**PRIMARY AND SECONDARY TROILITE IN ORDINARY-CHONDRITE CHONDRULES: IMPLICATIONS FOR CHONDRULE FORMATION.** Alan E. Rubin[1] and Alan L. Sailer[1,2]; [1]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA; [2]Rockwell Science Center, Thousand Oaks, CA 91358, USA.

Troilite in the chondrules of type-3 chondrites may be primary (i.e., part of the original chondrule melt) or secondary (i.e., introduced during parent-body thermal metamorphism [1], shock metamorphism [2] or aqueous alteration [3]). To determine the origin of troilite in chondrules we examined 225 intact chondrules of all textural types in thin sections of eight unshocked to weakly shocked ordinary-chondrite (OC) falls of low petrologic type (LL3.1,S2 Bishunpur; L/LL3.4,S1 Chainpur; LL3.1,S3 Krymka; LL3.4,S1 Piancaldoli; LL3.3,S2 St. Mary's County; LL3.0,S2 Semarkona; H3.4,S3 Sharps; H/L3.6,S3 Tieschitz); 68 chondrules are from Semarkona.

Secondary troilite occurs in a few percent of Semarkona chondrules. Some chondrules (particularly in one portion of section USNM 4128-4) are adjacent to massive troilite and contain numerous thin troilite veins that cut across mafic silicate grain boundaries and patches of mesostasis; some of the veins are connected to the massive troilite in the chondrule rim. The troilite-rich veins resemble those in silicate fractures in artificially heated Krymka [4] as well as veins in some lightly shocked equilibrated OC wherein molten metal and troilite were injected into silicate fractures [2]. Although the olivine phenocrysts in the chondrules with the troilite veins lack planar fractures (i.e., they are not shock stage S3), it seems plausible that heterogeneous energy deposition melted the external troilite and injected it into chondrule interiors. Another variety of secondary Fe sulfide (troilite or pyrrhotite) in the outer portions of some chondrules occurs within opaque nodules in association with magnetite, carbide, Ni-rich sulfide, Ni-rich taenite and Co-rich kamacite [3]. These assemblages are identical to those in the Semarkona matrix and probably formed by hydrothermal alteration of metallic Fe-Ni and troilite on the LL parent-body [3].

Most troilite-bearing chondrules in Semarkona lack secondary troilite; ~70% of them contain troilite grains or troilite-bearing assemblages within one-half radius of the chondrule center that are completely surrounded (in two dimensions) by mesostasis or embedded in mafic silicate phenocrysts. Such isolated troilite grains are unlikely to be products of fluid-induced alteration or to have formed by inward diffusion of S from the matrix during mild metamorphism. We conclude that these troilite grains are primary.

Low-FeO (type I) porphyritic chondrules in Semarkona typically contain several spherules composed entirely of metallic Fe-Ni and no spherules composed entirely of troilite. Some metallic Fe-Ni spherules are surrounded by 0.5-3 µm-thick partial or continuous troilite rinds constituting ~5-15% of the spherule diameter. The spheroidal shapes of the metal-troilite blebs resulted from the surface tension of their precursor droplets which were immiscible in the surrounding silicate melt. In metal-sulfide droplets in relatively slowly cooled silicate chondrules, metal crystallizes first, and the residual, increasingly sulfide-rich liquid is pushed to the margins of the droplet. Eventually, troilite crystallizes as a rind around the metal.

A few low-FeO chondrules possess metallic Fe-Ni spherules that contain 0.5-2-µm-size polygonal to rounded grains of troilite. In rapidly cooled metal-sulfide droplets, pockets of residual sulfide-rich melt may become trapped by surrounding solidified metal. Troilite crystallizes in these pockets.

High-FeO (type II) chondrules in Semarkona have much higher mean troilite/metallic-Fe-Ni ratios than low-FeO chondrules: 1.8 *vs.* 0.05 wt.% [5,6]. Few spherules composed entirely of metallic Fe-Ni occur; in contrast, spherules and irregular grains composed entirely of troilite are common. Troilite rinds on metallic-Fe-Ni-rich spherules tend to be thicker than those in low-FeO chondrules, typically constituting ~50% of the spherule diameter. The high troilite content of high-FeO chondrules probably reflects that of their precursors.

