PLANETARY ACCRETION AS INFORMED BY METEORITIC SAMPLES OF EARLY SOLAR SYSTEM PLANETESIMALS.
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In the Beginning: Impact events are a key part of the formation of planets, both during the initial accretional phase and late in the growth of a planet when giant impact events may dramatically alter the final outcome. Large collisions, for example, have been implicated in the formation of the Moon from the Earth [1-3], the stripping of Mercury's mantle [4], the northern-southern hemisphere dichotomy of Mars [5-8], and the formation of Charon from Pluto [9]. Periods of enhanced impact bombardment of post-accretion planetary surfaces have also been deduced from Solar System exploration studies. Apollo, for example, demonstrated that the Moon was heavily cratered sometime during the first ~600 million years of its existence in what has been termed by some to be the period of Late Heavy Bombardment (LHB). The cadence of that event is still uncertain, but it is clear there were a large number of basin-forming impact events in that first half-billion years.

Dusty circumstellar disks around young stars outside our Solar System indicate the collisional evolution of young planetary systems can be violent. Spitzer Space Telescope data indicate that some systems have dust signatures well above the average at ages from 100-600 Myr [10]. Observations by Su et al. [11] and Beichman et al. [12], for example, support the idea that the ~350 Myr-old A star Vega and the ~2 Gyr-old G star HD 69830 recently experienced collisions between large planetesimals that generated these elevated dust signatures. Both Vega and Fomalhaut may have planetesimal rings akin to the precursor of our main asteroid belt [13].

The Accretional Epoch Among Chondritic Planetesimals: Our record of collisional processes among planetesimals is extraordinarily ancient. We have, for example, a fragment of rock from a collision among planetesimals that occurred during the accretion of Earth and prior to the formation of the Moon. The MIL 05029 meteorite is an impact melt breccia that was produced in a collision ~4.54 Ga that created a 25-60 km diameter crater and shattered the interior of the 100-200 km diameter L-chondrite parent body [14]. A similar study showed that the Portales Valley meteorite may have been produced beneath the floor of a >20 km diameter crater on the 150-200 km diameter H-chondrite parent body [15] in an event that occurred >4.46 Ga [16]. On the R-chondrite parent body, impacts appear to have occurred 4.34-4.38, 4.4, and 4.47 Ga ([17] and references therein]. Other collisions during the accretional epoch have been detected on the E-chondrite (~4.53 Ga), IAB (>4.47 and perhaps >4.52 Ga), HED (~4.48 Ga), and L-chondrite (4.46 and 4.43) parent bodies ([18] and references therein).

On at least two planetesimals, the impact events produced significant volumes of melt that differentiated to form the IAB-MG and IAB-sLM groups of iron meteorites (e.g., [19]). Cooling rates of those meteorites [20] suggest craters ~150 to 300 km in diameter on planetesimals ~300 km diameter or larger.

Collectively, these data indicate sizeable impact events were occurring among planetesimals as the accretional phase wound down and the largest planetary collisions (e.g., the Moon-forming giant impact) were occurring. They also suggest, but do not prove, that collisional velocities and dynamic stirring of the nascent planetary disk were relatively high.

The Accretional Epoch Among Differentiated Planetesimals: Variable planetesimal accretion rates and, thus, abundances of short-lived isotopes for interior heating, produced equally variable outcomes. While some planetesimals remained chondritic, as described above, and largely preserve a nebular record, other planeteismals became hot enough to differentiate. It is difficult to discern impact-reset radiometric systems in meteoritic samples of these objects, because simple cooling of a planetesimal may not reach radiometric closure temperatures until 4.47-4.49 Ga, as seen in silicates among IIE iron meteorites (e.g., [18] and references therein). That is, if an impact occurred, the planetesimal may be too warm to quench a radiometric age of that impact. At some point, the objects were involved in collisions sufficiently energetic to strip away the mantle and expose the differentiated cores. As most of the planetesimals represented by meteoritic relicts are among iron meteorites, that type of collisional erosion may have been common. That, too, implies relatively high collisional velocities and, thus, an excited dynamical system.

