^{60}FE-^{60}NI CONSTRAINTS ON CORE FORMATION AND RAPID ACCRETION OF VESTA AND MARS.

H. Tang[1] and N. Dauphas[1], [1]Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637. (cafetang@uchicago.edu)

Introduction: Extinct radionuclides have proven to be particularly important as they can help establish the context of solar system formation, the relative chronology of early formed solids, the timescale of nucleosynthetic process, and the thermal history of planetary bodies [1-4]. Iron-60 has been focus of much work because it cannot be produced by particle irradiation in the solar protoplanetary disk and a high ^{60}Fe/^{56}Fe ratio in meteorites ($>3\times10^{-7}$) would tie the birth of the solar system to the explosion of a nearby supernova [5]. The initial ^{60}Fe/^{56}Fe ratio in the solar system has been a subject of debate [6-15]. We recently reported measurements of ^{58}Fe/^{54}Fe and ^{60}Ni/^{58}Ni isotope ratios in whole rocks and constituents of differentiated achondrites (ureilites, aubrites, HEDs, and angrites), unequilibrated ordinary chondrites Semarkona (LL3.0) and NWA 5717 (ungrouped type 3.05), metal-rich carbonaceous chondrite Gujba (CBa), and several other meteorites (CV, CI, EL, H, LL chondrites), demonstrating that the ^{60}Fe/^{56}Fe initial ratio in the solar protoplanetary disk was $(11.5 \pm 2.6) \times 10^{-9}$ and that ^{60}Fe was homogenously distributed among large planetary objects.

Because metal-silicate partitioning can fractionate the Fe/Ni ratio, ^{60}Fe-^{60}Ni systematics can be used to establish the time of core formation in planetary bodies. Here we report Ni isotope measurements of HED and SNC meteorites to establish the timescale of core formation on Vesta and Mars.

Vesta: To calculate the age of core formation of Vesta, a two stage model was used. From t=0 (CAI formation) to t_{core}, the parent-body evolves with chondritic composition. At t_{core}, it differentiates into a mantle (high Fe/Ni ratio) and a core (low Fe/Ni ratio). The mantle then differentiates into distinct reservoirs leading to additional Fe/Ni and Mn/Cr fractionation, an event that is recorded by bulk rock isochron. A 2-stage model age of core formation can be calculated by building a 2-point isochron between the bulk planetary object with chondritic composition and the mantle.

The Fe/Ni ratio of the bulk mantle of HEDs was estimated by [16] based on MgO-Ni and MgO-FeO correlations to be ~2,000 (^{56}Fe/^{58}Ni~2,700). Using this ratio and the bulk HED isochron presented in [15], we obtain a ε^{60}Ni value of 0.23 ± 0.13 for the bulk mantle of Vesta. The bulk Fe/Ni ratio of Vesta is taken to be chondritic ~17 (^{56}Fe/^{58}Ni~22; [17,18]). The HEDs cannot be tied to any chondrite groups, so we take the average ε^{60}Ni value of all chondrite measurements published so far (-0.08 ± 0.06; [19-22]).

Using these parameters, we obtain a ^{60}Fe/^{56}Fe initial ratio at the time of core formation in Vesta of $(4.49\pm2.04)\times10^{-9}$. This estimate is robust as the ^{60}Ni-excess in the bulk mantle of Vesta is well resolved. Using a ^{60}Fe/^{56}Fe initial ratio in the solar protoplanetary disk of $(11.5\pm2.6)\times10^{-9}$, we calculate a time of core formation of $3.7^{+2.5}_{-1.7}$ Myr after CAI (Fig. 1). It is the first solid estimate of the time of core formation on Vesta and is consistent with results of a thermal model of radioactive heating of Vesta by ^{26}Al-decay suggesting a time of core formation of 4.6 Myr after CAI [23]. For comparison, the ^{182}Hf-^{182}W system gives a very uncertain age of 3 ± 6 Myr for core formation in the HED parent-body [24].

