THE IMPACT HISTORY OF VESTA. D. P. O'Brien[1], S. Marchi[2], A. Morbidelli[3], W. F. Bottke[2], P. Schenk[4], C. T. Russell[5], C. A. Raymond[6], [1]Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719 (obrien@psi.edu), [2]NASA Lunar Science Institute, Southwest Research Institute, Boulder, CO, [3]Observatoire de la Cote d'Azur, CNRS, Nice, France, [4]Lunar and Planetary Institute, Houston, TX, [5]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA, [6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

From radiometric dating of HED meteorites, we know that Vesta dates back to the beginning of the Solar System [e.g. 1], and hence its cratered surface may potentially hold a record of impacts dating back to that early era. Understanding Vesta's impact record requires a crater chronology curve that relates crater density to surface age (which may either be the formation age of the local crust or the time since the last major resurfacing event).

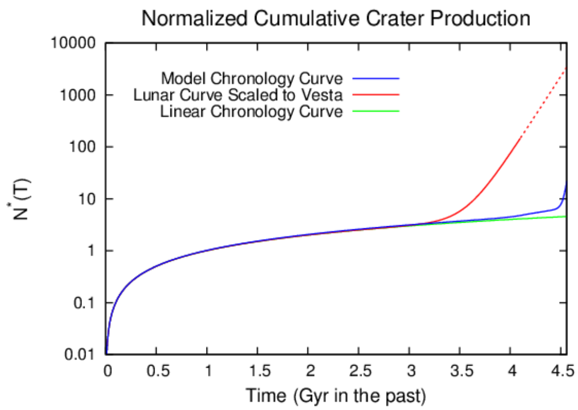
It is common practice to scale the crater production rate from one body (generally the Moon) to another in the inner Solar System using estimates of the orbital distribution of impactors (namely the Near-Earth Asteroids, NEAs) and scaling laws for crater production [eg. 2]. While this is not without its difficulties and uncertainties, it is generally a reasonable approach given that the different terrestrial bodies are all targets being hit by a single source population, the NEAs. The same scaling approach can not be applied to adapt the lunar crater production rate to the asteroid belt, however, since in the former case the source of projectiles on the Moon and terrestrial planets is the subset of bodies that leak out of the asteroid belt, while in the latter case the entire asteroid belt is the source of impactors on Vesta. A simple scaling from the moon to the asteroid belt ignores the fact that the dynamical history that delivers impactors from the main belt to the terrestrial planet region may imply a much different collisional history for the asteroid belt itself.

We have developed a chronology based on models of the primordial depletion and subsequent dynamical evolution of the main belt under the influence of giant planet migration and chaotic diffusion processes. The asteroid belt since ~4.1 Ga likely experienced a factor of ~4 depletion due to the combined effects of the resonance sweeping during the Nice Model instability [3] and the subsequent decay of unstable asteroids [4]. The E-Belt hypothesized by [5], while it would have dominated the impacts on the terrestrial planets, would have only been a relatively small fraction of the mass in the primordial belt, although E-belt bodies that hit Vesta would have likely had high velocities and may be responsible for resetting the Ar-Ar ages of HED meteorites [6].

At the earliest times, immediately following the formation of the Solar System, the asteroid belt may have had significantly more mass than it currently does, which would have been depleted over the first ~100 Myr [7-9] and led to an increased impact rate in the belt during that time. Another possible contributor to the early impact rate in the asteroid belt could be leftover scattered planetesimals from the terrestrial planet region, although the effect of such bodies on the asteroid belt has not been fully quantified. Regardless of the source of these earliest impactors, it is likely that there was a somewhat larger impact rate in the asteroid belt immediately following the formation of the Solar System, which would have decayed to ~4 times the current rate and stayed at that level until ~4.1 Ga, then decayed to its current rate following the destabilization of the asteroid belt and E-Belt. This destabilization and depletion at ~4.1 Ga would correspond to the beginning of the Late Heavy Bombardment on the Moon.

The largest uncertainty in this model chronology is the initial mass of impactors (which is related to this initial impact rate). If we assume that the largest craters on Vesta, impact basins larger than ~200 km in diameter, represent all craters of that size that have formed over its history (ie. no basins of that size have been erased), we can place a constraint on the initial impact rate and hence constrain the chronology curve. Using this approach suggests a primordial impacting mass in the asteroid belt region of roughly 1 Earth mass, broadly consistent with other estimates of the mass that would have been initially present in that region [7-9, see 10 for a review]

The resulting model chronology curve is plotted on the following page in normalized form $N^*(T)$, which gives the number of craters of a given size that accumulate over a given time for every one crater of that size formed per billion years. Also shown on the plot for comparison are a linear chronology curve, in which the rate of crater formation is the same at all times (no increased flux in the past), and a scaled version of the lunar chronology curve [eg. 11]. The dashed section prior to 4.1 Ga is an extrapolation, as the lunar impact history is not well-constrained prior to that time.



