HEATING BY LIGHT AND THE SIZE DISTRIBUTION OF CHONDRULES;

D. D. Eisenhour, T. L. Daulton, and P. R. Buseck, Departments of Geology and Chemistry, Arizona State University, Tempe, Arizona 85287.

Introduction: One of the most notable characteristics of chondrules is their limited sizes which range from ~0.1 to 3.0 mm in diameter with chondrules < 0.1 mm conspicuously rare [1]. Two commonly proposed explanations for this restricted size range are evaporation and sorting [2-4]. However, there are observational and/or theoretical difficulties with both of these interpretations. Sorting models provide a reasonable explanation for the chondrule population in any single meteorite but run into difficulties when all meteorites are considered collectively. Evaporation models have the advantage of relating the size distributions of chondrules to the heating events responsible for their formation but agree poorly with chondrule and chondrite compositions and are physically implausible. A more reasonable explanation is found in the formation of chondrules by electromagnetic radiation. When chondrules are heated by predominantly visible light, their size distributions are easily accounted for as a natural product of the heating process.

Discussion: Sorting theories assume that a broad chondrule distribution formed initially and that some physical process later separated them into different size bins. Regions containing different chondrule populations then supposedly accreted to form chondrites with the restricted chondrule distributions we observe today. This scenario reasonably explains the chondrule populations in individual chondrites but has difficulty explaining the chondrule population when all chondrites are considered collectively. Meteorites containing 0.1 to 3.0 mm chondrules are common, but those with chondrules < 0.1 mm are disproportionately rare. If sorting is responsible for the size distributions of chondrules in chondrites, then small chondrules are largely unaccounted for, posing a difficult problem for sorting theories. An additional difficulty with sorting is that the bulk compositions of chondrites are similar regardless of the proportion of chondrules (more refractory) to matrix (less refractory). This complementary relationship suggests that the chondrules and matrix of individual chondrites were derived locally without significant transportation and fractionation as is implied by sorting.

The complete destruction of chondrules < 0.1 mm through evaporation has also been proposed to explain the size distribution of chondrules. However, there is little support for this process, either observationally or theoretically. Two prominent problems exist: small surviving chondrules should be highly depleted in volatile elements, which is not generally observed, and more importantly, it is highly unlikely that evaporation would eliminate small chondrules from the population in the first place. The evaporation process could destroy small chondrules < 0.1 mm but would replace them by the incomplete evaporation of larger chondrules. Small chondrules would never be eliminated from the population!

Close examination of the heating properties of electromagnetic radiation provides a plausible solution to the difficult problem of chondrule size distributions. Chondrules with different sizes reach different peak temperatures when heated by predominantly visible light because larger chondrules absorb visible light more efficiently than do smaller chondrules, or stated more precisely, at a given temperature larger chondrules absorb visible light more efficiently relative to their ability to emit radiative energy than do smaller chondrules. This is not because larger chondrules have a larger geometric cross-section, but because their greater thickness makes them more opaque to visible light (visible light has a large extinction distance in chondrule-forming silicates). Over a limited size range, this means heating is roughly proportional to a chondrule's volume rather than its cross-section. Conversely, because both large and small chondrules emit a large portion of their energy in the infrared (~10,000 - 40,000 nm) where the extinction distance is small, cooling ability is roughly proportional to surface area. This translates to a radius dependence for heating; i.e., larger chondrules get hotter than smaller chondrules when heated by predominantly visible light.

Figure 1 shows the results from computer simulations of heating initially cold (400 K) chondrules for 300 seconds with predominantly visible light emitted from a 4000 K blackbody source. Calculations are based on both the wavelength-, and size-dependent absorption and emission efficiencies of typical olivine-pyroxene chondrules [5]. Peak chondrule temperatures are plotted as a function of chondrule size. Different curves represent heating at various distances from the light producing source and are labeled in units of flux normalized to the flux at the source (f/f_0). Note the mm-sized chondrule distribution that would be produced from this kind of radiative heating. Smaller chondrules reach lower peak temperatures because of their inability to efficiently absorb visible light, while very large chondrules remain cool because of the short exposure to heating (larger chondrules have greater thermal inertia). Similar results are obtained for a variety of heating conditions provided the incident radiation is predominantly located in the visible portion of the spectrum. Longer heating times simply stretch out the tail on the large chondrule end of the peak (which is only important if pre-chondrule aggregates of this size existed in chondrule formation regions initially).

