], and therefore appear to represent one of the main stages in the development of the rocky planets. They are products of widespread heating in the protoplanetary disk, however, the nature of this event is poorly understood. Pb-Pb ages of chondrules indicate they formed in the first few Myrs of the solar system [2]. As such, chondrules provide evidence of energetic processes occurring in the early solar system. Proposed chondrule formation mechanisms vary from shockwaves in the solar nebula [3] to impacts between planetesimals [4]. Chondrule cooling rates are one of the important constraints on chondrule formation and can be used to distinguish between competing chondrule formation models. 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} [1]. In order to assess whether this is a true representation of chondrule cooling rates, it should be validated or better constrained using a more direct method. Modelling of diffusion profiles observed across the boundary between forsteritic-olivine relict grains and more fayalitic overgrowth provides such an approach to determining chondrule cooling rates.

2. 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, with 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, composition, and proportion of each phase identified in each chondrule [6]. The composition of each phase was determined by electron microprobe analyses using the Cameca SX-100 electron microprobe at The Open University. Fe-Mg 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 crystals is highly anisotropic, the crystal orientations have been determined by Electron Back Scatter Diffraction (EBSD) using the Zeiss SUPRA^{TM} 55VP FEG-SEM equipped with an Aztec HKL EBSD system and HKL Nordlys Nano high-sensitivity camera at The Open University. For oxygen fugacity, we use a value of 1 log unit beneath the Iron-Wüstite buffer.

3. 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.

4. 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, e.g. Fig. 1. 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.

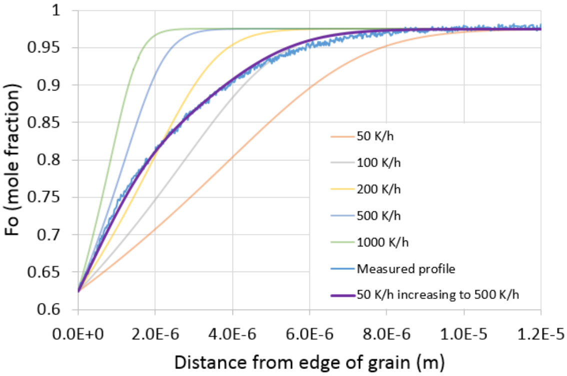

Figure 1: Fe-Mg diffusion profile showing model runs for constant cooling rates. The purple line shows a model fit with an initial cooling rate of 50 Kh^{-1} which increases to 500 Kh^{-1} and matches well with the measured profile.

5. Discussion

These cooling rates of 5 to 2000 Kh^{-1} are broadly consistent with experimental constraints on chondrule formation [1]. 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 a forsteritic-olivine relict grain 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 been modelled so far 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.

Acknowledgements

This work is funded by an STFC PhD studentship to Shannon Stockdale. We would also like to thank the MWG, NASA JSC for the loan of the sample that makes this work possible.

References

[1] Hewins, R., Connolly, and H. C. Jr.: Experimental Constraints on Chondrule Formation, Chondrites and the Protoplanetary Disk, ASP Conference Series, Vol. 341, pp. 286-316, 2005.

[2] Connelly, J. N., Bizzaro, Krot, A. N., Nordlund, Å., Wieland, D., and Ivanova, M. A.: The Absolute Chronology and Thermal Processing of Solids in the Solar Protoplanetary Disk, Science, Vol. 338(6107), pp. 651-655, 2012.

[3] Morris, M. A. and Desch, S. J.: Thermal Histories of Chondrules in Solar Nebula Shocks, Astrophys. J., Vol. 722(2), pp.1474, 2010.

[4] Johnson, B. C., Minton, D. A., Melosh, H. J., and Zuber, M.T.: Impact jetting as the origin of chondrules, Nature, Vol. 517(7534), pp. 339-341, 2015.

[5] Danyushevsky, L. V. and Plechov, P.: Petrolog3: Integrated software for modelling crystallization processes, Geochem. Geophy. Geosy., Vol. 12(7), 2011.

[6] Berlin, J., Jones, R. H., Brearley, A. J. and Spilde, M. N.: Determining Bulk Compositions of Chondrules by Electron Microprobe: Modal Recombination Analysis versus Defocused Beam Analysis, Microsc. Microanal., Vol. 14(S2), pp. 110, 2008.

[7] Schneider, C. A., Rasband, W. S. and Eliceiri, K. W.: NIH Image to ImageJ: 25 years of Image Analysis, Nature methods, Vol. 9(7), pp. 671-675, 2012.

[8] Dohmen, R. and Chakraborty, S.: Fe-Mg diffusion in olivine II: point defect chemistry, change of diffusion mechanisms and a model for calculation of diffusion coefficients in natural olivine, Phys. Chem. Miner., Vol. 34, pp. 409-430, 2007.

[9] Miyamoto, M., Mikouchi, T. and Jones, R. H.: Cooling rates of porphyritic olivine chondrules in the Semarkona (LL3.00) ordinary chondrite: A model for diffusional equilibration of olivine during fractional crystallization, Meteorit. Planet. Sci., Vol. 44(4), pp. 521-530, 2009.

[10] Hewins, R. H., Ganguly, J. and Mariani, E.: Diffusion modelling of cooling rates of relict olivine in Semarkona chondrules, 40th Lunar and Planetary Science Conference, #1513, 2009.

[11] Boley, A. C., Morris, M. A. and Desch, S. J.: High-temperature processing of solids through solar nebular bow shocks: 3D radiation hydrodynamics simulations with particles, Astrophys. J., Vol. 776, pp. 101, 2013.