The Model Production Function (MPF) for Vesta derived by [12] can be used to convert the normalized $N^*(T)$ curves to actual crater densities on Vesta, and hence for a given crater density we can estimate the absolute age of a surface. We find an age of ~1 Ga for Rheasilvia using our model chronology, consistent with previous estimates [12]. This young age is also consistent with several other lines of evidence. Rheasilvia has a very fresh appearance relative to all other large impact basins. The size distribution of the Vesta family members, or "vestoids," is quite steep compared to the background population. This steep size distribution would collisionally grind down if the family were older than ~1 Gyr, suggesting its relatively recent formation [13,14]. A young age is also consistent with the much lower abundance of exogenic hydrogen within Rheasilvia Basin compared to the rest of the surface, as found by the Gamma Ray and Neutron Detector (GRaND) on Dawn [15]. For the Hghly Cratered Terrain (HCT) regions in the northern hemisphere identified by [12], we find an age of ~4.3 Ga, consistent with them being amongst the oldest terrains on Vesta. It is somewhat odd that an age of 4.5 is not obtained for that region. [12] find that while the HCT regions are not saturated (such that for every crater created, another is erased), they may be close enough to saturation that erasure processes may be affecting the crater counts and the measured crater population may be somewhat lower than the production population. Thus, the actual age of the HCT regions could be closer to 4.5 Ga, the age of Vesta itself.

In contrast to our model chronology, the scaled lunar chronology [eg. 11] predicts a much larger impact rate prior to ~3.5 Ga, such that even the entire surface of Vesta, as dated by its largest impact basins, is only ~4 Ga. This is difficult to reconcile with its radiometric age of ~4.5 Ga, and would require either that there were no impacts on its surface prior to ~4 Ga, which is hard to fathom from a dynamical standpoint, or that the impact rate prior to 4 Ga was so intense that the entire surface (even craters on the scale of Rheasilvia) was reset, which would have likely eroded away Vesta's basaltic crust.

In addition to the cratering record, we have meteorites from Vesta, the HEDs, that record the ages of major impact events in their Ar-Ar ages. The Ar-Ar ages of eucrites suggest that several such events occurred between 3.4 and 4.1 Gyr ago, and that an especially large impact event (or events) occurred 4.48 Gyr ago, but few impacts capable of resetting the Ar-Ar chronometer occurred in the interval from 4.1 to 4.5 Ga [16]. Zircons in HED meteorites also suggest a period of very early impacts [17]. The scaled lunar chronology, if extrapolated back to 4.5 Ga, would predict a much larger number of resetting events in the 4.1 to 4.5 Ga timespan than in the 3.4 to 4.1 Ga timespan, which would be difficult to reconcile with the meteorite data. On the other hand, dynamical and impact modeling consistent with the theoretical chronology discussed here is able to reproduce the main features of the eucrite Ar-Ar age distribution [6].

Acknowledgements

D. P. O'Brien is supported by grant NNX10AR21G from NASA's Dawn at Vesta Participating Scientist Program.

References

[1] L. E. Nyquist (2009) *Geo. Cos. Acta* **73,** 5115.
[2] B. A. Ivanov (2001) *Space Sci. Rev.* **96**, 87.
[3] A. Morbidelli (2010) *AJ* **140**, 1391.
[4] D. A. Minton (2010) *Icarus* **207**, 744.
[5] W. F. Bottke (2011) *Nature* **485**, 78.
[6] S. Marchi (2013) *Nat. Geosci.* **6**, 303.
[7] G. W. Wetherill (1992) *Icarus* **100**, 307.
[8] J.-M. Petit (2001) *Icarus* **153**, 338.
[9] D. P. O'Brien (2007) *Icarus* **191**, 434.
[10] D. P. O'Brien (2011) *Space Sci. Rev.* **163**, 41.
[11] N. Schmedemann (2013) LPSC 44, 2155.
[12] S. Marchi (2012) *Science* **336**, 690.
[13] F. Marzari (1996) *A&A* **316**, 248.
[14] F. Marzari (1999) *Icarus* **142**, 63.
[15] T. H. Prettyman (2012) *Science* **338**, 242.
[16] D. D. Bogard (2011) *Chemie der Erde* **71,** 207.
[17] M. D. Hopkins (2012) LPSC 43, 2109.