Microchondrules in OC have been reported in two principal settings: (1) as rare individuals in the fine-grained matrices of many type-3 chondrites [3,11] and in the clastic matrix of the Dimmitt H regolith breccia [3]; and (2) as the predominant or exclusive chondrule size in a few unequilibrated clasts in LL3.4 Piancaldoli [3], the Rio Negro L regolith breccia [3], L3.7 Mezö-Madaras [12], and LL3.1 Krymka [13].

The 150 × 200-μm Krymka clast contains ~30 olivine microchondrules (Fa_{22-46}), 3–31 μm in apparent diameter, embedded in fine-grained matrix material. The 5-mm Rio-Negro clast contains about 30 radial pyroxene (RP) chondrules 5–74 μm in apparent diameter as well as a few normal-sized chondrules and chondrule fragments embedded in fine-grained silicate matrix. The 1-mm Piancaldoli clast contains ~100 RP chondrules (0.25–64 μm in apparent diameter) embedded in fine-grained silicate matrix; ~15% of the chondrules are compound. The mean composition of the low-Ca pyroxene grains is $Fs_{4.0}Wo_{1.3}$. The 6 × 8-mm dark clast in Mezö-Madaras contains >140 chondrules (2–150 μm in apparent diameter), lithic fragments, and mineral grains embedded in fine-grained silicate matrix. One microchondrule was also found in a troilite-rich rim around a porphyritic olivine (PO) chondrule in Mezö-Madaras [12].

We report here another major setting for microchondrules, one that sheds new light on their origin and has important implications for the general problem of chondrule formation. We have found that several fine-grained rims of matrixlike material around normal-sized porphyritic chondrules contain numerous microchondrules with apparent diameters of <20 μm.

A dumbbell-shaped 850 × 1500-μm type I PO chondrule in L3.4 EET90161 is surrounded by a 50–80-μm-thick fine-grained rim containing a high abundance (>100) of microchondrules. The microchondrules are homogeneously distributed in the rim and vary in diameter from 2–20 μm; they have similar textures and compositions.

A 500-μm-diameter porphyritic olivine-pyroxene (POP) chondrule in L3.4 EET90261 is surrounded by a 50–70-μm-thick fine-grained rim containing ~30–50 microchondrules, 2–10 μm in apparent diameter. The microchondrules have similar textures and compositions.

A 1250 × 1850-μm chondrule in LL3.1 Bishunpur is a compound object consisting of a PO primary and two POP secondary adhesions. The whole compound chondrule is surrounded by a 100–150-μm-thick fine-grained rim containing a high abundance (>100) of homogeneously distributed microchondrules. The microchon-drules vary in apparent diameter from 2 μm to 50 μm and have similar textures and compositions.

The occurrence of discrete clasts and chondrule rims consisting of abundant microchondrules of similar textures and compositions within fine-grained matrix material indicates that each set of microchondrules formed as a "cloud" of microdroplets during a single chondrule-forming event; they are analogous to normal-sized "sibling" compound chondrules [14]. The occurrence of compound microchondrules also indicates that they formed at high number densities as independent free-floating objects. The microchondrules either formed by simultaneous melting of dust concentrations within a large dustball or by disruption of a normal-sized chondrule droplet. These observations lead to two principal conclusions:

1. Because a microchondrule "cloud" would dissipate quickly due to random motions, it seems inescapable that the fine-grained material that now composes the matrixlike clasts and rims was in the immediate vicinity of the microchondrules when they formed. This same material may even have been the immediate precursor of the microchondrules. If the matrix-rich clumps in which the microchondrules are entrained were the same precursors from which they formed, the present ferroan compositions of the clumps (e.g., 34 wt% FeO in the matrix of the Piancaldoli clast [3]) relative to the microchondrules (e.g., 2.7 wt% FeO in Piancaldoli) implies that matrix material became increasingly oxidized with time.
2. The survival of dusty material during chondrule formation, as indicated by the coexistence of microchondrules and fine-grained matrix material, suggests that chondrule formation in general occurs in small (centimeter-sized) regions. Highly localized heat sources such as lightning seem particularly suitable melting mechanisms.

The very small weight fraction of microchondrules in OC could have resulted from a formational process, which preferentially destroyed microchondrules by efficient recycling into larger chondrules or by nebular size-sorting subsequent to chondrule formation [15]. Collisonally induced collapse of the microchondrule-bearing dust clumps may have led to the formation of the chondrule rims and clasts.

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THE JET MODEL OF CHONDRULE FORMATION.

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We estimate the size range of particles that are ejected from a protostellar accretion disk by a protostellar jet. An n-body code is used to determine the subsequent motion of the ejected particles, where the particles are subject to two forces: the gravitational attraction from the protostar, and the gas drag from the halo gas of the accretion disk.

It is highly probable that a protosolar jet existed at the very beginning of the solar system. Such a jet may have influenced the chemical structure of the solar nebula by recycling heated material back into the nebula. Protostellar jets eject a considerable amount of mass (10^{-3}–10^{-1} $M_\odot$) over a long lifetime (10^6–10^7 yr)[1,2]. A protosolar jet, if it existed, could have ejected 10^{-5}–10^{-3} $M_\odot$ of "rocky" material (i.e., all elements excluding H and He) from the solar nebula. If only 10% of this material were to fall back to the solar nebula then we would have 10^{-6}–10^{-4} $M_\odot$ of rocky (possibly refractory) material being contributed to the solar nebula over a 10^6–10^7-yr period. Given that the "rock" mass of the planets is of order 10^{-4} $M_\odot$, a protosolar jet may have made a significant contribution to the chemical structure of the solar nebula. Indeed, it is possible that ejecta from the jet flow may have been incorporated into the best preserved samples of the solar nebula: the chondritic meteorites.

