Sears D. W. G. (1998e) The origins of chondrules and chondrites. *Antarctic Meteorites XXIII* (*Papers presented at the twenty-third symposium of antarctic meteorites),* 134-138.

THE ORIGINS OF CHONDRULES AND CHONDRITES. Derek W. G. Sears, Cosmochemistry group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701.

Introduction

The question of the origins of chondrules and chondrites is two-hundred years old (Fig. 1). The essential details are known; chondrites are as old as the solar system (4.6 Ga), have solar composition in all but the most highly volatile elements, and have unique textures that include chondrules [1]. Yet despite this there is considerable controversy as to the origin of the chondrites and the chondrules they contain [2,3]. A great many suggestions involving pre-solar, nebular and parent bodies processes have been discusssed [4,5]. There are important clues. The nature of the chondrules, and their diversity, tell us something about conditions in the early solar system and accounts for many bulk properties of chondrites, as does their abundance in the various classes of meteorite [6]. The size and abundance of chondrules and metal grains tell us that sorting was important in making chondrites [7]. The peaks in the cosmic ray exposure age histograms and K-Ar ages tell us that most chondrites originated on very few parent bodies [8,9], and the spectral reflectivity of the asteroids tells us that very few asteroids are potential meteorite parent bodies [10]. Even if space weathering is a real and important process, less than 11% of the asteroids are potential parent objects. If space weathering is unimportant, then less than 1% of the known asteroids are potential parent bodies. We also know that the chondrites may be sorted into a number of discrete groups depending on bulk composition, the oxidation state of the iron, the relative abundance of metal, chondrules and matrix, and the relative abundance of the three isotopes of oxygen (Table 1). It seems likely that several of these are related through chondrule formation and the so-called metal-silicate fractionation. Finally, we know that surface processes have been important in the history of meteorites, since virtually all chondrites are breccias, gas-rich regolith breccias occur in all classes, and many meteorites are now thought to be impact melt rocks [11,12]. In attempting to put all this together to identify an origin for chondrules and chondrites, I think two processes stand out as particularly important. These are the formation of the chondrules and the metal-silicate fractionation, and I think that there is a high likelihood that they were both processes that occurred on the surface of their small parent bodies.

Table 1. The chondrite classes, particle sizes and metal abundances and certain compositional properties*.

	Ref	EH	EL	H	L	LL	CV	CO	CM	CI
Physical properties										
Chondrule diam. (mm)	13, 14	0.2-0.6	0.8	0.3	0.7	0.9	1.0	0.2-0.3	0.3	--
Metal grain size (mm)	7	--	--	0.20	0.18	0.14	--	--	--	--
Chondrule abund. (vol %)	13, 14	20-40	20-40	65-75	65-75	65-75	35-45	35-40	~15	0
Metal abund. (wt %)	15	22	18	16	6	2	0-7	0-5	0	0
Matrix abund. (vol %)	13, 14	<5	<5	10-15	10-15	10-15	40-50	30-40	~60	100
Compositional properties										
Carbon (wt %)	16	0.42	0.32	0.11	0.12	0.22	0.43	0.38	1.82	2.8
Water (wt %)	16	1.9	1.6	0.22	0.46	0.71	0.25	3.3	10.4	16.9
Fe_m/Fe_t (a/a)	15	0.76	0.83	0.58	0.29	0.11	0-0.3	0-0.2	0	0
Fe/Si (a/a)	15	0.95	0.62	0.81	0.57	0.52	0.76	0.77	0.80	0.86
Mg/Si (a/a)	15	0.77	0.83	0.96	0.93	0.94	1.07	1.05	1.05	1.05
Ca/Si (a/a)	15	0.035	0.038	0.050	0.046	0.049	0.084	0.067	0.068	0.064
$\delta^{17}O$ (‰)	15	3.0	2.7	2.9	3.5	3.9	~-4.0	~-5.1	~-4.0	~8.8
$\delta^{18}O$ (‰)	15	5.6	5.3	4.1	4.6	4.9	~0	~-1.1	~12.2	~16.4

* Major classes only. Small classes like CK, CH, CR, and R chondrites, the primitive achondrites and many anomalous chondrites are not considered here.

