ROLE OF PLANETARY IMPACTS IN THERMAL PROCESSING OF CHONDRITE MATERIALS. H. J. Melosh[1], P. Cassen[2], D. Sears[3] and G. Lugmair[4], [1]Lunar and Planetary Lab (University of Arizona, Tucson AZ 85721 jmelosh@lpl.arizona.edu), [2]SETI Institute (46999 Dunlap Rd. Miramonte, CA 93641 pcassen@mail.arc.nasa.gov) [3]Cosmochemistry Group (Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701). [4]Max Planck-Institute for Chemistry, Cosmochemistry, (P. O. 3060, 55020 Mainz, Germany).

Introduction: The origin of chondrules remains one of the central unsolved problems of meteorite science. Theories purporting to explain their origin abound, but consensus on any one theory is still elusive. A major complication is that chondrules are highly diverse and can be classified in several different groups. The most primitive "chondrites" apparently lack chondrules altogether. Everyone agrees that these ubiquitous structures record a history of sudden melting followed by rapid quenching, but the source of the heat, whether it is nebular electrical discharges, shock waves or something else, has not been established. One early suggestion for the origin of chondrules was impact melting [1]. Glassy, chondrule-like spherules are common in the lunar soil [2], where they are attributed to distal impact ejecta [3]. Microtektites, microkrystites [4] and highly altered spherules occur as distal impact ejecta in many parts of the Earth [5]. Thick beds of these objects in Archean rocks of Australia and South Africa closely resemble the texture of chondritic meteorites, although the terrestrial spherule beds are now highly altered from their original composition.

Can Impacts Make Chondrules? In terrestrial and lunar experience, impacts seem to be uniquely capable of producing small liquid droplets that cool to form glass or crystalline spherules [6]. However, impacts also produce a much larger volume of fragmented rock debris. Only the sorting provided by distance can separate the low volume, but fast-moving, melt and vapor fraction from the much larger volume of slow-moving rock debris in normal impacts. Impacts on asteroidal-size bodies cannot appeal to this separation mechanism because of their low escape velocity, so such impacts must inevitably eject far more fragmental material than molten droplets. Some fragmental material does, indeed, occur in several classes of chondrules, but it is usually not the dominant component. Unless one makes the apparently extreme assumption of liquid target bodies (Sanders, this conference), it seems difficult to make a plausible case for an impact origin of chondrules, and so this mechanism has fallen out of mainstream consideration (but, in the light of recent data on ^{60}Fe, whose heat input lasts longer than ^{26}Al [7], perhaps this possibility should not be dismissed).

Nevertheless, it seems worthwhile to examine once again this mechanism in the light of modern theories of planetary accumulation and recent spacecraft data. In particular, current accretion models [8] suggest that the present mass in the asteroid belt may be only about 0.01% of its original mass. Most of that mass may have been in the form of lunar to Mars-sized protoplanets whose mutual collisions could have ejected large masses of material (In contrast, the most numerous bodies were much smaller. The predominance of mass is due to the approximate 1/diameter^2 cumulative number distribution). In this case, the substantial escape velocities of such large bodies may have served as the filter that separated melt/vapor from fragmental material, just as distance sorts molten tektites from impact breccias on the present Earth.

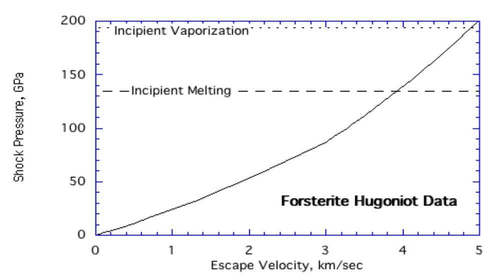

Figure 1. Shock pressure versus impact velocity for Forsterite [9]. Fully dense Forsterite is quite refractory. However, if the target is porous, melting and vaporization may take place at considerably lower pressures [10] and escape velocity.

Giant Impacts: The basic physics of a planetary scale impact is the same as a small-scale asteroidal or even laboratory impact. The principal difference is the escape velocity of the target. Typical asteroidal escape velocities are a few m/sec, whereas the escape velocity of a moon-size body is about 2.5 km/sec. In such an impact only the fastest material can escape from the surface into space. Although the discovery of Martian meteorites has highlighted the process by which a small amount of solid material can escape a planetary-size body without serious shock damage

[11, 12], the bulk of the ejected material is subject to shock pressures large enough to melt or vaporize the rock (Figure 1). Slower-moving solid ejecta falls back onto the surface of the parent planet—which eventually either suffers a catastrophic collision that entirely disrupts it or, more likely, is ejected from the solar system by interactions with the newly-formed Jupiter. The ejected melt and vapor then condense and may accumulate on the surface of smaller bodies to form the progenitors of the chondritic meteorites.

