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CONFERENCE ON CHONDRULES AND THEIR ORIGINS

NOVEMBER 15-17, 1982

Sponsored by

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PREFACE

This volume contains papers which have been accepted for publication by the Program Committee of the Conference on Chondrules and their Origins. These abstracts address three major topics: Chondrule Parent Materials, Chondrule Formation, and Post-Formational History. Contributions within this general framework involving mineralogy-petrology, geochemistry, geochronology, isotopic measurements, physical measurements, experimental studies, and theoretical studies are included.

Members of the Program Committee were D. Clayton (*Rice University*), M. B. Duke (*NASA-JSC*), E. K. Gibson (*NASA-JSC*), E. A King, Chairman (*University of Houston*), J. L. Gooding (*NASA-JSC*), D. Heymann (*Rice University*), and P. H. Jones (*Conference Administrator, LPI*).

Logistic and administrative support for this conference has been provided by Pamela Jones and LeBecca Turner (*Projects Office, Lunar and Planetary Institute*). This abstract volume was prepared by Karen Hrametz (*Publications Office, Lunar and Planetary Institute*).

Papers are arranged alphabetically by the name of the first author. An author index is included.

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CONDENSATION OF CHONDRULES, Milton Blander, Argonne National Laboratory, Argonne, IL.60439

It is important to understand the origin of chondrules within the context of the genesis of meteorites. Primary consideration will be given to the formation of chondrules as metastable condensates from a nebula. We will also consider their formation as condensates from impact generated vapors.

Because nucleation constraints on the condensation of solids are greater than those for liquids one can condense metastable liquid silicates (or other oxides) directly from a nebula. At a given pressure, equilibrated molten magnesia-silica rich condensates have a higher Mg/Si ratio at higher temperatures than at lower temperatures. Nucleation of crystals in such metastable subcooled liquids is a stochastic (probabilistic) process with a range of crystallization temperatures (probably near 1300-1400K). Thus, since each liquid drop constitutes a separate physico-chemical system, each should nucleate crystals at a different temperature with different compositions (e.g., Mg/Si ratios) and crystal forms. Because equilibration with the nebula is slowed after crystallization, the varied compositions of the crystallized droplets is largely preserved.

Condensation at temperatures lower than 1300K would form small particles of relatively volatile materials which could accrete (probably non-uniformly) on to the surfaces of chondrules. Reactions between solids in contact are usually much more rapid than those between a solid and the gas so that a major mechanism for compositional changes of crystallized droplets (chondrules) are reactions and interdiffusion of low valent ions (e.g., Na^+, Mg^{++}, Fe^{++}, and Ca^{++}) between the chondrules and accreted later condensates. For example, it is likely that Na^+ ions can diffuse into the chondrules to replace divalent ions, especially if there is a residual glass in which such interdiffusion is rapid.

Metals are wetted by molten silicates and are condensation nuclei for molten droplets. Oxidizable metals (e.g., Fe and Ni) can have significant (but low) concentrations of their oxides in the silicate and diffuse through the droplets and (even the crystallized chondrules) to equilibrate whereas the more noble metals can not. Siderophile contents of chondrules will be variable as they depend on the number, size, and compositions of metal particles which have been picked up by the molten droplets.

At higher pressures, materials condense at higher temperatures so that a larger fraction of the magnesia and silica can condense as metastable liquid droplets. From the fraction of chondrules contained in different meteoritic classes and other aspects of meteoritic chemistry and mineralogy one can deduce that different classes of chondrites formed in different ranges of pressure (i.e. for E chondrites, $p \sim 10^0 - 10^{-2}$ atm., for H, L, LL $p \sim 10^{-3}$, for C $p \sim 10^{-4} - 10^{-6}$).

Turbulence and convection in a nebula can lead to accretion and quantization of compositions of chondrules and of meteorites. For example, if one has a convection cell in a cooling nebula, the temperature decreases more

CONDENSATION OF CHONDRULES

M. Blander

rapidly than average in the motion radially outward from the center of the nebula and molten droplets will condense at some stage. Each cycle of the convection cell will condense material in a fixed range of temperatures. Inertial forces will tend to move chondrules and dust relative to each other when the gas turns radially inward so that chondrules and dust can collide and partially accrete. The chondrules will be reheated during the fall inward. Crystallized chondrules produced from metastable liquids will not necessarily remelt during this reheating stage. Collisions between chondrules and dust can lead to accretion to "chunks" of different size. "Chunks" formed before a high temperature reheating would have a higher metamorphic grade than those accreting during a lower temperature convective cycle. Because condensed materials have a general tendency to fall to the center of a nebula, materials condensed in different temperature ranges in a given location will not necessarily end up in the same meteorite. Each meteorite will represent a collection of condensates from specific ranges of temperature in the convective cells from which it received materials. For example, refractory materials such as calcium-aluminum rich inclusions (which appear to be similar in origin to chondrules) could have formed further from the center of a nebula than chondrules in the same meteorite. The quantization of meteorite compositions in this picture is related to the interplay between convection and the inward motion of condensed material in a nebula. This makes possible differences in the chemical and isotopic compositions of different meteorite classes.

A large fraction of compositional, textural and mineralogical data on chondrules in different meteorite classes has been shown to be consistent with their formation as metastable condensates in a convecting nebula. However, there is data which remains to be examined in this light.

A feasible alternative model is the formation of chondrules as molten condensates from impact generated vapors. The chemistry of such vapors has never been carefully examined in order to test this possibility.

TRACE ELEMENTS IN RIM AND INTERIOR OF CHONDRULES FROM CHAINPUR.

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Since our first report on this work (Wilkening *et al*., 1982), in which we presented data from four chondrules, we have increased the total number of chondrules studied in Chainpur to nine. Following neutron activation, the rims were removed from the chondrules by grinding in four successive stages; the first sample (A) was nearly pure rim and the last sample (D) was pure interior. Each sample of removed powder was gamma counted for INAA using our new fast anti-coincidence spectrometer (FACS). Our physical separation procedure contrasts with that of a similar work by Grossman and Wasson (1982), in which rims were removed from six chondrules by chemical dissolution.

Typical results are presented in Fig. 1 for chondrule number 5. The rim sample, 5A, shows greater amounts of siderophile and volatile lithophile elements than the interior samples, 5B-5D. The rim sample is not as volatile or siderophile-rich as the Chainpur whole rock (Fig. 2), but this result may be due to the presence of some chondrule interior in the rim sample. Our results generally show a somewhat larger difference between rim and interior than the chemical dissolution data of Grossman and Wasson (1982). For example, the five chondrules of our most recent experiment show an average rim/interior ratio for Zn of 5.1, whereas the average ratio for the six chondrules studied by Grossman and Wasson is 1.7. This difference may reflect differences between the physical and chemical techniques or may indicate that the Grossman and Wasson procedures for removing chondrules from the meteorite may have removed most of the rims.

It is clear from our data that neither the chondrules nor the rims on chondrules can account for the complete volatile inventory in Chainpur; another component, probably the matrix, must contain the missing volatile and siderophile elements. This result supports the two-component model of Larimer and Anders (1967), in which the volatile trace elements in chondrites are due to a mixture of volatile-rich matrix and volatile-poor chondrules.

References

Grossman J. N. and Wasson J. T. (1982) *Geochim. Cosmochim. Acta* 46, p. 1081-1099.

Larimer J. W. and Anders E. (1967) *Geochim. Cosmochim. Acta* 31, p. 1239-1270.

Wilkening L. L., Hill D. and Boynton W. V. (1982) Meteoritical Society Meeting Abstracts, p. II-10.

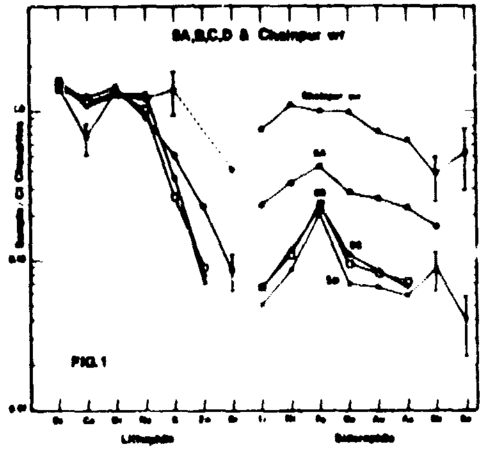

FIG.1

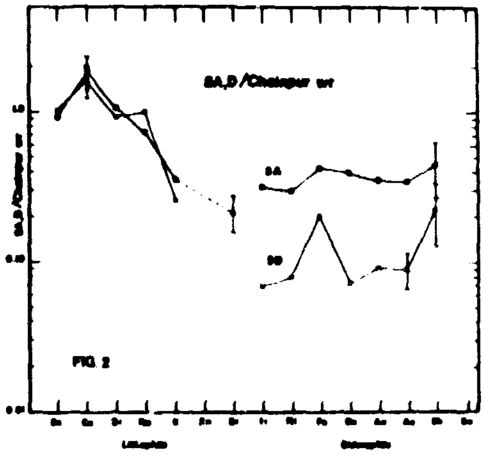

FIG. 2

SiO_2-RICH CHONDRULES IN ORDINARY CHONDRITES

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The solar system abundances of Mg, Fe, and Si dictate that chondritic meteorites are silica-deficient compared to most terrestrial or lunar igneous rocks; thus olivine-orthopyroxene assemblages are commonly observed in ordinary chondrites. However, in the unequilibrated H-chondrites Sharps, Bremervörde, and Dhajala, we have observed chondrules and fragments which contain either tridymite or cristobalite as a major phase. Coexisting with the SiO_2 is predominantly low Ca pyroxene, as expected for a well-crystallized, silica-saturated chondrule. These chondrules are striking in being conspicuously depleted in Ca and Al-rich phases: no feldspar was observed and only tiny grains of Ca-rich pyroxene and material of apparently glass composition have been found. To date, we have observed approximately twenty of these chondrules/fragments; their abundance is $\geq 3/cm^2$ of section. A typical object from each of the three meteorites is described below.

The Bremervörde chondrule (spherical, 0.3 mm radius) is about 40% SiO_2 (by area) with the SiO_2 concentrated towards one side, except for a few laths in the center and a discontinuous inner rim of SiO_2 grains around the pyroxene part of the chondrule. Some grains appear to be crystals which nucleated on the rim and grew inward. The chondrule is completely surrounded by an outer pyroxene rim. The interior pyroxene varies in composition, roughly radially, from $En_{66}Wo_{0.4}$ to $En_{85}Wo_{0.1}$. In the center of the chondrule is a very small region of glass and clinopyroxene. The U content of the SiO_2 phase is 33 ppb.

The Dhajala chondrule (spherical, 0.4 mm radius) is approximately 86% pyroxene, 8% SiO_2 phase and 6% metal. The SiO_2 occurs as angular laths, thin concentric arcs or lamaellae oriented parallel to linear chains of metal blebs. Some pyroxene regions show a lamaellar (exsolution?) texture. Two analyses give $En_{74}Wo_2$ and $En_{36}Wo_{19}$. The upper limit for the U content of the SiO_2 is ≤ 8 ppb.

The Sharps chondrule/fragment (half-circle, 0.6mm radius) has small (~10 micron) SiO_2 grains (~43%, volume) surrounded by interstitial layers of essentially pure fayalite. This fragment was completely rimmed by fine-grained olivine after being broken. Pyroxene in this object is somewhat more Mg-rich ($En_{88}Wo_{0.2}$) than that in other SiO_2-bearing chondrules and appears uniform in FeO content.

The bulk composition of these chondrules is probably similar to some reported by McSween [1] from unequilibrated ordinary chondrites and Kakangari, except that ours are more deficient in CaO and Al_2O_3. Presumably, the SiO_2-rich phase in the chondrules of McSween is typical chondrule glass; ours generally is crystalline.

A simple explanation for the SiO_2-rich, low Ca, Al chondrules found in Bremervörde and Dhajala is a process involving fractional condensation of a nebular gas. If the high temperature fraction ($\geq$1350°K) is removed after condensation, there is excess SiO_2 left in the gas which can condense as SiO_2. The SiO_2-rich chondrules from Sharps are clearly different from those observed in Bremervörde and Dhajala. The texture of the Sharps objects is suggestive of alteration or decomposition. The fayalite-SiO_2 assemblages observed in Sharps could be explained by rapid quenching of the immiscible liquids formed in the two liquid regions of the FeO-MgO-SiO_2 system. One of these liquids would yield Mg-rich pyroxene and SiO_2; the other would produce ferrosilite and SiO_2 which would decompose to form fayalite and SiO_2.

References: [1] McSween H.Y. (1977) Geochimica-Cosmochim. Acta <u>41</u>, 1843-1860.

METEOR ABLATION SPHERULES AS CHONDRULE ANALOGS, D. E. Brownlee,[1] B. Bates[1] and R. H. Beauchamp,[2] [1]University of Washington, Seattle, WA 98195, [2]Battelle Northwest, Richland, WA 99352.

The production of meteor ablation spherules by the atmospheric melting of small meteoroids is an analog chondrule formation process in which certain boundary conditions are known. Stony "cosmic spheres" found in deep sea sediments apparently formed predominantly from fine grained parent materials with carbonaceous chondrite composition. The spheres formed and cooled on a time scale of seconds in a gas of $\sim 10^{-5}$ atm. pressure. Ablation spherules have strong similarities to chondrules but differ from typical chondrules in several ways. These differences and similarities provide some insight into the environments and processes which formed chondrules in the solar nebula. An additional aspect of the spheres is they are samples of "planetary chondrules" which form on all planetary bodies that have permanent or transient atmospheres with appropriate densities and scale heights.

The deep sea spheres are composed of olivine with minor amounts of magnetite and interstitial glass. The common spheres occur with both barred and porphyritic textures. Barred structures are by far the most common although usually they are not rimmed and commonly they have coarse mosaic textures. Remarkably more than 99% of the spheres which totally melted during atmospheric entry contain only olivine as the crystalline silicate phase. Roughly 5% of the spheres of 0.5mm size contain relic grains which did not melt during sphere formation. The grains are usually enstatite or forsterite and they have well defined equilibration rims where they contact recrystallized material. A small fraction of the "spheres" are highly vesicular and are products of only moderate heating of chondritic material.

The elemental composition of the spheres is remarkably chondritic except for depletion of siderophile and volatile elements. Sulfur, Rb and Na are usually highly depleted in the particles in contrast to their relatively chondritic abundances in chondrules. The observed spherules range from mildly heated ones which retain abundant vesicles and relic grains to those which have lost Na by volatilization. These effects imply a wider range of maximum temperature for the spheres than for chondrules. Extreme ranges of heating can occur for ablation spheres because of differing entry velocities. Siderophile depletion in the spheres is believed to be predominantly due to the loss of a single metal bead during entry. This process is illustrated by fractionation in stony spherules which contain metal. The metal occurs as a bead and apparently the bead is usually ejected from the sphere due to deceleration or centrifugal force. There is evidence that the metal phase is created by rapid reduction of silicates by finely dispersed carbon. This process has been simulated in the laboratory under entry conditions.

ISOTOPIC MEASUREMENTS IN INDIVIDUAL CHONDRULES,

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Isotopic measurement of individual chondrules have been performed on two elements: oxygen and xenon. Xenon measurements have mostly been iodine-xenon analyses that attempt to discover something of the chronology of chondrule formation. Oxygen isotopic studies have been used to attempt to delineate nuclear and chemical effects in chondrules and to characterize chondrule-chondrule and chondrule-host meteorite relationships.

Xenon (Iodine)

We have performed xenon isotopic measurements on 10 chondrules from Bjurbole [1] and 12 from Allende [2]. The Bjurbole chondrules and nine of the Allende chondrules had previously been irradiated with thermal neutrons for iodine-xenon analysis.

There are some similarities between the chondrules from the two meteorites. In all the chondrules analyzed, the xenon is dominated by iodine-derived gas. In fact, after contributions from spallation and instrumental effects are removed, some temperature fractions of some chondrules have no detectable trapped xenon (^{130}Xe/^{129}Xe<10^{-4}). Even for the chondrules richest in trapped gas, the ratio of iodine-derived ^{129}Xe to trapped ^{129}Xe is greater than 10. For the irradiated chondrules, this absence of trapped gas means that computation of a "model" initial iodine ratio is usually quite simple. The range of initial iodine isotopic ratios observed overlap, although the total range in the Bjurbole chondrules is only about seven percent (which would correspond to about 1.5 million years in a chronological interpretation), while the total range observed in the Allende chondrules is 15 to 20 percent (4-5 million years).

In both sets, the amount of radiogenic gas is more variable than the amount of trapped gas. In most chondrules, the concentration of trapped ^{130}Xe is between 10^{-12} and 10^{-11} cm^3/g. The amount of radiogenic ^{129}Xe (in units of 10^{-12} cm^3/g) ranges from about 70 in both sets up to 500 in Bjurbole and up to 12,000 in Allende.

However, there is also a major difference between the two sets of chondrules.

Bjurbole (L4)

Most of the Bjurbole chondrules (8 of the 10) give reasonably well-defined isochrons, yielding initial iodine compositions corresponding to ages from about 1 million years before Bjurbole whole rock to about 0.5 m.y. after [1]. It is not clear what the whole rock is dating, however, because Bjurbole "whole rock" consists of matrix, chondrule fragments and chondrules. It is clear that the trapped gas in the whole rock is dominated by matrix, since the amount of trapped gas is an order of magnitude higher than in the chondrules. But the amount of radiogenic xenon is within the range of the individual chondrules, indicating that it might simply be a mixture of gas from the many chondrules and chondrule fragments in the whole rock sample. If this is the case, the age of the whole rock is meaningful only in that it is an average over a large number of chondrules.

Allende (CV3)

On the other hand, only two Allende chondrules give isochrons, but five of them show a pattern of increasing antiquity with increasing temperature of extraction [2]. The simplest explanation of this pattern is that it reflects relatively slow cooling (about 100 to 200 K/m.y.) at the time of xenon closure in the high temperature phases. If this is the correct interpretation, then it poses profound problems. It would have to mean that when the chondrules were in the temperature range over which we see the cooling pattern, they were not isolated in cold space, but were in thermal conduct with some larger body, such as a hot nebular gas or a parent body (or its regolith). But if this is the case, it is difficult to see how chondrules remained mineralogically distinct from their surroundings for the several million years necessary to cool.

The cooling sequence interpretation is by no means certain. It is also possible that the pattern represents memory of isotopic inhomogeneity in the early solar system. If the chondrules formed with iodine from two (or more) isotopically distinct reservoirs, then a range in initial iodine ratios might be seen. This interpretation may in fact be required in at least some cases since there are four chondrules (two from each meteorite), whose I-Xe isotopic structure can't be explained either by slow cooling (correlation between initial iodine ratio and temperature) or instantaneous cooling (isochron). However, if iodine isotopic inhomogeneity is responsible, it is difficult to see why the same correlation between initial iodine ratio and temperature is seen in so many chondrules.

It might be possible that the correlation between release temperature and initial iodine ratio could be explained if the xenon is released primarily by diffusion from a small number of types of sites, with ^{128}Xe more abundant in the low-temperature fractions and thus under-abundant in the high-temperature fractions. However, from previous experience we believe that this is not the case. Stepwise heating seems to degas specific sites at specific temperatures. If so, the 10 to 15 data points we record are really samples of gas from that many distinct sites. We hope to have a more definitive experiment on this completed before this conference.

Further work on the I-Xe systems of chondrules is planned. In particular, since we are not quite operating at the limit of our system's capabilities, we plan in future studies to do noble gas analysis on only half of each chondrule, preserving the other half for petrological characterization, etc.

Oxygen

The Chicago group has performed oxygen isotopic measurements on some 43 chondrules. In the first study [3], of 10 petrologically characterized chondrules from three unequilibrated ordinary chondrites, it appeared that the chondrule data all fell on the mixing line between the bulk composition of H-chondrites and that of L- and LL- chondrites. Later studies [4, 5] have shown that the chondrule trend line is not quite the same as the H-L mixing line, which has been interpreted as indicating that mass fractionation as well as mixing of distinct nuclear components must be considered, although fractionation is probably only a second-order effect [4].

While the bulk oxygen composition of H-chondrites is distinct from that of L- and LL-chondrites, the range of compositions in chondrules from unequilibrated chondrites is variable and shows no relationship to the chemical classification of the host meteorite. It is suggested [5] that there could be differences in the mean compositions of chondrules from the different types, but that the present sample isn't large enough to detect them. On the other hand, the current data gives a mean composition for chondrules in H-chondrites nearly equal to that of L-chondrules and L-chondrites, which is ^{16}O-depleted relative to H3's. This suggests that the H3 matrix may be responsible for the difference in bulk compositions. Isotopic studies of "holy smoke" samples (presumably matrix) from four chondrites give compositions indistinguishable from the bulk meteorite. Tieschitz (H3) is enriched in the heavier isotopes relative to the bulk meteorite.

Correlations are observed between isotopic structures and some petrological parameters [3, 4]. Most tests find trends of questionable statistical significance, but the correlations are in general stronger among non-porphyritic chondrules than for porphyritic chondrules, lending support to the argument that the two groups may have formed from different precursor materials. A strong correlation is observed in non-porphyritic chondrules between amount of heavier oxygen mixed in and Ir/Au ratio. The correlation is quite weak among porphyritic chondrules. The mixing of heavier oxygen is inversely correlated with total bulk Fe and correlated with total bulk rare-earth elements and bulk ratio $(CaO + Al_2O_3)/MgO$. The latter two may suggest mixing of mafic with felsic materials, as might be expected for melting of pre-existing material [4].

References: [1] Caffee M. W., Hohenberg C. M., Hudson B., and Swindle T. D. (1982) Proc. Lunar Planet Sci. Conf. 13th, in press. [2] Caffee M. W., Hohenberg C. M., Lindstrom M. M., Swindle T. D., and Hudson B. (1982) In Papers Presented to the 45th Annual Meteoritical Society Meeting, p. V-5. [3] Gooding J. L., Keil K., Mayeda T. K., Clayton R. N., Fukuoka T., and Schmitt R. A. (1980) Meteoritics 15, p. 295 (abstract). [4] Gooding J. L., Mayeda T. K., Clayton R. N., Keil K., Fukuoka T., and Schmitt R. A. (1982) In Lunar Planet. Sci. Conf. 13th, pp. 271-272. [5] Clayton R. N., Mayeda T. K., and Olsen E. J. (1982) In Papers Presented to the 45th Annual Meteoritical Society Meeting, p. II-6.

