**CHARACTERIZING THE EARLY IMPACT BOMBARDMENT.** **Donald D. Bogard**, ARES, code KR, NASA-JSC, Houston, TX 77058, donald.d.bogard@nasa.gov.

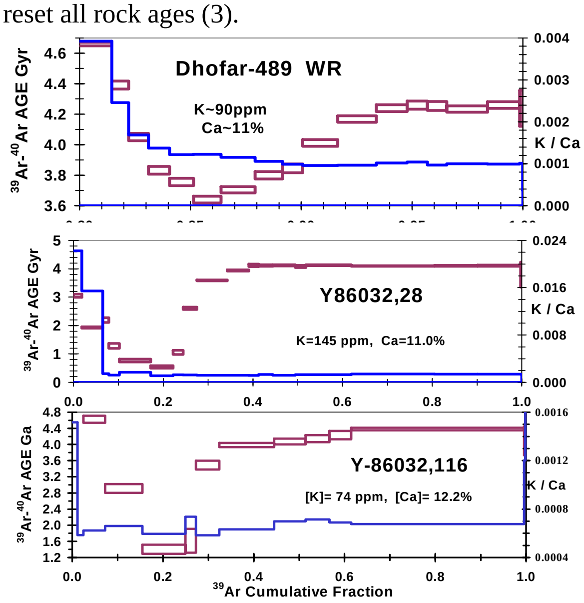
**Introduction.** The early bombardment revealed in the larger impact craters and basins on the moon was a major planetary process that affected all bodies in the inner solar system, including the Earth and Mars. Understanding the nature and timing of this bombardment is a fundamental planetary problem. The surface density of lunar impact craters within a given size range on a given lunar surface is a measure of the age of that surface relative to other lunar surfaces. When crater densities are combined with absolute radiometric ages determined on lunar rocks returned to Earth, the flux of large lunar impactors through time can be estimated (1). These studies suggest that the flux of impactors producing craters >1 km in diameter has been approximately constant over the past ~3 Gyr. However, prior to 3.0-3.5 Gyr the impactor flux was much larger (1) and defines an early bombardment period. Unfortunately, no lunar surface feature older than ~4 Gyr is accurately dated, and the surface density of craters are saturated in most of the lunar highlands. This means that such data cannot define the impactor flux between lunar formation and ~4 Gyr ago.

Early radiometric age dating of lunar highland rocks by multiple techniques revealed a strong grouping of their ages in the range ~3.8-4.2 Gyr. This led in 1974 to the suggestion that the moon experienced a period of enhanced bombardment ~3.9 Gyr ago that was termed a cataclysm (2). An opposing viewpoint holds that the early bombardment was a steady decline in impactor flux after lunar formation and that a significant cataclysm, or flux increase, did not occur (3). In this model the highland rock ages are the result of continual impact resetting of ages until the flux dropped low enough that the last reset rock ages were preserved (3). Another view is that ejecta from the late Imbrium event dominates most of the lunar front side (4), and that Imbrium may have partially or totally reset the ages of many returned lunar samples. By this view the ages of impact basins older than Imbrium are generally undetermined.

**A Cataclysm or Not.** Ryder (5) examined lunar bombardment models in terms of mass accreted to the moon over time, where accreted mass was estimated from the sizes of impacted basins whose ages were presumed to be known. He considered the most recent 15 basins, Oriental through Nectaris, for which the estimated projectile mass is 0.0029% that of the whole moon, to have formed in a period of ~80 Myr. Ryder argued that if these 15 basins formed in such a short period, then extrapolation of the impactor flux back in time would imply an impossibly high flux prior to ~4.1 Gyr. This he argued required a cataclysm, which he suggested formed all major lunar basins in the time period ~3.8-4.0 Gyr ago.

The formation times of Imbrium and probably Serenitatis, which are two of the most recent lunar basins (6), appear reasonably well-determined at ~3.85-3.87 Gyr (7,8). Although several rock types give ages of ~3.85 Gyr, Dalrymple & Ryder argued that the ages of Ap-15 and Ap-17 impact melt rocks give the most reliable age for Imbrium (3.85 ±0.02 Gyr) and Serenitatis (3.89 ±0.01 Gyr). Recently (9) reported the age of Apollo 16 melt rocks to vary over 3.83-4.19 Gyr, with an average age of 3.88 Gyr. The distribution in ages for Apollos 15, 17, and 16 melt rocks totally overlap, however, and resolution of separate events from these data is problematic. If Nectaris formed at 3.92 Gyr (7), what events reset the older ages shown by many other Apollo 16 rocks? Warren (10) noted that on a plot of Ar-Ar age versus K concentration, those Ap-16 rocks with K>400 ppm give an average age around 3.9 Gyr, whereas those rocks with K<400 ppm give an average age around 4.1 Gyr. Many workers today consider the age of Nectaris not to be well known. Yet, the intensity of the cataclysm is dependant upon the range in formation times of the youngest ~15 lunar basins. If most formed in a relatively short period (<200 Myr), then a substantial increase in impactor flux above the background seems required. On the other hand, if basin formation occurred throughout the first 0.8 Gyr of lunar history, with the last few basins determining the chronology of returned highland rocks, then any increase in flux above the background may have been modest or even non-existent.

