A NEW INTERPRETATION OF ^{40}AR-^{39}AR AGES OF EUCRITES AND IMPLICATIONS FOR VESTA'S COLLISIONAL HISTORY.
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Introduction: Radiometric ages of extraterrestrial and terrestrial rocky samples have been successfully used to investigate the past evolution of the terrestrial planets and asteroids (e.g. [1],[2],[3]). For instance, radiometric ages of lunar samples provide evidence for an intense period of bombardment around 3.9 Ga ago, the so-called Late Heavy Bombardment (LHB; [4], [5]). Similar measurements have also been performed on other meteorite classes, like ordinary chondrites and achondrites (e.g., howardites, eucrites and diogenites, HEDs; [3]). Among the different radiometric chronometers, the Ar-Ar chronometer is of particular interest given the relatively low closure temperature that can be achieved as a result of impact-driven heating, implying that the Ar-Ar chronometer can be used to investigate the collisional history of the body. Thus, the Ar-Ar ages of Vesta's samples, namely HEDs meteorites, can be used to study its collisional evolution.

Here we present new results that may significantly affect our interpretation of HED Ar-Ar ages and their implications for the collisional evolution of Vesta.

Ar-Ar age distribution: Eucrite and howardite Ar age distributions have been the subject of several studies (e.g. [3],[6]). One of the key feature of the Ar age distribution is the strong and narrow spike at ~4.45 Ga, which is mainly composed of unbrecciated, cumulate and monomict eucrites (Fig. 1). On the other hand, the interval 4.1-4.4 Ga is characterized by much fewer Ar reset events, recorded mainly in howardites and brecciated eucrites. The period 3.3-4.1 Ga is characterized by a sudden increase in the number of Ar reset events, some of which were large enough to reset unbrecciated and cumulate eucrites at depth.

The overall Ar age distribution has intrigued researchers for decades. In particular, the fact that the period 4.1-4.4 Ga has ~4-5 times fewer reset events that the period 3.3-4.1 Ga seems to suggest that something important in the history of Vesta happened at about 4.1 Ga, although we caution that the relative intensity of the peaks shown in the Ar distribution may be strongly affected by selection effects (e.g., several samples of the same event). In this respect, the lack of events in the period 4.1-4.4 Ga could be the result of observational biases that can play against the detection of older ages, as has been suggested for the Moon [7]. However, this contrasts with the observation that many eucrites have an age of ~4.45 Ga. This spike has been traditionally interpreted, on the basis of petrological arguments, as the result of a major collision [3], although some of these Ar ages may record the primordial cooling of Vesta. Finally, it is unclear why there is a lack of Ar ages younger than ~3.3 Ga.

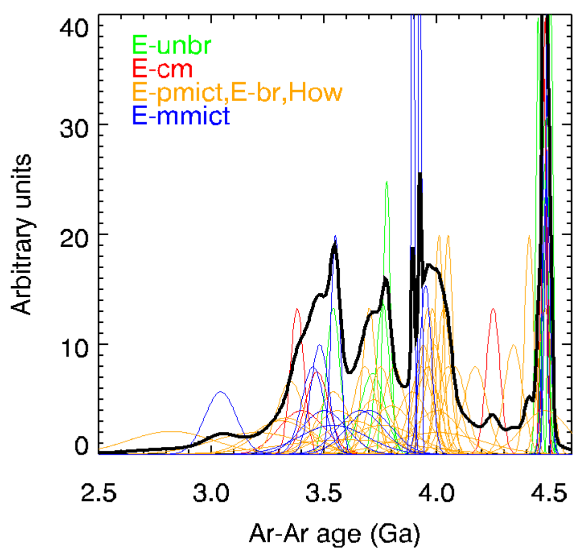

Figure 1: *Ar-Ar ages of eucrites and howardites. Each dated sample is reported with a gaussian profile with center and sigma corresponding to the more probable age and 1-sigma error. Profiles are color coded according to the class of the parent meteorites. The black curve is the overall probability distribution obtained by the sum of all gaussians divided by 5. The plots contain 54 Ar-Ar ages from [6,9,10,11] (and references therein) plus 15 new howardite ages [12].*

Surprisingly, similar characteristics are also seen for Ar ages of other meteorites (e.g., H, LL, L chondrites; [8]), as well as for lunar samples [5]. The comparative analysis of Ar ages coming from different bodies like the Moon and asteroids, however, may be misleading given the very different impact conditions throughout the inner solar system. In the next section, we address this issue with the aid of new numerical simulations.