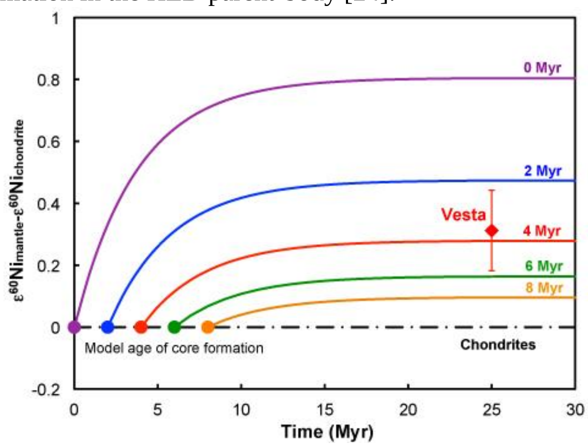

Figure 1: ε^{60}Ni isotope evolution of the mantle of Vesta (^{58}Fe/^{56}Ni=2696, [16]) for different model ages of core formation. The estimated Ni isotopic composition of the bulk-mantle of HEDs ($\varepsilon^{60}Ni_{mantle}$-$\varepsilon^{60}Ni_{chondrite}$) constrains core formation on Vesta to have occurred 3.6 ± 1.9 Myr after CAIs [15] .

Mars: Using Hf-W-Th systematics in SNC meteorites and chondrites, Dauphas and Pourmand [25] showed that Mars accreted very rapidly and reached about half of its present size in only $1.8^{+0.9}_{-1.0}$ Myr or less, indicating a stranded planetary embryo origin for Mars. Because ^{60}Fe ($t_{1/2}$=2.62 Myr) has a shorter half-life than ^{182}Hf ($t_{1/2}$=8.9 Myr), it is very well suited for investigating processes that took place in the first few million years of solar system formation. To constrain the accretion timescale of Mars, we measured 5 typical SNC meteorites (Shergotty, Chassigny, Nakhla, Zagami, Lafayette). The Ni isotopic composition of Martian meteorites is constant and identical to the terrestrial value. Igneous processes that fractionated Fe/Ni ratios in different SNC meteorites occerred late, after complete decay of ^{60}Fe, so no correlation is found between ε^{60}Ni and ^{56}Fe/^{58}Ni. The average of ε^{60}Ni (-0.01 ± 0.02) of SNC meteorites is interpreted to reflect the Ni isotopic composition of the bulk martian mantle, To calculate the time of core formation on Mars, we also need to know the ε^{60}Ni value of the bulk planet. Based on the oxygen isotope mixing models and other constraints, Lodders & Fegley estimated that Mars was made of 85.4±0.4% H-, 10.9±0.4% CV-, and 3.6±2.8% CI-chondritic material [17,26]. ε^{60}Ni in bulk chondritic parent materials for Mars therefore can be calculated from mass balance using the Ni isotopic compositions of these end-members, some of which were not well constrained. In order to address this issue, we have also measured the Ni isotopic compositions of 6 H-chondrites and 5 C-chondrites, all of which are falls.

ε^{60}Ni values of H- and CI chondrites are identical to the terrestrial value, while CV chondrites show ^{60}Ni deficit (-0.095±0.035), which is consistent with previous work [20-22]. The Fe/Ni ratio in the core and mantle are taken to be 400 and 10.6 [16, 17].

During runaway and oligarchic growth, the mass of an embryo can be parameterized as $M_{Mars}(t)/M_{Mars}=\tanh^3(t/\tau)$ [4]. If Mars had accreted rapidly at the formation of solar system (τ=0), our precision should allow us to resolve a ε^{60}Ni excess of +0.2 in SNC relative to chondrites (Fig. 2). Instead, we find that SNC meteorites have the same Ni isotopic composition as chondrites, which constrains the accretion timescale of Mars to τ>1 Myr (Fig. 2.), consistent with the previous estimate based on ^{182}Hf-^{182}W [27]. Constrants on the growth of large planetary bodies are scarce and this is a major development in our understanding of the chronology of Mars.