For simplicity, grains were assumed to be spherical in the calculations for the temperature distributions shown in Figure 1. This assumption is well suited for chondrules, individual mineral grains, and roughly-spherical, compact grain aggregates. The temperature values shown in Figure 1 are less accurate for fluffy pre-chondrule aggregates, or aggregates with abundant opaque mineral inclusions. For the case of abundant opaque inclusions, the prominent heating peak would become less pronounced due to the preferential rise in temperature of chondrules, grains, or aggregates smaller than ~1.0 mm. For the case of fluffy aggregates, temperatures would be lower for all sizes and the heating peak would shift to the right as individual constituent grains would behave more like independent absorbers and emitters; the overall shape of the curve would remain the same, however.

The ability of light to produce chondrule-like size distributions through preferential heating is in itself compelling evidence for the existence of such a process, especially considering the apparently limited alternatives. However, additional support for this process is provided by the existence of inclusions of dispersed opaque minerals in chondrules, features which are characteristic of heating by intense visible light [5-7]. The ability of these unique opaque mineral assemblages to record the existence of intense visible light relies on the markedly different absorption properties of opaque minerals and silicates. Similar to the size-dependent heating described above, opaque minerals are preferentially heated because of their ability to preferentially absorb visible light; the difference being that for opaque minerals increased absorption is due to the small extinction distance for visible light rather than greater thickness as is the case for larger chondrules. Together, the existence of these characteristic, dispersed, opaque mineral inclusions and the size-dependent heating properties of light provide strong evidence for the formation of chondrules by radiative heating and suggest that the size distribution of chondrules is a natural consequence of the formation process.

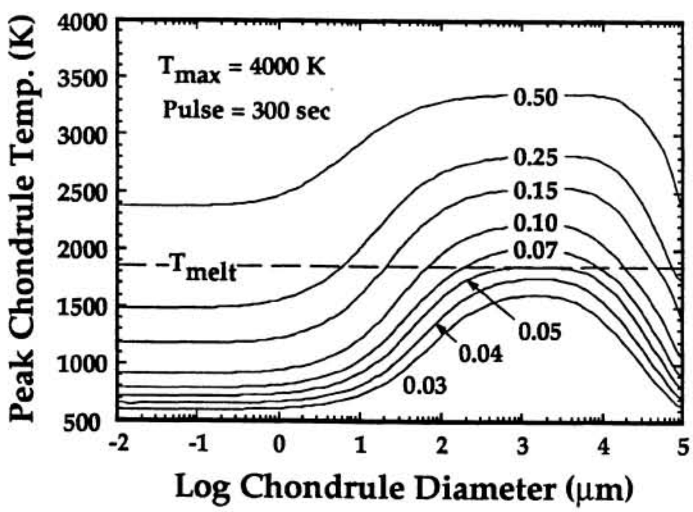

Fig. 1. Peak chondrule temperature as a function of size produced by heating chondrules for 300 sec. with light emitted from a 4000 K blackbody source. T_{melt} is the melting point of typical chondrules. Curves represent heating at different distances from the light producing source (see text).

References: **[1]** Grossman, J. N., *et al.* (1988) in Meteorites and the Early Solar System, J. F. Kerridge and M. S. Mathews eds., (University Tucson Press): 619. **[2]** Dodd, R. T. (1976) *Earth Planet. Sci. Lett.* **30:** 281. **[3]** Rubin, A. E., *et al.* (1982) *Geochim. Cosmochim. Acta* **46:** 1763. **[4]** Rubin, A. E., and Keil, K. (1984) *Meteoritics* **19:** 135. **[5]** Eisenhour D. D., *et al.* (1994) *Science*: (submitted). **[6]** Eisenhour, D. D., and Buseck, P. R. (1993) *LPSC* **XXIV:** 437. **[7]** Eisenhour, D. D., and Buseck, P. R. (1993) *Meteoritics* **28:** 344.