# Timing and environment of chondrule formation

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**Introduction:** Chondrules are sub-mm to cm-sized silicate spherules preserved in primitive meteorites. Shape, texture, and composition of chondrules suggest formation at high temperatures in an environment with high dust/gas ratios, followed by fast cooling [1,2]. A multi-dimensional and multi technical study of chondrules from unequilibrated (type 3) meteorites was done, including 3D X-ray tomographic imaging, chemical composition and X-ray mapping, Al-Mg dating, and noble gas isotope studies, with the aim to establish a connection between temporal (formation ages) and spatial information (environment) on the chondrule forming process.

**Method:** In more than 250 cycles of freeze-thaw and gently scratching with needles to remove matrix and rims, individual chondrules were separated from eleven unequilibrated meteorites from the carbonaceous, ordinary, and enstatite chondrite groups, including Allende (CV3.6), Northwest Africa 8276 (L3.00), and Qingzhen (EH3). These chondrules were analysed for their shape, porosity, textures, opaque content, and density by 3D X-ray micro- or nano-tomography. Chondrules were then broken into two fragments. One fragment was embedded in epoxy resin and analysed for chemical composition with SEM and EPMA. Chondrules containing Al-rich phases (glassy mesostasis and plagioclase) are selected for $^{26}$Al-$^{26}$Mg dating on the SwissSIMS (SIMS 1280HR). The remaining other half was analysed for He, Ne, and Ar isotope concentrations with a static noble gas mass spectrometry.

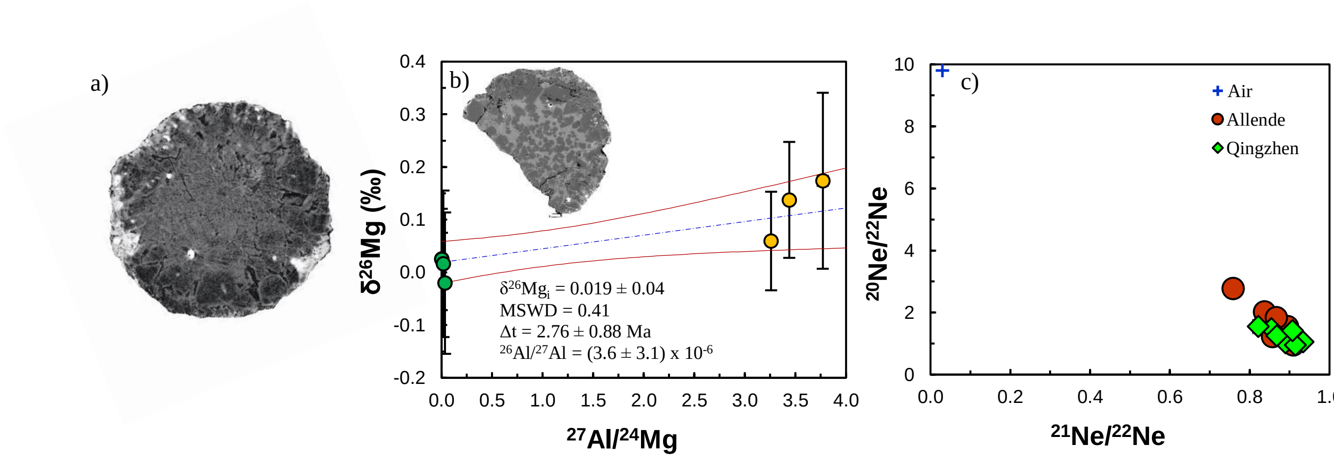


Fig. 1: a) A micro-CT scan of Allende chondrule CH#2. b) Al-Mg isochron diagram of Allende chondrule CH#2. c) Neon three isotope diagram of Allende and Qingzhen chondrules.

**Results:** A representative micro-CT scan of Allende chondrule CH#2 is shown in Fig.1a. Part of the chondrule was used for Al-Mg dating (Fig. 1b). Neon isotope ratios of Allende and Qingzhen chondrules are shown in Fig. 1c.

**Discussion:** Texture, density, shape, and size of the extracted chondrules can be characterized by quick and non-destructive micro- or nano-tomography. The differences between opaque phases and silicates are easily identified. However, with this technique it is very difficult to clearly resolve different silicates with similar density, such as olivine and pyroxene/mesostasis (Fig.1a). In some of the scanned chondrules there are no phases with high Al/Mg, hence they cannot be used for Al-Mg dating. The Al-Mg age of chondrule CH#2 shown in Fig. 1 is 2.76 ± 0.88 Ma relative to CAIs [3]. Most chondrules analysed so far have Al-Mg relative ages from 1.1 to 2.8 Ma, which is consistent with previous studies [4, and references therein]. Variations of $^{20}$Ne/$^{22}$Ne and $^{21}$Ne/$^{22}$Ne measured in the chondrules are in range 2.76-0.95 and 0.93-0.76, respectively, which is consistent with Ne being predominantly cosmogenic with minor contributions from trapped, likely atmospheric contamination [5]. Though limited, the results so far suggest that chondrules from enstatite and carbonaceous chondrites have not experienced pre-compaction irradiation by cosmic rays in the solar nebula. Furthermore, the data suggest that there is no correlation between $^{26}$Al abundance and cosmogenic noble gases in these chondrules, indicating that formation and/or storage of the chondrules was in a region shielded from cosmic-rays.

**References:** [1] Hewins R. H. and Radomsky P. M. (1990) *Meteoritics* 25:309–318. [2] Alexander C. M. O′ D. et al. (2008) *Science* 320:1617–1619. [3] Jacobson B. et al. (2008) *Earth and Planetary Science Letters*, 272:353–364. [4] Pape J. et al. (2019) *Geochimica et Cosmochimica Acta* 244:416–436. [5] Leya and Masarik (2009) *Meteoritics and Planetary Science* 44:1061–1086.