THE EVOLUTION OF GIANT IMPACT EJECTA AND THE AGE OF THE MOON. W.F. Bottke[1], D. Vokrouhlicky[2], S. Marchi[1] T. Swindle[3] E. R. D. Scott[4] J.R. Weirich[5] [1]Southwest Research Institute and NASA SSERVI-ISET team, Boulder, CO, USA (bottke@boulder.swri.edu) [2]Institute of Astronomy, Charles University, V Holesovickach 2, CZ-18000, Prague 8, Czech Republic Univ., Czech Republic. [3]Lunar and Planetary Laboratory, U. Arizona, Tucson, AZ, USA. [4]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA5 [5]Dept. of Earth Sciences, Western University, London, ON, Canada.

Introduction. The Moon likely formed in a collision between a very large protoplanet and the proto-Earth [e.g., 1,2]. This giant impact (GI) occurred during the late stages of Earth's accretion; the abundance of highly siderophile elements in Earth's mantle indicate the Earth only accreted ~0.5% of its mass from broadly chondritic projectiles after this time [e.g., 3]. Thus, the GI was probably the youngest largest collision to take place in the terrestrial planet region.

A long-standing mystery, however, is precisely when the GI took place. This age is needed to help us understand the starting time of many events in Earth/Moon evolution (e.g., magma oceans) and constrain planet formation simulations. Unfortunately, ancient samples from the Earth/Moon are rare and hard to decipher. This has led to a wide range of GI age estimates, from ~10 My [4] to >200 My after CAI formation [5].

This uncertainty prompted us to examine a novel method to calculate the timing and effects of the GI. Consider that the GI likely produced an enormous amount of debris. Numerical hydrocode simulations of the GI by R. Canup [e.g., 2] show that, on average, ~5% of an Earth-mass escapes the Earth-Moon system as ejecta; this is equivalent to 100 times the mass of the asteroid belt! Before being collisionally and dynamically eliminated, however, considerable ejecta will be driven onto asteroid belt-crossing orbits by planetary perturbations and resonances. This will allow some ejecta fragments to slam into primordial main belt asteroids at very high velocities (>10 km/s).

Two key aspects about V > 10 km/s impactors striking main belt asteroids are that (a) they mostly come from projectiles on orbits outside the main belt, and (b) they are particularly good at heating target body material and thereby producing Ar-Ar shock degassing ages [6]. In contrast, main belt asteroids, which typically hit at 5 km/s, produce little heating. Thus, very ancient shock heating events in stony meteorites are telling us about terrestrial planet region impactors (e.g., leftover planetesimals, GI ejecta).

Here we argue that impacts on main belt asteroids by GI ejecta were responsible for many of the ancient Ar-Ar shock degassing ages found in asteroidal meteorites. Moreover, we claim these "fingerprints" can be used to determine the age of the Moon.

Dynamical Model. To explore the evolution of GI ejecta, we tracked 5000 test bodies started with isotropic trajectories from Earth's Hill sphere. They were given initial velocities "at infinity" of V = 1, 3, 5, 7, 9 km/s. The terrestrial and giant planets were on orbits as described in [7]. The test bodies were followed for 400 My. Our simulations show GI ejecta spreads rapidly across the inner solar system over tens of My, with most bodies going away by hitting the Earth (20-40%), Venus (20-40%), the Sun, or by being ejected out of the Solar System via an encounter with Jupiter. Details on their dynamical evolution can be found in [8].

Impact Heating and Flux. As our test bodies evolved, we used Opik-like algorithms to compute the collision probabilities and impact velocity distributions between them and our representative primordial asteroid (4) Vesta every 0.01 My [e.g., 6]. We found the mean impact velocities for most test bodies with Vesta over this interval were > 10 km/s. These data were then combined with estimates of the ejection velocity distribution of GI material from hydrocode simulations [e.g., 7] and impact heating relationships for bodies striking Vesta over all velocities [see 6 for details].

Our results yielded an estimate of the relative frequency of Ar-Ar resetting events on Vesta (and other asteroids) immediately after the GI. Our profile indicates Ar-Ar shock ages from GI ejecta should peak at ~8 My after the GI before slowly fading over 100 My.

Collisional Evolution. A key uncertainty in our work involves the initial size frequency distribution (SFD) of GI ejecta and how it is affected by collisional evolution (i.e., how GI ejecta beats up on itself). To deal with this, we tested a wide range of SFDs in a collision evolution code designed to model planetesimal evolution in the terrestrial planet region [3, 9, 10]. Our results show that massive SFDs quickly grind themselves down to fairly low-mass states; the larger they are, the faster they grind [e.g., 9]. We found the initial mass/shape of the SFD does not strongly affect our results, provided a good share of the starting mass is in D > 100 km bodies. Scaling factors accounting for these effects are included in our results.