The Puzzle of Sources. As this is a workshop designed for discussion, let me wade into the curious problem of the sources of the accreting material and impactors. Isotopic signatures of volatile elements suggest the Earth, Moon, and Mars were accreting carbonceous chrondritic material (e.g,. [21-23]), sometime between the main accretional phase of Earth [24] and the solidification of the lunar crust from a magma ocean [23]. As noted in the introduction, planetesimals continued to hit the Earth and Moon (and other inner solar system planets) for several hundred million years. Analyses of lunar impact melts point to sources of those impactors that remain contested: some suggest the objects evolved, over time, from carbonaceous impactors to ordinary chondrite impactors, with one or more iron projectiles stochastically hitting during that evolution, while others suggest end member mixing among carbonaceous and iron impactors (see, for example, the discussion of [25] and references therein). Curiously, the first mineralogical relicts of impactors found in ancient regolith breccia samples [26], produced near the end of the LHB, are entirely carbonaceous. A diverse array of other impactors, more reflective of the current population of meteorite falls, is not found until much later in lunar history.

If carbonaceous impactors were entering the inner solar system, and if they were accreting at vastly different times (e.g., during primary accretion and later during the LHB), does that mean they were scattered by a single process or more than one process?

Also, if carbonaceous chondritic objects were entering the inner solar system and, presumably, passing through the inner asteroid belt, why do we not see abundant clasts of them among regolith samples of ordinary chondrite planetesimals?

This is where dynamical modeling is providing a complementary perspective. At least one other paper submitted to this workshop [27] will present one of those models.

Although the sources of the accreting material over time currently remain a puzzle, renewed attention on impactor signatures (geochemical, isotopic) in Earth, on impactor signatures (geochemical, isotopic, mineralogical, and geologic) in lunar samples, on meteoritic samples of planetesimals that either co-accreted with planets or later pummeled them, and in dynamical models that complement those data, the community may be in a position to soon accelerate our understanding of this earliest epoch of solar system history.

References: [1] Hartmann W.K. and Davis D.R. (1975) *Icarus, 24*, 504–515. [2] Cameron A.G.W. and Ward W.R. (1976) *Lunar Science VII*, 120–122. [3] Canup R.M. and Righter K. (eds.) (2000) *Origin of the Earth and Moon*, 555 p., Univ. Arizona Press. [4] Benz W. et al. (1988) *Icarus, 74*, 516–528. [5] Wilhelms D.E. and Squyres S.W. (1984) *Nature, 309*, 138–140. [6] Andrews-Hanna J.C. et al. (2008) *Nature, 453*, 1212–1215. [7] Marinova M.M. et al. (2008) *Nature, 453*, 1216–1219. [8] Nimmo F. et al (2008) *Nature, 453*, 1220–1223. [9] Canup R.M. (2005) *Science, 307*, 546–550. [10] Rieke G. et al. (2005) *ApJ, 620*, 1010–1026. [11] Su K. et al. (2005) *ApJ, 628*, 487–500. [12] Beichman C. et al. (2005) *ApJ, 626*, 1061–1069. [13] Su K. et al. (2013) *ApJ*, *763*, 118, 14p. [14] Weirich J. R. et al. (2011) *Meteoritics & Planet. Sci., 45,* 1868–1888. [15] Kring D. A. et al. (1999) *Meteoritics & Planet. Sci., 34,* 663–669. [16] Bogard D. D. and Garrison D. H. (2009) *GCA, 73*, 6965–6983. [17] Righter K. et al. (2016) *Meteoritics & Planet. Sci., 51,* 1678–1684. [18] Bogard D. D. (2011) *Chemie der Erde, 71*, 207–226. [19] Worsham E. A. et al. (in press) *Earth Planet. Sci. Letters*. [20] Goldstein J. I. et al. *(2014) Geochim. Cosmochim. Acta*, *140*, 297–320. [21] Alexander C. M. O. D. et al. (2012) *Science, 337*, 721–723. [22] Marty B (2012) *Earth Planet. Sci. Letters, 313–314*, 56–66. [23] Barnes J. J. et al. (2016) *Nature Comm., 7*:11684, doi: 10.1038/ncomms11684. [24] Fischer-Gödde M. and Kleine T. (2017) *Nature, 541*, 525–528. [25] Liu J. et al. (2016) *Geochim. Cosmochim. Acta, 155*, 122–153. [26] Joy K. H. et al. (2012) *Science, 336*, 1426–1429. [27] Kretke, K. A. et al. (2017) this conference.