THE CASE FOR CHONDRULES AND CAI BEING RARE IN THE EARLY SOLAR SYSTEM: SOME IMPLICATIONS FOR ASTROPHYSICAL MODELS. Derek W. G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701.

The abundance of chondrules (and CAI) is often considered a major constraint on models for the early solar nebula. While this may be true, it is also possible that these high-temperature meteoritic components are rare and that observational biases caused by passage through the atmosphere and ejection mechanisms in the asteroid belt cause us to over-emphasize the role of the chondrules in nebula processes. Consistent with this, asteroid reflectivity spectra suggest that ordinary chondrite-like asteroids are rare, even assuming that space weathering has altered their surfaces. It is possible that small localized stochastic events were responsible for the formation of chondrules and that the implications for nebula-wide processes in the early solar system are very limited.

Chondrules (and their refractory relatives, the CAI) in certain classes of meteorite clearly require that high-temperature events of relatively short duration occurred in the early solar nebula [1]. The very large number of processes that have been proposed to account for these objects is a measure of the degree of uncertainty in identifying that process [2]. Despite this, the suggestion is often made, implicitly or explicitly, that chondrules (and to some extent CAI) place major constraints on astrophysical processes occurring in the early solar nebula. Arguments have been made that the energy to form chondrules was a significant fraction of total nebula energy [3], that chondrules must have been formed during the gravitational collapse of the nebula [4] or that CAI and chondrules are the result of bipolar solar outflows and have travelled large distances across the inner solar system [5]. Certainly chondrules and CAI provide new insights into processes occurring in the early solar system. However, it is also possible to argue that they are rare, requiring special circumstances for their formation, and that the total energy involved in their formation was small relative to nebula energetics.

The argument for chondrules being rare in the early solar system

Chondrule abundance varies widely in the chondrite classes, chondrules being least abundant in the most primitive (*i. e.* volatile-rich) classes (Table 1). The ordinary chondrites are richest in chondrules, with 65-75 vol %, but the EH, EL, CV and CO chondrites are <50 vol % chondrules. The CM chondrites contain <15 vol% (normally 5-10 %). The CI chondrites are completely devoid of chondrules. Silicate inclusions in iron meteorites and HED meteorites contain chondrules, but they are very rare. By any reckoning CAI are rare, constituting 6-13 vol % of a class that is 0.84% by number of observed falls. CV-chondrite-like asteroids are ~0.3% by number.

Statistics for meteorites falling to Earth give a very biased view of the composition of the asteroid belt, their presumed source region. According to fall statistics (Table 2), 89.5% of observed falls are ordinary chondrites or other classes with similar physical properties, 5.0% are irons and 2.26% are CI and CM chondrites. Thus chondrules should be abundant in the asteroid belt and maybe as much as one-half of solar system material has been through the energetic chondrule-forming process [3]. However, three factors bias these statistics:

- The atmosphere screens all but the most robust meteorites from falling to Earth. One would expect irons to be over-represented and CI and CM chondrites to be under-represented among observed falls relative to ordinary chondrites. Baldwin and Shaeffer [11] calculate that "carbonaceous" (by which they mean CI and CM) chondrite masses decrease by a factor of 10^3 during atmospheric fall while ordinary chondrites suffer little destruction (Fig. 1). They argue that carbonaceous chondrites should dominate the meteoroid flux beyond the atmosphere. If we assume the likelihood of recovery of a meteorite on Earth is proportional to its mass, we should correct the fall statistics by multiplying the number of carbonaceous meteorite falls by 1000. Their abundance among observed falls then increases from 2.26% to 96.5% [11]. Collectors carried by aircraft flying along fireball trails confirm the much greater fragmentation and ablation of carbonaceous meteorites [12,13]. Since CI chondrites are ~20% water [14], while CM chondrites <10 vol% water, we expect a major bias against CI chondrites relative to CM chondrites.
- Very particular orbital evolution may be required to deliver an object from the asteroid belt to Earth (the "orbital evolution" model of ref. 15), *e. g.* close proximity to a secular resonance. Thus

- the belt is not randomly sampled, but objects that are fortuitously close to the resonances are preferred. For instance, Gaffey argues that a single S(IV) asteroid near the t_6 resonance, 6 Hebe, which also has the appropriate spectrum, is the sole H chondrite source [16].
- If fragmentation events are required to eject and deliver asteroid fragments to Earth (the "collisional model" of ref. 15) then sampling is stochastic and depends on the nature of the impactors. Cosmic ray exposure ages [17], induced TL data [18], and Ar-Ar ages [19] indicate that the ~500 ordinary chondrites come from remarkably few parent bodies and that fragmentation is an important event in the history of meteorites. Maybe the second and third points are related, *i. e.* impacts are more likely near resonances or impacts are required for injection into resonances.