Chondrule classification

Attempting to understand objects as diverse as chondrules starts with their classification. The recently proposed compositional classification scheme for meteoritic chondrules divides the chondrules into groups depending on the composition of their two major phases; olivine (or pyroxene) and the mesostasis, both of which are genetically important [17, 18]. The scheme is described in Table 2. Compositional fields enable the identification of eight discrete classes, of which four are found in primitive (*i. e.* essentially unmetamorphosed) chondrites and

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Table 2. Definition of the chondrule groups and frequency of occurrence in two primitive ordinary chondrites, Krymka (LL3.1) and Semarkona (LL3.0)*.

	CL	Mesostases Composition†	CL	Olivine %FeO	%CaO	Frequency‡ Krymka (51)	Semarkona (76)
A1	yellow	Pl(An>50%)	red	<2	>0.17	3.6	10.5
A2	yellow	Pl(An>50%)	none/dull red	2-4	0.1-0.2	0.0	25.0
A3	blue	Pl(An>50%)	red	<4	>0.2	33.3	0.0
A4	blue	Pl(An>50%)	none/dull red	>4	0.16-0.3	7.3	0.0
A5	blue	Pl(An<50%)	none	>4	<0.25	14.5	5.0
B1	none	>30% Qtz	none	4-25	0.08-0.3	0.0	56.9
B2	none	30-50% Qtz	none/dull red	10-25	0.08-0.3	36.4	0.0
B3	purple	15-30% Qtz	none	15-20	<0.08	0.0	2.6

* Phase compositions given as a guide, the group fields are not rectangular (see Sears et al., 1992, 1995, for details). 'CL' refers to cathodoluminescence color.

† Normative composition (wt%) of the mesosotasis: Pl, plagioclase; An, anorthite; Qtz, quartz.

‡ The figures in parentheses indicate the number of chondrules on which the statistics are based. Semarkona data from [19], Krymka data from [6].

four are found in metamorphosed chondrites and are the result of metamorphism of the primitive groups. Group A5 is unique in that it appears in both metamorphosed and unmetamorphosed chondrites, although the degree of compositional heterogeneity decreases with metamorphism. The compositional classification scheme for chondrules is compared with previous schemes in Table 3. The main advantage of the present scheme is that (aside from its suitability for rapidly classifying chondrules in a survey mode using their CL), the scheme relies entirely on the properties of the individual chondrules and avoids subjective descriptions and a knowledge of the petrographic type of the host meteorite. This is especially important for breccias. The CL of chondrules and relative abundance of chondrule classes is so sensitive to metamorphism that the scheme can be used to assign petrographic types to type 3 ordinary chondrites with a precision comparable to that of induced thermoluminescence [18].

Table 3. Comparison of the compositional classification scheme for chondrules with previously proposed schemes.

Compositional Class	Approximate previous equivalents
A1	Includes some of the droplet chondrules of Kieffer [20], some of the non-porphyritic pyroxene chondrules of Gooding and Keil [21], the type I chondrules of McSween [22], metal-rich microporhyritic chondrules of Dodd [23], and the type IA chondrules of Scott and Taylor [24].
A2	Includes the poikylitic pyroxene and type IB chondrules of Scott and Taylor [24] many of the type IAB chondrules of Jones [25, 26]
A5	There appear to be no previous observations of this chondrule group in unmetamorphosed meteorites.
B1	Dodd's [27] "lithic" or "clastic" chondrules and Dodd's [23] metal-poor microporphyritic chondrules are included in this group, as are the type II chondrules of McSween [22], Scott and Taylor [24] and Jones [28].