CHONDRULE-RELATED PROCESSES IN THE PRIMITIVE SOLAR NEBULA,

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In the collapse and fragmentation of an interstellar cloud which results in the formation of the primitive solar nebula, the temperature falls to about 5 to 10K, and all atoms and molecules except hydrogen and the noble gases attach themselves to interstellar grains. If the gas is turbulent, as I think most likely, then the grains will also collide among themselves (1), and it is an interesting question as to how many of them will stick together. At these low temperatures it is not reasonable to expect the grain surfaces to be smooth, since it is too cold for migration of the atoms around the surface seeking minimum energy sites. Hence the surface is likely to be rough and perhaps filamentary, so that low energy collisions between grains may well lead to mutual adherence. A certain degree of growth of grain clusters may thus occur. However, the greater the mass of a grain cluster, the greater its velocity is likely to be relative to a turbulent gas, and the more destructive the collisions between grain clusters, in which the fragile bonds between the grains in the clusters are increasingly subject to fragmentation (2). These processes are most imperfectly understood, but they suggest that a certain degree of grain clustering occurs among the grains during the formation of the primitive solar nebula.

This should be the situation in the gas that accretes onto the solar nebula. In the nebula itself there is expected to be a great deal of turbulence, driven by mixing from infalling accretion (3), meridional circulation currents (3), and thermally-driven convection (4). This turbulence leads to a large-scale viscosity within the nebula, and hence to dissipation. In the dissipation, energy and angular momentum are transported outwards, and mass is transported inwards near the center and outwards near the outer boundary. The situation is likely to be complicated by large-scale gravitational instabilities in the gas forming giant gaseous protoplanets (3), but the effects on the present discussion are only indirect, and hence these complications will be ignored here. Within the nebula, temperature and pressure gradients will be established, and near the center in the vicinity of the forming protosun the temperature will in due course become high enough for the complete vaporization of solid condensed materials.

The effects of diffusion of condensed materials within the solar nebula were recently discussed by G. Morfill (5). Morfill considered a simplified situation in which a single substance is free to condense or evaporate as a grain moves to cold or warm regions in the nebula. He also made the very doubtful assumption that grains will easily adhere upon contact.

Certain qualitative aspects of this diffusion are basic to the mechanisms discussed here. Because the gas density is low, convection is rather inefficient in transporting heat (3), and hence convective velocities tend to be a substantial fraction of sound speed. Meridional circulation currents also tend to run at an appreciable fraction of sound speed (6). These velocities are large compared to the bulk inward drift velocity of the matter in the nebula near the center as a result of the dissipation which brings matter in to form the sun. Hence solid condensed material may be repeatedly transported between hot and cold regions of the nebula. In moving toward a hotter region, a grain will evaporate constituents with lower boiling points. Because of the general low densities in the nebula, these evaporated constituents will take quite a long time, on the order of months or years, to collide with a grain, and hence turbulence in the gas can transport uncondensed vapors quite long distances into regions within the nebula in which they can condense on solid surfaces before that condensation takes place (4).

As a cluster of interstellar grains, newly accreted into the primitive solar nebula, moves into regions of higher temperature, its very nonequilibrium chemistry must be expected to change. The most volatile substances will be evaporated. Stored chemical energy is released as a large number of small heating events at a large number of discrete temperatures. Molecules become free to migrate around the surfaces within the cluster, and the net result of this should be a great reduction in surface energy of the assembly as the surface area is reduced and the structure becomes increasingly filamentary. This should strengthen the bonds between the grains in the clusters, so that clusters are likely to be able to grow larger upon mutual collision with intertangling of the filamentary structure. This growth will still be limited by the destructiveness of mutual collisions at larger sizes due to larger turbulently-driven velocities relative to the gas. Chemical interactions between the gas and the solid phases, together with solid state diffusion, will cause the assembly to approach the equilibrium composition expected at the higher

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Cameron, A.G.W.

That leaves evaporation and condensation processes for consideration. The important region of the solar nebula for such processes is the "total evaporation front" within the nebula where the bulk constituents of solids will become evaporated. Bruce Fegley and I (4) have calculated the structure of the solar nebula for this region under typical conditions that will persist qualitatively for a long time. Figure 1 shows the results obtained for the case when the protosun has grown to half a solar mass and the time scale for moving mass into the protosun is 10^5 years. The evaporation front shows where corundum evaporates, and almost coincident with it is the evaporation front for hibdonite. At a significantly lower temperature forsterite and iron evaporate.

Condensation is much harder for a gas with these constituent vapors moving toward lower temperatures. Fegley and I (4) used a nucleation theory due to Salpeter to estimate how far inside the evaporation front gas must move before corundum can nucleate. The shaded area in Figure 1 shows this region. Some self-nucleation may well occur in this manner, but it seems more likely that the normal process will be nucleation on unevaporated solids moving into the condensation region and mixing with ι ⁻condensed vapors coming from hotter regions.

Cabot and Savedoff (7) have recently examined the properties of meridional circulation currents occurring in a hot disk. They found the sense of the current to be outward in midplane and inward at higher altitudes off the plane. The velocity of the current is a significant fraction of sound speed. Such a current would carry grains and grain clusters from the colder regions of the nebula into the region where the midplane is within the evaporation front, and the grains are in the region near the nebular photosphere. Turbulence will maintain a continual vertical diffusive mixing, leading solids to evaporate as they cross the evaporation fronts and vapors to become supersaturated as they rise toward cooler temperatures.

A number of refractory trace metals survive in condensed form to higher temperatures beyond the evaporation front of Figure 1. In order of increasing volatility these are Os, W, Re, Mo, Ir, Ru, Pt, and Rh. There is plenty of time in the evaporation of a grain cluster for the residual trace elements to diffuse together to form a small nucleus (4). Such refractory trace metal nuggets are commonly found in course grained inclusions with sizes in the submicron range. A nugget in the immediate submicron range is likely to be the residue of a grain cluster of 0.01 cm radius or somewhat larger. It seems likely that many much smaller nuggets exist that have not been noticed in the examination of samples.

It seems likely that both not-completely-evaporated grain clusters and refractory trace metal nuggets will have acted as condensation centers for the formation of calcium-aluminum inclusions in the region between the corundum and forsterite evaporation fronts of Figure 1. When gas that has been partly or fully depleted in these refractory compounds rises into the region above the forsterite evaporation front in Figure 1, further condensation on the many available condensation nuclei should lead to the formation of objects that we would call chondrules, at least from a compositional point of view. What additional physical processing would be needed in such chondrules is a matter for additional investigation.

These processes should act rather efficiently on a significant fraction of the condensed mass within the nebula. Turbulent diffusion should spread chondrules and inclusions rather quickly throughout the nebula. It will also act to keep these small objects dispersed with the gas perpendicular to the midplane of the nebula, so that there is no possibility of a gravitational instability operating on a central sheet of condensed matter in the manner of Goldreich and Ward (8) until most of the gas in the nebula has disappeared and the turbulence has vanished. In the subsequent gravitational precipitation the matter initially collecting at midplane will be rich in chondrules and inclusions relative to grains and grain clumps, and this should be the primary material from which asteroids are formed. The grains and grain clumps are likely to be in higher proportion among the materials later collecting on the surfaces of asteroids.

(1) Cameron, A.G.W. (1973) Icarus, **18**, 407-450. (2) Cameron, A.G.W. (1975) Icarus, **24**, 128-133. (3) Cameron, A.G.W. (1978) Moon Planets, **18**, 5-40. (4) Cameron, A.G.W. and Fegley, M.B. (1982) Icarus, in press. (5) Morfill, G. (1981) Talk at Workshop on Star Formation, Aspen. (6) Cameron, A.G.W. and Pine, M.R. (1973) Icarus, **18**, 377-406. (7) Cabot, W. and Savedoff, M.P. (1982) Astron. Astrophys., **112**, L1-L2. (8) Goldreich, P. and Ward, W.R. (1973) Astrophys. J., **183**, 1051-1061.

temperatures.

These considerations are entirely qualitative. The physical parameters affecting grain cluster size are poorly known or unknown, and we have only the general expectation that there should be a size spectrum extending from individual grains of submicron size (continually generated in cluster collisions) to a few clusters of some unknown maximum size (from observational arguments probably in the range of centimeters or less).

Many theories of chondrule formation postulate that solids in the solar nebula collided at velocities high enough to produce extensive melting. That requires velocities of 10 km/sec or higher. The sound speed in the gas is 10 km/sec for a temperature of 10,000K, much higher than of interest for the solar nebula. Turbulence within the gas cannot accelerate grain clusters to supersonic speeds. Hence collisionally-produced chondrules can arise only from collisions between solids after the solar nebula has disappeared. There may be a significant yield from such processes, but the relative inefficiencies argue against this as a primary source of the observed chondrules.

There are also a number of chondrule formation proposals that call upon nonequilibrium processes in the gas. Shock heating of the gas above the chondrule melting temperature would require very strong shocks, travelling very supersonically. The colder the gas, the stronger the shock must be. Apart from the issue of how such shocks might be generated, except near the protosun where the temperature is near the chondrule melting point anyway, such shocks would accelerate the solar nebula gas to greater than escape velocity, and the gas would then carry away small solids with it as it left the solar system. Electromagnetic processes such as lightning strokes are unlikely to be effective, because even if they can deliver enough energy to a grain cluster to melt it, the time scale is so short that the energy is likely to be dissipated in vaporizing the surface layers rather than being conducted into and melting the interiors.

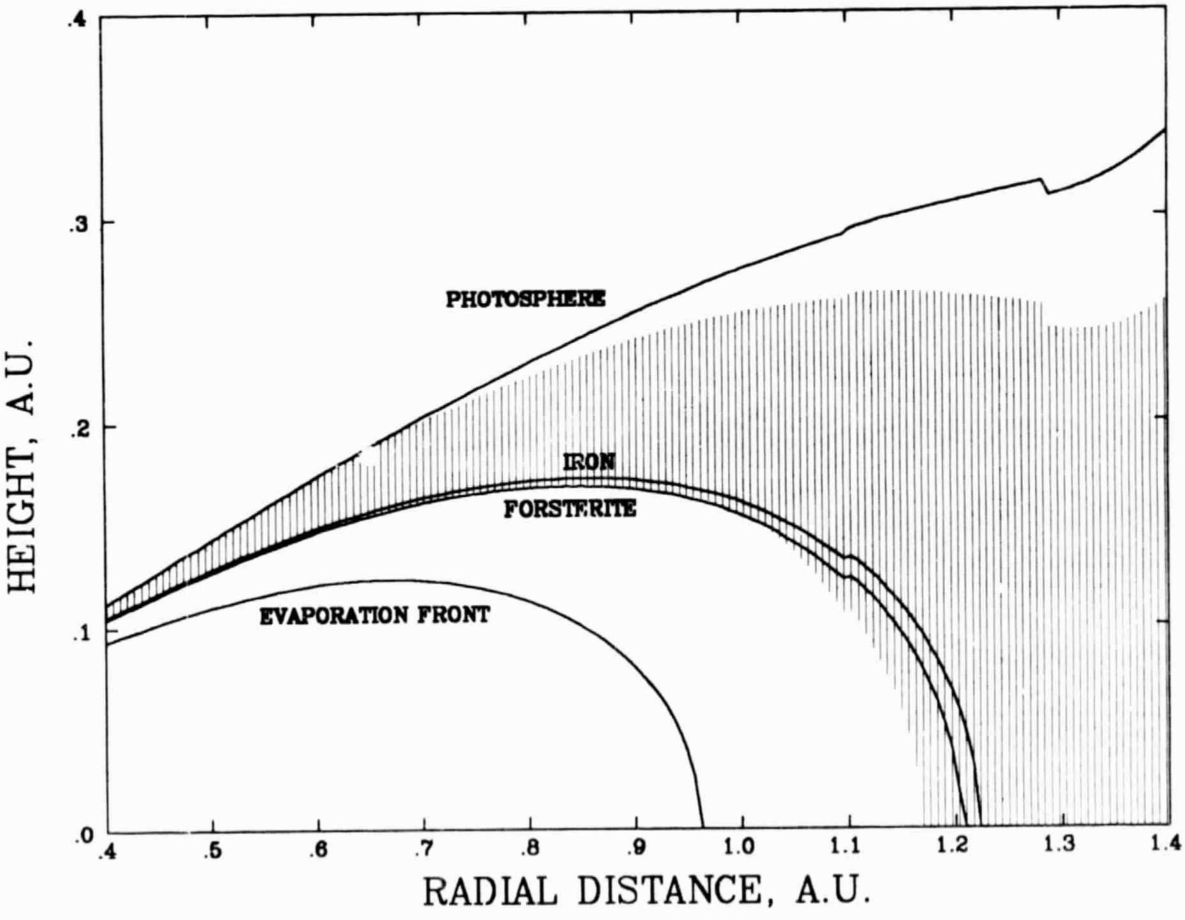

Figure 1. Section of solar nebula model.

A SPECIAL CASE OF ASSOCIATED CHONDRULES IN ALLENDE : SNAPSHOT OF A PUNCHING-OUT PROCESS ?

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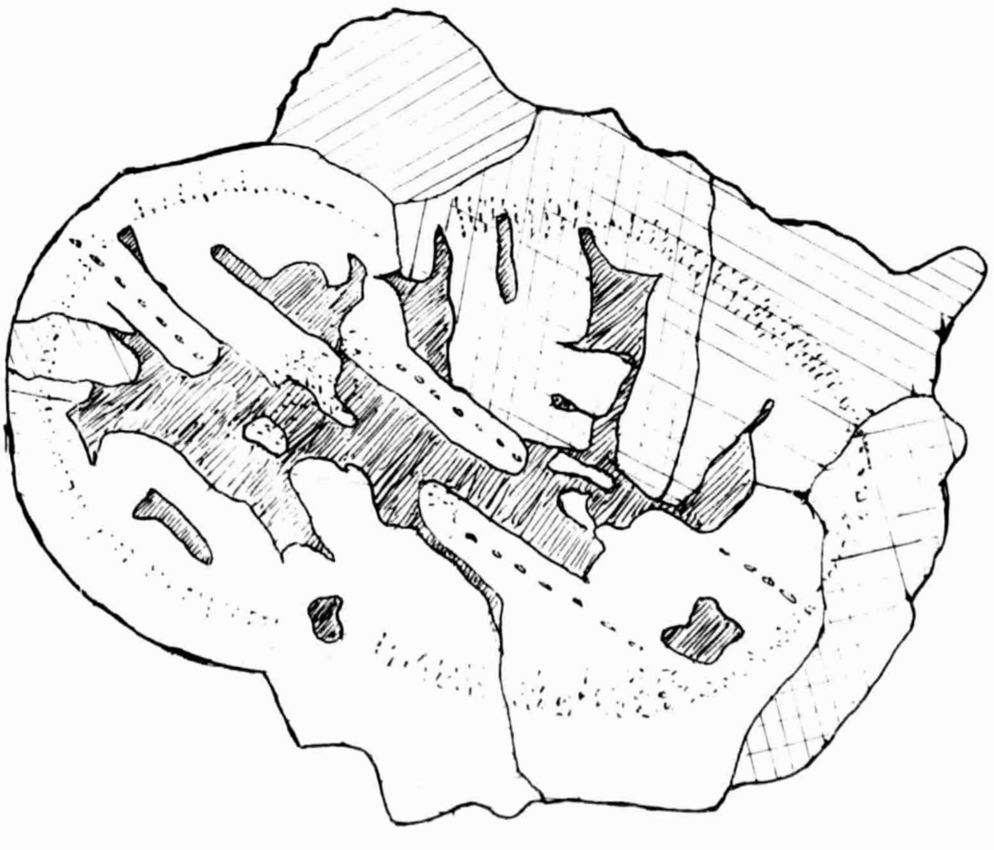
That chondrules represent reworking of previously condensed material is more and more accepted, but the mechanism of this reworking is in question. We present here the case of a rock fragment containing 6 main olivine-crystals and devitrified glass (presently pyroxene + anorthitic feldspar), which, under careful examination is shown to consist of two chondrules ; these may be recognized because of the occurrence of two crowns of tiny chromites, which are made of radiating short files of a few micron wide grains. In front of one of them, at 25-30 µm the spherical shape of the chondrule is clearly seen cross-cutting the olivine-crystals. The other crown of tiny chromites is not accompanied by any rounded figure limiting the rock-fragment ; the olivine-crystals have irregular outlines. Numerous bubbles are present. Some of them may underline healed cracks, others are parallel to olivine bars, they are specially abundant at the geometric center of the rounded chondrules ; many pores are also present between the tiny crystals of the devitrified glass.

The order and the nature of the events that lent to what we observe presently is not at all obvious but may lead to more general considerations. That is why this case is submitted to your subtility.



INITIAL CHEMICAL STATE OF PRECONDENSED MATTER

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Although the chemical state of matter in a cold molecular cloud is very hard to specify with confidence, we can be fairly confident that it must be relevant to the understanding of some questions relating to isotopic composition and chemical disequilibration in early solar-system aggregates. This talk will nonetheless attempt to describe types of material structures that one could expect to have been present at the time of solar collapse. Although it is known that refractory elements do not reside in the gaseous state within molecular clouds, one can only speculate on the kinds of dust that must have contained them, and in what relative proportions. Both questions will be addressed, but the latter is more elusive than the former. Refractory-mineral-like dust will exist by virtue of near-equilibrium condensation sequences during mass loss from stars; but by no means all refractory elements will have been in this form. Some will not have condensed at those times, some will have been sputtered away by the interstellar history of supernova shock waves, and some will have been evaporated by recycling through the outer envelopes of stars followed by partial recondensation. Thermal sputtering in the hot ISM will accentuate the refractory nature of dust therein, and will impose some isotopic fractionation. Whether any dust aggregates can occur before cloud collapse remains uncertain. Refractory gaseous atoms will reaccrete onto dust in all ISM phases to some degree, but, in the molecular cloud prior to collapse, virtually all remaining atoms and molecules will reaccrete in cold mantles bearing also volatiles and the possibility of later exothermic chemical energy. Millimeter-sized aggregates of these multicomponent particles can be expected during turbulent cloud collapse to a solar disk, whereafter the thermal and transport properties of the disk will moderate the growth of disk particles. Heating of the first aggregates, even of chondrule size, either chemically or environmentally, will be accompanied by alteration, perhaps hydrothermal.

DUST GROWTH IN TURBULENT SOLAR DISK

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If the solar disk is turbulent, dust grains within it collide. If they stick efficiently, their growth rates can be computed. The time available for growth is limited by the radial drift of particles toward the sun owing to the radially inward gas flow due to viscous transport and owing to the gas drag upon the particles. We present calculations of this problem, which show that growth of micron-sized dust to millimeter- to centimeter-sized aggregates is expected. Without further assumptions, these aggregates all flow into the sun.

OBJECTS WE CALL CHONDRULES

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One hundred eighty years after de Bournon first described chondrules (1), we still lack a definition of these objects on which all workers would agree. Hence we come to this conference with quite different conceptions of -- and preconceptions about -- our subject.

Just what are chondrules? A review of definitions put forward in the last 20 years shows that all include a restricted range of sizes and nearly all stress regularity of form ("spherical,""spheroidal,""ellipsoidal" -- 2,3,4,5,6). A few definitions include evidence of solidification from melts (5,6,7), and one notes the dominance in chondrules of silicate minerals. Curiously, no definition includes the fact that chondrules occur almost exclusively in chondritic meteorites, though this fact is a major reason why they have proved so hard to interpret: We can usefully compare eucrites with basalts and howardites with lunar regolith, but the chondrites resemble no other rock types more than superficially.

For the sake of discussion, I propose the following definition of chondrules: "Polyminerallic particles, typically of millimeter or submillimeter dimensions and with drop-like to irregular shapes, which occur almost exclusively in chondrites and whose texture and mineralogy testify to solidification of molten, chiefly silicate, material." This definition may be too broad for some workers and too restrictive for others. By discussing it point by point, I hope to sharpen both our definition of chondrules and our perception of the properties of these objects that must be explained by genetic models.

References:

1. In Howard, E. (1802) Phil. Trans. Roy. Soc. London 92, p. 168-212.
2. Mason, B. (1962) Meteorites, p.82.
3. Wood, J.A. (1963) In Middlehurst, B. and Kuiper, G.P., eds., The Moon, Meteorites and Comets, p. 337-401.
4. Wasson, J.T. (1974) Meteorites: Classification and Properties, p.13.
5. McSween, H.Y., Jr. (1977) Geochim. et Cosmochim. Acta 41, p.1843-1860.
6. Gooding, J.L., Keil, K., Fukuoka, T. and Schmitt, R.A. (1980) Earth Plan. Sci. Lett. 50, p. 171-180.
7. Dodd, R.T. (1981) Meteorites: A Petrologic-Chemical Synthesis, p. 30.

SPINEL-RICH CHONDRULES AND THE CONDENSATION OF METASTABLE LIQUIDS IN THE SOLAR NEBULA.

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Large coarse-grained Ca,Al-rich chondrules have been studied since it was recognized that they probably formed at high temperature in the solar nebula (1). They were first interpreted to be aggregates of refractory, crystalline condensates (2). Later it was recognized that many were at least partially molten at some stage (3-5). Major modal minerals in typical coarse-grained Ca,Al-rich chondrules in C3(V) chondrites are perovskite, spinel, melilite, Ti-Al-pyroxene, and anorthite. These refractory chondrules usually contain significant amounts of CaO (>20 wt. %) and SiO_2 (>25 wt. %) (6).

There is a distinctive suite of refractory chondrules in carbonaceous chondrites with markedly different bulk chemistry and mineralogy. These are small, igneous objects that consist of spinel, spinel+perovskite, or spinel+perovskite+hibonite. Spinel-rich chondrules are the most abundant refractory objects in the CM chondrite Murchison (7). Fine-grained Ca,Al-rich inclusions in the C3(V) chondrites Mokoia (8) and Allende (9) are interpreted as aggregates of tiny, spinel-rich igneous objects embedded in a porous, silicate matrix.

