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Evaporation of nebular fines during chondrule formation

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Abstract

Studies of matrix in primitive chondrites provide our only detailed information about the fine fraction (diameter <2 μm) of solids in the solar nebula. A minor fraction of the fines, the presolar grains, offers information about the kinds of materials present in the molecular cloud that spawned the Solar System. Although some researchers have argued that chondritic matrix is relatively unaltered presolar matter, meteoritic chondrules bear witness to multiple high-temperature events each of which would have evaporated those fines that were inside the high-temperature fluid. Because heat is mainly transferred into the interior of chondrules by conduction, the surface temperatures of chondrules were probably at or above 2000 K. In contrast, the evaporation of mafic silicates in a canonical solar nebula occurs at around 1300 K and FeO-rich, amorphous, fine matrix evaporates at still lower temperatures, perhaps near 1200 K. Thus, during chondrule formation, the temperature of the placental bath was probably >700 K higher than the evaporation temperatures of nebular fines. The scale of chondrule forming events is not known. The currently popular shock models have typical scales of about 10^5 km. The scale of nebular lightning is less well defined, but is certainly much smaller, perhaps in the range 1 to 1000 m. In both cases the temperature pulses were long enough to evaporate submicrometer nebular fines. This interpretation disagrees with common views that meteoritic matrix is largely presolar in character and CI-chondrite-like in composition. It is inevitable that presolar grains (both those recognized by their anomalous isotopic compositions and those having solar-like compositions) that were within the hot fluid would also have evaporated. Chondrule formation appears to have continued down to the temperatures at which planetesimals formed, possibly around 250 K. At temperatures >600 K, the main form of C is gaseous CO. Although the conversion of CO to CH_4 at lower temperatures is kinetically inhibited, radiation associated with chondrule formation would have accelerated the conversion. There is now evidence that an appreciable fraction of the nanodiamonds previously held to be presolar were actually formed in the solar nebula. Industrial condensation of diamonds from mixtures of CH_4 and H_2 implies that high nebular CH_4/CO ratios favored nanodiamond formation. A large fraction of chondritic insoluble organic matter may have formed in related processes. At low nebular temperatures appreciable water should have been incorporated into the smoke that condensed following dust (and some chondrule) evaporation. If chondrule formation continued down to temperatures as low as 250 K this process could account for the water concentration observed in primitive chondrites such as LL3.0 and CO3.0 chondrites. Higher H_2O contents in CM and CI chondrites may reflect asteroidal redistribution. In some chondrite groups (e.g., CR) the Mg/Si ratio of matrix material is appreciably (30%) lower than that of chondrules but the bulk Mg/Si ratio is roughly similar to the CI or solar ratio. This has been interpreted as a kind of closed-system behavior sometimes called "complementarity." This leads to the conclusion that nebular fines were efficiently agglomerated. Its importance, however is obscured by the observation that bulk Mg/Si ratios in ordinary and enstatite chondrites are much lower than those in carbonaceous chondrites, and thus that complementarity did not hold throughout the solar nebula.

Keywords: Meteorites; Solar nebula

1. Introduction: the fine fraction of chondrites

Primitive chondrites consist of coarse materials that experienced melting (chondrules and extrachondrule metal grains) and unmelted fine materials ("matrix"). These fine materials, called "holy smoke" by K. Fredriksson (Rambaldi et al., 1981), differ from chondrules in composition (e.g., Huss et al., 2005).

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Two main origins for chondritic fines have been proposed: (1) as primitive, presolar matter that experienced only minor alteration prior to chondrite agglomeration (e.g., Alexander, 2005); or (2) as solids formed by vaporization and (re)condensation in chondrule-forming regions in the solar nebula (Wasson and Trigo-Rodriguez, 2004). Scott and Krot (2005) suggested that the heat associated with chondrule formation can also cause amorphous solids to crystallize.

It is widely accepted that chondrules formed by flash-melting preexisting solids. The temperature necessary to produce a fully molten chondrule is about 1800 to 2100 K (Hewins and Radomsky, 1990; Wasson, 1996). Reducing the melt fraction to 60% lowers the median temperature by about 100 K. For purposes of this paper I will use a mean chondrule melting temperature of 1900 K.

In contrast, in a canonical nebula with a pH_2 of 0.1 Pa (10^{-6} atm) the 50%-condensation temperatures of Mg as forsterite (Mg_2SiO_4) and of Fe as Fe–Ni metal are about 1250 K; at a nebular pressure of 1 Pa the condensation temperatures are about 1300 K (e.g., Wasson, 1985). To condense 50% of Si requires that some enstatite ($MgSiO_3$) or silica (SiO_2) also condense, resulting in a condensation temperature perhaps 30 K lower than for Mg. Evaporation of 50% of these elements from nebular solids under equilibrium conditions occurs at the same temperatures. These three elements and their oxides account for about 90% of the nebular solids stable at temperatures of 650 to 1250 K. It follows that, during chondrule formation events, the precursor nebular solids reach temperatures at least 600 K higher than their evaporation temperatures.

