ACCRETIONARY PROCESSES: CLUES FROM CHONDRITES:

Edward R.D. Scott and G. Jeffrey Taylor, Institute of Meteoritics and Department of Geology, University of New Mexico, Albuquerque, NM 87131

Nature of nebular record in chondrites. Most workers agree that chondrites retain a record of accretion processes in the solar nebula (1,2). The Table shows the proportions of the various kinds of chondritic ingredients in the six classes of chondrites. Chondrules are mm-sized silicate spheroids that formed by brief melting of solids in the nebula and subsequent cooling at rates of 1-5000 °C/hour (3,4). Refractory or Ca, Al-rich inclusions are commonly larger and formed by complex sequences of evaporation and condensation in the nebula (5,6). Some inclusions crystallized from liquids at cooling rates of 1-50°C/hour (7). Matrix is a fine-grained mixture of chondrule precursor material, altered and heated precursor material, nebular condensates, and assorted chondritic debris (8). Lithic and mineral fragments formed by fragmentation of other ingredients in the nebula and in parental asteroids. The sequence, E, H-L-LL, CV, CO, CM, CI, may be one of increasing heliocentric distance of their formation locations; possibly 1-5 AU (9) but probably 2-3 AU, their present locations (10). Chondrule production probably peaked at 2.5 AU, refractory inclusions at 2.5-3 AU. Brief high temperature events that produced chondrules and inclusions were rare at $\geq$3 AU and matrix dominated there.

Extent of planetary processing of chondrites. Most chondrites (>90%) are rocks that have been grossly affected by planetary processes of metamorphism, recrystallization, alteration, deformation, compression, and repeated mixing and fragmentation by impacts (11, 12). Rare type 2 and 3 chondrites show minimal processing and suggest that the nebular record can generally but not always be disentangled from the planetary processing, although some workers are less optimistic (13). Because chondritic material was generally weak, ingredients in most, perhaps all, chondrites experienced many cycles of compaction and brecciation, possibly during accretion, but certainly afterwards. Thus, chondrites are not rocks that formed during accretion.

Chondrules and refractory inclusions. These formed by the melting of pre-existing dust aggregates. Therefore, dust had already accreted into mm- to cm-sized aggregates. Because chondrules vary in their ratio of olivine to pyroxene, unknown processes must have fractionated these minerals during accretion of mm-sized aggregates. Heating may have been from nebular flares (14), reconnecting magnetic field lines (15), lightning (16) or other sources (17) and could have been triggered by the onset of accretion and the consequent decrease in opacity. Evidence for collisions of hot, plastic chondrules shows that dust densities during chondrule formation were high: 1-10^6 chondrules per m^3 (18), i.e., 10^{2-8} times more dust than at 10^{-5} atm. Thus, dust-gas ratios were already enhanced by 10^{2-8}, possibly as a result of settling to the nebular midplane. Chondrule sizes vary among chondrite classes (CV > H,L,LL = E > CO = CM) and even between chondrites of the same class (19); this may be largely due to the dependence of settling rate or gas drag forces on aggregate size (20). Chondrules collided with dust aggregates and acquired rims typically 10-50 μm wide, (21-22) some of which were sintered during or after chondrule formation (23). Erosion of chondrule rims during periods of increased turbulence (23a) cannot be excluded, but impact velocities were <25 m/sec (24), as unrimmed chondrules or fragments are rare in some type 3 chondrites such as Semarkona. Cm-sized chondritic inclusions with fine-grained rims may be accretionary remnants. Rapid accretion of rimmed chondrules is suggested by the high frequency of collisions between hot plastic chondrules (25).

Chondrules to planetesimals. Evidence concerning the physical properties and nature of chondritic aggregates during accretion is lacking, and little can be deduced about the role of gravitational instabilities, rate of accretion, etc. However, firm conclusions can be drawn about the degree of mixing of chondritic ingredients between the accretion zones of various chondrite classes. Oxygen isotopic data for 32 chondrules from ordinary chondrites, 22 from E and 26 from CV show that each group has distinct populations of chondrules (26). Lack of mixing between zones implies rapid accretion (8). Within zones, chondritic ingredients were well mixed: elemental concentrations in 1g samples of H, L or LL chondrites differ by $<10\%$, except for volatiles. Thus chondritic asteroids are amazingly homogeneous, and chondrules, dust aggregates, inclusions etc. must have been thoroughly mixed in this brief interval. Correlations between chemistry and degree of metamorphism in ordinary chondrites constrain the nature of planetesimal accretion (27). Clasts of foreign chondrites are also rare ($<1\%$), implying little subsequent collisional mixing of asteroids. How $>99\%$ of the solids in the asteroid belt could be removed (28) without causing more mixing or impact melting is not known. Removal must have predated chondrule formation.

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Ingredients	Enstatite	Ordinary	Carbonaceous			
(vol.%)	EH	H,L&LL	CV	CO	CM	CI
Refractory inclusions	1	1	10	15	5	0
Chondrules	30	50	45	40	10	0
Lithic/Mineral fragments	50	30	2	10	10	0.1
Matrix	<1	10	40	30	70	80
Metal, metal oxides and sulfides	20	5-15	5	5	1	20