If we multiply the likelihood of making it through the atmosphere with the likelihood of being sufficiently close to a resonance or undergoing fragmentation sufficient to send the fragments to Earth, then perhaps >95% of objects in the asteroid belt are not chondrule- or CAI-bearing. Spectral reflectivity observations (Table 2) suggest that <11% of the asteroids are ordinary chondrite-like, maybe <<11%. Only if space weathering is camouflaging their surfaces [20], and this is highly controversial, does the number of ordinary chondrite-like asteroids rise to 11%. Proposed ordinary chondrite parent bodies are the Q asteroids (0.41 % by number of classified asteroids) or a subset of the S(IV) asteroids. The remaining asteroids are CI- or CM-like or differentiated [21].

Astrophysical implications

It can thus be argued that chondrules and CAI were probably rare in the early solar system and do not require nebula-wide mechanisms involving nebula-scale energy input. They may be the result of highly localized processes where the amounts of energy involved are large only on a highly localized basis. Detailed objections can be made to some of the nebula-scale models for chondrule-formation (*e.g.*, chondrules formed several million years after the first-formed solar system solids, and if CAI travelled nebula-scale distances why are they only abundant in a small, rare class of chondrites) but, regardless of these details, the fundamental premise of these models can be reasonably questioned. Similar arguments to these have been made from the perspective of meteorite data and asteroid studies [22].

[1] King (ed.) (1983) *Chondrules and their origins*. [2] Boss (1996) In *Chondrules and the protoplanetary disk*, 257. [3] Levy (1988) In *Meteorites and the early solar system (MESS),* 697. [4] Wood (1995) *LPS* **26**, 1517. [5] Shu *et al.* (1996) *Nature* **271**, 1545. [6] Grossman (1988) In *MESS*, 619. [7] Zhang *et al.* (1996) *JGR (Planets)* **100**, 9417. [8] Sears and Dodd (1988) In *MESS*, 3. [9] Tholen (1989) In *Asteroids II*, 1139. [10] Gaffey *et al.* (1993) *Icarus* **106** 573. [11] Baldwin and Shaeffer (1971) *JGR* **76**, 4653. [12] Folinsbee *et al.* (1967) *GCA* **31**, 1625. [13] Folinsbee et al. (1968) J. Roy. Astron. Soc. Canada **63**, 61. [14] Jarosewich E. (1991) *Meteoritics* 25, 323. [15] Greenburg and Nolan (1979) In Asteroids II, pp. 778. [16] Gaffey (1996) *Meteoritics* 4 Suppl. A46. [17] Marti and Graf (1992) *Ann. Rev. Earth Planet. Sci.* **20**, 221. [18] Benoit and Sears (1996) *MAPS* 31, 81. [19] Bogard (1995) *MAPS* **30**, 244. [20] Chapman (1996) *MAPS* **31**, 699. [21] Gaffey *et al.* (1993) *Meteoritics* 28, 161. [22] Bell (1995) *Meteoritics* **30**, 484.

Table 1. Volume percent of chondrules in chondrites [6,7].

H, L, LL	65-75
CV	35-45
CO	35-40
EH, EL	20-40
CM	<15 (usually ~9)
CI	0

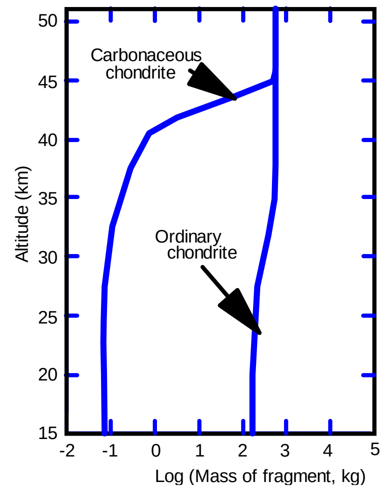

Fig. 1. Altitude *vs.* log mass for a carbonaceous and ordinary chondrite entering the atmosphere at 14.2 km/s, 52^o (relative to the vertical) with tensile strengths of 10^6 and 1.776×10^8 N m^{-2}, respectively [11].

Table 2. Class abundance of observed meteorite falls and asteroids [8-10].

Chondrite class	% by no.	Asteroid class	% by no.
CI	0.06	D	6.2
CM	2.2	P	4.3
CO	0.60	C	22.8
CV	0.84	T	1.3
H,L,LL	79.5	B+G+F	9.1
EH,EL	1.56	Q	0.41
HEDM	7.02	V	0.41
Irons	4.95	R	0.10
		S(IV)	11.0
		S others	25.9
		A	0.71
		M	4.3
		E	1.3