Major-element compositions of nebular fines are known for a handful of highly primitive, unweathered chondrites. More detailed characterization by bulk techniques is difficult because excavated samples include appreciable amounts of chondrule fragments and because the chondrites having high matrix fractions have generally experienced aqueous alteration. There is no doubt that much of the Fe in fines is present as FeS or FeO and that some of the solids are amorphous (e.g., Brearley, 1993; Huss et al., 2005; Nuth et al., 2005). Troilite evaporates at ∼650 K (e.g., Wasson, 1985). Both FeO-rich solids and amorphous solids are more volatile than magnesian mafic silicates and metal; thus the mean evaporation temperature of fines is appreciably lower than those cited above for mafic silicates and metal. A conservatively high estimate is 1200 K. The indicated conclusion is that the difference between the mean evaporation temperatures of fines and mean chondrule-surface temperatures (and the associated thermal bath) is ∼700 K or greater.

2. Estimates of matrix fractions in chondrites

The best way to determine the abundance of matrix in chondrites is with S X-ray maps such as that of CR LAP 02342 shown in Fig. 1. In CR chondrites most chondrules have low FeO contents and essentially no FeS; a shimmer of FeS decorating the metal grains was probably introduced during aqueous alteration. Although metal is common on chondrule surfaces, FeS is generally not present. Based on this map the matrix fraction of LAP 02342 is estimated to be 31 vol%.

Literature estimates of matrix fractions in primitive chondrites are summarized in Table 1. The column labeled % fines gives my working estimates based mainly on the values listed by Brearley and Jones (1998) and by Alexander (2005).

3. Energetics of chondrule formation

Wasson (1996) reviewed the energetics of chondrule formation. The as-yet uncertain chondrule formation mechanism had

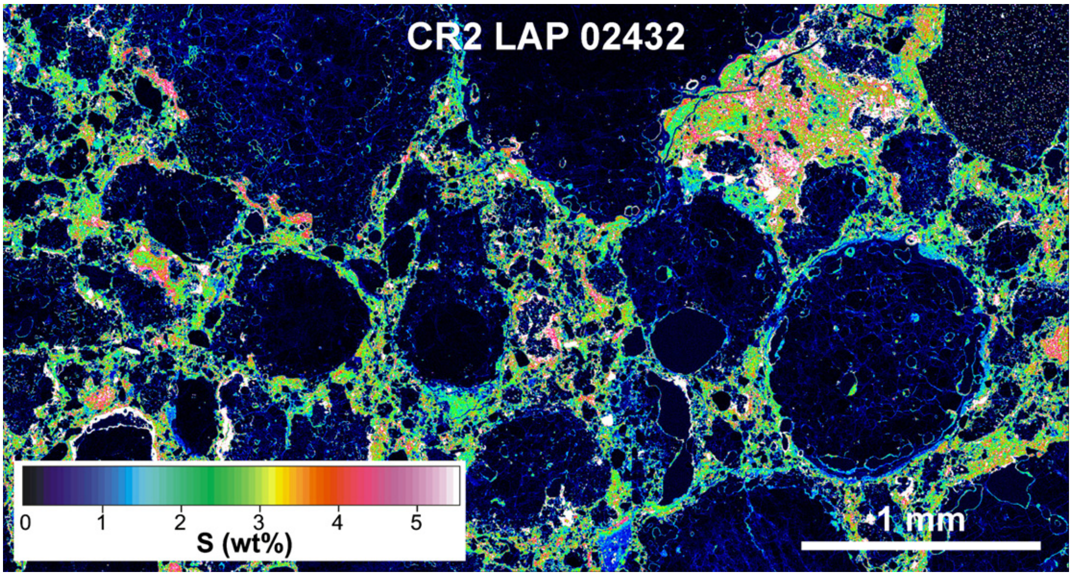

Fig. 1. Sulfur X-ray image. In this 5 × 2 mm area of the CR chondrite LAP 02342 the areas containing fine matrix are recognized by their high S contents. The S concentrations were determined by moving the sample stage of an electron-microprobe in 2 μm steps. The fraction of S inside chondrules is very small, and the fraction on chondrule surfaces is minor. In separate experiments using arrays of about 50 points the mean S content of the matrix was found to be 3.4 mg/g; about 80% of the S in LAP 02342 is in the matrix.