The cool and distant formation of Mars

R. Brasser[1,2], S. J. Mojzsis[2,3], S. Matsumura[4], S. Ida[1]

[1]ELSI, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8550, Japan; brasser@elsi.jp

[2]CRiO, Dept. of Geological Sciences, University of Colorado, UCB 399, 2200 Colorado Avenue, Boulder, Colorado 80309-0399, USA; mojzsis@colorado.edu

[3] Institute for Geological and Geochemical Research, Hungarian Academy of Sciences, Budapest, Hungary

[4]School of Science and Engineering, Division of Physics, University of Dundee, Dundee DD1 4HN, UK

Bulk elemental, and isotopic data for martian meteorites demonstrate that key aspects of Mars' composition are markedly different from that of Earth. This suggests that Mars formed outside of the terrestrial feeding zone and has always remained far from the Sun. Its growth was stunted early and its mass remained low, compared to Earth and Venus. Here we show a robust dynamical pathway in the framework of the recently-elaborated 'Grand Tack' scenario of terrestrial planet formation [1,2] that forms and keeps Mars outside of Earth's accretion zone while at the same time accounting for strict age and compositional constraints, and mass differences.

In the Grand Tack, Jupiter and Saturn together migrated towards the inner solar system, but they reversed their direction near 1.5 AU. This radial migration caused a pileup of solid material inside of 1 AU. Thus, almost all protoplanets and planetesimals in the intervening space between 1 AU and 1.5 AU were cleared by Jupiter.

Owing to the fact that Mars is currently at 1.5 AU from the Sun and formed farther than the Earth, it somehow escaped Jupiter's Grand Tack incursion. We propose a scenario wherein proto-Mars formed in a few million years beyond 1 AU and remained there as Jupiter migrated inwards and then reversed direction. Proto-Mars was then pushed towards 1.5 AU by the dynamical interaction with other protoplanets and planetesimals in the disk.

We tested our hypothesis by performing a large number of N-body Grand Tack simulations of terrestrial planet formation, and with a probability of 50% we form and keep Mars beyond 1.25 AU if the tack occurred at 2 AU.

We predict that Mars' volatile budget is different from Earth's and additionally predict that Venus formed close enough to our planet that it is expected to have similar bulk composition, including the oxygen isotopes.

[1] Walsh *et al.* (2011) *Nature* **475**, 206-209. [2] Morbidelli *et al.* (2012) *Ann. Rev. Earth Planet Sci.* **40,** 251-252.