Models of chondrule origin that invoke the melting of precondensed material cannot readily account for the extreme high temperatures and mineralogical fractionation needed to produce molten spinel droplets in the solar nebula. The sequence of the most refractory Al-rich condensates is corundum, hibonite, $CaAl_4O_7$, and gehlenite (10). Spinel and Ca-silicates form at a lower temperature by reaction of the nebular gas with these condensates. Melting any of the calculated condensate assemblages would produce a liquid that contains more CaO and SiO_2 and less MgO than is observed in the spinel-rich chondrules. The condensation of metastable liquids in the system CaO-MgO-Al_2O_3 (CMA) may be a more appropriate model to explain the origin of these, the most refractory chondrules.

Several factors combine to make the condensation of metastable liquids a particularly attractive model. First, the recent nebular model of Cameron and Fegley (11) includes a region called the total evaporation front where the major constituents of chondritic matter will evaporate. This evaporated material can subsequently recondense along vapor-solid or vapor-liquid condensation paths. The nucleation constraints for vapor-solid condensation (4,11) lead us to believe that vapor-liquid condensation may be an important condensation process in this region of the solar nebula where the most refractory condensates formed. Second, the recent availability of thermodynamic data and mixing models for oxide liquids (12-16) now allows a quantitative treatment of condensation of oxide liquids.

The purpose of this work is twofold. First, we develop a model to describe the thermodynamic properties of liquids in the system CMA and calculate the composition of metastable liquid condensates at different (P,T) points along a vapor-liquid condensation path in the nebula. Second, we compare the petrology of the spinel-rich chondrules with the calculated compositions of and crystallization sequences in these metastable liquids.

References: (1) Marvin, U.B. et al. (1970) EPSL **7**, 346-350; (2) Grossman, L. (1972) GCA **36**, 597-619; (3) Grossman, L. (1975) GCA **39**, 433-454; (4) Blander, M. and Fuchs, L.H. (1975) GCA **39**, 1605-1619; (5) Stolper, E. (1982) GCA, in press; (6) Mason, B. and Taylor, S.R. (1982) Smithson. Contrib. Earth Sci., in press; (7) MacDougall, J.D. (1981) GRL **8**, 966-969; (8) Cohen, R.E. (1981) Meteoritics **16**, 304; (9) Kornacki, A.S. (1981) LPS XII, 562-564; (10) Fegley, M.B. (1982) LPS XIII, 211-212; (11) Cameron, A.G.W. and Fegley, M.B. (1982) Icarus, in press; (12) Allibert, M. et al. (1981) J. Am. Ceram. Soc. **64**, 307-314; (13) Fegley, B. (1982) Bull. Am. Ceram. Soc. **61**, 808; (14) Spencer, P.J. (1973) NPL Report Chem 21; (15) Rein, R.H. and Chipman, J. (1965) Trans. AIME **233**, 415-425; (16) Burnham, C.W. (1975) GCA **39**, 1077-1084.

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CHONDRITES ARE NOT METAMORPHIC ROCKS -----

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> "Indeed the confused structure shown by many meteoric stones has given rise to an equal confusion on the part of students as to their causes" (Merrill, 1929).

Most early students of meteorites, mainly petrologists, recognized the fragmental and brecciated nature of chondrites, and considered it a fact that chondrules, which they were able to distinguish from lithic fragments, once had been individual droplets which crystallized and subsequently accreted to form chondrites together with comminuted chondrules, other fragments and dust. Some even considered violent shock caused by extraterrestrial impacts as the cause of the brecciation. The varying degrees of crystallinity and induration of different stones, as well as in different parts of single chondrites, was also commonly noted. G. P. Merrill, in his 1929 book, reviewed much of this earlier work and wrote of chondrules, "-------, before their true nature was known, ---. Their origin has been made the subject of much discussion and wordy warfare among students, but the matter need not be gone into further here." About chondrites, in the following paragraph he stated, "Occasionally meteorites of this tuffaceous and chondritic type show signs of changes subsequent to their consolidation, which are comparable to a form of metamorphism produced in terrestrial rocks by heat."

However, already in his "Handbook" of 1916, he was patently aware that conventional thermal metamorphism could not be implied, "since a heat sufficient to render crystalline the pisolites (fragments) in a tuff, as argued by some, would certainly produce a more marked degree of metamorphism in the surrounding matrix." Furthermore, as early as 1888 in his description of San Emigdio he stated, "There are no evidences to indicate that after the first period of solidification and crystallization was brought to a close by cooling, there was a second rise in temperature sufficient to allow certain of the silicate constituents to take on more perfect forms." (metamorphism). These arguments are still viable.

In the early 1950's Wahl reemphasized the brecciated structure of many chondrites, and being unaware of in situ high pressure shock transformations, exaggerated the abundance of (now rare) polymict breccias over monomict or, recently, genomict types. The renewed interest in chondrites led to the establishment of the remarkably similar bulk composition of chondrites, with the exception of total iron and its oxidation state, and especially through the work of Mason and others, of the constant olivine and pyroxene compositions within most individual chondrites. Thus many considered the possibility of a common parent material and in the early 1960's Wood advanced a radical metamorphic model implying a direct relation between chondrites of different crystallinity and complete exchange and equilibration of Fe and Mg between chondrules and "oxidized" matrix. This concept even as moderated by Dodd and others was questioned, especially by petrologists, but also by some chemists and rare gas specialists. However, these ideas at the same time served Van Schmus and Wood as basis for a new petrologic classification scheme for chondrites within the different chemical (iron) groups. Because of its simplicity, a letter for chemical group and a number 1-6 (7) for petrologic type, this classification rapidly gained wide usage, and is indeed useful for curators, for simple comparisons of different specimens and in the search of like samples, particularly the popular type 3 ("unequilibrated") chondrites.

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CHONDRITES ARE NOT METAMORPHIC ROCKS

Fredriksson K.

In spite of warnings by the authors the 1 through 6 "grades" (first partly metamorphic, then petrologic and now more appropriately petrographic) were sometimes improperly used as a quantitative, if not linear, scale. Thus various correlations were searched for and sometimes claimed, e.g. higher In and Ar, in the lower grades. However, in that case contrary to expectations the In/Ar ratio remained constant through the sequence, apparently requiring a closed system. Other studies, especially by Purdue and Chicago groups, have led to similar contradictions. Some results require a system open to at least a few volatiles, others apparently a closed system, while a few researchers want both. Part of the explanation for this may lie in the fact that the works reviewed by Merrill considered whole rocks, while a large number of modern studies, thanks to sophisticated techniques, deal with small samples, even fragments, individual chondrules and matrix grains. Thus the concept of the "forest" may be lost because of all the individual trees - and a good many bushes.

Studies with regard to evidence for metamorphism, and possible heat sources, have been summarized in Wasson's 1974 book and more recently in Dodd's 1981 Meteorites. However, chondrites are breccias which obviously may contain fragments recrystallized (metamorphosed) to different degrees as well as chondrules and even, as recently shown, "primitive" (perhaps "primordial") matrix materials which, although extremely finegrained, exhibit no recrystallization and are in complete disequilibrium with other constituents. These observations alone, which will be reviewed briefly, should make it clear that chondrites are not metamorphic rocks, not even necessarily Shaw, L7; in that case we may have received a singular fragment - one unique specimen out of the forest.

As for the individual chondrules themselves, our recent analyses of some 336 chondrules from 16 different chondrites indicate that if thermal metamorphism was involved in "equilibrating" Fe-Mg in chondrites and fragments, some so far inexplicable conditions must have existed because:

In "Equilibrated" Chondrites: 1. The Fe/Mg ratio is constant (by definition!) in larger (>5 μm) olivine and pyroxene grains, but apparently not in the ultrafine matrix minerals. 2. Al and Ca are negatively correlated. 3. Al/Ti and Ca/Ti ratios vary between chondrules by factors >5; still, these ratios for the bulk meteorite are nearly constant and also practically independent of iron groups (H, L, LL). 4. The average CaO content of chondrules is ~30% higher than that of the bulk.

In "Unequilibrated" Chondrites: 1. The Mg/Fe ratio (again by definition!) in olivine and pyroxene is variable. 2. Al and Ca (and Ti) are positively correlated. 3. Al/Ti and Ca/Ti ratios are reasonably constant and similar to those of all chondrites.

Thus a metamorphic process would necessarily have to accomplish: 1. equilibration, by diffusion, of olivine and pyroxene while, 2. separating Ca from Al (and Ti) and subsequently, 3. mixing together again the variable chondrules and different matrix components, recrystallized or not, to achieve the common bulk composition for H, L and LL as well as the constant Al/Ti and Ca/Ti ratios. This appears, at least, to require a well closed system during, or after, chondrule formation and all through the final break up. Probably the answer to many of these problems lies in multiple, repetitious processes, e.g. impacts, resulting in the (con-)fused structure of chondrites (with constant composition) alluded to by Merrill.

CONSTRAINTS ON THE HEATING AND COOLING PROCESS OF CHONDRULE FORMATION BY "LIGHTNING"

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Heating of chondrule precursors by lightning discharge or acceleration of electrons (1) could occur in the turbulent primordial gas-dust mixtures at the stage of planetesimal formation by the gravitational instability of densely accumulated dust layer. From petrologic observations such as the presence of relic minerals and slow cooling rates for chondrules in ordinary chondrites (2,3), constraints on the heating and cooling process are specifically presented in the case of "lightning" model (1).

For an externally heated spherical chondrule with relic minerals inside (2), the maximum temperature (Tx) at a radial distance (r/R) should not exceed liquidus for some duration (Δt), if the surface temperature (To) were above liquidus (Fig. 1). With values of thermal diffusivity $k=0.01$ cm^2/s and typical radius R=0.3 mm, Δt becomes about 10 msec for Tx/To~0.75 (To of about 2500°C). This duration tends to infinity as To approaches to liquidus.

Experimentally observed cooling rates of chondrules range a few to 10^{-4} K/s between 1600 and 1200°C (3). However, the cooling rate of isolated chondrules with R=0.3 mm range 100 to 10 K/s which is much faster than that of observed. So, some volume of the primordial gas-dust mixture surrounding chondrules should cool as a whole. By assuming radiative conduction cooling of the cylindrical gas-dust mixture from near liquidus temperature to ambient temperature of solar nebula (~550K), the cooling rate of this cylindrical medium becomes 1 to 0.1 K/s for $k=60$ m^2/s (thermal diffusivity of H_2 at $P=10^{-4}$ atm and T~2000 K) and for radius of 600 m.

It is concluded that events of "lightning" should frequently occur in the chondrule forming region and should closely be spaced so that the cooling of chondrules were governed by the surrounding gas-dust mixture with a few kilometers wide. Instead, the duration of each heating event should be less than about ten milliseconds if relic minerals would exist commonly in chondrules. Above constraints seem concordant with the "lightning" model, although more detailed investigations are needed together with other heating mechanisms.

References: (1) Whipple, F.L. (1966), Science, 153, 54-56., Cameron, A.G.W. (1966), EPSL, 1, 93-96., Sonett, C.P. (1979), GRL, 6, 677-680. (2) Ikeda, Y. (1980), Mem. Natl Polar Res. Sp. Issue, 17, 50-82., Nagahara, H. (1981), ibid, 20, 145-160. (3) Tsuchiyama, A. et al., (1980), EPSL, 48, 155-165.

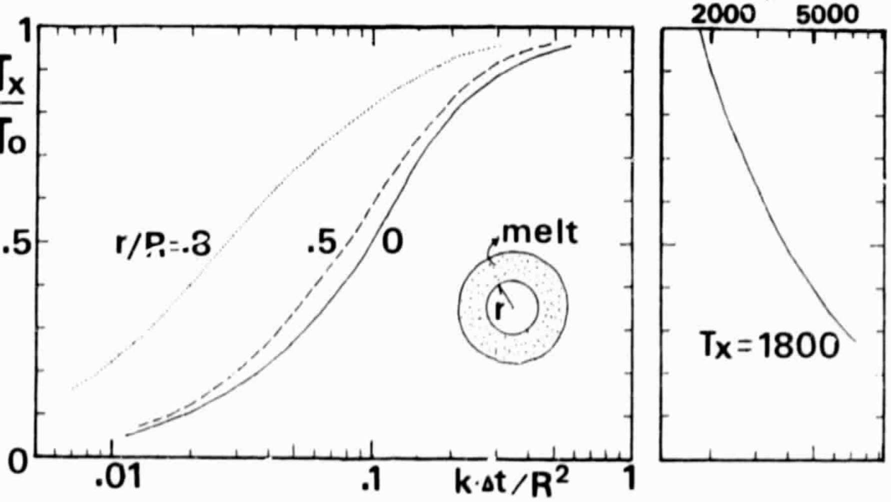

Fig.1. Conditions for the presence of relic minerals. Tx/To vs $k\Delta t/R^2$ (left) and Tx/To vs To (right).

ORIGIN OF CHONDRULES IN ORDINARY CHONDRITES BY INCOMPLETE MELTING OF GEOCHEMICALLY FRACTIONATED SOLIDS.

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New data accumulated since 1977 provide a strong case for origin of chondrules in ordinary chondrites by incomplete melting of geochemically fractionated solid precursor materials very early in solar system history. Pertinent observations are as follows:

(a) Geometric-mean elemental compositions of chondrule suites are virtually the same among H-, L-, and LL-chondrites (1). (b) Relative abundances of chondrule primary textural types are essentially the same in H-, L-, and LL-chondrites and are dominated by porphyritic types (2). (c) Oxygen isotopic compositions of chondrules exhibit similar ranges among H-, L-, and LL-chondrites (3) and can be resolved into mixing and fractionation components (4). (d) Relative to the condensible bulk solar system, chondrules are generally enriched in lithophile elements and depleted in siderophile elements although volatile/refractory elemental fractionations are only weakly apparent (1, 5). (e) Ni-Fe metal (kamacite, taenite, and "martensite") occurs in chondrules both as spherical and as angular particles but with a bulk Ni concentration less than that of metal in whole-rock chondrites (6). (f) Glass transition temperatures for chondrule droplets are estimated to be 600-700°C (bulk compositions) to >800°C (mesostasis compositions) (7). (g) Chondrules from Parnallee (LL3) yield a Rb-Sr age of 4.5×10^9 yr (8) although younger Rb-Sr (8) and I-Xe (9) ages are observed in "equilibrated" chondrites.

Observations (a)-(c) and (g) show that chondrule formation was pervasive, probably independent of whole-rock chondrite formation, and occurred within the first $\sim10^8$ yr of solar system history. Observation (d) shows that chondrule precursors experienced separation of silicates from Ni-Fe metal but not in a manner explicable by a volatility-sensitive nebular condensation sequence. Angular metal particles are probably unmelted relics such that (e) argues for most of the metal/silicate separation to have occurred prior to melting. From (b), the preponderance of porphyritic chondrules shows that either large relict silicate grains were not completely melted or that crystallization of most droplets was relatively slow and probably aided by heterogeneous nucleation. In either case, superliquidus temperatures must have been rare or of short duration and, from (f), most droplets were solid by ~700-800°C. Thus, oxygen isotopic compositions of chondrules were determined by mixing of their precursor phases but possibly with minor fractionations by liquid-gas exchange reactions above 700°C. The precursors were heterogeneous assemblages of crystalline solids which were not extreme igneous differentiates but which could have been nebular condensates passed through less severe geochemical processing with metal/silicate fractionation. The clearly non-equilibrium temperature cycle for melting must have been (i) rapid rise to peak (1600°C??); (ii) rapid fall to metal liquidus (~1500°C) and below; (iii) slower fall to silicate liquidii (≥1200°C) and below; (iv) fall to droplet "solidii" (~700-800°C).

References: (1)Gooding J.L. et al. (1980) Earth Planet. Sci. Lett., 50, p 171-180. (2)Gooding J.L. and Keil K. (1981) Meteoritics, 16, p. 17-43. (3) Gooding J.L. et al. (1980) Meteoritics, 15, p. 295. (4)Gooding J.L. et al. (1982) Lunar Planet Sci. XIII, p. 271-272. (5)Grossman J.N. and Wasson J.T. (1982) Geochim. Cosmochim. Acta, 46, p. 1081-1099. (6)Gooding J.L. et al. (1979) Meteoritics, 14, p. 404-407. (7)Gooding J.L. and Keil K. (1981) Lunar Planet Sci. XII, p. 353-355. (8)Hamilton P.J. et al. (1979) Lunar Planet Sci. X, p. 494-496. (9)Caffee M.W. et al. (1982) Lunar Planet Sci. XIII, p. 75-76.

REFRACTORY SPHERULES IN CM CHONDRITES AND CHONDRULE FORMING PROCESSES.

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Some of the refractory spherules found in CM chondrites have textures that suggest their formation from liquids, and can thus be termed as chondrules (Macdougall, 1981). In order to obtain additional information about these rare objects, we have isolated more than a dozen refractory spherule-like compact objects from a set of chondrules and compact objects hand-picked from disaggregated samples of the CM chondrites Murchison and Murray. The refractory objects comprise less than a few percent of this collection, and range in size from 75 to about 300 micron. The cut-off at the lower end could be a sampling artifact. The composition of the constituent mineral phases of the refractory spherules were studied using a SEM equipped with an EDX analyser. Most of these objects are spinel-rich, a few have hibonite as the dominant phase with perovskite occurring only as a minor phase in all of them. These observations are similar to those reported earlier (1). We have also concentrated on the morphological studies of these refractory objects. A couple of them have irregular shape, and perhaps be better termed as inclusions, although their compact nature readily distinguish them from the irregular, fluffy and fine-grained refractory inclusions in CM chondrites which break-up during the disaggregation process. Some of the other features observed are: (I) a few micron thin partially preserved continuous mantle of diopside on a refractory spherule, (II) a compound refractory spherule, (III) melt-like features on the surface of two refractory objects, and (IV) a spherule with diopside as the major phase.

The presence of refractory inclusions in CM chondrites with mineral composition and chemistry similar to those observed in refractory spherules, and the sharp transition in composition of refractory spherules (chondrules) and silicate chondrules in these meteorites indicate that the refractory spherule-like compact objects were derived from the refractory inclusions through localized heating or collisional events. Production of refractory spherules from any other precursor material should have led to a continuum of spherule composition which is not the case. The presence of compound refractory spherule and melt-like features on some refractory objects suggest collisions involving these objects. An additional feature worth noting is the abundance of refractory spherules, which is a few percent of the refractory inclusions in the CM chondrites, a value similar to the relative occurrence of compound chondrules among refractory spherules in CM chondrites, and also among silicate chondrules in ordinary chondrites. The collision hypothesis, however, must satisfy rather stringent conditions as far as kinetics are concerned to produce melt of refractory composition. Thus the choice between the collisional hypothesis and localized heating events, soon after the formation of the refractory inclusions in the early solar system, remains open. Direct condensation, which is generally favoured as the mode of formation for the refractory inclusions in CM chondrites, is a difficult proposition to accept for the formation of the refractory spherules and compact objects in the CM chondrites.

References: 1. Macdougall J.D. (1981) Geophys. Res. Lett. 8, 966.

SIZE-DISTRIBUTION AND MORPHOLOGY OF CHONDRULES IN DHAJALA(H-3) AND MURCHISON (CM) CHONDRITES. J.N.Goswami, Physical Research Laboratory, Ahmedabad-380 009, India; and McDonnell Center for the Space Sciences, Washington Univ., St. Louis, MO 63130.

Samples of Dhajala, a H-chondrite, and Murchison, a CM chondrite, were disaggregated using an ultrasonic processor, and chondrules were individually picked from different sieve-size fractions of the disaggregated samples. In the case of Dhajala meteorite, chondrule size-distribution was also measured in sections. Chondrule morphology was studied using both optical and scanning electron microscopes. The results obtained from the size-distribution studies support the earlier observations (e.g. King and King, 1978) that the chondrule size-distributions in all meteorite types do not follow a single pattern. The Murchison chondrules have a smaller mean diameter compared to Dhajala chondrules. Further, in Dhajala, the chondrules comprise about 10% of the total mass of the sample, almost an order of magnitude higher compared to the corresponding value for the Murchison CM chondrite.

Compound chondrules were found, both in sections and disaggregated samples of Dhajala. No definite evidence for compound chondrule was found among Murchison chondrules. The sampling statistics, however, do not rule out presence of such chondrules in Murchison at less than 1% level.

Different size-sorting processes, following copious production of chondrules in single events, is generally considered as responsible for the differences in the measured size-distribution patterns, and also the restricted ranges in chondrule sizes in different meteorite types. An easier way to understand these observations will be to postulate differences in the grain-size distributions of the precursor materials from which the chondrules were produced. The chondrule formation mechanism in such a case could either be particle-particle collisions or localized heating events, as has been proposed by various authors.

Whether the over-abundant and somewhat irregular chondrules found in <u>CM chondrites</u> should be considered as abraded lithic fragments (chondrules) needs further attention. If abrasion indeed took place, this could not have occurred in the parent bodies of the CM chondrites, as regolith growth processes in these objects are restricted to the upper few tens of meters with very little mechanical mixing and redistribution of matter. An efficient alternate mechanism could be abrasion in space during low velocity collisions between chondrules and micron size particles in the early stages of solar system history. The presence of solar flare tracks in less than a few percent of chondrules in CM chondrites (Goswami and Macdougall, 1982) indicates that such abrasion process, if occurred, must have happened when the gas pressure and matter density in the early solar nebula was high enough to stop the solar flare particles from reaching most of the chondrules. The formation of chondrules thus precedes the formation of parent bodies of CM chondrites in this scenario.

References: 1. King T.V.V. and King E.A. (1978) Meteoritics <u>13</u>, 47.
2. Goswami J.N. and Macdougall J.D. (1982) JGR (In press).

MECHANISMS FOR THE DEPLETION OF METAL IN CHONDRULES.

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Most chondrules from unequilibrated ordinary chondrites contain identifiable metal and sulfide. The modal amounts of these phases covary over a wide range. Chondrules are in general depleted in metal and sulfide compared to the whole rock; porphyritic types are less depleted than norporphyritic types. Several mechanisms have been suggested which might generate these trends: 1) Metal/sulfide assemblages were among the precursor materials available for chondrule formation, but metal/sulfide was underrepresented in most silicate-rich chondrules. 2) Metal and sulfides formed via the reduction of an initially oxidized chondrule precursor material. 3) Metal/sulfide loss occurred during chondrule melting by the separation of immiscible liquids. There is now evidence that all three of these mechanisms operated, with the first and third being most important.

