VERY RAPID ACCRETION OF MARS AND IMPLICATIONS FOR ITS MAGMATIC EVOLUTION.

N. Dauphas[1] and A. Pourmand[2], [1]Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, USA, [2]Rosenstiel School of Marine & Atmospheric Science, Division of Marine Geology and Geophysics, University of Miami, USA.

Introduction: There is considerable uncertainty as to how and when Mars formed. In particular, its small mass compared to Earth and Venus is difficult to explain and some have suggested that Mars could be a stranded planetary embryo that escaped collision and merging with other embryos [1-3]. A diagnostic parameter to assess this idea is its accretion time [4]. Terrestrial planets like Earth are thought to have accreted by collisions between embryos over several tens of million years, a process known as chaotic growth [2,3,5-8]. Embryos, on the other hand, are thought to have formed from accretion of planetesimals on a timescale of a few million years at most [5,6]. The timescale of Mars accretion can be constrained from ^{182}Hf-^{182}W systematics of martian meteorites [4,11,12]. Unfortunately, the Hf/W ratio of the martian mantle is very uncertain, resulting in model age estimates that range between 0 to >10 My after solar system birth [4 and references therein]. Here, we present a new method to estimate the Hf/W ratio of the martian mantle, leading to the conclusion that Mars accreted very rapidly [13].

Hf/W ratio of the martian and terrestrial mantles: Hafnium and tungsten have different behaviours during melting and crystallization. Therefore, the Hf/W ratio of SNC meteorites is of little value to constrain the bulk Hf/W ratio of the martian mantle. Instead, the Hf/W ratio is best calculated by writing

$$(\mathrm{Hf/W})_{\mathrm{Mars\ mantle}}=(\mathrm{Th/W})_{\mathrm{SNC}}/(\mathrm{Th/Hf})_{\mathrm{CHUR}},$$

where CHUR stands for CHondritic Uniform Reservoir. This follows from the similar behaviours of Th and W during magmatism, so the ratio of these two elements in SNC meteorites is expected to be representative of the bulk martian mantle. In addition, Th and Hf are both refractory lithophile elements, so they should be in chondritic proportions in the martian mantle. The atomic Th/W ratio in SNC meteorites is not very variable, with a mean value of ~0.752. On the contrary, the Th/Hf ratio in chondrites varies by a factor of 3 and is the main source of uncertainty in age estimates [4].

To better constrain the Th/Hf ratio of CHUR, we have measured the concentrations of Lu, Hf, U, Th by isotope dilution, as well as ^{176}Hf/^{177}Hf isotopic ratios of 43 chondrites from all major groups of chondrites (i.e., 1 CI, 1 CM, 2 CO, 3 CV, 8 EH, 8 EL, 4 H, 5 L, and 6 LL) [13]. To avoid issues associated with terrestrial alteration during residence at Earth's surface, most of the samples selected for analysis were observed falls. The samples were digested by flux fusion to ensure complete digestion of even the most chemically resistant phases. The analytes were separated from matrix elements by using column chromatography based on TODGA and Ln-Spec resin. All measurements were carried out with a Neptune Multi-Collector Inductively Coupled Plasma Mass Spectrometer at the University of Chicago. The protocol is described with ample details by Pourmand and Dauphas [14] and will not be repeated here. The rationale for undertaking those measurements is that the Lu/Hf ratio is also variable in chondrites [15,16] and Th is expected to behave like lanthanides, so one may be able to use the known CHUR Lu/Hf ratio to estimate the CHUR Th/Hf ratio.

In bulk chondrites, the Th/Hf ratio correlates with the ^{176}Hf/^{177}Hf (and Lu/Hf) ratio (Fig. 1). Carbonaceous chondrites show limited variation, ordinary chondrites show some variation and scatter a bit around the correlation line, and enstatite chondrites show the most variation but define a clear correlation. The difference between different meteorite groups is probably related to the carrier phase of lanthanides and actinides and to the degree of metamorphism. In ordinary and carbonaceous chondrites, Lu and Th are carried by phosphates while in enstatite chondrites, they are carried by oldhamite (CaS).

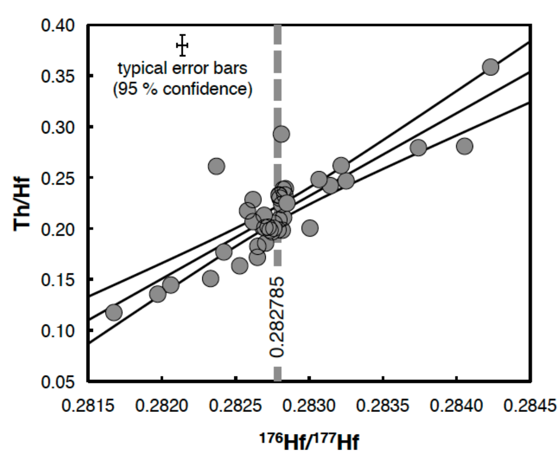

Fig. 1. *Correlation between the Th/Hf and ^{176}Hf/^{177}Hf (Lu/Hf) ratios in bulk chondrites. This correlation reflects redistribution of Lu and Th in trace phases (i.e., phosphate, oldhamite) during parent-body metamorphism. The CHUR ^{176}Hf/^{177}Hf ratio is estimated to be 0.282785 [16], from which we estimate a CHUR Th/Hf ratio of 0.2144.*