Protostellar jets appear to be formed from the innermost regions (≤0.1 AU) of protostellar accretion disks. At such close proximity to the protostar, one would expect any nongaseous disk material to be in a molten or semimolten state. We have undertaken an analytic analysis of the expected droplet size that can be ejected by the jet flow and find that the droplet radius is ≤1 cm. The gas densities and speeds required to eject such large objects from the close environs of a protostar have been shown (in previous studies) to be well within theoretically expected and observationally confirmed ranges [1–3]. The subsequent motion of these objects, once they are decoupled from the jet flow, is shown to be a linear path across the face of the accretion disk.

If these ejected particles pass through a sufficiently large section of the accretion disk's upper atmosphere, then their speed will become smaller than the escape velocity, and the particles will settle back to the accretion disk (see Fig. 1). It is shown that the denser and larger a particle is, the further it can travel through the gas halo of an accretion disk, thereby producing density-dependent size sorting of particles. Since chondrules have sizes (≤1 cm) that are inversely proportional to their density, it is suggested that chondrules are ablation droplets produced by a protostellar jet.

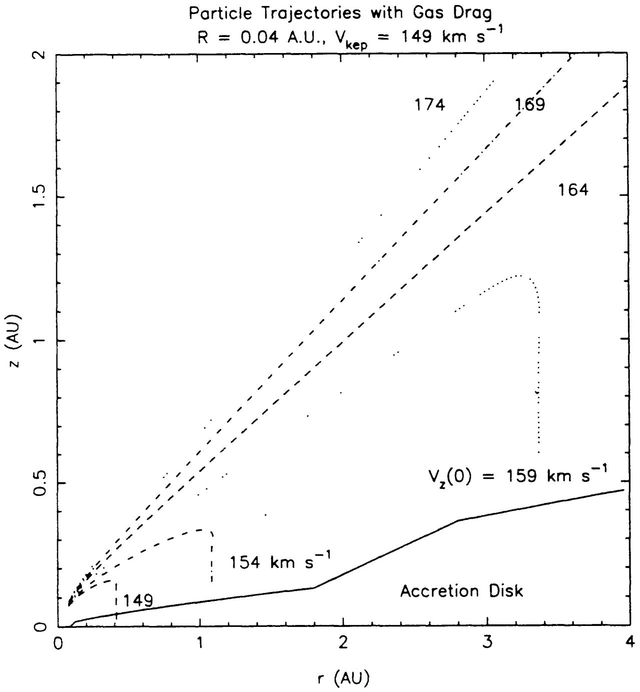

Fig. 1. A solar-mass protostar is located at r = 0, z = 0. Surrounding the protostar is an accretion disk, the scale height of which is shown in profile. Particles are initially in a circular Keplerian orbit of radius R = 0.04 AU. The particles are then given a vertical "boost" velocity, the magnitude of which (in units of km s^{-1}) is shown next to the particles' trajectories. Particles that are subjected to sufficiently high gas drag are later recaptured by the accretion disk.

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EXPERIMENTAL CONSTRAINTS ON MODELS FOR THE ORIGIN OF CHONDRULES: COOLING RATES.

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There has long been a fascination with chondrules, and one of the first questions is how fast do they cool, or how long was the chondrule-forming event? Stefan-Boltzman calculations for 2-mm molten droplet chondrules suggest they would cool in a few seconds [1]. But most chondrules are porphyritic and such textures require longer to crystallize. Porphyritic textures in fact suggest slow rates, but how slow?

In one of the earliest systematic, dynamic crystallization studies of cooling rate, Tsuchiyama et al. [1] reproduced porphyritic, barred, and radial olivine textures from three different melt compositions. They found the cooling rates to be in the range 3000°–7200°C/hr, although the best olivine porphyritic textures developed at 1200°C/hr. They attributed the varying textures to compositional differences, with the textures becoming finer grained as silica content increases. Hewins et al. [2] studied a pyroxene-rich chondrule composition and found that cooling from a total melt produced radial pyroxene textures at cooling rates of 50°–3000°C/hr. Planner and Keil [3] produced microporphyritic chondrules with cooling histories that contained a temperature plateau, which they found necessary to get the more Fa-rich olivine compositions observed in porphyritic chondrules. Lofgren and Russell [4] applied knowledge gained in the study of the nucleation characteristics of terrestrial basalts [5] to a dynamic crystallization study of pyroxene-rich (and later olivine-rich) chondrule melts [6]. While it was clear that porphyritic chondrule textures could be produced at very slow cooling rates (< 5°C/hr), it would be more compatible with current models if they could be produced at faster rates. These latter studies combined with [7,8] systematically showed that with nuclei present in the melt, cooling rates up to 1000°C/hr and even higher would still produce porphyritic textures. Barred olivine and pyroxene and radial textures could be produced from an even larger range of cooling rates, 5°–3000°C/hr.

The Lofgren studies [4–7] help to explain the observation of [1] that the primary variable in producing texture was the composition of the melt. In fact, the primary variable is heterogeneous nucleation. Tsuchiyama et al. [1] used three compositions with increasing silica content ranging from olivine-rich to pyroxene-rich chondrule melts. With increasing silica, the liquidus temperature decreases. They used a constant melting temperature of 1600°C. Their most olivine rich was not totally melted so that nuclei remained in the melt at that temperature and upon cooling a porphyritic texture resulted. The other two compositions were totally melted at 1600°C and nucleation did not occur until significant supercooling had developed and barred and radial textures resulted. The pyroxene-rich composition was superheated so much at 1600°C that only olivine, not pyroxene, nucleated upon cooling, resulting in the radial olivine texture. Hewins et al. [2] were able to get radial pyroxene from a melt of similar composition because they melted their starting material just above the liquidus and pyroxene was able to