While most chondrules have Fe/Si and Ni/Fe ratios < whole rock (w.r.), metal-rich ones are often > w.r. Mechanism 1 can more easily produce these effects than can 2; w.r. values should be an upper limit for Fe/Si and Ni/Fe in mechanism 2. Chondrules rich in FeO but poor in metal are always poor in siderophiles. This too is more consistent with mechanism 1 than 2. Reduction of oxidized material certainly occurred in chondrules. Ni-free dusty metal, as well as generally low Co/Fe, Ni/Fe ratios have been reported in chondrule metal. However, this is probably a second-order effect on the origin of the metal.

Metal/sulfide loss has been postulated for chondrules by many workers. Physical evidence for it may be found in chondrule thin sections. Droplets of opaques may be observed on or near the surfaces of metal-rich chondrules. They also commonly fill "craters" on chondrules' surfaces. In fact, the size distribution of chondrule craters is more consistent with an origin by loss of metal/sulfide droplets than by impact. Metal/sulfide loss may be the chief mechanism for producing both the relative depletion of siderophiles and many of the craters observed in nonporphyritic chondrules.

^{40}Ar-^{39}Ar DATING OF INDIVIDUAL CHONDRULES.

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If chondrules have been formed from aggregates of interstellar molecules by a sudden melting process followed by rapid radiative cooling as proposed by (1), there is a chance of preserving radiogenic ^{40}Ar from the presolar history of the chondrule. Thus, for chondrules ^{40}Ar-^{39}Ar ages in excess of 4.53 AE could be found, similar as in the case of some Allende inclusions (2),(4).

Here we report on ^{40}Ar-^{39}Ar dating of individual chondrules from the ordinary chondrites Chainpur (LL3), Mezö Madaras (LL3), Seres (H3,4), Saratov (L4), Bjurböle (L4) and Ochansk (H4). Since chondrules with a high concentration of refractory elements are primary candidates for having inherited interstellar material, we have also selected chondrules with high Ca- and Al contents from carbonaceous chondrites.

Neither the chondrules from carbonaceous nor from ordinary chondrites gave ^{40}Ar-^{39}Ar ages significantly in excess at 4.53 AE. The ages of carbonaceous chondrite chondrules cluster at 4.5 AE, while for ordinary chondrite chondrules we do also find ages, significantly lower than 4.50 AE.

For the 10 dated Chainpur chondrules 5 groups of different chemical characteristics are indicated (3) which point towards specific chondrule formation processes for each group. It could be that these genetic differences are reflected in differing chondrule ages. Unfortunately, however, most of the ^{40}Ar-^{39}Ar spectra for Chainpur chondrules are heavily disturbed due to ^{39}Ar-recoil effects because of inhomogeneous K-distributions thus diminishing the age resolution. A significant age difference was found only between one barred olivine and two porphyritic olivine chondrules.

REFERENCES

(1) Clayton, D.D. (1980), Astrophys.J. 37, p. 239.

(2) Jessberger, E.K. (1982), to be published.

(3) Kurat, G., Pernicka, E., Herrwerth, I., El Goresy, A. (1982) these abstracts.

(4) Jessberger, E.K. and Dominik, B. (1980), Nature 277, p. 554.

ARGUMENTS IN FAVOR OF A VOLATILIZATION-RECONDENSATION MODEL FOR CHONDRULE FORMATION. Jan Hertogen, Fysico-chemische geologie, Leuven University, Belgium.

The average Mg/Si atomic ratio of the abundant granular olivine chondrules in unmetamorphosed C3 chondrites is significantly higher (1.4xC1 for C3V and 1.25xC1 for C3O) and the average Fe/Si atomic ratio considerably lower (ca. 0.15xC1) than in whole rock C3's (1). Since the C1 Mg/Si and near C1 Fe/Si ratios of whole rock C3's can be hardly fortuitous, it follows that chondrules and 'matrix' (a) must be complementary in a chemical sense, and (b) must have been accreted in nearly the same proportions as they were formed.

These observations imply that the chondrule formation process was a very efficient one, and leave little room for impact melting models or any other model that calls for preferential accretion of chondrules. They also cast some doubt on the plausibility of chondrule formation during the chaotic infall stage of the nebula (2), as it appears rather improbable that chondrules and complementary fine fraction could stay together in a turbulent nebula.

If chondrules have formed through melting of pre-existing solids (3,4) volatilization of a considerable fraction of Mg, Si and Fe needs to be invoked to explain the Mg/Si and Fe/Si fractionations in C3 chondrules. The concentrations of moderately volatile and volatile elements in chondrules are then expected to be very low, which is obviously not the case (1).

Many chemical properties of chondrules can be explained by a model involving almost complete evaporation of dust-enriched patches in the nebula, followed by metastable liquid condensation (2,5). However, the complementarity of 'matrix' and chondrules requires that gas-liquid and gas-solid condensation took place more or less simultaneously. The presence of fine-grained rims around chondrules (6) suggests that gas-solid condensation became the dominant process in the final stages of recondensation.

Granular olivine chondrules in unequilibrated ordinary chondrites differ from C3 chondrules in their lower Mg/Si atomic ratios and higher Na/Si and Mn/Si ratios. As there is no obvious reason to postulate a different origin for chondrules in C3 and ordinary chondrites, these data could imply that the liquid condensates in ordinary chondrites comprised a larger fraction of the more volatile elements.

(1) McSween H.Y. (1977) Geochim. Cosmochim. Acta, 41, p.1843-1860. (2) Wood J.A. and McSween H.Y. (1977) In Comets-Asteroids-Meteorites, A.H. Delsemme, Ed., University of Toledo Press, Toledo, p. 365-373. (3) Gooding J.L., Keil K., Fukuoka T. and Schmitt R.A. (1980) Earth Planet. Sci. Lett., 50, p. 171-180. (4) Grossman J.N. and Wasson J.T. (1982) Geochim. Cosmochim. Acta, 46, p.1081-1099. (5) Blander M. and Katz J.L. (1967) Geochim. Cosmochim. Acta, 31, p.1025-1034. (6) Allen J.S., Nozette S. and Wilkening L.L. (1980) Geochim. Cosmochim. Acta, 44, p. 1161-1175.

DYNAMIC CRYSTALLIZATION EXPERIMENTS AS CONSTRAINTS ON CHONDRULE ORIGINS, Roger H. Hewins, Dept. of Geological Sciences, Rutgers University, New Brunswick, N.J. 08903.

Major constraints on chondrule origins include textures, chemical (including isotopic) data and experiments which reproduce chondrule-like spherules. The presence of relict grains within some chondrules (1,2) shows that they formed by melting of pre-existing solids. The oxygen isotope differences between chondritic particles (3,4) indicate that the pre-existing solids were primitive and never equilibrated in a parent body. These observations rule out many models for chondrule formation but give little information on the heating event which generated droplet chondrules. Dynamic crystallization experiments which reproduce the textures of natural chondrules throw light on the physical environment in which chondrules cooled and hence constrain heating mechanisms somewhat.

There is some broad agreement in recent (5,6,7) dynamic crystallization studies: a wide range of cooling rates is required to reproduce the textural range of chondrules; cooling times are all relatively short and are measured in hours; chondrule morphology can be reproduced by cooling from the liquidus without directly imposing any large initial supercooling. We (7) disagree with (5) that chondrules were "quenched" (sensu stricto). Experimental attempts to quench runs may produce two generations of the *same* phase, which we have not observed in natural chondrules. The observed faceted olivine plus dendritic pyroxene can be produced by continuous cooling and in pyroxene excentroradial chondrules continuous cooling is indicated down to at least 1000°C (7). On a cosmic scale, of course, this continuous cooling is little different from quenching.

Textural, isotopic and experimental data appear to rule out condensation from the nebula and impact on a regolith as origins for chondrules. Although there is currently widespread agreement that chondrules formed by the heating of primitive particles, there is a wide variety of conceivable heating models. The requirement that droplet chondrules cool at least 450°C in a matter of hours may eliminate some heating mechanisms. Models in which the proto-Sun is the main heat source (8) appear to be unable to cool the chondrules fast enough. The heating seems best described as "transient high-temperature events of unknown nature" (9).

References

1. Rambaldi E.R. and Wasson J.T. (1981) Geochim. Cosmochim. Acta 45, 1001-15.
2. Nagahara H. (1981) Nature 292, 135-136.
3. Mayeda T.K., Clayton R.N. and Olsen E.J. (1980) Meteoritics 15, 330-331.
4. Gooding J.L. et al. (1980) Meteoritics 15, 295.
5. Planner H.N. and Keil K. (1982) Geochim. Cosmochim. Acta 46, 317-330.
6. Tsuchiyama A. and Nagahara H. (1981) Mem. Nat. Inst. Polar Res. 20, 175-92.
7. Hewins R.H., Klein L.C. and Fasano B.V. (1981) Proc. Lunar Conf. 12, 1123-33.
8. King E.A. (1982) Proc. Lunar Planet. Sci. Conf. 13th, in press.
9. Wood J.A. (1982) Earth Planet. Sci. Lett. 56, 32-44.

STELLAR CHEMICAL PROCESSES (1)

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The overwhelming majority of the atomic nuclei of chondritic meteorites, hence of chondrules, have been formed by stellar nucleosynthesis. All sources exhale matter into their local interstellar media either gently and continuously (stellar winds), or violently and more sporadically (novae, supernovae). From sources to chondritic meteorites, this matter experiences chemical processing which will be introduced by a number of other topical presentations (2-6). This topical paper deals with chemical and isotopic signatures of matter at the time of its issuance from the sources.

The primary cosmochemical considerations are:

1 The composition (= elemental isotopic abundances) of bulk matter which is exhaled over long time periods from a given source changes with time according to the chemical evolution of the source itself.

2 The composition of bulk matter exhaled by novae and supernovae varies from source-to-source, even for sources which belong to the same "clan" (e.g. stars with masses greater than about $10\ M_\odot$ (7))

3 The exhalations from Type I and II supernovae are initially compositionally stratified (7).

4 Because of this stratification, the traditional geochemical "rules" may be violated in unsuspected ways.

5 Records from "radiometric clocks" can begin to accrue in matter anywhere the moment that the first chemical fractionations occur.

6 The assumption of a compositionally uniform Milky Way galaxy ("cosmic abundances") is a useful first approximation, but the uniformity is bound to be significantly violated locally and transiently.

Considerations one and two are anchored on the well-deduced sequences of thermonuclear burning in stars, but also on the idea that the composition of the local environment must depend on the exact physical evolution of the source. Thus, the compositions of dust-laden circumstellar cocoons may depend on the nature of stellar "dredge-up" and on the processes by which matter is transferred from stellar surfaces to the circumstellar cocoons (8). Also, the exact duration and geometry of convection loops in massive stars may determine the massfractions of rare nuclear species whose formation has no detectable consequences for the stars' energy budgets.

The third and fourth considerations have important implications if condensates appear in unmixed, or else only partially mixed, supernova exhalations (9). Even after "condensation" there are distinct compositional zones of the residual gas phase. Only the outer zone has a residual gas phase whose composition resembles that of a "solar nebula". There will be a massive middle zone in which oxygen (atomic and/or molecular) and neon are the most abundant species. There will be an inner zone which is essentially free of hydrogen and oxygen, but contains primarily helium and argon. The chemistry which might occur when these zones begin to mix has hardly been investigated.

In this context, one must keep in mind that certain isotopes of geochemically very similar elements, e.g. the *p*-isotopes of Kr and Xe, may find themselves initially in chemically very different environments (10).

Consideration five bears on the question whether extinct radionuclides such as ^{129}I and ^{26}Al did, or did not, occur "live" in the solar nebula.

An even intenser collaboration between astrophysicists and cosmochemists is needed now and in the future to resolve the current controversies.

STELLAR CHEMICAL PROCESSES

Heymann, D.

A "portfolio of desiderata" might include:

- continued search for extinct radionuclides, e.g. ^{135}Ba,
- continued search for "FUN" anomalies,
- improved theories for the physical state of matter and of physical processes in the immediate environments of sources,
- improved condensation theories.

The role of chondrules in such a programme is still unclear. There are many orders of magnitude more condrules than there are chondritic meteorites. What we need is a quick and reliable surveying tool to sort out the unusual chondrules from the "run of the mill" chondrules. The ion microprobe technique is probably still the best bet.

References and Notes: (1) This title has been assigned. I prefer: "Stars, birthplaces of atoms in chondrules". (2) Clayton, D. D., "Presolar Materials" (1982) This volume. (3) Cameron, A. G. W., "Processes in the Solar Nebula" (1982) This volume. (4) Grossman, L., "Which objects in Allende went through a molten stage" (1982) This volume. (6) Fredriksson, K., "Metamorphism in Chondrules and Chondrites" (1982) This volume. (7) Weaver, T. A., Zimmerman, G. B., Woosley, S. E. (1978) *Astrophys. J.* **225**, p. 1021-1029. (8) Ray, J. and Heymann, D., in *The Ancient Sun*, p. 491-512. Pergamon Press. (9) Lattimer, J. M., Schramm, D. N., and Grossman, L. (1978) *Astrophys. J.* **219**, p. 230-249. (10) Heymann, D. (1982) In *Lunar and Planetary Science XIII*, p. 328. Lunar and Planetary Institute, Houston.

ON THE COMPOSITION AND STATE OF ALLENDE CHONDRULE PRECURSOR MATERIAL.

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1. The ratio of chondrules and inclusions to matrix in Allende is considerably lower than in ordinary chondrites. Another important difference is also immediately apparent at low magnification. Many chondrules in Allende have indistinct boundaries and seem to grade continuously into the matrix. We have recently presented strong evidence that most or all matrix olivine in Allende formed by a reaction between enstatite and FeO. This reaction drastically altered all 13 pyroxene containing chondrules that we examined in detail. Enstatite itself in Allende chondrules tends to be concentrated in the rims [1] and poikilitically encloses small rounded forsterite grains. These observations lead us to believe that past efforts to infer the composition of Allende chondrule precursors from measured chondrule compositions [2] are subject to considerable uncertainty. We will discuss possible composition ranges in comparison with similar data for ordinary chondrites.

2. An additional source of information on the nature and state of Allende chondrule precursor materials is the inclusions trapped in crack-free forsterite crystals. These include silicate glass, Ni-rich metal, magnetite and sulfides. They also include numerous spherical vesicles frequently containing euhedral Ca-phosphate crystals. We will also discuss the possible implications of these observations.

[1] Clarke R.S., Jarosewich E., Mason B., Nelen J., Gomez M., and Hyde J. R. (1970) The Allende, Mexico, meteorite shower, Smithsonian Contrib. Earth Sci. 5, 1-53.

[2] Simon S.B. and Haggerty S. E. (1980) Bulk compositions of chondrules in the Allende meteorite. Proc. Lunar Planet Sci. Conf. 11th, p. 901-927.

CONDITIONS AND TIME OF CHONDRULE ACCRETION.

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It is generally argued that the ordinary chondrites formed by cold accretion of chondrules, metal, sulphide and low-temperature matrix (1,2) followed by thermal metamorphism under either closed (1,2) or open (3) system conditions. Such a history requires two sources of heat, the earlier for chondrule production, the later for metamorphism; extreme "metamorphic" heating could have led to melting and the formation of differentiated meteorites. Alternatively, if the ordinary chondrites accreted hot (4,5), the second heat-source becomes unnecessary provided that an early, single source of heat was responsible for both chondrule formation and crystal-liquid fractionation, the latter to produce differentiated meteorites. Evidence in favour of hot accretion is reviewed, and it is argued that some unbrecciated ordinary chondrites have components which formed by crystal-liquid fractionation. Age and isotopic data are consistent with formation of the ordinary chondrites contemporaneously with eucrites and some groups of irons (6).

HOT ACCRETION: In the H3 chondrite, Tieschitz, several chondrules were plastically deformed by the impingement of solid chondrules (7). Mesostases of two deformed chondrules are nepheline-normative. Chondrules and clasts have dark rims, some of which have been deformed, indicating that they were added to chondrules while some were still hot (7). Ashworth, from TEM studies, likens dark rims in Tieschitz (and Chainpur, LL3) to fine grained chondrule mesostases, i.e. the product of crystallization of liquids (8). In narrow channels between chondrules occurs nepheline-rich white matrix (9) which is interpreted as mildly shocked crystals from fractionated, undersaturated chondrule liquids (7). Such liquids require high ambient temperatures to allow flow along inter-chondrule channels at acceptable pressure gradients. No evidence for metal-FeS flow in situ was observed, in contrast to the H4, Quenggouk, and H6, Kernouve, which may have accreted at higher temperature than Tieschitz. This conclusion was independently reached by Cristophe-Michel-Levy (5). Structure and calcium contents of low-Ca pyroxenes in H-group chondrites are probably best interpreted in terms of cooling at different rates from high temperatures. In H3s, twinned monoclinic px is intergrown with pigeonite; in H4s and H5s "striated orthopyroxene" occurs; and in H6s there is only orthopyroxene. Ca contents are typically about 0.5 wt% throughout (4). One L5-6 and one L6 chondrite probably cooled more slowly than their H-group equivalents.

FRACTIONATED COMPONENTS IN ORDINARY CHONDRITES: Nepheline-normative mesostases occur in chondrules of some type 3 chondrites (7,10,11). These must have had a different source from "hypersthene"-normative chondrules, unless vapour fractionation is invoked, which seems unlikely for Tieschitz at least (7). Although clasts of igneous rocks are well documented in ordinary chondrites (12), most exhibit no evidence of fractionation within the silicate. Exceptions do occur, such as anorthositic glass in Bovedy (L3) (13), and noritic chondrules in Goodland (L4) (14) and Kramer Creek (L4) (15). Two noritic clasts were found in Tieschitz (6). Some evidence exists for the fractionation of divalent Eu from trivalent rare earth elements (16,17). Bevan and Axon (18) interpreted polycrystalline taenite in Tieschitz as modified dendrites produced by rapid solidification of Ni enriched liquids. In addition, in the unshocked H6 Kernouve metal grains with bulk Ni from 10-15 wt% exhibit a pseudo-widmanstätten pattern, yet most of the metal is either kamacite or zoned taenite. The isolated grains have not exchanged Ni with their surroundings and hence probably represent metal particles with primary Ni contents significantly greater than that of the bulk metal in the meteorite (9 wt%, ref.19). (One particle of "zoneless plessite" in Barwell, L5-6, was figured by Sears and Axon, ref.20).

AGE AND ISOTOPIC DATA: Rb-Sr (21) and U-Pb (22) ages of ordinary chondrites do not differ significantly from 4.55 Ga, regardless of petrologic type. Ar-Ar ages tend to be slightly younger (23). U-Pb (24) and Sm-Nd ages of some eucrites (e.g.25) are close to the same figure. Silicates of IAB and IIE irons have yielded Ar-Ar ages from 4.50 to 4.57 Ga (26,27). All these ages are indistinguishable. Furthermore, the isotopic ratios of lead from Cañon Diablo troilite are consistent with initial lead isotopic ratios of various ordinary chondrites (22), indicating that Cañon Diablo metal plus troilite fractionated from silicate (i.e. U) at the time of formation of the chondrites. I-Xe ages of chondrites overlap those of IAB irons (28); the IIE iron Weekeroo Station, has a younger age (27). I-Xe ages assume uniformity in I isotopic ratios at any time. Finally, the presence of ^{107}Ag anomalies in some IVB irons (29) suggests that these meteorites are from a body which differentiated early enough to record the former presence of an isotope (^{107}Pd) with a half-life of only 6.5 Ma. The evidence indicates that ordinary chondrites accreted and cooled to isotopic closure temperatures at the same time as several types of differentiated meteorite.

CONCLUSION: Our preferred model for the origin of ordinary chondrites is as follows: Collision between differentiated, partly solidified planetary objects produced a hot cloud with liquid droplets of metal-sulphide and silicate, together with solid clasts of similar materials that were representative of pre-existing rocks. An extra-solar system component or source is required for at least one colliding object to account for O-isotopes and ^{129}I. Sedimentation, with size sorting (30), from the cloud on small, planetary bodies led to a stratigraphic sequence of chondritic materials with petrologic 6 or 7 at the base and type 3 at or near the surface. Petrologic type was determined by cooling rate, especially below about 700° C. Further planetary collisions produced new generations of chondrules which could have become mixed with pre-existing type 4-6 rocks. This model seems consistent with the ideas of Smith (31) and Zook (32). Dark rims and metal-sulphide armour around clasts and chondrules are interpreted as splashed liquids. Introduction of volatiles into ordinary chondrites poses a problem. We can only suggest that they may have been deposited by condensation from the cloud during deposition of solids. There may also have been exchange between gas and chondritic sequence after deposition had ceased. The strength of the model lies in its requirement of a single, short-lived heat-source early in the history of the solar system.

REFERENCES: (1) Larimer and Anders (1967) GCA 31, 1239-1270. (2) Larimer (1973) GCA 37, 1603-1623. (3) Wasson (1974) Meteorites Springer. (4) Hutchison et al. (1980) Nature 287, 787-790. (5) Cristophe-Michel-Levy (1981) EPSL 54, 67-80. (6) Hutchison (1982) Phys. Earth planet. Int. (in press). (7) Hutchison et al. (1979) Nature 280, 116-119. (8) Ashworth (1981) Proc. R. Soc. Lond. A 374, 179-194. (9) Cristophe-Michel-Levy (1976) EPSL 30, 143-150. (10) Kurat (1971) Chem. Erde 30, 235-249. (11) Dodd (1978) EPSL 40, 71-82. (12) Rubin et al. (1981) GCA 45, 2213-2228. (13) Graham et al. (1976) GCA 40, 529-535. (14) Hutchison and Graham (1975) Nature 255, 471. (15) Gibson et al. (1977) Meteoritics 12, 95-107. (16) Nakamura (1964) GCA 38, 757-775. (17) Evensen et al. (1978) GCA 42, 1199-1212.