**Lunar Meteorite Characterization.** The earliest lunar crust is thought to have formed ≥4.4 Gyr ago and to have had a ferroan anorthosite composition. Unfortunately such rocks have low trace element concentrations (K often ≤100 ppm) and are hard to age date. Thus, any contamination by material rich in trace elements from the lunar nearside (PKT) could affect their determined ages. Some lunar meteorites are breccias containing clasts of highland material, and many undoubtedly derive from the lunar farside, away from PK-Terrain. Cohen et al. (11) reported Ar-Ar ages of ~2.5-4.1 Gyr for a suite of tiny impact melt clasts from four lunar meteorite breccias, for which they suggested impact events at ~2.7, 3.0, 3.4, and 3.9 Gyr. Because 77% of these ages are <3.8 Gyr, it seems likely that most (or all) of these melt clasts were produced by moderate-sized craters formed from the background bombardment, not the early bombardment. The JSC lab has measured Ar-Ar ages on a few anorthositic clasts from lunar highland meteorites. Our results for four such anorthositic clasts from three meteorites are shown in Fig. 1. The Ar-Ar ages of these clasts, plus a clast from MAC88105, range over 4.07-4.4 Gyr. Two different clasts from Y-86032 give distinctly different ages, implying this breccia was assembled from materials that experienced different impact resetting events. These old anorthosite ages are suggestive that impact resetting occurred over much of early lunar history. Although this could be consistent with a systematic decrease in impactor flux, it does not support the idea that impacts prior to ~4.1 Gyr ago reset all rock ages (3).




**Eucrites and Impact Resetting on Vesta.** Basaltic meteorites called eucrites are believed to derive from the large asteroid 4-Vesta. Eucrites commonly show resetting of Ar-Ar ages and occasionally disturbance of other radiometric chronometers as a result of impact heating on their parent body (12,13,14). Although impact age disturbance occurs for some other meteorite types, it is much more common in eucrites. Vesta, likely being larger than the asteroid parents of most other meteorite types, can sustain larger impacts producing more surface heating, although it cannot survive impacts the size of those which formed the lunar basins. Figure 2 is a histogram of 28 eucrite Ar-Ar ages, presented as age probability plots. These indicate impact resetting over the range of ~3.5-4.0 Gyr, and the summed (heavy black) curve suggests impact events at ~3.45, 3.55, 3.7, and 4.0 Gyr. Several additional unbrecciated eucrites give a sharp age peak at ~4.48 Gyr, but very few eucrites ages fall in the region of 4.1-4.4 Gyr. These eucrite ages suggest three characteristics of the early bombardment in the vicinity of the asteroid belt: 1) It was not so severe that most Rb-Sr and Pb-Pb ages were totally reset, like the moon. This suggests that Vesta did not experience a much more intense bombardment at 4.0-4.4 Gyr than it did at 3.5-4.0 Gyr. 2) The range of impact reset ages for Vesta differs in detail compared to that for the moon, suggesting possible variations in the size of impacting objects with time. 3) The enhanced bombardment had ended by ~3.4 Gyr.

**The Early bombardment.** Impact reset ages from the moon and Vesta suggest that early impactors did include an increase above the decaying background flux that remained from planet formation. Although (5) suggested this cataclysm may have been ≤100 Myr in length, the eucrite data imply and the lunar data are consistent with a much longer period of enhanced bombardment ending ~3.4 Gyr ago. Thus, the magnitude of the impactor increase above the decreasing background flux is poorly defined. Measured reset ages on both the moon and Vesta may be the result of only a few large impacts. The source of these bombarding bodies has been widely speculated. Recent interest has focused on gravitational interactions of the giant planets with the early Kuiper belt as the planets migrated outward (15), which might explain the timing of the heavy bombardment.

**References.** (1) Neukum et al., *Space Sci. Rev. 96*, p.48, 2001; (2) Tera et al., *EPSL 22*, p.1, 1974; (3) Hartmann, *MAPS 38*, p.579, 2003; (4) Haskin, *JGR 101*, p.1679, 1998; (5) Ryder, JGR 107, 6-1, 2002; (6) Petro & Pieters, JGR 109, E06004, 2004; (7) Stöffler & Ryder, Space Sci. Rev. 96, p.1, 2001; (8) Dalrymple & Ryder, JGR 98, p.13085, 1996; JGR 101, p.26069, 1996; (9) Duncan et al., LPSC #1328, 2004; (10) Warren, 3rd Intl Conf. Large Meteorite Impacts, 2003; (11) Cohen et al., Science 290, p.1754, 2000; (12) Bogard, Meteoritics 30, p.244, 1995; (13) Kunz et al., Planet. Space Sci. 43, p.527, 1995; (14) Bogard & Garrison, MAPS 38, p.669, 2003; (15) Gomes et al., 36th DPS Meeting, #40.04, 2004.