EVIDENCE FOR DELAYED CHONDRULE FORMATION IN THE OUTER SOLAR SYSTEM

M. Bizzarro[1], J. Bollard[2], J.N Connelly[1] and M. Schiller[1]
[1]Centre for Star and Planet Formation, University of Copenhagen, Copenhagen, Denmark (Bizzarro@snm.ku.dk)
[2]Center for Space and Habitability, University of Bern, Bern, Switzerland

Elucidating the timescales of solid formation in the early Solar System is critical for a better understanding of disk processes. Although short-lived radionuclides such as ^{26}Al can theoretically provide high resolution ages, such decay systems critically depend on the disputed assumption of homogeneous distribution of their parent nuclides [1,2]. A such, only the decay of U to Pb can provide assumption free ages with sufficiently high resolution to determine the timing of individual meteoritic components formed in the first few Myr of the Solar System's history. Using this approach, it has been established that the formation of chondrules, the most abundant chondritic component, started simultaneously with the condensation of the Solar system's first solids – calcium- aluminium-rich inclusions (CAIs) – and lasted ~4 Myr [3,4]. However, it is uncertain whether this distribution of chondrule ages is representative of the whole protoplanetary disk. Critically, better understanding the formation history of chondrule populations formed in distinct disk reservoirs may provide insights into the mechanism(s) responsible the thermal processing of disk solids.

To address this issue, we report on the U-corrected Pb-Pb ages of two populations of chondrules understood to have formed in spatially isolated disk reservoirs based on their nucleosynthetic ^{54}Cr compositions. Indeed, it is well established that the mass-independent ^{54}Cr/^{52}Cr composition (expressed as μ^{54}Cr, i.e. the 10^6 deviations relative to the terrestrial value) of disk solids as well as asteroidal and planetary bodies can be used to track their accretion regions [5]. For example, inner Solar System material is typically characterized by deficits in μ^{54}Cr values whereas outer Solar System solids are characterized by excesses. The first chondrule population investigated consists of 15 individual objects from the NWA 5697 ordinary chondrite and Allende carbonaceous chondrite that are characterised by μ^{54}Cr values ranging from -87±12 to -24±12 ppm, i.e. typical of inner disk material [6], suggesting that these objects were formed in the accretion region(s) of the terrestrial planets. The second population comprises 17 individual objects from three CR chondrites (NWA 6043, NWA 7655 and NWA 7502) and have μ^{54}Cr values ranging from 44±6 to 137±4 ppm that suggest formation beyond the orbits of the gas giants [7,8]. The inner disk population displays U-corrected Pb-Pb dates ranging from 4567.61±0.54 Ma to 4564.71±0.30 Ma whereas the outer disk chondrules have ages that span from 4567.26±0.37 Ma to 4563.24±0.62 Ma. Although the age range recorded by the two populations are similar, their mean ages appear distinct. The inner disk population records a mean U-corrected Pb-Pb age of 1.00±0.62 Myr whereas the outer disk population displays a mean age of 2.38±0.53 Myr. To assess the statistical significance of this age offset, we performed a Mann-Whitney U test, which evaluates the null hypothesis that the medians of the two populations are identical. The results indicate that the null hypothesis can be rejected at the 3σ confidence level, establishing that the age difference of 1.4±0.8 Myr between the two populations is statistically meaningful.

It has been suggested that the preponderance of chondrules with ages that are within 1 Myr of Solar System formation reflects an early and efficient chondrule production mechanism. In this view, it is hypothesized that shock fronts associated with spiral arms generated in a gravitationally unstable early disk can provide an adequate energy to promote the melting of disk solids. Shocks generated in this regime are modelled to be highly efficient in the inner disk region thereby providing a possible mechanism for the thermal processing of disk solids at early times. However, because accretion to the disk decreases and the envelope dissipates, the resulting disk mass at later times is thought to be far too low to sustain gravitational instabilities. Thus, a distinct source of shock is required for the production of chondrules formed at a later time in the outer disk. A possibility is bow shocks associated with giant planet formation and migration during the disk lifetime [9]. Preliminary results indicate that nebular shocks caused by the presence of a large planet such as Jupiter can induce chondrule formation, in particular if Jupiter migrated inwards in the early times of the disk [10]. Collectively, our new age data support the view that multiple chondrule formation mechanisms existed in the early Solar System albeit perhaps with contrasting efficiencies. Finally, the mean outer Solar System chondrule age of 2.38±0.53 Myr reported here may record the migration of the gas giant planets.

References: [1] Larsen, K. et al. (2011) *ApJ* 735, L37. [2] Schiller, M. *et al.* (2015) *EPSL* 420, 45. [3] Connelly et al. (2012) *Science* 338, 651. [4] Bollard, J. *et al.* (2017) *Sc. Adv.* 3, e1700407. [5] Warren, P. (2011) *EPSL* 311, 93. [6] Trinquier, A. et al. (2007) *ApJ* 655, 1119 [7] van Kooten et al. (2016), *PNAS* 113, 211. [8] Olsen, M. *et al.* (2016) GCA 191, 118. [9] Ciesla et al. (2004) *MAPS* 39, 1809. [10] Bodénan, J.-D. et al. (2018*) 81st Annual Meeting of The Meteoritical Society* (LPI Contrib. No. 2067).