(18) Bevan and Axon (1980) EPSL 47, 353-360. (19) Hutchison et al. (1981) Proc. R. Soc. Lond. A 374, 159-178. (20) Sears and Axon (1975) Meteoritics 10, 486-487. (21) Minster and Allegre (1979) EPSL 42, 333-347. (22) Unruh (1982) EPSL 58, 75-94. (23) Turner et al. (1978) Proc. Lunar Planet. Sci. Conf. 9th, 989-1025. (24) Manhes et al. (1981) Meteoritics 16, 353-354. (25) Hamet et al. (1978) Proc. Lunar Planet. Sci. Conf. 9th, 1115-1136. (26) Niemeyer (1979) GCA 43, 1829-1840. (27) Niemeyer (1980) GCA 44, 33-44. (28) Niemeyer (1979) GCA 43, 843-860. (29) Kaiser et al. (1980) Meteoritics 15, 31-311. (30) Dodd (1976) EPSL 30, 281-291. (31) Smith (1979) Mineralog. Mag. 43, 1-89. (32) Zook (1980) Meteoritics 15, 390-391.

IRON LOSS FROM FLUID DROP CHONDRULES BY PARTIAL EVAPORATION

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In order to obtain some common chemical compositions and petrographic types of fluid drop chondrules by fusion of dust approximating solar composition, substantial losses of volatile elements and iron are required. While the loss of volatile elements such as hydrogen and sulfur can easily be demonstrated accompanying the fusion of predominantly silicate dust at relatively low temperatures, the loss of iron and some siderophiles has presented a more difficult problem (e.g. 1). Melting and partial evaporation experiments in a vertical access solar furnace in both vacuum and hydrogen have permitted the direct observation of the formation of immiscible molten metallic iron spherules by reduction of iron in silicate melts of bulk Allende and bulk Murchison starting compositions. In response to high temperature heating, some sample runs in excess of 2980°C, molten metallic iron spherules were visually observed to form and grow on the surfaces of predominantly silicate melt beads. However, continued heating over periods of minutes to tens of minutes caused the molten iron spherules to shrink and eventually to disappear by apparent evaporation, thereby resulting in an almost total loss of iron by the silicate melt. During the course of several sample runs, this process was interrupted by quenching in order to document the visual observations. Iron spherules and coatings commonly occur on and near the surfaces of the experimentally produced silicate melt beads. These textures closely resemble those seen in many meteoritic fluid drop chondrules, which may indicate that those chondrules have been heated to high temperatures for similar periods of time in the solar nebula and have lost a portion of their initial iron contents by reduction and partial evaporation of the molten iron spherules. These observations and conclusions are consisent with the general model for the formation of many, perhaps most, fluid drop chondrules presented by King (2, 3), which includes the fusion of primitive dust in the solar nebula, spattering of molten drops, and continued heating of at least some molten drops to produce vapor fractionated chondrule compositions.

References

(1) Gooding, J. L., K. Keil, T. Fukuoka and R. A. Schmitt (1980) Earth and Planet. Sci. Letters 50, p. 171-180.

(2) King, E. A. (1982) Lunar and Planetary Science XIII, Part I, p. 389-390.

(3) King, E. A. (1982) Proc. Lunar and Planet. Sci. Conf. 13th, Jour. Geophys. Res., suppl., in press.

SPATTERING: THE DOMINANT PROCESS OF FLUID DROP CHONDRULE FORMATION

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Dust samples approximating solar composition, bulk Murchison and bulk Allende, as well as basalt standard BCR-1, were observed in solar furnace fusion and partial evaporation experiments to form many chondrule-like spherules by spattering (1, 2). Dozens to hundreds of synthetic spatter chondrules were formed in all sample fusion runs regardless of heating rate or maximum temperature attained. The spatter mechanism is most efficient in the production of chondrules at high heating rates and high temperatures in volatile-rich samples, but also occurs in samples that are heated very slowly to melting and in samples of refractory compositions. Many of the synthetic spatter chondrules have textures and mineralogies that are similar to some meteoritic chondrules, particularly non-porphyritic fluid drop chondrules. Such similarities in textures and mineralogies have been observed by many previous workers, who produced chondrule-like spherules from molten drops by a variety of processes (e.g. 3, 4, 5). However, in addition to similarities in textures and mineralogies, at least some populations of synthetic spatter chondrules have been produced that closely resemble some populations of meteoritic fluid drop chondrules in grain size frequency distribution characteristics, including sorting (1, 2). Problems of generating populations of meteoritic fluid drop chondrules with the observed grain size and sorting have been a serious constraint on proposed mechanisms of chondrule formation and history (e.g. 6, 7, 8). However, if the spatter mechanism is the dominant process of fluid drop chondrule formation, there is no necessity for a complex two-step process to yield the observed sorting and other grain size characteristics. It should be noted that only an average of more than one spatter chondrule need be produced from each fluid drop chondrule formed by some other process, e.g. direct melting, for the spatter mechanism to numerically dominate the fluid drop chondrule populations. Such spatter chondrule dominated populations, if derived from the same primary melt or from chemically similar primary melts, should be chemically related chiefly by a range in amount of vapor fractionation. This appears to be the case in at least some chondrule composition data sets in which many of the compositional differences between individual chondrules might be explained by different amounts of partial evaporation of iron and some siderophile elements, including iridium (e.g. 9, 10). Temperature, surface tension, viscosity and volatile content of the primary melt are believed to be the most important factors in determining the number of spatter chondrules formed from a primary melt. These same factors also probably control the exact grain size frequency distribution characteristics of the spatter-produced fluid drop chondrule population. Bulk composition, temperature history and content of unmelted grains, partially melted grains, bubbles and other nucleation sites may be the most important factors in determining exact fluid drop chondrule texture.

References: (1) King, E. A. (1982) Lunar and Planet. Sci. XIII, 1, p. 389-390. (2) King, E. A. (1982) Proc. Lunar and Planet. Sci. Conf. 13th, Jour. Geophys. Res., Suppl., in press. (3) Rinne, F. (1897) Neues Jahrbuch 1, p. 259-261. (4) Fredriksson, K. and A. E. Ringwood (1963) Geochim. Cosmochim. Acta 27, p. 639-641. (5) Nelson, L. S., M. Blander, S. R. Skaggs and K. Keil (1972) Earth and Planet. Sci. Lett. 14, p. 338-344. (6) Dodd, R. T. (1976) Earth and Planet Sci. Lett. 30, p. 281-291. (7) King, T. V. V. and E. A. King (1978) Meteoritics 13, p. 47-72. (8) King, T. V. V. and E. A. King (1979) Meteoritics 14, p. 91-96. (9) Osborn, T. W. and R. A. Schmitt (1971) Meteoritics 6, p. 297-298. (10) Gooding, J. L., K. Keil, T. Fukuoka and R. A. Schmitt (1980) Earth and Planet. Sci. Lett. 50, p. 171-180.

CHONDRULES AND THE ISOTOPIC VIEW OF INTERSTELLAR COMETS.

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It is argued by (1),(2),(3),(4) and (5), that comets are of interstellar origin. In their view it was not possible for the Oort comet cloud to survive since her formation. As the solar system passed through the spiral arms of the galactic system, tidal forces exerted by molecular clouds should have depleted the original Oort cloud (6). On the other hand, while passing through a molecular cloud, the Oort cloud is thought to be episodically replenished by the capture of interstellar comets which have condensed in these clouds (6). Further it is argued that we can follow for these captured comets the view that comets are the main source of large Apollo-asteroids and meteor streams (7),(8).

Since Earth-crossing asteroids are considered today as a prime source for major impact events throughout the Earth's history (9), and meteor streams provide a lot of meteoritic matter,one has to conclude, following (1)-(5), that quite a lot of the meteoritic material in our possession is derived from interstellar sources.

This forces us to evaluate some meteoritic material for a critical check of this chain of deductions. As shown by (10), it is most likely that because of their short cosmic ray exposure ages chondritic meteorites have broken off from parent bodies in Earth-crossing orbits. Since a large percentage of meteoritic material (≈50%) of primitive origin is in the form of chondrules, they should be, following the above argumentation, the largest available amount of interstellar condensed material. If this has to originate from different molecular clouds, we would expect a large variety of isotopic structures in the chemical elements, caused by the scattered sites and nucleosynthetic histories of the MC's in the galaxy. It seems as if chondrules would be the best material for a critical search of the required large isotopic anomalies. It is well known that isotopic anomalies in chondrules do exist (see eg (11)). But in all cases of isotopic deviations from the normal solar system values are they not as large as we'd expect it from many different nucleosynthetic sources. A critical review of the possibilities of stellar nucleosynthesis leads us to the conclusion, that in case of an extra-planetary-system origin of chondritic meteorites, their isotopic heterogenties should be larger than detected until now. All observed isotopic anomalies in chondrules are in agreement of a view involving a source cloud with isotopic variations of the initial chemical components in it (12). Furthermore, if more recently synthesized stellar material should be included in chondrules, we would expect to find anomalies in the isotopic structure of longer-lived radionuclides as ^{235}U. No evidence for that has been found (13).But as comets from the outer solar system are not certain as a meteorite source (14), we aren't forced to abandon the whole view of interstellar comets. Instead we should rely on future investigations of more realistic cometary material, like interplanetary dust, rather than of chondrules.

References:(1)Clube,SVM, Napier,WM, Nature 282,455 (2)Clube,Napier Earth Pl.Sci.Lett.57,251 (3)Clube,Napier(1982) Q.J.R.ast.Soc.23,45 (4)Clube,Napier(1982)Lecture at IAU G.Ass.Patras (5)Clube(1982) Proc.W.Int.Comets,Obs.Edinburgh (6)Napier,like (5) (7)Öpik(1963) Adv.A.Astr.phys.2,219 (8)Opik(1966)Adv.Astr.Ap.4,301 (9)Shoemaker et al,in:Gehrels,Asteroids (10)Heymann(1978)Meteoritics13,291 (11) Wasserburg et al(1980)in Lal:Proc.E.Fermi Sc.144 (12)Clayton(1982) Q.J.R.ast.S.23,174 (13)Unruh,E.pl.Sci.Lett.58,75 (14)Kresák,as (9).

IMPACT ORIGIN OF CHONDRULES. Gero Kurat, Naturhistorisches Museum, A-1014 Vienna, Austria.

Of the many models of chondrule and chondrite formation several variations of impact model can accommodate most - if not all - observations and data on chondrules and chondrites. Actually, no serious models can neglect the role of collisions in the chondrite formation process(es):

(1) Collisions are unavoidable during the early accretion stage of planets and planetesimals. Old planetary surfaces give evidence for very high collision rates persisting during that stage. There is also plenty of evidence for shock events in meteorites and collisions apparently are responsible for breaking up small bodies into those pieces, which we can collect as meteorites.

(2) Chondrites are chaotic microbreccias consisting of a variety of lithologies - typical products of impact processes. For some chondrites a regolith origin has been established by track and noble gas contents and isotope studies. These studies in addition suggest high gardening (=impact) rates.

(3) Chondrule mineralogies and chemical compositions appear to be random mixtures of different lithologies derived from a variety of sources with different pre-chondritic histories and degrees of fractionation. Impact mixing and melting apparently is the most logical model that can also account for the evaporation-recondensation phenomena observed on chondrules.

(4) Some chondrules contain relict minerals from the precursor rock(s). The most common Mg-Al spinel and olivine relicts have chemical compositions which are far out of equilibrium with the enclosing melt. Their presence thus gives evidence for fast melting and subsequent cooling. These constraints are easily met by impact but not by other processes.

(5) There is now abundant isotopic evidence (^{16}O) for mixing of different lithologies into chondrules.

(6) Beside chondrules a variety of melt rocks has been identified in chondrites - typical products of impact melting.

(7) It is well established that impact did create chondrules on the moon. Compositional differences between the lunar surface and the chondrite parent bodies and the time constraints placed by the planetological evolution of the moon (low gardening rate) can account for the deficit in chondrules (and glassy droplets) in the lunar regolith.

(8) Chondrule and xenolith formation ages can differ from one another and from the whole rock age and thus evidence late mixing of lithologies and chondrules of different ages.

Upon request a list of references will be available at the conference.

GEOCHEMISTRY OF CHAINPUR CHONDRULES; EVIDENCE FOR EVAPORATION AND RECONDENSATION.

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Bulk and mineral chemical data were collected by INAA and electron microprobe on a suite of 10 chondrules from the Chainpur LL3 chondrite, which have been selected for $^{40}Ar/^{39}Ar$ age determination (1). On this set of data we made the following observations:

(a) As previously recognized (2) chondrules are on average depleted in siderophiles and consequently enriched in lithophiles.

(b) The lithophile component of some of our chondrules appears to be primitive and a relationship between different chondrule compositions can be established by a few simple processes. In Fig.1 the relationship of Na and K is shown. Three groups of chondrule silicate compositions can be distinguished: A primitive group forming a sequence of increasingly devolatilized chondrules: 1 (~ chondritic),8,2,3,4,9. Volatiles and moderately volatiles are strongly depleted in the most refractory chondrules by factors of 0.1 for K and 0.5 for Mn relative to chondritic composition. The second group consists of two chondrules (6 and 10), which are slightly enriched in Na but depleted in K. Chondrules 5 and 7 form the third group, which is enriched in the volatiles K and Na (1.9x and 1.1xCI respectively) and in Mn (1.3xCI). These different chondrule compositions can probably be related to each other by evaporation-recondensation processes, evidence of which has been reported a long time ago (3).

(c) Metal compositions in all chondrules are fractionated. They are depleted in Ir and Au to different extents (down to 0.1xCI for Ir). In order to account for the Chainpur bulk metal composition two additional types of metal (rich in Ir and Au) must be postulated, one of which has been identified recently (4). However, both were not sampled in our chondrule suite.

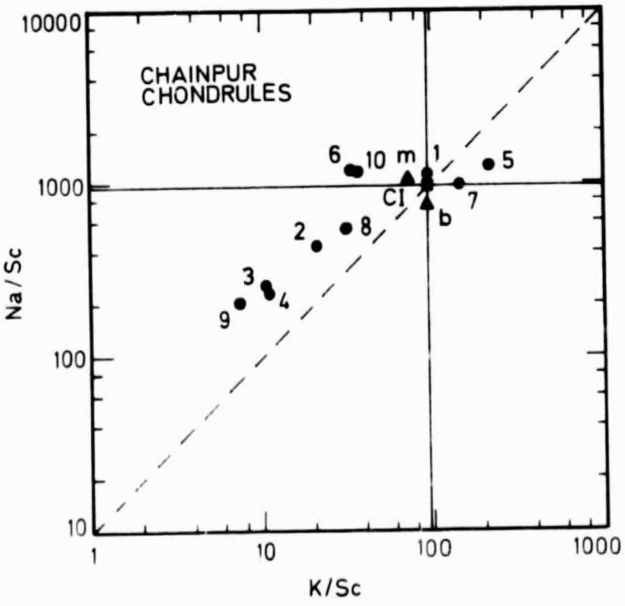

Fig.1: Na/Sc versus K/Sc in chondrules from Chainpur compared to CI, Chainpur matrix (m), and Chainpur bulk (b) (ref.4) compositions.

References
(1) Herrwerth I. et al.,this volume.(2) Dodd R.T.(1978) Earth Planet.Sci.Letts.39,52.(3)Kurat G. (1967) Geochim.Cosmochim. Acta 31,1843; Walter L.S. and Dodd R.T. (1972) Meteoritcs 7, 341.
(4) Grossman J.N. and Wasson J.T. (1982) Geochim. Cosmochim. Acta 46, 1081.

FLUID INCLUSIONS IN CHONDRULES AND HISTORY OF THE METEORITE HOSTS.

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Fluid inclusions (F.I.) have been found in chondrites ALHA 77230 (L4), ALHA 77299 (H3), Bjurbole (L4), Faith (H5), Holbrook (L6), Jilin (H5), Peetz (L6) and St. Severin (LL6). In addition to the study of the inclusions (previously reported by (1)), characterization of shock and thermal history of the host minerals, chondrules and groundmass has been carried out on all of the above meteorites with the exception of St. Severin. Petrographic character, relative chronology and approximate conditions of the post-formational events are deduced in comparison with data from impact cratering and shock-annealing experiments on olivine, pyroxene and Fe-Ni (2-4).

F. I. found in meteorites share several common characteristics. They are small, generally <10 µm, variable in shape, they occur in olivine and pyroxene hosts as isloated clusters (primary looking inclusions). Less commonly, inclusions are found along healed fractures (secondary inclusions). Compositions of the fluids are not yet known in detail but may be dominantly aqueous, based on microthermometric characteristics (1). This is consistent with primary laser Raman spectroscopic measurements, which also show the possible presence of complex aliphatic hydrocarbons (5).

Type 3 ALHA 77299 has a polymict breccia texture and includes fragments of higher petrologic type. The clastic debris matrix is unannealed. The degree of shock metamorphism varies from clast to clast. These characteristics suggest: (1) shock-impact is likely process by which the rock has been assembled (chondrite formation), (2) the chondrite has not been significantly shocked nor heated since it was formed. Inversely all other F.I. chondrites have been significantly reprocessed by shock and thermal metamorphism since they were assembled. They have been severely heated at least once ($T \gtrsim 700^{\circ}C$). Except for Holbrook, they have been shocked up to three times with at least one relatively strong shock ($20<P<50$ GPa) resulting in shock deformation in silicates, hardening in metal, communition in the matrix. The strong thermal event mentioned earlier, postdate the later strong shock, as inferred from differential recovery between the various minerals, recrystallization in the matrix, along grain boundaries and fractures. The history of individual F.I. chondrules may be even more complex. Some chondrules have probably experienced shock and thermal annealing before incorporation in the actual chondrite, as exemplified by the two F.I. chondrules in the type 3 ALHA 77299 chondrite.

Conclusions: F.I. are found in chondrites representing a variety of petrologic grades and types. Despite this variety there are similarities in terms of physical properties, morphological characteristics and location of F.I. and in terms of complexity, nature, and overall P-T conditions of events to which F.I. hosts have been subjected. It is noteworthy that these common characteristics are also shared by the F.I. diogenite ALHA 77256. All F.I. carriers, thus far identified in meteorites, have suffered shock in the range 20-50 GPa and reheating $\gtrsim 700^{\circ}C$. This puts severe constraints on any attempt to interpret F.I. as primary inclusions in meteorites. Most likely, the volatiles associated with F.I. were released, transported and trapped well after both chondrules and chondrite formation. Such recycling of volatiles could have occurred in a wide variety of environments and possibly over a relatively extended period of time after formation of each meteorite as indicated by the variety of meteorites bearing F.I. and by the multiplicity of post-formational events. Secondary origin of essentially all F.I. in meteorites would have important implications in terms of significance of F.I. morphologies in general, and on origin and evolution of both planetary volatiles and chondrites. An answer might come from a better understanding of the behavior of fluid inclusions under shock conditions.

References:
1. Warner J.L. et al. (1983) Proc. Lunar and Planet. Sci. Conf. 13th (in press).
2. Impact and Explosion Cratering (D.J. Roddy, R.O. Pepin and R.B. Merrill, eds.), Pergamon Press, N.Y. 1299pp, 1977.
3. Bauer J.F. (1979) Proc. Lunar and Planet. Sci. Conf. 10th, 2573-2596.
4. Lambert P., et al. (1982) Meteoritics (submitted)
5. Ashwal L.D., et al. (1982) Planetary Volatiles Conf. abs.

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COMPLEX CHEMISTRIES OF 24 INDIVIDUAL INDARCH (EH4) CHONDRULES RELEASED BY HCl TREATMENT.

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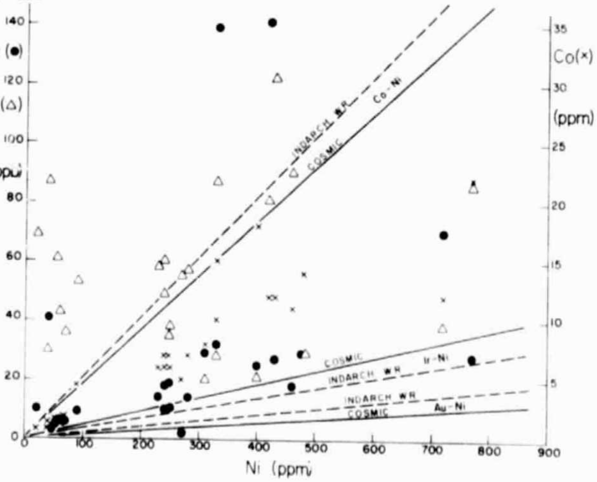
Studies pertinent to unequilibrated chondrites may help elucidate processes for chondrule formation. Previous models have suggested progressive equilibrium condensation augmented by complex nonequilibrium fragmentation and igneous crystallization [1]. This report presents some of our findings based on preliminary INAA results obtained for chondrules ranging in mass from 0.2-3.5 mg. Procedures involved three activations: a 10 min., a 7 hr and a 100 hr. On the basis of major and minor element chemistries, the chondrules represent nearly identical mineralogies consisting of ≈88% enstatite and ≈10.5% albitic plagioclase. Very low metal contents ($\leq 2\%$) suggest metal-silicate immiscibilites in chondrule formation.

Both figures below indicate that these chondrules represent a diverse sampling of complex processes, presumably associated with initial condensation and heterogeneous agglomeration followed by incomplete igneous and/or metaigneous differentiations and finally redistribution by possible planetesimal collisions. The chaotic siderophile data suggest heterogeneous agglomeration of metal-sulfide phases. Igneous processes are evidenced by the diversity of the lithophile trace element patterns. Highly positive and negative Eu anomalies of two chondrule groups suggest that Eu^{+2} resides in Ca^{+2} lattice sites. In all cases those chondrules with +Eu anomalies have ∿2X more Ca than the average chondrule (0.4% vs. 0.2%). However, there is no correlation with the plagioclase indicator elements, Na and Al. Monotonically decreasing patterns from La to Lu for some chondrules are reminiscent of residual liquids and the V-shaped REE pattern of s8 and s14 suggest a possible T.L. component rich in La mixed with equilibrated pyroxene. Overall, the obvious 70% depletion in REE relative to Indarch WR and the very low metal component ($\leq 2\%$) indicate that the majority of the REEs separated into phases immiscible with silicates.

The siderophile abundances are not consistent with simple equilibrium condensation models. Overall Co/Ni ratios are depleted although three smooth chondrules have cosmic Co/Ni ratios. Generally, there seem to be two end members with Co/Ni ratios at 0.25 and another which approximates Indarch WR or cosmic abundances (∿0.05). In light of these observations, complex condensation schemes [2] and possibly two body collisions [1] not only seem plausible but are necessary to explain the complex chemistries associated with enstatite chondrules. Min-pet-isotopic work is in progress.