The role of impact velocity: One key aspect for Ar age studies is: what conditions are needed for a sample to degas Ar? The process requires a combination of heating above the closure temperature and enough time for the Ar to diffuse within the minerals. Our studies of Ar diffusivity in pyroxene show that the required time scale is of the order of ~10 Myr and ~100 yr, respectively at temperatures of 1100 K and 1400 K (the latter is the melting point). Temperatures below 1000 K are inefficient in resetting Ar-Ar ages.

In this respect, we used iSALE hydrocode simulations ([13] and reference therein) to study the impact-induced temperature increase in a basaltic target at different velocities (Fig. 2).

We find that for typical main belt impact velocities (V=5 km/s), the resulting temperatures are generally too low to trigger Ar release. For V=7 km/s, which are only attained by 10% of all impacts in the main belt, the only region reaching reset temperatures is near the impact point, and the volume of affected affected is minimal. When V=15 km/s, the volume of highly shocked material increases and, thus, more material experiences high post-shock temperatures. Most of this material (above the excavation depth) is ejected, though some of it may fall back to the surface. The ejecta deposit itself can be hot enough to reset Ar-Ar ages. Some of the displaced material (i.e., the region between excavation and transient crater depths) also experienced high temperatures, but stays within the crater. This implies that crater floors and ejecta blankets can have reset material.

The simulations also place constraints on the efficiency of impact melt production. We find that typical impact conditions in the main belt do not produce significant amounts of heating/melting. This result is supported by the paucity of impact melts found among the HEDs and other stony meteorite groups as well as the lack of evident impact melt pools observed on Vesta itself.

Discussion: Our results imply that V>15 km/s is required to produce Ar-Ar impact degassing ages on Vesta. Numerical results indicate that only ~0.1% of present-day main belt impacts strike Vesta at such velocities (e.g., [14]). Thus, to produce the Ar-Ar age cluster between 3.3-4.1 Ga, we postulate we need an external source of projectiles, namely high velocity impactors from planet-crossing orbits with high eccentricities and/or inclinations.

The primary source these putative projectiles is currently under investigation, though preliminary analyses suggest they may come from the primordial asteroid belt itself! The Nice model predicts that numerous asteroids are pushed out of the main belt by sweeping resonances as a consequence of late giant planet migration [15, 16]. This destabilized population would not only go on to strike the Moon, producing the Late Heavy Bombardment, but would also continue to hit Vesta and other main belt survivors [17]. Other possible sources of high velocity impactors are also under investigations.

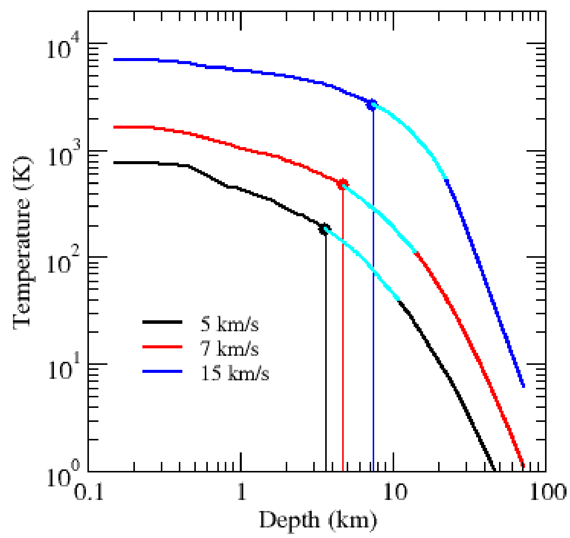

Figure 2: *Impact induced post-shock temperatures determined by 2D iSALE hydrocode simulations of a 10 km projectile hitting head-on (vertically) a basaltic target at different velocities. Vertical solid lines indicate the excavation depth (computed as 1/3rd of the transient depth). Cyan lines highlight the regions comprised between the excavation and transient depth, corresponding to material compacted at the bottom of the crater.*

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