PRIMORDIAL LIGHTNING: EVIDENCE PRESERVED IN CHONDRITES; D. Eisenhour and P. R. Buseck, Departments of Geology and Chemistry, Arizona State University, Tempe, Arizona 85287.

Introduction: An increasing body of evidence suggests that transient heating events were important in forming or modifying many constituents of chondritic meteorites. For example, chondrule compositions and textures imply high cooling rates (~5 to >2000°C/hr) with only limited exposure to elevated temperatures (>1200°C) [1]. Similarly, experimental studies of CAIs exhibiting igneous textures suggest cooling rates from 0.5 to 1000°C/hr [2], and thermal pulses as short as milliseconds may be responsible for CAI rim formation [3]. Additionally, the spectrum of organic compounds observed in chondrites suggests that transient heating may also have played an important role in their formation [4]. The exact nature of these transient events is less clear. A variety of mechanisms have been proposed (e.g., shock melting, drag heating, volcanism, electric discharges, and magnetic reconnection). However, a consensus is lacking as to which or what combination of these mechanisms was responsible for the range of features we observe in chondrites today. Much of the difficulty lies in the inability to identify features unique to any given process. Here we discuss electric discharges ("lightning") as a transient heat source and describe its unique signature preserved in chondrites.

Discussion: Previous discussions of electric discharges have focused on those mechanisms considered most efficient: a) heating by collisions with electrons and ions within the conducting channel [5], and b) by the magnetic pinch effect, i.e., heating by channel collapse resulting from a self-induced magnetic field [6]. Unfortunately, the products produced by these mechanisms are unlikely to preserve unambiguous evidence of the unique character of their formation. Primordial lightning has, therefore, been evaluated more in terms of its physical plausibility than on its record preserved in meteorites [5,6,7].

We address the less efficient, but far more diagnostic mechanism of radiative heating produced by the electromagnetic pulse associated with an electric discharge. The property of the EM pulse that makes it unique is its frequency-dependent interaction with various types of chondritic matter. Terrestrial lightning, which produces an EM pulse that can be approximated by a blackbody radiating at ~20,000 to 25,000 K, emits approximately 90% of its EM energy in the 300 to 1100 nm range [8]. For lower pressures, such as those expected in the solar nebula at 3 AU (although we by no means presume such a setting *a priori*), channel temperatures of ~10,000 K may be more plausible [5]. Under these conditions, the corresponding blackbody curve would be shifted to slightly lower frequencies, and lower channel opacities would make atomic transition lines more pronounced. However, for the present argument the exact spectral distribution is not important, only that the bulk of the EM output be between ~300 and 1600 nm, which is easily satisfied.

Over thicknesses of several to several tens of micrometers, most chondritic silicates absorb little energy in the visible and near infrared (typically less than 10%) [9], especially those silicates low in transition metal cations (e.g., forsterite, enstatite, gehlenite). These minerals are heated inefficiently by a passing EM pulse in this frequency range. Other minerals such as magnetite, pentlandite, troilite, and metals absorb strongly in this energy region and are, therefore, heated much more efficiently. The result is preferential melting and or evaporation based on optical properties rather than on volatility. (For a similar discussion on grain survival in a supernova environment see [10].) This preferential heating is still not helpful in itself, because little is gained by comparing the thermal history of one grain to another, both of uncertain parentage. We already know that some components of chondrites were heated and cooled more rapidly than others. However, the preferential heating effect is distinctive when opaque phases are enclosed in non-opaque silicates. The ensuing quench produces a variety of "dirty snowball" textures similar to that shown in figure 1. These "dirty snowballs" occur in a variety of chondrite components and are composed of a range of phases. In chondrules they appear as <1- to 20-μm assemblages of spherically dispersed opaque minerals such as troilite, pentlandite, taenite, and magnetite in a matrix of olivine or pyroxene. Similar features also occur in individual matrix olivines. In CAIs they are most commonly distributed within or adjacent to rims exhibiting a wide range of compositions, from pentlandite and taenite within andradite to refractory noble metals dispersed in olivine, pyroxene, melilite, and spinel hosts. The only feature these "snowballs" have in common is that all are composed of optically opaque phases spherically distributed in optically transparent hosts.