Considerable work has been done on Lu-Hf systematics of chondrites [15,16]. Study of primitive chondrites give a CHUR $^{176}Hf/^{177}Hf$ ratio of 0.282785 [16]. Using the correlation in Fig. 1, we estimate the CHUR Th/Hf ratio to be 0.2144. This value is much more precise and accurate than previously reported values. Using the Th/W ratio of 0.752 for SNC meteorites, we estimate the Hf/W atomic ratio of the martian mantle to be 3.51±0.45. Similarly, we can combine the W/U atomic ratio of the terrestrial mantle (i.e., 0.84 [17]) with the CHUR Th/Hf (0.2144) and U/Th (3.56) ratios charactertized here to estimate the Hf/W ratio of the terrestrial mantle (19.8±2.0). The improvement in precision on the latter ratio does not significantly affect model ages of core formation on Earth.

Implications for the time of Mars accretion: The W isotopic composition of the martian mantle is known from measurements of Shergottites, $\varepsilon^{182}W_{Mars\ mantle}$=+2.6 (deviation in 0.01 % of the $^{182}W/^{183}W$ ratio relative to CHUR) [4,11,12]. The simplest model of core formation is to assume that Mars remained undifferentiated until the time of core formation, at which point the planet was fully accreted and differentiated instantaneously into a core and a mantle. Taking the large uncertainty in the Hf/W ratio of the martian mantle, previous studies had concluded that Mars' core could have formed anytime between 0 and >10 Myr after solar system birth [4 and references therein]. With our new estimate, we calculate a model age of core formation of ~4 Myr after solar system formation. However, this value is of limited use in discussions about the formation of Mars. Indeed, if Mars was a planetary embryo as some models suggest [1-3], then its mass should have increased with time by accretion of planetesimals on a timescale of a few million years at most [9,10]. If Mars accreted early from relatively small planetesimals, it is highly probable that whenever meteoritic matter was accreted by protoMars, its W isotopic composition was equilibrated with the whole mantle before segregation of metal into the core (equilibrative plumbing model). The mass of Mars as a function of time can be parameterized as $M(t)/M_{final}=1-\exp(-t/\tau)$, where t is an accretion timescale that corresponds to the time when Mars reached ~2/3 of its present size. Using the mathematical derivation presented in ref. 18, we can calculate the predicted $\varepsilon^{182}W$ value in the mantle of Mars for different values of τ. The measured value of $\varepsilon^{182}W_{Mars\ mantle}$=+2.6 can only be reproduced with an accretion timescale of ~2 Myr. Objects formed in the first few million years of the formation of the solar system would have incorporated enough ^{26}Al to melt from the radioactive heat release by the decay of this nuclide [19]. We thus demonstrate that an early magma ocean powered by ^{26}Al-decay must have formed on Mars.

Mars is a stranded planetary embryo: The very short accretion time compared to Earth is difficult to reconcile with an Earth-like mode of accretion involving collisions between planetary embryos over several tens of million years. For comparison, the completion of terrestrial accretion is best dated by the Moon-forming impact, which is estimated to have occurred >50 Myr after solar system birth [8]. The fact that Mars is a planetary embryo explains its small size compared to terrestrial planets. Dynamically, Mars is an embryo, not a terrestrial planet like Earth.

References: [1] Wetherill G.W. (1991) *LPS XXII*, 1495. [2] Chambers J.E. and Wetherill G.W. (1998) *Icarus 136*, 304. [3] Raymond S.N. et al. (2009) *Icarus 203*, 644. [4] Nimmo F. and Kleine T. (2007) *Icarus 191*, 497. [5] Yin Q. et al. (2002) *Nature 418*, 949. [6] Kleine T. et al. (2002) *Nature 418*, 952. [7] Dauphas N. et al. (2002) *Geophys. Res. Lett. 29(6)*, 1084. [8] Touboul M. et al. (2007) *Nature 450*, 1206. [9] Chambers J. (2006) *Icarus 180*, 496. [10] Kobayashi H. et al. (2010) *Icarus 209*, 836. [11] Kleine T. et al. (2004) *GCA 68*, 2935. [12] Foley C.N. et al. (2005) *GCA 69*, 4557. [13] Dauphas N. and Pourmand A. (2010) *Nature, submitted*. [14] Pourmand A. and Dauphas N. (2010) *Talanta 81*, 741. [15] Blichert-Toft J. and Albarède F. (1997) *EPSL 148*, 243. [16] Bouvier A. et al. (2008) *EPSL 273*, 48. [17] Arevalo R.Jr. and McDonough W.F. (2008) *EPSL 272*, 656. [18] Jacobsen S.B. (2005) *Annu. Rev. Earth Pl. Sc. 33*, 531. [19] Grimm R.E. and McSween H.Y.Jr. (1993) *Science 259*, 653.