History of chondrules

Many laboratory experiments have been performed that reproduce the textures observed in chondrules [28], stress the role of nucleation centers, and constrain temperatures and cooling rates of chondrules during formation [29, 30]. A great many potential processes might have occurred during the transient heating and cooling that was clearly the central feature of the processes, such as reduction by ambient gases and carbon, impact by dust, recondensation of valatiles as surface rims and diffusion of volatiles into the interiors of the chondrules [31, 32]. Most of these effects involve gas phases, but some will also involve liquid phases [33]. The major uncertainly, concerns whether chondrules acted as open or closed systems during formation [34, 35]. "Open-system" means that relatively volatile elements (like Fe, Na and K) were lost and the chondrules underwent chemical reactions with species in the environment during formation, while "closed-system" means that the various properties of the chondrules were inherited entirely from the precursors (Fig. 2). Of course, both processes probably occurred, so the discussion is really concerns the relative degree of the two processes. The refractory composition, low-FeO silicates, relatively high metal abundance and low-Ni content of the metal of group A1,2 chondrules are consistent with open-system behavior. A closed-system scenario would require that chondrule precursors were the products of earlier volatility-oxidation processes. The trend in the olivine to pyroxene ratio (which decreases from group B1 to A2 and then increases again in group A1), the smaller mean size of group A1 and A2 chondrules compared to group

B1 chondrules, the relationships between oxygen isotope composition and chondrule size and peak temperature, diffusion of Na into chondrules, and the greater abundance of thick fine-grained rims around group A chondrules relative to group B chondrules are consistent with major evaporative loss, first of FeO and later SiO_2, accompanying the formation of groups A1 and A2 [36, 37]. These properties are difficult or impossible to understand in terms of closed-system behavior. It is concluded that while group A1 and A2 chondrules formed by reduction of FeO and major evaporative loss from precursors originally resembling those of CI chondrites, evaporative loss from group B1 chondrules was restricted to only the most highly volatile trace elements like Ga, Sb, Se and Zn. Thus the process that formed chondrules was capable of acting with a variety of intensities and was responsible for much of the redox differences that separate the chondrite classes.

Nebula origin of chondrules

The theories for chondrule origin involving condensation in the nebula require very high pressures, considerable subcooling, dust enrichments, or H_2 depletion and have difficulty explaining the abundance of the volatile elements and heterogeneity of certain chondrules [4, 5]. Thus they have not proved popular. 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 [4, 5]. 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. In some instances ~ 80 vol% of the meteorite is chondrules. However, ordinary chondrites might be over represented in the terrestrial meteorite collection, because of selection effects in the ejecting meteorites from the asteroid belt and passing through the atmosphere and, as spectral reflectivity data suggest, might be rare in the asteroid belt. Thus the process might be sometimes be highly efficient, but only happens rarely.
- A $P(O_2)$ in the ambient gases that is enriched over the cosmic value by factors of about 1000. Some authors point out that increasing the dust-to-gas ratio by factors of ~1000 would have achieved the required high $P(O_2)$.
- Aerodynamic sorting requires high gas and dust densities.
- The "complimentary" composition of components suggests that the components were not separated during their chemical processing.
- Elemental and isotopic exchange during chondrule formation [38, 39] requires much higher gas densities than "nebula".
- Chondrule cooling rates were much slower than possible in the solar nebula; 1-1000 ^{o}C/h c.f. 10^6/h.
- Charged particle tracks are absent suggesting that the chondrules were not independent entities in the nebula [40].

Origin of chondrules by regolith impact

It appears that the difficulties of forming chondrules in a nebula setting are formidable. It is time to reconsider the possibility that chondrules formed by impact. In fact, most of the objections raised twenty years ago to the formation of chondrules by impact on an asteroidal regolith [41] are no longer viable.