An estimate of the magnitude of a discharge necessary to produce the observed features can be made by using terrestrial lightning as an analogue. We use as an example a dirty troilite + olivine "snowball" of radius 5 µm, with each phase constituting one half by volume. The pre-lightning assemblage would then be an r ~ 4-µm sphere of troilite enclosed within olivine. If we assume an ambient temperature of 500 K, an olivine liquidus temperature of 2000 K (~Fo_{85}), mean heat capacities of 185 and 65 J mol^{-1} K^{-1}, and heats of fusion of 75 and 32 kJ mol^{-1} for olivine and troilite, respectively, a minimum of ~40 ergs is required to melt the assemblage, assuming no heat is conducted to the remaining host olivine. Taking 50 μm^2 as the cross section of the initial troilite sphere gives a time integrated flux (net energy density) of 80,000 J m^{-2}. Assuming olivine and troilite reflectances of 10 and 40%, respectively, and neglecting olivine absorption, raises the value to 150,000 J m^{-2}.

Measurements of terrestrial lightning indicate a mean, 300 to 1100 nm, single-stroke EM density of 15,000 J m^{-2} at the lightning channel surface [11]. Given the magnitude range of terrestrial lightning [8], ~1% of strokes may have outputs as high as 150,000 J m^{-2}. Considering that the EM energy accounts for only ~0.5% of the total input energy [11], the electrical potential energy released in a single discharge is equivalent to that required to form 10,000,000 millimeter-sized chondrules. Of course no real process would form chondrules at 100% efficiency, and this says nothing about the frequency with which these discharges may have occurred. However, it is clear that discharges of this magnitude would release ample energy to form chondrules by one of the more efficient mechanisms mentioned earlier. It should be noted that the use of the terms "electric discharge" and "lightning" here are not meant to exclude the potentially similar processes associated with magnetic reconnection [12]. The important point is that an intense EM pulse of short duration is characteristic of the process.

Although evidence of lightning is preserved in chondrites, it is unlikely that this was the sole means of transient heating. While it is easily argued that chondritic material can be melted in an electric discharge, it is more difficult to account for cooling rates as low as ~5°C/hr. A combination of processes, inclusive of lightning, seems more plausible. In fact, it may not be unreasonable to envision these processes working together. Other proposed mechanisms such as heating in turbulent shear zones [13] may, as a byproduct, provide the differential gas/grain velocities necessary to produce the charge separation required for the production of lightning. Estimates of discharge magnitude, similar to those presented here, may help to constrain such associated processes. The important point, however, is that a process analogous to lightning did play an important role in producing the features we observe in chondrites today.

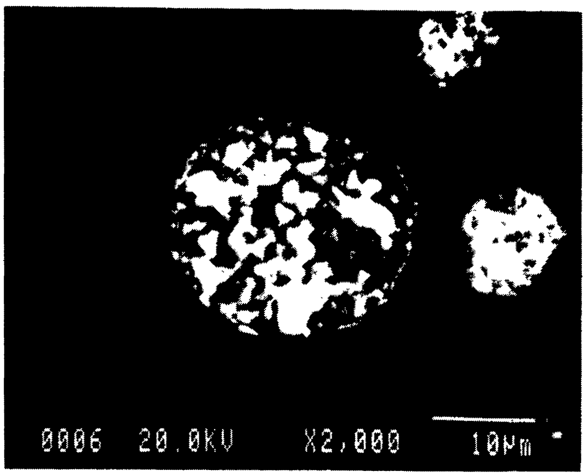

Fig. 1. "Dirty Snowball" composed of troilite and olivine (from Allende).

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