# IRON ISOTOPE EVIDENCE FOR VERY RAPID ACCRETION AND DIFFERENTIATION OF THE PROTO-EARTH.

M. Schiller[1], M. Bizzarro[1] and J. Siebert[2,3], [1]Centre for Star and Planet Formation, University of Copenhagen, Øster Voldgade 5–7, DK-1350, Denmark (schiller@ign.ku.dk), [2]Institut de Physique du Globe de Paris, Université Sorbonne Paris Cité, 75005, Paris, France, [3]Institut Universitaire de France, France.

**Introduction:** Terrestrial planet formation is thought to proceed in stages, where the final assembly of the terrestrial planets occurred over several tens of millions of years via large collisions between embryos [1], many of which will have differentiated into metal cores and silicate mantles. In these models, oxidised solids and volatile elements such as water are inferred to have been delivered to the Earth towards the end of accretion, possibly by volatile-rich, outer Solar System bodies scattered inward by the outward migration of Jupiter [2]. However, a recent study of the isotope composition of the siderophile element ruthenium in Solar System objects, including Earth and the parent bodies of chondrite meteorites, suggest that Earth's volatile element budget may have been acquired much earlier [3], perhaps during its main accretion phase. Moreover, new planet formation models based on the rapid accretion of pebbles onto asteroidal seeds suggest that Earth's main accretion phase may have been completed within the ~5 Myr lifetime of the protoplanetary disk [4]. Here, we take advantage of nucleosynthetic iron (Fe) isotope variability amongst early Solar System objects to distinguish between rapid and protracted terrestrial planet growth to elucidate the timescales of Earth's accretion. Iron is a redox-sensitive, siderophile major element whose partitioning between mantle and core on rocky planets is a proxy of the overall oxidation state of a planet. More importantly, iron readily oxidises in the presence of water, significantly lowering its partitioning into the metal core. Therefore, if Earth became more oxidised during accretion and core formation, the mass-independent Fe isotope composition of Earth's mantle is predicted to be dominated by that of the late (volatile-rich) accreting material. The existence of nucleosynthetic Fe isotope variability in Solar System objects can thus provide a powerful tool to fingerprint the source of the material responsible for the delivery of water and oxidised solids to the Earth and the subsequent oxidation of Earth's mantle.

**Methods:** In order to establish the presence of nucleosynthetic Fe isotope variability, we analysed the Fe isotope composition of dissolution steps of the CI chondrite Ivuna that have been previously measured for their strontium, chromium, magnesium and calcium isotope signatures [5-7]. In addition, we measured whole rock samples from chondritic and achondritic solar reservoirs. Iron was separated from the matrix following published methods [8] and measured by MC-ICP-MS at the Natural History Museum of Denmark relative to the IRMM-014 Fe isotope standard. We report our data in the $\mu^{54}$Fe-notation, which refers to the deviation of the $^{54}$Fe/$^{56}$Fe ratio from the terrestrial value in parts per million (p.p.m.) when corrected for kinetic mass fractionation using a $^{57}$Fe/$^{56}$Fe ratio of 0.023261 [9].

**Results and Discussion:** The step wise dissolution experiment reveals that labile phases dissolved in the early dissolution steps exhibit elevated $\mu^{54}$Fe values of around +46 p.p.m., whereas later dissolution steps contain both negative as well as positive $\mu^{54}$Fe values. In particular, the dissolution step that exhibits a large $^{84}$Sr deficit linked to the dissolution of presolar silicon carbide (SiC) grains [5] is also characterized by the highest $\mu^{54}$Fe value. This signature can be understood when considering that SiC grains are also known to have large $^{57}$Fe overabundances [10]. As such, variable presence of these presolar carriers of nucleosynthetic Fe isotope heterogeneity can impart variability in disk solids. Apart from bulk CI chondrites, which have a $\mu^{54}$Fe identical to Earth's mantle, all analysed achondrites, chondrites and individual chondrules are characterized by resolvable excesses in $\mu^{54}$Fe ranging from +5.4 to +28.8 p.p.m. As such, our data establish the presence of disk wide nucleosynthetic iron isotope variability, where apart from CI chondrites, none of the meteorites analysed here, including all main chondrite groups, match the terrestrial mantle composition. A single reservoir origin (CI chondrites) of the Earth's mantle iron is difficult to reconcile with stochastic collisional accretion models of the Earth. Instead, the iron isotope signature of the mantle is consistent with a very rapid main accretion and differentiation of the Earth that occurred during the ~5 Myr disk lifetime. During this stage volatile-rich CI-like material is accreting onto the proto-Sun via the inner disk, thereby delivering CI-like solids to the accretion region of the Earth. As such, our findings support the recent suggestion that changes in the nucleosynthetic signatures of bulk planets track the progressive admixing of pristine CI-like dust to an initially thermally processed inner protoplanetary disk [11].

**References:** [1] Walsh, K.J. et al. (2011) *Nature* 475:206–209. [2] O'Brien et al. (2018) *Space Science Reviews* 214:47. [3] Fischer-Gödde, M. and Kleine, T. (2017) *Nature* 541:525–527. [4] Johansen, A. et al., 2015. *Science Advances* 1:e1500109. [5] Paton, C. et al. (2013) *The Astrophysical Journal Letters* 763:L40. [6] Schiller, M. et al. (2014) *Journal of Analytical Atomic Spectrometry* 29:1406–1416. [7] Schiller, M. et al. (2015) *Geochimica et Cosmochimica acta* 149:88–102. [8] Dauphas, N. et al. (2004) *Analytical Chemistry* 76:5855–5863. [9] Völkening, J. and Papanastassiou, D.A. (1989) *The Astrophysical Journal* 347:L43–L46. [10] Marhas, K.K. et al. (2008) *The Astrophysical Journal* 689:622. [11] Schiller, M., et al. (2018) *Nature* 555:507–510.