CONSTRAINING THE PRE-IMPACT ORBITS OF SOLAR SYSTEM GIANT IMPACTORS

A.P. Jackson[1], T.S.J. Gabriel[2], E. Asphaug[2]. [1]Centre for Planetary Sciences, University of Toronto, Toronto, ON, Canada, [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.
Email: ajackson@cita.utoronto.ca

Introduction: Giant impacts are the final stage in the formation of small planets. In our own Solar system giant impacts have been proposed to explain features including the formation of the Moon [1], the Martian Borealis basin [2], and the formation of the Pluto-Charon system [3]. The ability to trace the origins of the impactors in these events greatly benefits our understanding of Solar system formation. For the Moon in particular there are concerns about matching the isotopic similarity with Earth. Meteorites display a diversity of isotopic signatures, which are widely believed to be the result of chemical gradients and inhomogeneities in the Solar nebula [4]. While there is evidence of a decrease in isotopic diversity for larger bodies [5] it is still expected that giant impactors and their targets will have different isotopic signatures [6]. Outlining the origin of giant impactors can thus provide testable geochemical constraints.

Relating impactor and target orbits: Our key to relating the impactor orbit to that of the target is the relative velocity. Jackson et al. [7] presented a set of equations for the orbital change of a body after a velocity kick, we use these here with the 'kick' being the relative velocity. We assume the target orbit is similar to that of the final body, which in most cases should be a good approximation since the target dominates the momentum budget, and allows us to reduce the parameter space under consideration. Armed with these equations we can take the relative velocity from giant impact models and predict the range of orbits allowed for the impactors. This is much faster than N-body approaches (e.g. [8]), albeit less nuanced, allowing us to rapidly explore large parameter spaces. Specific regions can then be identified for detailed follow-up.

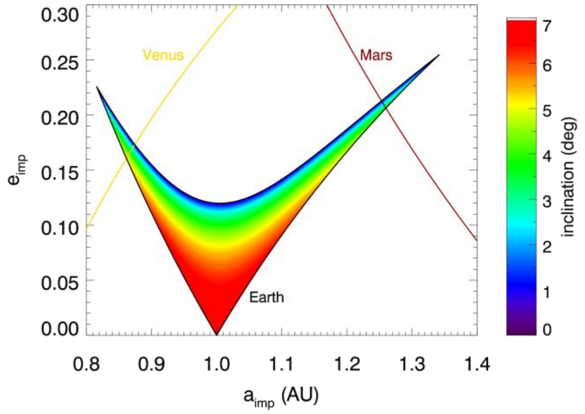

Figure 1: Allowed pre-impact orbits of Theia in the Canonical Moon formation scenario. Above the yellow and dark red lines orbits are Venus and Mars crossing respectively.

Canonical Moon formation: The canonical scenario for the formation of the Moon is a very low relative velocity impact [1]. The impactor, Theia, hits the proto-Earth at ~1.05v_{esc}, low compared with the 1v_{esc} of a pure free-fall impact, where v_{esc} is the mutual escape velocity. In this scenario the pre-impact orbit of Theia must have been close to Earth, as also suggested by [7]. Few of our computed orbits lie in the Venus and Mars crossing regions. We would expect the compositional difference between Earth and Theia to be smallest in this scenario. The model proposed by [9] of an impact between two nearly equal mass bodies uses a very similar impact velocity to the Canonical model, so while there is a complication in defining which is the 'target' in this case, the resulting range of allowed impactor orbits is very similar.

Reufer et al. Moon formation: An alternative scenario involving was proposed by [10] with a 'hit-and-run' type impact in which a substantial portion of Theia continues downrange after the impact and is not incorporated into the Earth-Moon system. This scenario uses a slightly higher impact velocity of 1.2v_{esc}. In comparison with the Canonical scenario the

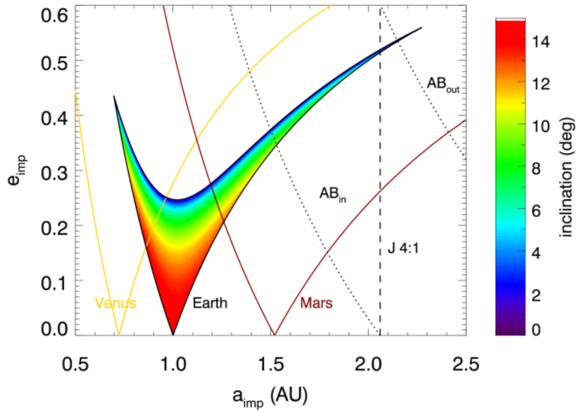

Figure 2: Allowed pre-impact orbits of Theia in the scenario of [10]. Above the yellow and dark red lines orbits are Venus and Mars crossing respectively. The dotted black lines indicate objects that cross the inner (2.06 AU) and outer (3.3 AU) edges of the asteroid belt, while the dashed line shows the location of the 4:1 mean-motion resonance with Jupiter.

allowed range of orbital parameters is increased substantially. A significant proportion of the parameter space is now in regions that cross the orbits of Venus or Mars, and there is a tail that spans the main asteroid belt (Figure 2).