[1] Leitch C. and Smith J.V. (1981) L.P.S. XII, p. 610-612.
[2] Sears D.W. (1980) Icarus 43, 184-202.



NON-SPHERICAL CHONDRULES: - POSSIBLE MECHANISMS OF FORMATION CONNECTED WITH DYNAMIC ANISOTROPY.

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In most cases the outline of a chondrule section, which is strictly related to the chondrule shape, does not appear to be considerably conditioned by the crystalline texture (1); such an observation suggests either crystallization of a drop, or recrystallization within a predetermined configuration.

Surface tension and isotropic conditions give rise to spherical shape, but the original shape of a minority of chondrules appears to be non-spherical. The relatively unfrequent observation of non-circular outlines is also related to the orientation of the sections: a pear-shaped chondrule may give rise to circular outlines.

Ellipsoidic shapes could be generated by rapid freezing of a drop subject to oscillation in a fundamental mode. However it should be noted that a similar shape could be the result of static uniaxial pressures, acting in a later stage.

As for pear-shaped or drop-shaped chondrules, see e.g.(2) and (3), whose configurations are identifiable by the presence of a preferred polarized cylindrical axis, it may be assumed that, during the cooling, anisotropic external conditions were present. A gravitational field or an electrostatic uniform field could not be directly responsible for such effects, which might instead be explained as a consequence of relative motion (4) in the presence of forces of viscous or dynamic nature, during final solidification of the chondrules. Such conditions could be present as an effect of the impact of particles with a cloud of gas or very fine dust. Another possible mechanism of formation could be found in a very quick cooling of impact melting generated drops, in the act of their separation from the matrix (5).

(1) Gooding J. L. and Keil K. (1981) Meteoritics 16, p. 17-43.
(2) Lange D. E. and Larimer J. W. (1973) Science 182, p.920-2.
(3) Levi-Donati G. R. et al (1976) Meteoritics 11, p. 29-41.
(4) Coradini A. et al (1978) The Moon and the Plan. 18, p.65-76.
(5) Keil K. et al (1973) UNM Ist. of Meteoritics, Sp. Pub. N°7.

THE IMPORTANCE OF HETEROGENEOUS NUCLEATION FOR THE FORMATION OF MICROPORPHYRITIC CHONDRULES; Lofgren, G.E., NASA Johnson Space Center, SN-6. Houston, Texas 77058

Experimental studies on the formation of chondrules (1,2,3) have shown that the spherulitic (excentroradial) and barred chondrule textures are readily produced by cooling melts of chondrule composition at various, but quite rapid rates. These studies support the long held supposition that these textures formed by the crystallization of melts under supercooled conditions (4). Of the chondrules with igneous appearing textures, however, chondrules with microporphyritic textures are much more common than the spherulitic and barred types (5).

Only recently have microporphyritic textures been produced experimentally. Tsuchiyama and Nagahara (6) produced microporphyritic textures by cooling a liquid that contained nuclei which immediately began to grow. The nuclei grew to microporphyritic proportions before additional phases nucleated or the charge was quenched. In this case, an uninterrupted linear cooling event produced the microporphyritic texture and the size and number of phenocrysts were related to the number of nuclei. Planner and Keil (7) produced microporphyritic textures by cooling complete liquids to a predetermined temperature and then holding the charge isothermal. The olivine grew during the cooling and enlarged during the isothermal period. They also suggest that the isothermal plateau is necessary to produce the partially equilibriated olivine composition they observe in chondrules. It would be possible, however, to produce this feature if heterogeneous nuclei are present. The temperature at which the nuclei are equilibriated will dictate the initial composition of the olivine and account for the most Fa-rich compositions than predicted by their fractionation model.

Microporphyritic as well as barred and spherulitic textures can all occur in chondrules of similar composition (8,9). It would be difficult to have melts cooled from a totally liquid state produce all three textural types with generally similar cooling histories. This could happen, however, if the presence of heterogeneous nuclei controlled the development of microporphyritic textures and their absence resulted in the development of barred and spherulitic textures. Similar differences in texture have been produced in terrestrial and lunar basaltic melts (10,11,12). The ideas proposed here are being tested by experiment.

References cited: (1) Blander M., et al., (1976) Geochim. Cosmochim. Acta. 40, p. 889-896. (2) Tsuchiyama A., et al., (1980) Earth Planet Sci. Lett., 48, p. 155-165. (3) Hewins R.H., et al., (1981) Proc. Lunar Planet. Sci. Conf. 12th, p. 1123-1130. (4) Sorby H.C. (1877) Nature, 15, p. 495-498. (5) Gooding J.L. and Keil K. (1981) Meteoritics, 16, p. 17-43. (6) Tsuchiyama A. and Nagahara H. (1981) Mem. Nat. Inst. Polar. Res. Spec. Issue, 20, p. 175-192. (7) Planner H.N. and Keil K. (1982) Geochim Cosmochim. Acta., 46, p. 317-330. (8) Lux G., et al., (1981) Geochim. Cosmochim. Acta., 45, p. 675-685. (9) Grossman J.N. and Wasson J.T. (1982) Geochim. Cosmochim. Acta., 46, p. 1081-1099. (10) Lofgren G.E. (1979) Geol. Soc. Amer. Abst. with Programs, 11, p. 467-468. (11) Lofgren G.E. (1980) In "Physics of Magnetic Porcesses" R.B. Hargraves, ed., p. 487-552. (12) Lofgren G.E. (in press) Effect of heterogeneous nucleation on basaltic textures: A dynamic crystallization study, J. Petrol.

REFRACTORY CHONDRULES IN THE CM METEORITES.

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In addition to conventional chondrules composed of olivine or olivine plus pyroxene and glass, the CM meteorites also contain spheroidal objects which have very refractory chemical compositions. Based on their shapes and textural characteristics, these objects are chondrules. They separate easily from the bulk meteorite as spherules, and at least the cores of many of the spherules show textural evidence for formation from a liquid. This is especially true for hibonite-bearing varieties in which clusters of hibonite crystals radiate inward, apparently having nucleated near the rapidly-cooling outer margin of the spherules.

The chemical compositions of the cores of these refractory chondrules do not vary widely. Typically they contain 70-80% Al_2O_3 and 20-30% MgO, with small amounts of calcium, titanium and silicon. The major mineral phase is a very pure Mg spinel; hibonite is sometimes present. Perovskite almost invariably occurs in amounts up to a few percent.

Most of the refractory chondrules exhibit two distinct rims, each a few microns in thickness. The outermost consists of diopside, sometimes grading into Ti, Al-rich pyroxene. The inner rim layer, sandwiched between the outer diopside rim and the spinel core, is somewhat variable in composition and is probably composite. It is very rich in iron (40-55% FeO) and low totals in microprobe analyses indicate that it is hydrous. It is almost certainly secondary.

Knowledge of the mode of origin of the refractory chondrules is important for understanding other chondrules in the carbonaceous chondrites. Unfortunately, the available constraints are too few to allow unambiguous specification of the processes which must have acted. Nevertheless, the presence of appropriate parent materials in the CM meteorites makes melting of previously condensed solids an appealing possibility. The appropriate parent material consists of very friable, irregularly-shaped inclusions which have been interpreted as indirect nebular condensates, and which have compositions similar to those of the refractory chondrules. If this was the case, very high temperature events were required, $\gtrsim$ 2000°C for some chondrule compositions. However, if the outer diopside rims, which are common to both refractory chondrules and the irregular, friable refractory inclusions, are condensates, then remelting must have taken place early in the condensation sequence, before diopside deposition and considerably preceding accretion to form larger objects.

CHONDRULES AND AGGREGATES: SOME DISTINGUISHING CRITERIA. Glenn J. MacPherson and Lawrence Grossman*, Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637. *Also Enrico Fermi Institute.

If the term chondrule is to be reserved for any object in a meteorite which was once an independent molten droplet, objective criteria must be recognized for distinguishing between such objects and things which do not satisfy this definition. We are particularly interested in distinguishing between chondrules and aggregates, *i.e.* mechanical mixtures of particles that are not necessarily related to one another. Our purpose here is to point out that such criteria exist and to describe what some of them are, using objects in the Allende meteorite as examples.

The presence of glass is almost universally accepted as evidence for a pre-existing liquid. As a result, virtually everyone would agree that those objects in Allende and other unequilibrated chondrites which contain glass, are olivine- and/or pyroxene-rich and which have barred or excentroradial textures were once molten. The term chondrule as defined herein can be applied with certainty only to the above objects which are spheroids, ellipsoids or fragments of these, as such shapes are a clear indication that the objects were once independent droplets. Ambiguity arises in applying the term chondrule to rounded, porphyritic, glass-bearing objects because some could conceivably be abraded fragments of much larger igneous bodies. Some features may be present that can be used to distinguish such objects from chondrules. For example, any mineralogical or chemical zonation that might be present in an abraded fragment would not be expected to be concentric with the external shape of the object, as it would in a chondrule. Also, a chilled margin would be a good indicator of a chondrule. We now turn our attention to glass-free objects which may have been neither independent droplets nor even molten in some cases.

If the shapes and/or sizes of crystals were constrained by their neighbors during growth, then it can be concluded that they solidified *in situ* and the host object did not form by random aggregation of independent crystals that formed elsewhere. An example of such growth interference is found in a Type B1 coarse-grained inclusion (1) in which melilite laths project from the margin of the object inward. The longest ones are at high angles to the inclusion surface, whereas shorter, stubbier ones at lower angles abut against and terminate at the sides of the longer ones.

Showing that the crystals in an object solidified *in situ*, however, is not even sufficient to demonstrate that it was molten, let alone that it is a chondrule. Because droplets solidify due to heat loss from their surfaces, unique features characteristic of such an origin may sometimes be produced which, if seen in an object, would indicate that it is a chondrule. It is reasonable to assume that chondrules were volatile-free, closed systems during solidification. Therefore, in cases where cooling from the outside of a droplet caused solidification to begin on its surface and to proceed inward with falling temperature, the phases nearest the margin should be those predicted to crystallize first from known phase equilibrium relations for the chondrule's bulk composition. Furthermore, the phase rule requires that the number of phases increase toward the center of such an object, unless quenching to a glass has occurred, reaction relationships can be demonstrated or the composition of the object is that of a eutectic. Minerals exhibiting solid solution might, in some cases, be richer in their high-temperature components in the outer mantle of such a chondrule than in the core of the object. An example of a chondrule like this is the Type B1 inclusion mentioned above (1) which has a mantle of spinel + melilite, the first phases predicted (2) to crystallize from a liquid having the bulk composition of this inclusion, and a core of the same minerals + fassaite + anorthite, phases predicted to crystallize later. Furthermore, the cores of individual melilite laths become progressively richer in åkermanite along their lengths toward the center of this inclusion. In contrast, a consequence of the above phase rule argument is that the concentric, multi-layered rims around coarse-grained inclusions (3) and spinel nodules in fine-grained inclusions (3) did not result from progressive crystallization of a liquid, since several of the layers are monomineralic. Some inclusions in Allende (4) have ophitic textures similar to those of terrestrial basic igneous rocks and, by analogy, have been interpreted as products of solidification of a melt. While this is a reasonable inference, it must be pointed out that it is not known that such textures could not also be produced by condensation of a gas. Other arguments, such as those developed above, would help to confirm the interpretation.

Aggregates are conglomerates: their primary constituents did not form in contact with one another and need not be in chemical equilibrium with one another. All would agree that the Allende meteorite fits this definition in that it consists of many diverse inclusions which accumulated with their matrix into a common body. Indeed, the texture of the matrix itself indicates that it is an aggregate (5): euhedral olivine plates which touch one another but are not intergrown and which are separated by abundant voids. Clastic rims (5) that mantle inclusions and chondrules are also aggregates, as their textures are similar to that of the matrix, though their mineral proportions are different. Another example is the amoeboid olivine aggregates (6) in which clumps of Ca-, Al-rich phases are separated from one another by material whose mineralogy and texture are like those of clastic rims. A further example is the fluffy Type A coarse-grained inclusions (7) which are composed of clumps of melilite + spinel + hibonite that are separated from one another by Allende matrix material, clastic rims or Wark-Lovering rims. Finally, the mineral grains and spinel-centered nodules in pink, fine-grained inclusions are not intergrown with one another and are separated by voids, indicating that these inclusions are also aggregates (8), although the above textures are sometimes obscured by post-aggregation alteration products.

References: (1) MacPherson, G.J. and Grossman, L. (1981) EPSL 52, 16-24. (2) Osborn, E.F., DeVries, R.C., Gee, K.H. and Kraner, H.M. (1954) Trans. AIME 200, 38-39. (3) Wark, D.A. and Lovering, J.F. (1977) In Proc. Lunar Sci. Conf. 8th, pp. 95-112. (4) Lorin, J.C., Christophe Michel-Lévy, M. and Desnoyers, C. (1978) Meteoritics 13, 537-540. (5) MacPherson, G.J. and Grossman, L. (1981) Lunar Planet. Sci. XII, 646-647. (6) Bar-Matthews, M., MacPherson, G.J. and Grossman, L. (1979) Meteoritics 14, 342. (7) MacPherson, G.J. and Grossman, L. (1979) Meteoritics 14, 479-480. (8) MacPherson, G J. and Grossman, L. (1982) talk given at 45th Ann. Mtg., Meteoritical Soc., St. Louis.

Physical Properties of Ordinary Chondrites and Implications of Their Accretion and Consolidation Processes

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Ordinary chondrites are considered to be originally aggregates of particulate matter with various sizes. They are now well-consolidated and retain some sort of inherent strength. They are a kind of rocks in this context. However, few attention has been paid on consolidation process of ordinary chondrites. To understand a nature of the consolidation process, we need data on physical properties of ordinary chondrites. Therefore, we measured physical properties (density, porosity, elastic wave velocities, thermal diffusivity and magnetic susceptibility) of 22 ordinary chondrites.

Main results of the measurement are summarized as follows:

(1) Porosity values are distributed in a wide range of 2 to 20 %. Such large porosity variation cannot be ascribed to secondary effect such as shock effect due to collision, since volume change before fracture is usually a few % or much smaller. Therefore, rearrangement of composing grains and some sort of sintering should have operated on ordinary chondrites.

(2) Porosity variation cannot be related to petrologic type, specifically for L chondrites. We can see a slight tendency of decrease in porosity with increase in petrologic type number for H chondrites.

(3) Both elastic wave velocities and thermal diffusivity are lower than those calculated for standard mineral composition of ordinary chondrites. They decrease very much with slight increase in porosity. Degree of decrease is much larger than that calculated assuming spherical pores. Many tiny cracks are suggested to exist in ordinary chondrites.

(4) Large magnetic susceptibility anisotropy (MSA) can be observed ($K_{max}/K_{min} > 1.3$). Shape of the susceptibility is exclusively oblate type, which suggests that deformation due to uni-axial compression is responsible for MSA.

Formation process of ordinary chondrite parent bodies is probably subdivided into three fundamental stages: accretion, metamorphism and destruction. Above results suggests that compaction and consolidation of ordinary chondrites take place during accretion stage and temperature has not played an important role in consolidation process. If chondrule is formed by impact, very high velocity and destructive impact is required. Such high velocity impact is not consistent with this model.

CHONDRULE POPULATIONS IN CARBONACEOUS CHONDRITES.

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CV chondrites contain two (I-II) and CO chondrites contain three (I-III) petrographically distinct types of chondrules (1). These are:

I - granular olivine (Fo90-100) ± pyroxene + glass, usually with disseminated metal grains;
II - porphyritic or barred olivine (Fo50-85) + Cr-spinel + glass;
III - excentroradial pyroxene (En90-100) + glass.

Although all types crystallized from liquids, some type I chondrules (~25-50 vol.% of these chondrites) may be rounded lithic fragments, whereas types II (~1-3 vol.%) and III (~1 vol.%) are fluid drops. In addition to mineralogical and textural differences, the redox conditions under which these chondrules formed varied. The three chondrule types also have distinct chemical compositions, although factor analysis suggests that types I and III may belong to one population. Normative compositions of average type I, II, and II chondrules are summarized in the table below.

The occurrence of discrete chondrule groups, also found in ordinary chondrites (2), must be explained in models for chondrule formation. Chondrule melts might be formed as metastable condensates (3) or equilibrium condensates from gas of non-solar composition (4,5). However, it seems unlikely that chondrules in carbonaceous and ordinary chondrites have different origins, and the discovery of relict grains in the latter (6,7) suggests that chondrules formed by melting pre-existing solids rather than by condensation. In the case of carbonaceous chondrites, these solids cannot have been inclusions or matrix; likewise, the solids were probably not igneous in origin, as such rocks would surely be basaltic, not like the compositions observed. If the solids were dust balls, the nebula must have consisted of very inhomogeneous material suspended in different local redox conditions. The presence of relict grains in chondrules (though not yet recognized in carbonaceous chondrites) may require precursor materials coarser than dust. Various mixtures of dust and coarser mineral grains might explain two of the chondrule groups but not three, as the chemical patterns are not colinear. If chondrule precursor materials were rocks, petrologic complexity is necessary to produce the observed chemical patterns. Shocked materials (impact melt rocks and breccias) might be adequate protoliths. However, multiple chondrules are invariably of the same type, indicating that chondrule types were formed at discrete sites and mixed during accretion. This argues against formation of chondrules in situ, i.e. in a regolith. Transient high temperature events in the nebula that melted complex source rocks or agglomerations may provide the best explanation for chondrule formation in carbonaceous chondrites.

Normative Compositions of Chondrule Types

	I	II	III
or	.29	-	.47
ab	5.05	-	15.17
an	8.68 (An62)	2.78	12.39 (An44)
ne	-	6.28	-
lc	-	.28	-
di	4.41 (En41)	1.96	18.53 (En37)
hy	10.49 (En86)	-	29.31 (En82)
ol	59.22 (Fo85)	87.52 (Fo54)	22.55 (Fo80)
il	.34	.23	.53
ch	.62	.59	.79
py	.89	.36	.26

References

(1) McSween H. Y. (1977) GCA 41, 1843.
(2) Gooding J. L. et al. (1980) EPSL 50, 171.
(3) Blander M. and Katz J. L. (1967) GCA 31, 1025.
(4) Wood J. A. and McSween H. Y. (1976) Proc. I.A.U. Colloq. 39, 365.
(5) Herndon J. M. and Suess H. E. (1977) GCA 41, 233.
(6) Nagahara H. (1981) Nature 292, 135.
(7) Rambaldi E. R. (1981) Nature 293, 558.

EFFECT OF HEATING TEMPERATURE ON THE TEXTURE OF CHONDRULES WITH SPECIAL REFERENCE TO THE PORPHYRITIC CHONDRULES

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Porphyritic, microporphyritic and granular chondrules show wide variations in many major elements, especially SiO_2, MgO and FeO compared to those with other textures such as barred, radial and glassy chondrules. The former chondrule is much more abundant than the latters (e.g., 83 and 17% respectively, in ALH-77015).

Recent finding of relict mineral grains in some porphyritic chondrules (1,2,3) revealed that they have been formed by melting of the pre-exisitng minerals and that the temperatures were subliquidus. The relict olivine shows 1) reverse zoning contrary to normal zoning in recrystallized ones, 2) lower CaO content than the latter, and 3) dusty inclusions. Olivine enclosed poikilitically in large pyroxene in many chondrules shows the same features as the relict olivine. It also has a different Fe/Mg ratio from that of euhedral olivine embedded in glass. Such enclosed olivine is also considered to be a relict mineral which was possibly a nucleus for growth of pyroxene. In ALH-77015, about 12% of all the chondrules have clear relic textures and 32% have poikilitic texture.

The liquidus temperatures of porphyritic chondrules estimated from both the bulk chemical compositions and the melting experiments lie between 1700° and 1400°C. The interval between the liquidus and solidus temperatures ranges from 400° to 200° (i.e., the solidus temperatures lie between 1500° to 1000°C). Spherical or ovoid chondrules may indicate the existence of considerable amounts of liquid. Such round chondrules with relict minerals would have been heated to about 1500 ± 200°C.

Experimental results on reproducing the textures of chondrules (4) and volatilization of Na (5) also support the subliquidus heating for the origin of some porphyritic chondrules. Mixtures of olivine, pyroxene and plagioclase easily formed porphyritic texture when they were heated to subliquidus temperatures and cooled at various rates. On the contrary, the same mixtures formed barred or radial textures when they were heated to super liquidus temperatures and cooled at the same rates(6). Thus, the difference in texture of the chondrules with similar bulk compositions can be easily explained by the difference in heating temperature.

Cooling rates for barred olivine and radial pyroxene chondrules as well as for porphyritic chondrules are estimated as 10^3 -10^2 °/hr and 10^1- 1°/hr, respectively (4,6). In order to obtain such a wide range of cooling rates, existence of dense gas in the early stage of the solar system is most plausible. The gas was probably most dense in the central portion and became less dense outwards. The dense gas with numerous aggregates of minerals as precursory materials was heated to have formed various chondrules depending both on the heating temperature or the amount of liquid and on the cooling rate; the aggregates in the central portion were cooled slowly and those in the outer portion rapidly. Whether they were thoroughly melted or not may also depend on their bulk chemical compositions.

REFERENCES (1) Nagahara,H. (1981) Nature 292, 135-136.(2) Rambaldi,E. R. (1981) Nature 293, 558-559. (3) Michel-Levy,M.C. (1981) Earth Planet. Sci. Lett. 54, 67-80. (4) Tsuchiyama,A.,Nagahara,H. and Kushiro,I.(1980) Earth Planet. Sci. Lett. 54, 155-165. (5) - - - (1981) Geochim. Cosmochim. Acta 45, 1357-1367. (6) Nagahara,H. and Tsuchiyama,A. (in prep.)