With increasing metamorphic grade, troilite rinds on metallic Fe-Ni spherules in low-FeO chondrules tend to become thicker (as documented experimentally [7]) and the textural differences between the metal-troilite assemblages in low-FeO and high-FeO chondrules diminish. For example, low-FeO chondrules in type-3.6 Tieschitz have much thicker partial and complete troilite rims around metallic Fe-Ni spherules than in type-3.0 Semarkona. The troilite within metallic-Fe-Ni-bearing spherules in type-I porphyritic chondrules in LL4 Bo Xian constitutes 35-70% of the diameter of the spherules.

The presence of primary troilite in some chondrules indicates that the chondrule droplets could not have remained molten for extensive periods. Otherwise, much of the troilite would have been lost. Unpublished calculations by J.T. Wasson indicate that a 200-µm-diameter sphere of troilite would have an evaporation half-life of 11 s at 1700 K and 4.5 s at 1800 K (at the low end of inferred chondrule peak temperatures: 1750-2150 K; [8,9]). Although in real chondrules most troilite is not exposed at the surface (as assumed in the calculations), these results suggest that chondrules remained at their peak temperatures only briefly. Brief chondrule heating is also indicated by the retention of moderately volatile Na in augite and glassy mesostasis in many low-FeO chondrules in Semarkona [6].

The occurrence of chondrules with igneous rims and relict grains and of independent enveloping compound chondrules indicate that many chondrules (≥25% of OC chondrules) were heated more than once [10]. Although some troilite-bearing chondrules may have been melted multiple times, it is clear that the last time they were melted, S was present. This indicates that ambient nebular temperatures had cooled below ~650 K (the 50%-condensation temperature of S at pressures between $10^{-4}$ and $10^{-6}$ atm [11]).

Eleven chondrules in the survey (two from Semarkona) are low-FeO objects that contain metallic Fe-Ni but no troilite. Either these chondrules or their precursors never contained troilite or the troilite was lost during or after chondrule formation. It is unlikely that troilite could have been quantitatively expelled by centrifugal force during chondrule melting because many of these chondrules contain a few volume percent metallic Fe-Ni. Because troilite and metallic Fe are completely miscible in the Fe-FeS system, it is improbable that troilite could have been expelled and metallic Fe-Ni retained in these chondrules while they were spinning molten droplets. It is also unlikely that troilite could have been completely volatilized because $Na_2O$-bearing augite and $Na_2O$- and $K_2O$-bearing mesostases have been retained in many of these chondrules. Experiments [e.g., 12] suggest that if significant amounts of Na and K survive chondrule melting, then some sulfide should also have been retained. It therefore seems likely that troilite was never present in the precursors of these chondrules. The chondrule-formation mechanism is inferred to have been active throughout the period it took ambient nebular temperatures to cool from ~910 K to ~650 K (the 50%-condensation temperatures of Na and S, respectively [11]).

**References:** [1] Zanda B. et al. (1995) *Meteoritics* **30**, 605; [2] Rubin A.E. (1992) *GCA* **56**, 1705-1714; [3] Krot A.N. et al. (1997) *GCA* **61**, 219-237; [4] McSween H.Y. et al. (1978) *PLPSC* **9th**, 1437-1447; [5] Jones R.H. (1990) *GCA* **54**, 1785-1802; [6] Jones R.H. and Scott E.R.D. (1989) *PLPSC* **19th**, 523-536; [7] Lauretta D.S. et al. (1997) *EPSL* **151**, 289-301; [8] Hewins R.H. and Connolly H.C. (1996) In *Chondrules and the Protoplanetary Disk (CPD)* (eds. R.H. Hewins et al.), pp. 197-204, Cambridge University Press; [9] Scott E.R.D. et al. (1996) *CPD*, pp. 87-96; [10] Rubin A.E. and Krot A.N. (1996) *CPD*, pp. 173-180; [11] Wasson J.T. (1985) *Meteorites: Their Record of Early Solar System History*, Freeman; [12] Yu Y. et al. (1996) *CPD*, pp. 213-219.