Impact velocities were too low. Petrographic observations indicate that chondrule formation, accretion, metamorphism, and brecciation overlapped in time [42] and radiometric observations indicate that aggregation and lithification occurred some up to 4 x 10^6 years after the onset of accretion (marked by the formation of the refractory inclusions in carbonaceous chondrites) [43,44]. Since Jupiter formed very quickly (within ~10^5 years of the onset of accretion, [45]) the asteroid belt was "stirred up" by resonances with proto-Jupiter (or the jovian core, [46]), 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 [47]. However, prompted by observations that Phobos and Gaspra may have thick regoliths [48], recent work indicates that asteroids with 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 [49, 50].

Chondrule size-sorting. The evaporation of water and other volatiles from the regolith of the meteorite parent body would produce a temporary atmosphere that would "fluidize" the dust and create conditions suitable for aerodynamic and gravity sorting of chondrules. The flux and velocities of the fluids required are both surprisingly

small because of the small size of the parent body. If chondrules formed in such a regolith, then the temporary atmosphere had an oxygen isotope composition near the terrestrial line on the oxygen three-isotope plot [38], similar to that of CI chondrites.
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, yet lunar chondrules are present in Apollo 14 breccias in about the same abundance as CM chondrites (~10 vol %). Simple ballistic calculations show that crystallized impact spherules require long flight times and that only craters comparable in size to the target can achieve this. Thus most impacts on the Moon produce agglutinates or glass spherules [51]. As images of Gaspra, Ida, Matthide demonstrate, such impacts can be important for certain asteriods and there will be bodies where chondrules dominate the local regolith.

It appears that the difficulties of forming chondrules in a nebula 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.

Origin of Chondrites

If chondrules formed by impact into a regolith, and chondrules behaved as open systems during their formation, then the diversity of chondrule compositions presumably reflects the diversity in the intensity of impact. It is a small step to then assuming that the redox state of the resultant chondrite similarly depends on the violence of impacts locally. The remaining factor in forming chondrites concerns the matter of assembling the components, and producing small variations in the amount of matrix and metal in relation to the chondrules. The size and distribution of the chondrules and metal, that are characteristic of many classes of chondrites, suggests sorting before or during accumulation. Again, I a great many mechanisms have been proposed for how this might have been achieved in the nebula, but I think it unlikely that this process occurred in the nebula because the meteorites managed to preserve compositions so close to cosmic and because aerodynamic sorting alone fails quantitatively. Density sorting is also required and this requires the presence of at least a weak gravity field. Some meteorite parent bodies must have experienced degassing in their early stage to turn CI compositions into ordinary chondrite compositions and may have had thick dusty surfaces that were easily mobilized by gases evolving from the interior. Density and size sorting may have occurred in the surface layers as the upward drag forces of gases (mainly water) acted against the downward force of gravity. This process is readily modeled quantitatively because it is analogous to the industrially important process of fluidization [52]. From fluid dynamics in porous media we calculate gas flow velocities and gas fluxes for the regolith of an asteroid-sized object heated by the impact of accreting objects and by ^{26}Al, and we find that both provide sufficient gas velocities and fluxes for fluidization (Table 4). The size and density sorting expected during this process can quantitatively explain metal and chondrule size-sorting and distribution in ordinary chondrites. This scenario is broadly in agreement with the major properties of chondritic meteorites (*i.e.*, redox state, petrologic type, cooling rate, matrix abundance, lithophile elemental ratio, etc.).

Table 4. Calculated and observed metal abundances in H, L and LL ordinary chondrite meteorites.

Flow rate* u (mm s^{-1})	$x_{LL} : x_L : x_H$ (weight ratio)
1.3 × u_{mf}	1.0 : 2.1 : 3.9
1.2 × u_{mf}	1.0 : 2.7 : 6.8
1.1 × u_{mf}	1.0 : 4.5 : 7.4
(observed)	1.0 : 3.0 : 8.0

* u_{mf} refers to the minimum flow rate of LL chondrules, calculated from the Ergun equation.

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