CHRONOLOGICAL AND DYNAMICAL CONSTRAINTS ON THE ACCRETION OF MARS. N. Dauphas[1], H. Kobayashi[2], M. Fornace[1], and H. Tang[1], [1]Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637 (dauphas@uchicago.edu), [2]Department of Physics, Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan.

Introduction: Twenty years ago, Wetherill asked the question "Why isn't Mars as big as Earth?" [1]. Indeed, models of terrestrial planet growth that start with embryo throughout the disk consistently predict that an Earth-mass planet should be present where Mars is. This led some to suggest that Mars may be a planetary embryo that escaped late-stage collisions [2]. The ^{182}Hf-^{182}W ($t_{1/2}$=8.9 Myr) extinct radiochronometer indicates that Mars grew very rapidly, having accreted most of its Mars in the first 4 Myr of solar system birth, consistent with the view that Mars is a stranded planetary embryo [3].

The dynamical context in which this can happen is still debated. Morishima et al. [4], Hansen [5], and Walsh et al. [6] suggested that Mars could have formed from a narrow annulus between 0.7 and 1 AU. Walsh et al. showed that this could have happened if the inward then outward migration of Jupiter truncated the disk at ~1 AU. Minton and Levison [7] suggested that Mars could be an embryo that migrated outwards by planetesimal-induced migration. Regardless of these complications, it is likely that Mars grew rapidly by accretion of planetesimals. We have investigated three connected aspects of the origin of Mars that shed light on conditions in the protoplanetary disk and the early magmatic evolution of this planet:

1. The ^{60}Fe-^{60}Ni extinct radionuclide system ($t_{1/2}$=2.62 Myr) can provide constraints on the timing of core formation in planetary bodies. Tang et al. [8] demonstrated that ^{60}Fe was homogeneously distributed among planetary bodies at an initial ratio of ^{60}Fe/^{56}Fe=(11.5±2.6)×10^{-9}. By measuring HEDs, they established the time of core formation on Vesta at 3.7 (+2.5/-1.7) Myr after solar system formation. We have measured the Ni isotopic composition of martian meteorites (SNCs), which provides a robust lower-limit on the accretion timescale of Mars [9].

2. The growth of embryos depends on a number of parameters, including the mass of the disk and the size of planetesimals. For example, small planetesimals are more easily disrupted by collisions and the fragments thus produced can experience gas drag and spiral towards the Sun, so smaller embryos are produced. On the other hand, interaction of fragments with gas dampens their velocities, so the embryos grow faster in the presence of small planetesimals. The disk mass has a simple effect by controlling the total solid mass available in the feeding zone of embryos. We have used statistical simulations of embryo growth to constrain the parameter space of planetesimal size *vs.* disk mass where a Mars-size body with the right accretion timescale can form [10].

3. Mars probably accreted before ^{26}Al had completely decayed, providing a possibly important heat-source that could have induced the formation of a magma ocean. Senshu et al. [11] had modeled the thermal evolution of Mars heated by planetesimal impacts only. They concluded that a magma ocean overlying a cold solid interior could have formed. We have revisited this question by taking into account heating by ^{26}Al and conclude that a global magma ocean most likely formed on Mars.