Ćuk & Stewart Moon formation: A very different Moon-forming scenario is proposed by [11], with a small Theia striking at high speed, ~2-2.5 v_{esc}. This allows a much broader range of impactor orbits, shown for both $2v_{esc}$ (top) and $2.5v_{esc}$ (bottom). Scattering with terrestrial planets cannot easily produce such high relative velocities so we can further constrain the orbit to lie in the Jupiter crossing region above the magenta line. In this scenario Theia must have been an outer Solar system object that would differ substantially from Earth in composition.

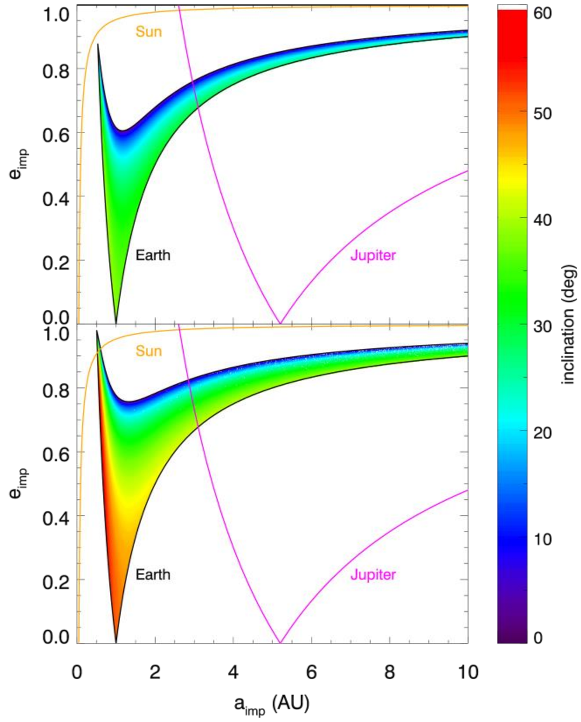

Figure 3: Allowed pre-impact orbits of Theia in the scenario of [11]. Above the gold and magenta lines orbits are Sun-grazing and Jupiter crossing respectively. *Top:* impact velocity of $2v_{esc}$, *Bottom:* impact velocity of $2.5v_{esc}$.

Borealis basin impact: The northern hemisphere of Mars is dominated by the massive Borealis basin. In a scenario proposed by [2] this basin was formed by the impact of a roughly 2000 km body with Mars. Like the Canonical Moon formation scenario this is a low velocity impact at around 1.1 v_{esc}. As such the impactor must have originated near Mars. The parameter space of impactor orbits overlaps only minimally with the other terrestrial planets (Earth), but origins in the asteroid belt are readily allowed due its proximity to Mars.

Mercury formation: One method of achieving the very high present-day core-mantle ratio of Mercury is to begin with a body that has a core-mantle ratio similar to that of the other terrestrial planets and then remove a large fraction of the mantle through a giant impact. This is achieved in the scenario proposed by [12] in which a proto-Mercury 2.25 times its present mass is hit at high speed (~30 km/s) by an impactor 1/6 of its mass. As with the Moon-formation scenario of [10] this results in a very broad distribution of possible impactor orbits, but the most plausible way of achieving such a high velocity is scattering by one of the giant planets. As with [10], the impactor in this case would then have been an outer solar system object.

Conclusions and implications: The relative velocity gives us a fast method of examining the possible origins of giant impactors. This method is less comprehensive than N-body simulations, but the speed enables use of much larger parameter spaces. In this way we can identify promising regions for more detailed study and regions that are implausible.

One of the assets of being able to identify the possible origins of a giant impactor in this way is that it enables us to use those origins, and the implications they have for the impactor composition, as quick comparators between different scenarios. In the case of the formation of the Moon in particular, the search for new impact scenarios has been driven by a desire to reduce the amount of Theian material entering the proto-lunar disk to decrease isotopic differences between Earth and the Moon. This must be tempered however with the knowledge that, aside from [9], all of the new scenarios result in Theias that likely originated from further afield than in the Canonical scenario.

Acknowledgements: The authors gratefully acknowledge support for from NASA through grant NNX16AI31G (Stop hitting yourself).

References:

[1] Canup R.M. (2004), *Annu. Rev. Astro. Astrophys.*, 42, 441

[2] Marinova M.M., et al. (2008), *Nature*, 453, 1216

[3] Canup R.M. (2011) *Astron. J.*, 141, 35

[4] Clayton R.N. (2003) *Space Sci. Rev.*, 106, 19

[5] Ozima M., et al. (2007) *Icarus*, 186, 562

[6] Kaib N.A, Cowan N.B (2015) *Icarus*, 252, 161

[7] Jackson A.P., et al. (2014) *MNRAS*, 440, 3757

[8] Quarles B.L., Lissauer J.J. (2015) *Icarus*, 248, 318

[9] Canup R.M. (2012) *Science*, 338, 1052

[10] Reufer A., et al. (2012) *Icarus*, 221, 296

[11] Ćuk M., Stewart S.T., 2012, Sci., 338, 1047

[12] Benz W., et al. (2007) *Space Sci. Rev.*, 132, 189