MELT DROPLET CHONDRULE IN MURCHISON: EVIDENCE FOR SLOW COOLING BEFORE QUENCH

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A systematic study is being made of melt-droplet chondrules in the Murchison C2 chondrite. These have been separated by freeze-thaw methods. The mean diameter (22 micrometers, N=434) of chondrules retrieved this way is an order of magnitude smaller than formerly reported by hand-picking, visual methods (420 micrometers, N=27)[1], and they can be called microchondrules, as defined by Rubin et al. [2]. Two chondrules were found with glasses that ranged up to 99% SiO_2. One of the larger such chondrules (300 micrometers) is a "microplanet" consisting of an interior of anhedral, porphyritic enstatite (Fs 1.0), minor Capx (Fs 0.0), a single trace grain of olivine (Fa 0.8) -- altogether comprising the "mantle" -- and masses of metal (Ni=5%) that are both centrally located and along one edge (i.e., not fully centrally segrated "core" masses). The outer edge consists of glasses that range from 54-75% SiO_2 -- the "granitic crust" -- containing ellipsoidal pods ("crustal batholiths") of almost pure SiO_2 (95-99%). The overall mineralogical arrangement indicates that during cooling nucleation did not take place from outside-inward, as in experimental and natural chondrules in the ordinary chondrites (as well as experimental charges in petrological experiments); rather, nucleation took place internally with residual magma rising to the surface. This suggests the chondrule was surrounded by equally hot gas during nucleation. Based on the bulk composition and the composition of the "crustal" glass, crystallization would start with forsterite at 1550°C, enter the pyroxene field, totally react forsterite to pyroxene, and end up at the pyroxene-tridymite cotectic at 1350°C, where tridymite would separate. The glasses are in equilibrium with the crystalline phases except for the minute residual bit of unreacted forsterite. This indicates that the cooling rate was substantially lower than a quench-rate, to the point where forsterite was reacted away, followed by stabilized temperature, 1350-1300°C, for long enough for silica to separate. This cooling pattern provides confirmatory evidence of the cooling process indicated by the experimental work of Planner & Keil [3], and inferred from the experimental work of Tsuchiyama et al. [4], for the ordinary chondrites. Although melt-droplet chondrules in Murchison differ from ordinary chondrite chondrules, in being poor in FeO and alkalies, the cooling pattern of some of them may be the same.

[1] Olsen, E. & Grossman, L. (1978), EPSL, 41, 111-127.
[2] Rubin, A., Scott, E. & Keil, K. (in press), GCA
[3] Planner, H. & Keil, K. (1982), GCA, 46, 317-330.
[4] Tsuchiyama, A., Nagahara, H. & Kushiro, I. (1980), Proc. 5th Symp. on Antarctic Meteorites, Mem. Nat. Inst. Polar Res. Spec. Issue 17, 83-94.

DYNAMIC CRYSTALLIZATION EXPERIMENTS ON AN AVERAGE CA-AL-RICH INCLUSION COMPOSITION. J.M. Paque & E. Stolper, Div. Geol. Planet. Sci., Caltech, Pasadena, CA 91125

Introduction. Despite the diversity of models for the origin of coarse-grained Ca-Al-rich inclusions from Allende, most authors agree that some inclusions were molten or partially molten at some stage in their history. In order to provide criteria for choosing between available models, which are distinguishable by the time-temperature histories that they imply for inclusions, we have conducted experiments designed to determine the effects of cooling history on the textures, crystallization sequences, and phase chemistries of CAIs. Crystallization experiments were conducted on an average Type B CAI composition (1) at 1 atm in air with approximately linear cooling rates varying from 2-1000°C/hr. Samples were quenched at different temperatures during the cooling sequence in order to determine the crystallization sequence and to observe the development of textures. Samples were held at maximum temperature (T_{max}) for 3 hrs before beginning the cooling sequence. T_{max} was varied from 1275°C (melilite field) to 1580°C (above liquidus).

Crystallization sequences. Petrographic observations of CAI textures have suggested that anorthite crystallized before or nearly simultaneously with pyroxene in most inclusions. Under equilibrium conditions, anorthite crystallizes before pyroxene for the composition that we have studied (1). Pyroxene crystallizes before anorthite for T_{max}=1580°C, for all cooling rates that we have studied. With T_{max} in the melilite field, pyroxene crystallizes before anorthite at fast cooling rates (>200°C/hr) and nearly simultaneously with it at slow rates (<20°C/hr).

Textures. T_{max} had more of an effect on the resulting texture than the cooling rate. Samples cooled from above the liquidus are dominated by dendritic melilites in a herringbone pattern, with pyroxene between the limbs of the melilites (2, 3). Experiments with T_{max} in the melilite field produced prismatic melilites (max. length≅120μm), anhedral to subhedral pyroxenes, and interstitial anorthite; although the experimentally produced textures are similar to those in natural inclusions, the grain sizes in the experiments are much smaller. Charges cooled from the spinel field at 20°C/hr produced large melilites (to 1.3mm) and pyroxenes, both poikilitically enclosing small euhedral spinel grains; the melilite grain size approaches that of melilites in coarse-grained CAIs.

Phase chemistry. Electron microprobe analyses of pyroxenes from run products show wide variations in TiO_2 (2-12 wt.%) and Al_2O_3 (12-32 wt.%). Pyroxenes from fast cooling rate experiments exhibit the widest scatter and differ systematically in composition from most Type B pyroxenes. Pyroxenes from slowly cooled and equilibrium experiments are similar in composition to those in Type B inclusions.

Conclusions. It is unlikely that coarse-grained CAIs passed through a totally molten stage, due to the absence of distinctive dendritic melilite textures in inclusions from Allende. This and comparisons between natural and experimental pyroxene compositions and crystallization sequences suggest that Type B CAIs from Allende cooled slowly (< several degrees per hour) from temperatures below the liquidus. The cooling rates that we have inferred for CAIs are several orders of magnitude lower than those that have been suggested for chondrules based on similar experiments in which chondrule textures have been duplicated (4).

References: (1) Stolper E. (1982) G.C.A. (in press). (2) Stolper E. et al. (1982) Lunar Planet. Sci. XIII, 772. (3) Beckett J.R. and Grossman L. (1982) Lunar Planet. Sci. XIII, 31. (4) Tsuchiyama A. et al. (1980) ESPL 48, 155.

A CHONDRULE FRAGMENT CONTAINING SILICA SPHEROIDS H.N. PLANNER, Los Alamos Nat. Lab., P.O. Box 1663, Los Alamos, NM 87545

A rectangular chondrule fragment measuring 0.61x0.43 mm in a thin section of the Piancaldoli (LL3) chondrite has spheroids embedded in a spherulitic host material. Superficially this chondrule fragment has a texture not unlike some experimentally devitrified magnesium silicate glass beads heated to temperatures between 800-925°C for up to 175 hrs. Detailed study of the chondrule fragment shows that despite the general comparability in texture with devitrified samples, distinct textural and mineralogical differences exist. This precludes the use of these experimental data to estimate the thermal conditions reflected in the chondrule texture. Certain features in the chondrule fragment, however, suggest a high temperature origin instead of reheating and devitrification.

DESCRIPTION. The fragment reported upon is assumed originally part of a chondrule because one fragment edge forms a smooth curved surface outline with an attached fine-grained Huss type rim (1). A minimum diameter for the original chondrule is estimated at 1.4 mm. In the plane of the thin section only 13.5% of the chondrule is represented by the fragment, leaving open the possibility that additional phases present in the original chondrule are not represented in the fragment.

Spheroids first thought to be devitrification structures form a closely packed rim ≤ 60 μm thick along the periphery of the curved fragment outline. Interior to this rim, as if projecting toward the chondrule center, prolate spheriods are arranged as double trains with each double train arranged in parallel and at a regular spacing of 85-90 μm. The spheroids consist of silica with minor amounts of iron (0.35-0.46 wt.% FeO) and Al_2O_3 (0.04-0.21 wt.%). Many of the spheroids display a rib-like structure visible in transmitted light, revealing dendrite arms ≤ 5 μm wide. These dendrites and the inter-dendrite voids do not affect the smooth curvilinear outline of spheroid surfaces suggesting crystallization from a silica melt or glass after host phase congealation.

The host material to the spheroids has a low-Ca pyroxene (Fs14.3-Wo3.6) composition. Its form is xenomorphic-granular with grains having feathery or fan-like spherulitic textures. Grains display off centered extinction crosses under crossed nicols but also have a biaxial interference figure. Although stoichiometrically low-Ca pyroxene, the host may consist of two phases, one forming microlites.

IMPLICATIONS. Evidence for a high temperature origin for this chondrule texture versus devitrification is based on the following: 1) unlike spherulites in devitrified samples there are marked compositional differences between spheroid and host material; 2) the precursor material to the silica dendrites would require either a melt or glass. A mechanism to achieve this condition through a devitrification process is unlikely.

REFERENCE

(1) Huss G. R. et al. (1981) Geochim. Cosmochim. Acta **45**, p. 33-51

DUSTY METAL IN CHONDRULES: IMPLICATION FOR THEIR ORIGIN.

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Recent studies of highly unequilibrated chondrites have shown that they preserve the textural and chemical imprint of nebular processes and can provide important informations concerning the origin of chondritic meteorites. In these chondrites there is a distinct population of chondrules that appear to have been incompletely melted during the chondrule formation process[1,2]. In the majority of cases the relict grains consist of forsteritic olivines which have dusty cores, due to the presence of very fine ($\ll 5\ \mu m$) metallic droplets. These droplets consist of almost pure ($\gtrsim 98\%$) metallic Fe and appear to have been produced by in-situ reduction of the fayalitic component of the olivine. The relict olivines are surrounded by clear metal-free rims that have crystallized from the chondrule melt around the dusty cores. Chemical and textural data on these chondrules suggest that the chondrule precursor material was more oxidized and underwent the reduction during the chondrule formation process[1,2]. Relict olivine grains containing dusty metal inclusions have been found in highly unequilibrated L and LL chondrites and the E3 chondrite Qingzhen[3].

We have initiated an SEM study of the various textural types of dusty olivines described by Rambaldi and Wasson[2] in order to acquire a better understanding of their mode of origin. The dusty areas appear to have never experienced melting and in the majority of cases the Fe-rich metal droplets tend to be oriented parallel the crystallographic planes of the host olivine or, less frequently, parallel to the surface of the grains. These planes are generally bent or badly broken, suggesting that the dusty areas have experienced various degrees of deformation.

In various cases the dusty areas are located on the surface of olivine grains with clear cores, as thin halos in the interior of the grains parallel to their surface or as irregular bands cutting across the grains[2]. SEM studies of these textural types have provided important clues to their mode of formation. A search for the pyroxene or silica-rich phases which must have accompanied the reduction process of the fayalitic component of the olivine has led to positive results only in a few cases. We speculate that in the majority of cases these phases must be either finely dispersed throughout the host olivine or have migrated toward the surface of the grains.

1. Rambaldi E.R. (1981) Nature 293, 558-561.
2. Rambaldi E.R. and Wasson J.T. (1982) Geochim. Cosmochim. Acta 46, 929-940.
3. Rambaldi E.R. and Wang D. (1982) 45th Annual Meteoritical Society Meeting (abstract).

CLUES TO THE GENESIS OF METEORITIC CHONDRULES

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Chondrules are the principal components of chondrites and occur in a variety of shapes, sizes, internal textures and mineralogies (1). Generally speaking, however, they are rounded to irregular voids 0.1-5 mm in diameter and contain olivine, low-Ca (Fe,Mg) pyroxene, diopsidic to augitic pyroxenes, troilite (FeS) and metallic Fe-Ni (Kamacite 5-6% Ni and taenite > 20% Ni) in glassy to microcrystalline interstitial ground mass (1).

Rambaldi described relict unmelted grains of olivine and pyroxene in chondrules (2). These grains of olivine and pyroxene might have resulted from the initial condensation process consistent with the basic nucleation theories and acted as nuclei for the molten ultrabasic silicate droplets. The problem of absence of relict unmelted grains of olivine and pyroxene in some chondrules will also be discussed. However, nucleation and growth starting with amorphous condensation clearly occurs at substrate temperatures and particle flux densities insufficient to support the formation of critically sized or stable nuclei (3), and material initially condensing in amorphous form will during early stage of growth change into crystalline form at a critical temperature by a process analogous to recrystallization (3). Crystalline clusters formed by this process will contine to grow (a) by adsorption and ordering of the impinging gas phase elements on crystalline clusters and more interestingly (b) by incorporation and crystallization of amorphous material condensed in the vicinity of crystalline clusters (3).

The above experimental results (3) support the hypothesis that chondrules represent the mineral assemblages formed in order from the condensation of primitive solar nebula (4). The author favours the view that lunar and terrestrial chondrules were produced from the impact melts.

REFERENCES:

1. Van Schmus W. R. (1969) Earth-Science Rev. 5, p. 145-184.

2. McSween H. Y. (1982) Geotimes 27, p. 21.

3. Krikorian E. and Sneed R. J. (1978) In Workshop on thermodynamics and kinetics of dust formation in space environment, LPI contrib. no 330, p. 34-37, Lunar and Planetary Institute, Houston.

4. McSween H. Y. (1977) Geochim. Cosmochim Acta 41, p. 1843-1860.

A NEW LIGHTNING MODEL FOR CHONDRULE FORMATION.

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Models for chondrule formation by lightning discharges in the solar nebula were proposed in 1966 by Whipple and in revised form by Cameron, but were largely rejected in recent years.

We propose a chondrule formation model based on the heating of chondrule precursor grains during lightning discharges in the highly turbulent boundary layer between the keplerian rotating dusty midplane layer and the overlying non-keplerian rotating gas layers in the nebula. The shear resulting from the difference in velocity between the gas-rich and dust-rich layers provides the energy source driving the lightning processes.

In a low-pressure gas the electric breakdown potential is too low to allow appreciable heating by lightning. The presence of particles increases the breakdown potential. In our model the dust component is assumed to consist of two grain-size populations: chondrule precursor particles of density ~ 0.1 g cm^{-3}, mass ~ 2 mg, and radius ~ 1 mm and fine, subμm particles of density ~ 1 g cm^{-3}, mass $\sim 7 \cdot 10^{-17}$ g and radius ~ 25 nm. The precursor grains were fluffy and had large surface-to-volume ratios; we picture them to have had textures resembling cotton candy. The subμm grains are assigned a size that has been observed in disequilibrium condensation of laboratory plasmas. We propose that 10% of the solid mass was present in large precursor particles and 90% in fine particles.

At 1 AU the radius of the lightning leader is estimated to have been ~ 3 cm, and the breakdown potential ~ 7 V cm^{-1}. The general picture is that as the electrons and protons impacted on the fluffy precursor grains, these were heated to the melting point on the surface. When the first liquid formed, the droplet started to incorporate interior grains, thus providing a mechanism to heat both the interior and exterior at the same rate. The total duration of the heat pulse is of the order of $\sim 10^{-2}$ s. Ca. 20% of the energy is dissipated by heating and generally vaporizing the fine particles, whereafter these materials promptly recondense.

Because of their increased density the chondrules slowly rain out of the production zone and in this way generally avoid experiencing a second heating event. Occasional chondrules or chondrule fragments that got trapped in fluffy precursor materials can account for unmelted relict grains.

Our model is consistent with the fact that chondrules contain volatiles such as FeS and therefore cannot have been heated for times longer than a fraction of a second.

ORIGIN OF CHONDRULES BY PREACCRETIONARY MELTING OF SILICATE MATRIX MATERIAL. E.R.D. Scott, G.J. Taylor, A.E. Rubin, K. Keil, and A. Kracher, Inst. of Meteoritics and Dept. of Geology, Univ. of New Mexico, Albuquerque, NM 87131.

Type 3 chondrites consist of several components (matrix material, chondrules, Ca-,Al-rich inclusions and chondrules, metallic Fe,Ni, sulfides) whose origins are probably related. Models for the origin of chondrules must depict: 1) The cosmic setting in which chondrules formed (i.e., nebular or planetary); 2) the heat source(s) responsible for melting; and 3) the nature of the precusor material. We consider the cosmic setting in a companion abstract and discuss the precusor material here.

Textural and chemical evidence suggests that chondrules formed in the solar nebula by melting of pre-existing dust. The dust may be preserved as the silicate matrix material in chondrites. This material is fine-grained, rich in FeO, and occurs as rims around chondrules, metal grains, and CAIs as discrete lumps, as lumps inside chondrules, and (in C3 chondrites) as matrix. The melting was accompanied by loss of iron by reduction of FeO to Fe metal, and separation of the metal from the molten silicate. Textural evidence: We found lumps of matrix material inside 15 chondrules in seven type 3 ordinary chondrites. These lumps must have been incorporated while the chondrules were still molten, demonstrating that lumps of matrix material were present in the nebula when chondrules formed. A lump inside a chondrule has the same composition as the matrix rim around the chondrule. The textures of matrix lumps and chondrule rims are distinct from those of chondrule groundmasses; the latter are clearly igneous, whereas matrix material is much finer grained and appears more clastic than igneous. Chemical evidence: The major difference between the average matrix and average chondrule composition is iron content. If normalized to FeO, the average matrix and chondrule are strikingly similar in composition. Exceptions are Ni and S, which would be lost with Fe, and Na, K, and P, which would be partially volatilized. The range in composition of matrix lumps and rim material is similar to that of chondrules. For example, Al_2O_3 ranges from 1 to 5 wt.% and Na_2O from 0 to 2.5 wt.% in matrix and chondrules. Individual matrix lumps are relatively homogeneous in composition. This indicates that aggregations of dust were heterogeneous in composition--arguments that melting of matrix-like dust would not yield the observed compositional diversity of chondrules are, therefore, not valid. Elemental correlations (e.g., Na, Ti, and Ca vs. Al; Cr vs. Mn) observed for chondrules are also observed for matrix, though more data are needed to test these correlations in detail. Finally, a chondrule with an unambiguous igneous texture in Tieschitz has the same composition as the matrix lump it contains, demonstrating that at least some material of matrix composition was melted.

The idea that chondrule matrices represent chondrule precusor material has several implications: 1) Because chondrules cool fast, the unmelted dustballs of matrix material must have been nearby in order to incorporate some of them into molten chondrules. This implies that melting was local, not nebula-wide. 2) The correspondence in composition between internal lump and chondrule rim suggest that rim material, like lumps, was acquired soon after chondrules formed. 3) Preservation of substantial amounts of matrix material suggests that the heat source for melting was not exothermic chemical reactions. 4) The presence of relict crystals in chondrules suggests either that chondrules with somewhat different compositions coalesced while still mostly molten or that the heat source operated repeatedly, thus recycling previously formed chondrules.

AN ELECTRICAL MECHANISM FOR CHONDRULE FORMATION

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Since chondrules appear to have been heated strongly, and if we identify pre-chondrular matter with carbonaceous matter, then the heat source should have been stochastic, missing some material entirely. Furthermore the heating must have not exchanged large amounts of momentum, for then the forms would have been rather completely dispersed, nullifying the accumulation phase. The first condition raises difficulty with insolation from a superluminous Sun (Wasson, 1974), while the latter raises difficulty wth the collisional hypothesis (Kieffer, 1975) for the minimum relative velocity quoted by her is 3 km/sec.

An alternate heat source is relativistic electrons brought to rest within pre-chondrular objects (Sonett, 1979). Stochastically oriented such electron beams arise naturally fom reconnection of magnetic fields in plasmas provided that certain conditions are met. The evidence for early magnetic fields is strong from meteorites. Either a solar field drawn out from the Sun or a field based upon a nebular dynamo suffices qualitatively (Levy and Sonett, 1978). Conditions on gas conductivity are poorly known; ionization would depend, if solar, on nebula opacity, while if locally based, on natural radio activity (Consolmagno and Jokipii, 1978).

For a chondrule of 0.2 mm radius, 0.2 joule is required for melting, which 10^{12} electrons of 1 Mev energy suffices. On the average over 10^{6} years some 10^{13} joules would be requird to melt all asteroidal matter. Calculations show that, provided that the electron ion drift velocity exceeds the ion sound speed as is the case in the present solar wind.

Wasson, J.T., Meteorites (1974) Springer-Verlag;Kieffer, S.W. (1975) Science 189, 333;Sonett, C.P. (1979) Geophys. Res. Lett., 6, 677;Levy, E.H. and Sonett, C.P., (1978) in Protostars and Planets, ed. T. Gehrels, Univ. of Ariz. Press, Tucson;Consolmagno, G.J. and Jokipii, J.R. (1978) The Moon, 19, 253

CAN CHONDRULES FORM FROM A GAS OF SOLAR COMPOSITION?

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Chemical composition and petrological texture of individual chondrules as observed by many investigators indicate melting and rapid cooling as well as relationships with elemental vapor pressures.

What would the properties of a dusty gas have to be, so that chondrules with the observed properties could form by sudden heating and cooling in a turbulent gas and in the bow shocks of collisons with larger objects?

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OF POOR QUALITY

EARLY MAGNETIC FIELDS RECORDED IN INDIVIDUAL CHONDRULES FROM THE ALLENDE METEORITE, N. Sugiura and D.W. Strangway, Department of Geology, University of Toronto, Toronto, Ontario, Canada, M5S 1A1.

The natural remanent magnetization (NRM) of several chondrules which are oriented with respect to the whole rock have been measured with a new highly sensitive cryogenic magnetometer. The noise level is about 2×10^{-8} emu, and in addition the geometry of the sensing coils permits the measurement of very small samples. The initial NRM directions were found to be scattered around the NRM direction of the whole rock (1). After AF demagnetization, removing the magnetically softer components, they move toward the whole rock direction. After thermal demagnetization however they either remain scattered or they move in direction even farther away from the whole rock direction. According to Wasilewski (2), the softer component of NRM is carried by magnetite or Fe-Ni alloy and the hard component is carried by a phase related to the sulfides. It is thus possible to explain the NRM in the chondrules as follows. Each chondrule acquired a TRM before accretion. This component is carried either by magnetite or by Fe-Ni alloy. This component has the high Curie point of the responsible phases but is magnetically softer than the component carried in the sulfide phase. At or after accretion, an event takes place which creates a sulfide phase and which both magnetizes the matrix and partially overprints the chondrules. This component is extremely stable to alternating fields but because of the lower Curie point of the sulfide phase it can be readily cleaned out leaving the primary scattered component. Thus the Allende chondrules preserve two magnetic fields. One preaccretion which satisfies the conglomerate test but which is softer than a lower temperature component which probably records either an accretion or post-accretion field.

References

(1) Sugiura, N., Lanoix, M. and Strangway, D.W., (1979) Phys. Earth Planet. Interi. 20, p. 342-349.