The relative impact velocity during the early phases of accretion must be low enough that impacts do not eject more than the impactor's own mass. However, during the later stages when relative velocities are increased by gravitational interactions with both Jupiter and other planetesimals, impact velocities increase and net accretion may give way to net erosion. For the present Moon, this transition occurs at about 10 km/sec [13], assuming vertical impacts. It is possible that oblique impacts may decrease this limit, but the necessary systematic computations have not yet been done. Oblique impacts also tend to enhance melting and vaporization by the process of jetting [14], a process implicated in current models of the moon's origin by giant impact [15].

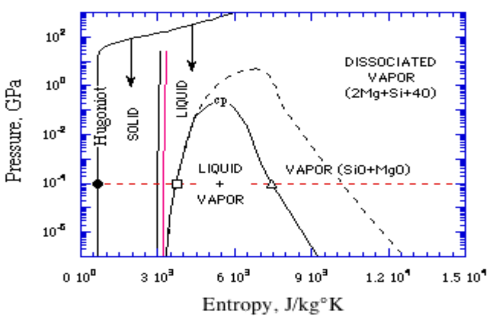

Figure 2. Shock Hugoniot and release curves for Forsterite from the updated ANEOS equation of state [16]. The release adiabat (vertical lines on this plot) that just passes through the complete melting curve is associated with a particle velocity of 4.5 km/sec.

Impact melting and vaporization: When an impact of any size occurs the collision results in a shock wave that compresses, then releases material from high pressure. The compression process is irreversible and, if strong enough, may cause a change of state of originally solid material to liquid or vapor. Studies of the equation of state of olivine, a major constituent of most chondrules, indicate that the immediate effect of a shock is to transform olivine to a supercritical fluid at high pressure and temperature. At velocities high enough to initiate melting or vaporization the release path is generally on the melt side of the critical point, so the expanding hot fluid essentially boils and disperses into droplets (Figure 2).

Because of the relatively large impact velocities necessary to cause both planetary erosion and substantial melting, chondrules formation by this impact mechanism must involve large bodies whose escape velocity regulates the average impact velocity of the planetesimal swarm [17]: As stated by many previous authors, impacts on small bodies produced much more fragmented rock than melt. Besides separating melt and clastic fragments, large body impact also have the advantage that large impacts produce the bulk of the melt, just because large bodies dominate the mass distribution. However, if chondrules do originate in large body impacts, a number of consequences follow: 1) Chondrule production must have occurred late in the accretion process, since the large bodies on which they originated take time to grow. This prediction accords well with the generally low ^{26}Al in chondrules [7]. 2) The accretion process must have allowed the formation of large, undifferentiated bodies. 3) Because impact melting and ejection requires rare, large collisions, the age distribution of chondrules should show several discrete spikes, each dating a single large collision. Future research must decide whether these predictions either support or rule out a chondrules origin by large impacts.

References:

[1] Urey, H.C. & Craig, H. (1953) *Geochem. Cosmochim. Acta* **4**, 36. [2] Scarlett, B. & Buxton, R.E. (1974) *Earth Planet. Sci. Lett.* **22**, 177. [3] Symes, S.J.K., *et al.* (1998) *Meteoritics and Planet. Sci.* **33**, 13. [4] Glass, B.P., Burns, C.A., Crosbie, J.R. & DuBois, D.L. (1985) *J. Geophys. Res. Suppl.* **88**, D175. [5] Simonson, B.M. & Glass, B.P. (2004) *Ann. Rev. Earth Planet. Sci.* **32**, 329. [6] Vickery, A.M. & Melosh, H.J. (1991) *Lunar Planet. Sci.* **XXII**, 1441. [7] Lugmair, G.W. & Shukolyukov, A. (2001) *Meteoritics and Planet. Sci.* **36**, 1017. [8] Chambers, J.E. & Wetherill, G.W. (2001) *Meteoritics and Planet. Sci.* **36**, 381. [9] Pierazzo, E., Vickery, A.M. & Melosh, H.J. (1997) *Icarus* **127**, 408. [10] Horz, F. & Schaal, R.B. (1981) *Icarus* **46**, 337. [11] Melosh, H.J. (1985) *Geology* **13**, 144. [12] Head, J.N., Melosh, H.J. & Ivanov, B.A. (2002) *Science* **298**, 1752. [13] O'Keefe, J.D. & Ahrens, T.J. (1977) *Science* **198**, 1249. [14] Melosh, H.J. & Sonnett, C.P. in *Origin of the Moon* (eds. W.K. Hartmann, Phillips, R.J. & Taylor, G.J.) pp. 621 (Lunar and Planetary Inst., Houston, 1986). [15] Canup, R.M. (2004) *Icarus* **168**, 433. [16] Melosh, H.J. (2000) *31st LPSC,* Abstract #, 1903. [17] Safronov, V.S. *Evolution of the protoplanetary cloud and formation of the Earth and planets* 1-206 (NASA Tech. Transl., TTF-667, 1972).