Conclusion: Using a new estimate of the initial ^{60}Fe/^{56}Fe ratio in the solar system [15], we present the first chronological application of the ^{60}Fe-^{60}Ni decay system to establish the time of core formation on Vesta at $3.7^{+2.5}_{-1.7}$ Myr after condensation of CAIs. We also constrain the timescale of Mars' accretion to >1 Myr after CAI formation. Combining our results with ^{182}Hf-^{182}W systematics and results from statistical simulations of oligarchic growth, planetesimal sizes and disk mass in the Mars forming region as well as the thermal evolution of early Mars can be constrained (see the discussion in companion abstract [27]).

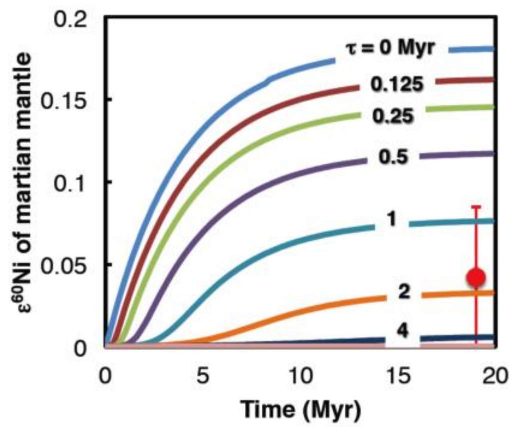

Figure 2: ε^{60}Ni isotope evolution of the mantle of Mars (^{58}Fe/^{56}Ni=548;[16]). The chondritic Ni isotopic composition of the bulk mantle of Mars constrains accretion timescale of Mars to τ>1 Myr after CAIs .

References: [1] McKeegan & Davis (2004) *Meteorites, Comets, and Planets. 1.16*, 431-475. [2] Wadhwa et al. (2006) *Meteorites and the Early Solar System II, 943* pp., p.715-731. [3] Wasserburg et al. (2006) *Nucl. Phys. A 777*, 5-69. [4] Dauphas & Chaussidon (2011) *Annu. Rev. Earth Planet. Sci. 39*, 351-386. [5] Wasserburg et al. (1998) *APJ 500*, L189-L193. [6] Shukolyukov and Lugmair (1993a) *EPSL 119*, 159-166. [7] Shukolyukov and Lugmair (1993b) *Science 259*, 1138-1142. [8] Tachibana et al. (2003) *APJ 588*, L41-L44. [9] Mostefaoui et al. (2005) *APJ 625*, 271-277. [10] Tachibana et al. (2006) *APJ 639*, L87-L90. [11] Guan et al. (2007) *GCA 71*, 4082-4091. [12] Mishra et al. (2010) *APJ 714*, L217-L221. [13] Quitté et al. (2010) *APJ 720*, 1215-1224. [14] Spivak-Birndorf et al. (2012) *LPS* XLIII, #2861. [15] Tang & Dauphas (2012) *EPSL* 359-360, 248-263. [16] Warren et al. (1999) *GCA 63*, 2105-2122. [17] Lodders (2000) *Space Sci. Rev. 92*, 341-354. [18] Righter (2008) *LPS XXXIX*, #1936. [19] Dauphas et al. (2008) *APJ. 686*, 560-569. [20] Regelous et al. (2008) *EPSL 272*, 330-338. [21] Tang & Dauphas (2010) *LPS XLI* #1773. [22] Steele et al. (2012) *APJ 758*, 59-79. [23] Ghosh & McSween (1998) *Icarus 134*, 187-206. [24] Kleine et al. (2009) *GCA 73*, 5150-5188. [25] Dauphas & Pourmand (2011) *Nature 473*, 489-492. [26] Lodders & Fegley (1997) *Icarus 126*, 373-394. [27] Dauphas et al. (2013) *LPS XLIV* #1305.