THE FORMATION OF CHONDRULES. Derek W. G. Sears, Shaoxiong Huang and Paul H. Benoit, Cosmochemistry Group, University of Arkansas, Fayetteville, Arkansas 72701.

Many properties of chondrules (cooling rate, efficiency of production, the large number of compound chondrules, complimentary composition relative to matrix, size-sorting, and the inferred composition of ambient gases) seem to be inconsistent with chondrule formation in a nebula setting. It also seems that the arguments levied against an origin by impact are no longer convincing: (1) Chondrules formed well after the formation of proto-Jupiter so that the relative impact velocities in the asteroid belt (especially near resonances) were high enough to produce melts; and (2) recent theoretical calculations for impact into weak asteroids, prompted by observations of Phobos and Gaspra, suggest that >50% of the ejecta returns to the asteroid surface; (3) arguments based on the lack of chondrules on the lunar surface ignore differences in the sizes of the parent objects, their locations in space and their surface compositions. We suggest that impact on a regolith remains the most likely mechanism for the origin of chondrules.

The origin of chondrules is one of the most important topics in meteorite genesis and yet one of the least well-understood. Chondrites, the most primitive of the meteorite classes, may consist of up to 80 vol% of chondrules. The theories for chondrule origin that have been advanced may be briefly summarized in terms of four scenarios [1]. *Condensation in the nebula* by mechanisms involving regions of very high pressure, subcooling, dust enrichment, or H_2 depletion. These ideas have proved unpopular because nebula temperatures and pressures were not high enough and because of the abundance of volatile elements in the many chondrules and the extreme heterogeneity of chondrules. *Fusion of interstellar dust in the nebula* by aerodynamic heating or chemical potential has not proved popular because of the "complimentary compositions" of matrix and chondrules and other reasons. *Fusion of nebula dust* by lightning, impact or magnetic processes in the midplane and off-plane (with or without mechanical abrasion) has been the most popular idea in recent years but requires what seem to be an alarmingly large number non-nebular (or unusual nebular) conditions. These are:

- A high chondrule density. About 80 vol% of meteorite may be chondrules, which implies that chondrites contain $\sim 1.5 \times 10^9$ chondrules per m^3 (assuming 1-mm diameter chondrules).
- A $P(O_2)$ in the ambient gases that is enriched over the cosmic value by factors of about 1000. This applies not only to the chondrules which contain high FeO, and cosmic compliments of volatile elements, but also to those that contain low FeO-silicates and are depleted in volatile elements [2]. Some authors have suggested that increasing the dust-to-gas ratio by factors of ~ 1000 might have achieved the required high $P(O_2)$ [3].
- Aerodynamic sorting requires high gas and dust densities [4].
- The "complimentary" composition of components suggests that the components were not separated during their chemical processing [3].
- There was elemental and isotopic exchange during chondrule formation, which implies much higher gas densities than "nebula" [2,5,6].
- Chondrule cooling rates were much slower than possible in the solar nebula; 1-1000 $^{o}C/h$ c.f. $10^6/h$ [1].
- Charged particle tracks are absent suggesting that the chondrules were not independent entities in the nebula [7].

Planetary impact on a regolith was popular for many years but fell out of favor in the face of several objections [8] which we will here discuss.

Impact velocities were too low. If chondrite parent bodies formed in circular orbits in the asteroid belt, then their relative velocities would be too low for chondrule formation. However, petrographic observations indicate that chondrule formation, accretion, metamorphism, and brecciation overlapped in time [9] and radiometric observations indicate that aggregation and lithification occurred some $n \times 10^6$ years after the onset of accretion (marked by the formation of the refractory inclusions in carbonaceous chondrites) [10].

Since Jupiter formed very quickly (within $\sim 10^5$ years of the onset of accretion, [11]) the asteroid belt was "stirred up" by resonances with proto-Jupiter (or the jovian core, [12]), so that mean relative velocities were ~5 km/s, prior to the formation of the chondrules and sufficient to produce impact melts.

Meteorite parent bodies were so small that chondrules would be ejected into space and lost. Early work concerning impact on rocky asteroids suggested that ejecta velocities exceeded escape velocities [13]. However, prompted by observations that Phobos and Gaspra may have thick regoliths [14], recent work indicates that asteroids with a lower strengths than that of solid rock used in earlier work would produce low ejecta velocities and 50-70% of the ejecta (depending mainly on impact velocity) would return to the parent asteroid [15, 16].

Chondrule size-sorting. We have pointed out that the evaporation of water and other volatiles from the regolith of the meteorite parent body would produce a temporary atmosphere which would "fluidize" the dust and create conditions suitable for separating metal and silicate in the manner observed for chondritic meteorites [17]. Such an environment would also result in the size-sorting of chondrules. The flux and velocities of the fluids required are both surprisingly small because of the small size of the parent body. Quantitative calculations indicate that the size distribution of the metal grains and chondrules found in each of the ordinary chondrite classes is consistent with this mechanism and also result in the observed metal-silicate ratios in the ordinary chondrite classes. If chondrules formed in such a regolith, then data for chondrules and refractory inclusions in CV chondrites and chondrules from ordinary chondrites suggest that the temporary atmosphere had an oxygen isotope composition near the terrestrial line on the oxygen three-isotope plot [5].

Lack chondrules on the lunar surface. The lack of chondrules on the lunar surface is often cited as an argument against impact origin for chondrules, and yet there are major differences between the Moon and the meteorite parent bodies [18]. The composition of the lunar surface is less conducive to melt formation, the Moon has a mass about 3×10^5 times greater than any likely meteorite parent body and impact mechanisms are quite different (gravity vs. strength regime) and the Moon was formed in a quiescent region of the nebula, instead of one with a large number of relatively small objects being put onto high inclination orbits by orbital interactions with the proto-Jupiter. In fact, the most noteworthy feature of the lunar surface is that despite these major differences, the lunar surface does contain a large number of small impact glasses in the form of the agglutinates, which constitute as much as 50% v/v of the lunar surface. It seems that the main relevance of lunar surface to the question of chondrule origins is why did agglutinates form on the Moon and chondrules form on the meteorite parent bodies? We suspect that the time interval between ejection of the melt droplets and their return to the surface of the parent body was the main factor.

It appears that the difficulties of forming chondrules in a nebular setting are formidable and that most of the objections to the idea that chondrules formed by impact on an asteroidal regolith are no longer viable. It also seems that surface processes, including variations in the energy and number of impacts, were probably the major factor in determining the properties of chondrules, chondrites and asteroidal surfaces.

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