Results. In a companion abstract, we report high precision measurements of ε^{60}Ni in martian meteorites [9]. A small complication for constraining the timing of core formation of Mars from ^{60}Fe-^{60}Ni systematics is that there are nucleosynthetic Ni isotope anomalies in meteorites [*e.g.*, 8,12] that can be mistaken for some radiogenic production. For this reason, we also measured the Ni isotopic compositions of chondrites that could have been the building blocks of Mars [13]. We found that there was no detectable ^{60}Ni excess in the martian mantle relative to chondrites ($\varepsilon^{60}Ni_{SNC}$-$\varepsilon^{60}Ni_{CHUR}$~+0.04±0.05). As a first approach, we parameterize Mars' accretion as $M(t)/M_{final}=\tanh^3(t/\tau)$ [3]. If Mars had accreted rapidly at the formation of the solar system (τ=0), we should have detected excess ε^{60}Ni of ~+0.2 in SNC relative to chondrites, which would be well resolvable given our uncertainties. Lack of excess ε^{60}Ni outside ~±0.05 constrains the accretion timescale of Mars to τ>1 Myr. A previous estimate based on ^{182}Hf-^{182}W had given a value for τ of 1.8(+0.9/-1.0) Myr, which is consistent with the new estimate given here. A virtue of the ^{60}Fe-^{60}Ni system relative to ^{182}Hf-^{182}W is that its half-life is much shorted (2.6 *vs*. 8.9 Myr) and it is particularly sensistive to the accretion history of Mars in the first few million years. A possible concern with chronometers that record core formation is whether metal in differentiated impactors was equilibrated with the silicate mantle of the protoplanet or whether the cores of the impactors merged with Mars' core without complete equilibration. As discussed by Dauphas and Pourmand [3], the fact that Mars' accretion probably proceeded by accretion of planetesimals would have favored equilibration. Indeed, for impactors that are smaller than the proto-Mars mantle, the sinking metal is expected to rapidly break down into blobs of <20 cm in size that can rapidly equilibrate with the surrounding mantle [14]. Morishima et al. recently looked at this using an N-body simulation of Mars and concluded that indeed, lack of equilibration for ^{182}Hf-^{182}W was a minor issue [15].

Using the constraints from ^{182}Hf-^{182}W systematics and the new constraints given by ^{60}Fe-^{60}Ni, we have evaluated the conditions in the disk that would have led to the formation of Mars with a small mass and a short accretion timescale [10]. Using statistical simulations, we have systematically explored the parameter space planetesimal size-disk mass. Because small planetesimals can be disrupted more easily than larger planetesimals, they produce more fragments that can be removed by gas drag, so a higher disk mass is needed in order to explain the mass of Mars. The fragments produced by small planetesimals have their velocities dampened by the gas and are more easily accreted by protoplanets, so small planetesimals tend to form embryos rapidly. We find that to explain the characteristics of Mars, small planetesimals in a large disk are required (Fig. 1). The formation of the cores of Jupiter and Saturn may require accretion from large planetesimals in a massive disk. Thus, there may have been a radial gradient of planetesimal sizes, increasing with distance from the Sun. The grand tack scenario provides a plausible explanation as to why Mars evaded accretion of large bodies in a late stage [6].

We have developed a 1D finite-difference model of Mars thermal evolution inspired by the work of Senshu et al. [11] that accounts for energy delivered by impacts, gravitational potential energy released by sinking metal, and radioactive heating by ^{26}Al-decay. Convective heat transport is modeled using mixing-length theory. Impact heating is treated by a parameterization based on the results of [16]. This model is simple, but the large uncertainties on model parameters (*e.g.*, viscosity) do not justify the development of a more sophisticated model. We are currently evaluating how the accretion history of Mars could have affected its magmatic evolution. A robust conclusion is that if Mars accreted within ~3 Myr after solar system formation, ^{26}Al provided enough heat to power melting of the martian mantle and allow the creation of a magma ocean.

Conclusions. We have combined constraints from extinct chronometers ^{60}Fe-^{60}Ni and ^{182}Hf-^{182}W together with results from statistical simulations of oligarchic growth to constrain planetesimal sizes and disk mass in the Mars forming region as well as the thermal evolution of early Mars. We conclude that Mars formed from small planetesimals in a massive disk. Most likely, impacts and ^{26}Al-decay provided sufficient heat to induce formation of a global magma ocean.

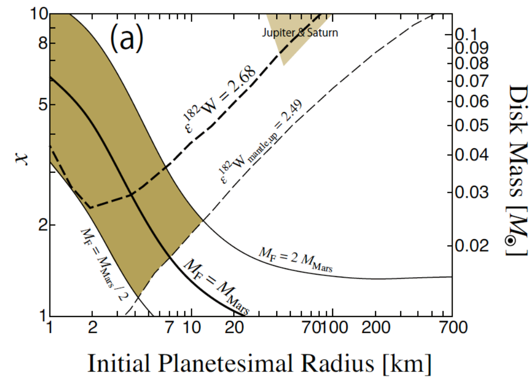

Fig. 1. Parameter space (disk mass *vs.* initial planetesimal radius) where a Mars-size embryo (M_{Final}=M_{Mars}) can be produced over the right timescale (ε_{Final}=ε_{SNC}) [10]. x is the scaling of the disk surface density to the minimum mass solar nebula.

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