(2) Wasilewski, P.J. and Saralken, C., (1981) Proc. Lunar Sci. Conf. 12th, p. 1217-1227.

COSMIC SETTING FOR CHONDRULE FORMATION.

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Two major categories of cosmic settings have been proposed for chondrule formation. One, designated "planetary," involves processes on planetesimals or parent bodies. The other, dubbed "nebular," envisages chondrules forming in the solar nebula before parent bodies accreted. We argue against a planetary and for a nebular origin. (Also see abstract by Scott et al.)

Problems with a planetary setting: Some models involve the formation of chondrules by impact melting on solid bodies, possibly during accretion. We argued at the 45th Meteoritical Society Meeting that impact on planetesimal surfaces was incapable of manufacturing chondrules in the abundance observed in chondrites. Impact is simply not efficient at producing molten material. It tends to comminute vastly more target rock then it melts. Impact models also do not explain why chondrules are coated with rims of fine-grained, iron-rich, silicate matrix material. One might argue that these dusty rims represent the target material that was melted to form chondrules. If so, why are there no meteorites consisting only of matrix material like that in type 3 chondrites? The existence of CI chondrites, which consist mostly of hydrated matrix material, shows that accretion of matrix materials took place without being accompanied by chondrule formation. Some authors have drawn attention to the association of recrystallized clasts and chondrules with unrecrystallized chondrules and matrix in many type 3 chondrites, and argued that this indicates chondrules formed by planetary processes (impact), just as the recrystallized chondrules were modified by a planetary process (metamorphism). However, it is more plausible that chondrites consisting of both primitive and recrystallized components are simply breccias, as we have shown for chondrites containing both unequilibrated chondrules with rims of primitive matrix materials and equilibrated ones without such rims. The formation of breccias is certainly a planetary process, but it does not imply anything about chondrule formation.

Some authors suggest chondrules could form by impact between molten planetesimals. Such models do not explain why chondrules are not uniform in their oxygen (and other) isotopic compositions or how chondrules acquired rims or matrix lumps within them. They also do not account for the compositions of chondrules (approximately CI minus Fe and volatiles); surely a body that melted substantially would produce fractionated liquids. In fact, it is not certain that a planetesimal could actually totally melt. As it heated up, the first liquids would be distinctly nonchondritic and would begin to separate from the residual solids, taking with them heat-producing elements like ^{26}Al.

Virtues of a nebular setting: We believe (as do most authors, including those advocating planetary models for chondrule origin) that chondrules formed by melting of preexisting dust. Our work on the matrix materials (chondrule rims, lumps within chondrules, and C3 matrices) in type 3 chondrites demonstrates that matrix materials vary widely in composition. Heterogeneous dust was available in the nebula, so there is no need to involve planetary fractionation to produce the compositional (and isotopic) diversity observed for chondrules. The morphologies of rims around chondrules and CAI suggest that rim materials accreted in space, not on a planetary object. Finally, one appeal of a planetary origin is that we understand at least some of the processes that operate on parent bodies (impact, metamorphism), and we know they actually operated. However, our ignorance of processes that may have operated in the nebula is not a valid reason for preferring a planetary setting for chondrule formation. We conclude, therefore, that chondrules formed in the nebula by melting of compositionally heterogeneous dustballs made of matrix material, with accompanying reduction of FeO to Fe and physical separation of the metal.

Conditions of chondrule formation: experimental reproduction of texture and volatilization of sodium from chondrules.

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Textures of chondrules have been reproduced by crystallizing melts at 1 atm under 10^{-9} to 10^{-12} atm p_{O_2} as a function of chemical composition, rate of cooling, and temperature and duration of heating prior to the cooling. When the charges are cooled from a completely melted state at cooling rates of 10000-1000°C/hr (1), PO (see footnote), BO, and RO to BO are respectively formed from melts of sample 1, 2 and 3 (Table). RP is formed from the sample 3 melt at cooling rates of 5-100°C/hr (2). On the other hand, the sample 3 is cooled from a partially melted state, either PO and POP (2 min heating at various sub-liquidus temperatures and a cooling rate of 3000°C/hr) (2), or PP (2 min heating at 20°C below the liquidus temperature and cooling rates of 1-100°C/hr) are formed (Table). It is concluded from these results that chondrules crystallize over a wide range of cooling rates (1-10000°C/hr) and that some chondrules, especially porphyritic ones, are likely to have crystallized from a melt + crystals.

Rates of volatilization of Na from melt spheres of chondrule compositions have been determined (3). These rates increase with increasing temperature, decreasing p_{O_2} and decreasing size of the sphere. From these results it is possible to estimate the amounts of Na_2O volatilizing from chondrules, if chondrules are formed by instantaneous heating followed by immediate cooling. Na_2O contents in chondrules indicate a maximum temperature of this heating to be 1400-2200°C with a dense gas surrounding the chondrules in order to prevent a large amount of Na_2O loss from the chondrules.

Presence of a dense gas is also required from the estimated range of the cooling rates; otherwise chondrules are cooled instantaneously. The upper limit of the heating temperature is also consistent with the results of the crystallization experiments. It is reasonable to consider that chondrules are formed by heating at temperatures around their liquidus temperatures (1200-1700°C) and then cooled under a variety of cooling rates (1-10000°C/hr) in a dense gas environment.

Table. Summary of crystallization experiments to produce chondrule textures.

Cooling rate (°C/hr)	Sample 1	Sample 2	Sample 3	
	SiO_2=45 wt%	46	55	
	MgO/FeO=2.2	2.0	1.8	
>10000	PO	G	G	
1000 - 10000	PO	BO/G (PO)	RO-BO	(PO)
100 - 1000			BO-BOP	(POP)
10 - 100			RP	(PP)
1 - 10			RP	(PP)

( ): Charges are cooled from the temperature of 20°C below the liquidus temp.
PO : porphyritic olivine
POP: porphyritic olivine and pyroxene
PP : porphyritic pyroxene
BO : barred olivine
BOP: barred olivine and pyroxene
RO : radial olivine
RP : radial pyroxene
G : glass

(1) Tsuchiyama A.,Nagahara H. and Kushiro I.(1980) Earth Planet.Sci.Lett.48, p.155-165. (2) Tsuchiyama A. and Nagahara H.(1981) Mem.Nat.Inst.Polar Res. Spec.Issue No.20,p.175-192. (3) Tsuchiyama A.,Nagahara H. and Kushiro I. (1981) Geochim.Cosmochim.Acta 45,p.1357-1367.

PROGRESS IN THE COMPOSITIONAL CHARACTERIZATION OF CHONDRULES.

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Important advancements in our understanding of chondrules have resulted from recent studies in which petrographic and chemical information were obtained on chondrules extracted from highly unequilibrated chondrites. Bulk compositions were determined by neutron activation and electron microprobe, textural information by optical microscopy, and phase compositions by microprobe. These supplement earlier studies that were limited to either bulk analysis or petrography. Most recent studies have been made on highly equilibrated ordinary chondrites, particularly (L-LL)3.4 Chainpur and LL3.0 Semarkona.

These studies yielded the following observations: (1) Mean chondrule abundances of lithophiles are essentially the same as those in the bulk chondrite. (2) Mean refractory abundances are not significantly elevated, thus there is no evidence for appreciable vaporization of the major elements during chondrule formation. (3) Compositions of individual chondrules vary widely, a property that is inconsistent with models such as condensation or remelting fine dust that predict uniform compositions. (4) Volatile and mobile elements such as Na and K are low in a few chondrules, suggesting devolatilization, but their abundances in most chondrules from ordinary chondrites are close to those in the whole rock. (5) Perhaps half of all chondrules have fine-grained rims; these show modestly elevated levels of some volatiles, but etching and abrasion experiments indicate that the bulk of the volatiles are in the interiors of the chondrules. (6) There is no relationship between composition and size. A decrease in volatile abundances with decreasing size predicted by some models is not observed. (7) Porphyritic and some barred olivine chondrules have higher abundances of siderophiles and refractory lithophiles than nonporphyritic chondrules; no other texture-composition correlations are known. (8) Siderophile abundances vary widely as expected from petrographic observations showing a large range of metal contents. (9) Independent refractory and nonrefractory metal components are required to account for the observed variance in siderophiles. (10) The variance in lithophiles indicates the presence of refractory and nonrefractory components; because these lithophile components account for >90% of the mass of most chondrules they vary antipathetically. The refractory lithophile and refractory siderophile components may be related. (11) The FeO/(FeO+MgO) ratio is low in the refractory, high in the nonrefractory lithophile component. (12) Modal olivine correlates with refractory lithophiles, modal pyroxene with nonrefractory lithophiles.

These compositional observations are most consistent with formation of chondrules by remelting mixtures of 4 or 5 preexisting components; since little volatile loss occurred, the heat pulse must have had a very short duration.

COMPOSITION OF CHONDRULES, FRAGMENTS AND MATRIX IN TIESCHITZ

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An electron microprobe study of the unequilibrated ordinary chondrite Tieschitz shows that chondrules and lithic fragments have different Fe/Fe+Mg distributions, Fig.1. Chondrules with a clear igneous glass matrix (A), with devitrified glass (B), irregular chondrules (C), and lithic fragments (D) form a series with increasing mean FeO-content :

	Chondrules			Fragments	Bulk silicate
Type (number anal.)	A (11)	B (60)	C (104)	D (98)	and matrix (1)
FeO (wt%)	3.8 ± 1	7.1 ± 4	11.5 ± 6	16.0 ± 7	16.5
Fe/Fe+Mg (mol%)	5.9	10.3	16.6	22.3	23.8

As this series seems to form an evolutionary sequence from fresh chondrules to degraded fragments, one may think of an FeO-enrichment during this same process. There is, however, no other indication of FeO movement, as e.g.a higher degree of equilibration in the fragments, see Fig.1. Chondrules and fragments may rather belong to different generations with different primary FeO-contents. In any case, if it can be verified for other chondrites also, that droplet chondrules are much lower in FeO than the bulk chondrite silicate, it would be an important clue to the evolution of chondrites.

A black matrix (2) forms rims around all chondrules and fragments, including metal grains. Its composition varies in narrow limits and is not related to that of the enclosed body. Its mean Fe-content (27.3%) is close to the total Fe of H-chondrites (27.5%). Also most other elements (if possible C and H_2O are neglected) are close to an average chondrite composition, except for lower Mg and higher Al, Na and K. The latter three feldspar elements can only partly be explained by infiltration with the white matrix (Na/K 24.8), as Na/K is lower (7.7) and closer to the chondritic ratio of about 8.

Tieschitz contains also a Ca,Al-rich component in the form of chondrules, Fig.2. In mineralogy (Ti-augite, spinel, olivine) and composition they are similar to the CAIs of carbonaceous chondrites (CAI in Fig.2) and clearly different from the main chondrule population. These Tieschitz chondrules are much more refractory (av.(Ca+Al)/Si rel.to C1 7.9) than the refractory chondrule precursor component inferred for the LL-chondrite Semarkona (3).

References: (1) R.Hutchison et al.(1981) Proc. R. Soc.Lond. A 374,159 (2) M.Christophe Michel-Lévy (1976) EPSL 30,143 (3) J.N.Grossman, J.T.Wasson (1981) Meteoritics 16,321.

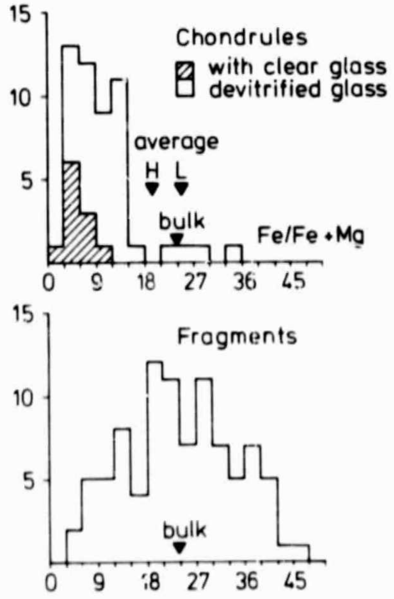


Fig. 1

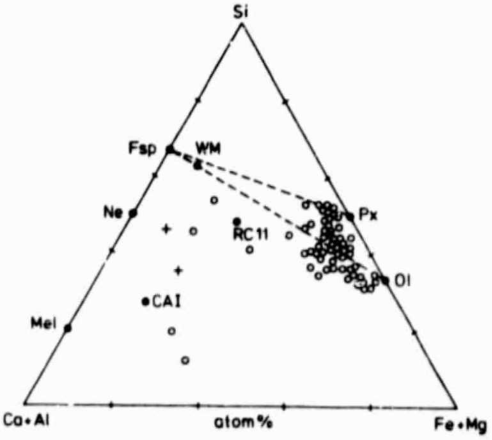
Fig. 2

Composition of chondrules (o) in Tieschitz,

\+ Ca,Al-rich fragments

WM white matrix

CAI Ca,Al-rich inclusions,av. from Allende



A REFRACTORY—RICH "BASALTIC" CHONDRULE FROM ORNANS

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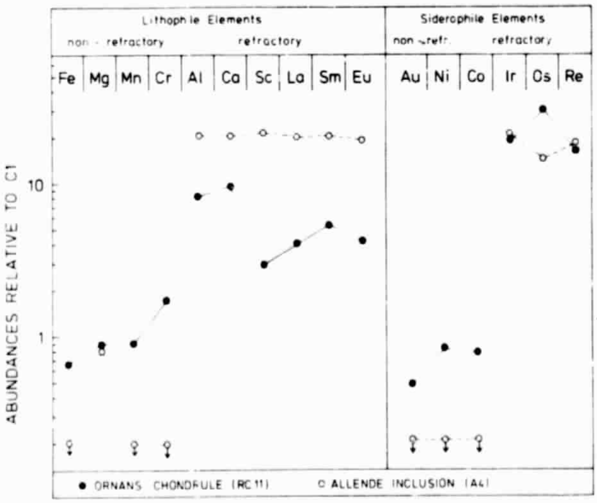
We have found a chondrule (780µg) in the C3 chondrite Ornans (1), which resembles in lithology closely the basaltic fragments described from Lancê (2) and Leoville (3). The bulk chondrule is enriched in the refractory lithophile elements Al, Ca, Sc, REE as well as in the refractory metals Ir, Os and Re, whereas Fe, Mn, Mg and the metals Ni, Co and Au are not enriched, see Fig.and Table, also point RC11 in Fig.2 in (4). The mineralogy and ophitic texture is more complex than that of normal Fe,Mg-chondrules: it contains two major pyroxenes, one a Fe-poor enstatite (A, see Table), the other a Ca-rich augite (B, outer rims enriched in Fe, Mn, Ti), intergrown with laths of Ca-rich plagioclase (50-75% An), and minor amounts of Fe-rich olivine (29% FeO). A residual melt texture contains a finegrained intergrowth of a third pyroxene (C, ferrosalite) and a Na-rich mixture of plagioclase and nepheline (8-18% Na_2O). Nepheline has also invaded the larger plagioclase crystals, in the same manner as described for the basaltic fragments (2). It is not clear, whether the Na and K enrichment (4-5 times over bulk Ornans) is primary and nepheline formed from a residual liquid, or alkalies were introduced later. Small amounts of troilite, magnetite and metal are also present.

Although the texture and the mineralogy are different, the simultaneous enrichment of lithophile and siderophile refractory elements relates this chondrule to the Ca,Al-rich inclusions, in the Fig. the Allende inclusion A4 is shown for comparison. This seems to exclude a basaltic differentiation in a large magma pool, as inferred for the basaltic fragments (2), but rather points to evaporation or condensation processes. It is also noteworthy that the same texture and composition, which up to now has only been found in the form of rock fragments (2,3) occurs here as a true droplet chondrule, judging from the smoothly rounded surface and the difference in texture between interior and exterior portion. Implications for the chondrule forming processes will be discussed.

References: (1) H.Palme, F.Wlotzka (1981) Meteoritics 16, 373. (2) G.Kurat and A.Kracher (1980) Z.Naturforsch. 35a,180. (3) J.C.Lorin et al.(1978) Meteoritics 13, 537. (4) F.Wlotzka (1982) Composition of chondrules, fragments and matrix in Tieschitz, Abstract, this Volume.



	Bulk	Pyroxenes A	B	C
SiO_2	50.2	57.9	53.8	50.0
TiO_2	0.23	-	0.30	0.75
Al_2O_3	12.72	0.70	2.09	1.89
Cr_2O_3	0.66	0.99	1.55	-
FeO	6.54	2.85	2.75	22.7
MnO	0.20	0.20	0.30	0.30
MgO	13.6	34.4	22.6	2.97
CaO	12.6	2.88	16.0	19.3
Na_2O	2.70	-	-	1.64
K_2O	0.16	-	-	-
	99.2	99.7	99.4	99.5

Table: Composition of the bulk chondrule and the three pyroxenes

MORPHOLOGICAL FEATURES OF PORE SPACES IN CHONDRULES

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Pore spaces are among those structural features of rocks which possibly carry the record of their origin and evolutionary history. Having this in mind we studied the morphological features of pore spaces in chondrules as extracted from six chondrites: Bremervörde /H-3/, Beardsley /H-5/, Faith/H-5/, Gnadenfrei /H-5/, Krymka /LL-3/ and Allende /CV-3/.

The surfaces of chondrules both original and broken were examined with TESLA scanning electron microscope at magnifications from 50 - 10000. The prepared of chondrules polished thin sections were viewed both in reflected and in transmitted light.

Five types of morphological features - nearly all earlier observed in a number of stony meteorites, chondritic matrices and achondrites, by Żbik /1/ - were identified in chondrules: 1/joints - strongly anisometric voids genetically related to mechanical stresses, 2/fissures - strongly anisometric void spaces traversing mineral grains, 3/intercrystalline pores - anisometric and isometric voids due to different orientation of adjacent crystals, 4/vesicles - anisometric and isometric hollow spaces originated from inclusions gaseous and mixed gaseous-liquid ones, 5/microcraters - impact produced negative superficial morphological forms.

The depletion of the meteorite parent bodies in volatiles makes presumably the porosity of chondrules rather low. It is represented mainly by vesicles - closed micropores of size ranging from 0.1 - 10 μm. With supposed enrichment of the parent bodies in volatiles /Allende/ the vesicles are larger reaching the size of mesopores /from 10 - 1000 μm/.

The occurrence of vesicles as dominating morphological feature of the pore spaces in chondrules, while being suppressed pores interconnected, open, like intergrain ones, channels and vugs - observed in chondritic matrices by Żbik /l.c./ - suggests formation of chondrules as solidified droplets of the molten rocky material as obtained from an impact event on the surface of the parent bodies.

REFERENCES

1/Żbik M. (1982) Submitted to Bull. de l'Acad.Pol. des Sciences, Série des Sciences de la Terre.

PLANETOIDS TO CHONDRULES? H.A Zook, NASA-Johnson Space Center, Houston, TX 77058 (until Aug., 1983 at the Max-Planck-Institut für Kernphysik, Postfach 103980, D-6900 Heidelberg).

A model that produces chondrules from the melted splash droplets expected to result from mutual collisions of planetoids with molten interiors has earlier been put forward (1,2,3) and some consequences were suggested. Additional potential consequences of such a model are explored below:

1) Once a collision between two multi-kilometer diameter objects has occurred, the resulting cloud of droplets will be initially so optically thick that droplets in the cloud interior will only cool slowly (over hours or days) while "quench" cooling of the outer droplets is expected - in agreement with chondrule petrographic observations. 2) Planetoid liquid metal cores should also be disrupted into metal chondrules. Upon later re-accretion and metamorphic heating, the iron droplets will deform and migrate along silicate grain boundaries to give observed metal-in-chondrite textures. 3) The ^{16}O-rich oxides in the carbonaceous parent material may reside in a component that combines preferentially with high melting-point minerals during planetoid melting. Support for such an idea follows from noting the high ^{16}O enrichment in olivine of the Eagle Station-type pallasites (4). Thus, as planetoid melting progresses and as the ^{16}O-rich minerals are increasingly ingested, the ^{16}O component of the resulting liquid may follow an ^{16}O mixing line. Collisions between planetoids in different stages of interior melting would then produce chondrules lying along an ^{16}O mixing line - as observed (5).

The chemical variations among individual chondrules earlier observed (6,7) remain, however, difficult to explain under the hypothesis of homogeneous liquid interiors in planetoids at various stages of partial melt. The large variation in Mg/Si ratio with little change in Fe/(Fe+Mg) ratio could be understood as a consequence of preferential volatilization of SiO$_2$ from droplets (6,7) brought to super-heat by the impact shock. SiO$_2$ evaporated from hot droplets in the cloud interior may deposit, to some degree, on cooler droplets in the cloud exterior. If so, Si-poor chondrules should be enriched in the heavy Si isotopes and vice-versa for Si-rich droplets. This could be experimentally verified. Na volatilization would also be expected. The rather large aluminum variations are less easy to explain, however. An alternative would be to postulate that many of the planetoids are hot (and dry?) in the interior but are neither melted nor has the oxidized iron yet been reduced by the interstitial carbon. Upon heating by planetoid-planetoid impact, Fe reduction by the carbon will occur releasing gas, which will, in turn, help disrupt the colliding planetoids. Such gas may keep the chondrules small. Chemical variations over mm distances would now also be reflected in the produced chondrules similar to an earlier suggestion (5).

REFERENCES: (1) Zook, H.A. (1980), Meteoritics 15, p. 380-391. (2) Zook H.A. (1981) In Lunar and Planet. Sci. XII, p. 1242-1244. Lunar and Planetary Institute, Houston. (3) Wänke H., Dreibus G., Jagouty E., Palme H., and Rammensee W. (1981) In Lunar and Planet. Sci. XII, p. 1139-1141. Lunar and Planetary Institute, Houston. (4) Clayton R.N. and Mayeda T.K. (1978) EPSL 40, p. 168-174. (5) Clayton R.N., Mayeda T.K., Gooding J.L., Keil K., and Olsen E.J. (1981) In Lunar and Planet. Sci. XII, p. 154-156. Lunar and Planetary Institute, Houston. (6) Kurat G. (1971) In Chemie der Erde, Band 30, Heft 1/4, p. 235-249. (7) Dodd R.T. (1978) EPSL 40, p. 71-82.

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