The bodies that survive tend to have net masses and SFDs that rival those that produced the Ar-Ar signatures made during the Late Heavy Bombardment era 3.5-4.1 Ga (i.e., several main belt masses) [6]. This suggests that GI impact signatures may indeed be found on main belt asteroids and in stony meteorites.

Comparing Ar-Ar Data to Model Results. The Ar-Ar data used here was collected from meteorite samples that were heavily shocked, shocked-melted, or otherwise had some evidence for having been part of a large collision. Within the E, H, L, LL chondrite and eucrite meteorite classes, we found 26 ages with ~4.35-4.56 Ga matching our criteria (**Fig. 1**) [11,12].

Next, we created model Ar-Ar profiles that could be directly compared to data. Each combined two elements: (i) a GI profile, as described above, and (ii) a profile designed to account for leftover planetesimals (which also can hit asteroids at $V > 10$ km/s). Model variables were age of the giant impact, set to vary between 0-200 My, and the ratio of the number of Ar-Ar resetting events between (i) and (ii), set to vary between 0.1 and 10. Goodness of fit between model and data were computed using K-S statistical tests (**Fig. 1**).

Results. *Our best fit results indicate the giant impact (GI) took place 100 ± 30 My after CAI formation (***Fig. 1***).* We consider this result to be highly encouraging; it is consistent with the best available ages of the oldest lunar crust [13] as well as ages derived from other lunar/terrestrial samples [e.g., see 14].

Our value is inconsistent with the 4.36 Ga age for the Moon suggested by [5]. We argue that if the GI had occurred at the time, we presumably would see numerous Ar-Ar ages near or beyond that time. Instead, we speculate that the source of the lunar magmatic events recorded at ~4.36 Ga were triggered by a massive impact event, possibly the formation of South Pole-Aitken (SPA) basin, as hypothesized by the same group. Interestingly, this age agrees with the 4.33-4.39 Ga age derived for SPA by [15] found using their new lunar chronology and new measurements of the spatial density of craters found on SPA.

What Else Did Giant Impact Ejecta Do? If GI ejecta blasted inner solar system bodies ~4.47±0.03 Gy ago, some interesting effects become plausible:

1. The GI ejecta population was most massive just after the launch (i.e., before collision evolution could take effect). If numerous GI impactors struck Vesta at this time, they would have brought warm interior material to the surface. This sudden quenching may explain why numerous unshocked eucrites have ~4.48 Ga Ar-Ar ages [e.g., 11].
2. The oldest martian and lunar zircons, found in breccias, are 4.428±0.025 Ga [16] and 4.417±0.006 Ga [17], respectively. These ages are a good match to our shock heating profiles created by GI ejecta hitting Mars/Moon at high velocities ($V > 10$ km/s). Our results suggest these zircons may be telling us about GI ejecta bombardment.
3. GI ejecta should mainly be composed of crust and mantle material from planet-sized differentiated bodies. Main belt impactors with this kind of composition are rare today. Accordingly, if ancient clasts with crust/mantle composition within asteroid/lunar samples can be identified, they might tell us about the nature of the primordial Earth and/or the Moon-forming impactor.

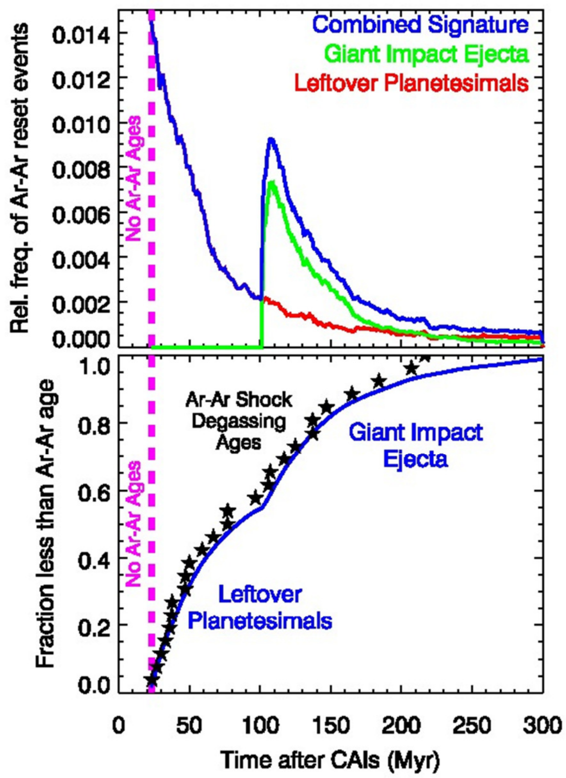

Fig. 1 (*Top*). Relative frequency of Ar-Ar reset events for leftover planetesimals, GI ejecta, and combined. The GI occurs at 102 My after CAIs. Ratio between leftovers and GI ejecta is set to 3.1. No Ar-Ar data is known for $T < 23$ Myr (*Bottom*) Comparison between combined signature (in blue) and mean ages for Ar-Ar data (black stars). Major components from top plot are labeled here. Statistical K-S probability is ~100%.

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