U-corrected Pb-Pb ages of chondrules: what are we dating?

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The disagreement between chondrule ages by different chronometers has been attributed to the typically older absolute Pb-Pb ages being unreliable due to the complex histories of chondrules [1, 2]. Chondrules will inherit initial Pb (Pb_i) from their precursor material that is not significantly evolved from the primordial Pb isotopic composition. The dual decay of ^{235}U and ^{238}U to ^{207}Pb and ^{206}Pb, respectively, generates radiogenic Pb (Pb_r) with a unique radiogenic $^{207}Pb/^{206}Pb$ ratio for any interval of time. Complete melting will mix/equilibrate original Pb_i and any Pb_r formed by that time, with some Pb likely lost by evapouration (potentially with Pb isotopic fractionation). The sum of mixing and fractionation of existing Pb will result in a new Pb_i that will be incorporated into any phase(s) able to accommodate Pb (e.g. sulphide). The phase(s) incorporating U will accumulate new Pb_r. The re-setting of Pb_i in Pb-hosting phases may happen multiple times until the last closure and final lock of the isotopic composition of Pb_i. From this point in time forward, Pb_r ingrowth in U-bearing phases will again define a unique radiogenic $^{207}Pb/^{206}Pb$ ratio formed since last melting. We find that U is hosted by the mesostasis, a phase readily linked to the chondrule's last melting. As such, the derived Pb_r age must date this event alone, without any record of the pre-history. Incomplete re-mixing of Pb during partial melting will result in a ternary mixture of Pb that will fail to define a statistically valid line and, therefore, fail to define an age. All combined, a successfully defined Pb array defines the Pb_r value related to the time of last melting, independent of a complex history prior to the last re-mixing of Pb. Given the rapid cooling of chondrules, all robust ages from different chronometers should yield the same age that reflects the last full melting event. We attribute the offset between the ^{26}Al-^{26}Mg ages and Pb-Pb ages to the inhomogeneous distribution of ^{26}Al in the protoplanetary disk. Using our Pb-Pb ages and Pb_i estimates for 22 individual chondrules, we infer that nebular chondrules started forming at the same time that calcium aluminium inclusions formed (4567.30±0.16 Ma, [3]) and continued to form for ca. 3.6 Myr [4]. Furthermore, we define a primary chondrule formation episode within the first million years of the Solar System followed by a period of reworking that lasted up to 3.6 Myr.

[1] Kita, N. et al. *MAPS*, 48, 1383. [2] Budde, et al. (2016) *PNAS*, 113, 2886. [3] Connelly, J.N. et al. (2012) *Science*, 338, 651. [4] Bollard J. et al. (2017) *Science Advances*, submitted.