Planetary Compositions – Clues from Meteorites and Asteroids

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Dedicated to Professor H. Wänke on the occasion of his 60th birthday

We review the chemical and mineralogical properties of primitive meteorites and chemical data for the Sun, Comet Halley and interplanetary dust particles. Regardless of where meteorites formed, concentrations of rock-forming elements in solar nebular solids could not have varied simply with distance from the Sun. Thus compositional differences between neighboring planets and the chemical and mineralogical diversity of chondritic asteroids may have been caused by local variations in the compositions of planetesimals, rather than transport of planetesimals over large heliocentric distances. Chemical variations were partly caused by differential transport and preferential agglomeration of various presolar and solar grains and aggregates, and the production from these aggregates of diverse types of chondrules, refractory inclusions and other chondritic components in brief, local high temperature events in the nebula. These processes were just as important in controlling solar system chemistry as effects due to changes in ambient nebular temperatures and pressures. Differences between the Fe/Si ratios of the Sun, CI chondrites, interplanetary dust particles and Comet Halley suggest that planetesimals in the outer solar system had diverse relative concentrations of rock-forming elements.

Key words: Meteorites, chondrites, asteroids, planets, comets.

Introduction

Very little is known for certain about the physical and chemical processes in the early solar system that controlled the composition of the planets [1]. The composition of the non-volatile parts of planets is believed to have been largely controlled by three factors: 1) radial and possibly temporal variation in the composition of solids in the solar nebula, 2) the location of the planetesimals that accreted into each planet, and 3) impacts between large planetesimals ($>10^{26}$ g) that may have vaporized significant amounts of material. Despite the absence of firm conclusions concerning the nature of planetary accretion and the role of large impacts, recent studies in these areas have illuminated several possible ways that these processes may affect planetary compositions [2, 3]. But studies of primordial chemical variations in the solar nebula have scarcely progressed since the equilibrium condensation theory was proposed.

Fifteen years ago it was commonly believed that solids within 4 AU of the protosun were once completely vaporized and that all planetary compositions were solely or largely controlled by the equilibration temperature of the accreting condensates [4, 5]. According to Lewis' elegant equilibrium condensation theory, planets are composed of materials that equilibrated with nebular gas in a narrow range of temperatures, and these temperatures decreased with increasing distance from the Sun. Variations in the metal-silicate ratio of chondritic meteorites, which could not be accommodated in this model, were considered by Lewis [4] to be 'artifacts of accretion of small parent bodies' that result from selective interparticle forces such as magnetism. Planets, he argued, 'are so massive that they must have accreted their material by gravitation, a totally non-selective process' [5].

Implicit in Lewis' equilibrium condensation model are several assumptions that now seem to many workers to be incorrect: 1) complete chemical and thermal equilibrium had to be maintained between gas and dust over a wide range of nebular temperatures, 2) nebular temperatures were high in the inner solar system, isothermal at a given radius, and decreased monotonically from the Sun, 3) nebular temperatures had to be held constant while each planet accreted or else the gas must have been removed from the dust prior to accretion, and 4) there had to be little overlap between planetary accretion zones [6]. Lewis' model

for Mercury, which has an Fe,Ni core that contains two-thirds of the planet's mass, requires that the constituent materials equilibrated in a very narrow temperature interval between the condensation of Fe,Ni and silicates, and that planetesimals composed of low-temperature material were excluded [7, 8]. Most workers now favor models for Mercury's origin that invoke mechanical fractionation of metal and silicate grains [9], planetary vaporization or planetary collisions [7].

Despite these problems, the equilibrium condensation model is the only available quantitative guide to primordial radial variations in solid compositions, and it is still widely used. Even though there is little supporting evidence, it is still commonly believed that solid compositions in the dense, central layer of the solar nebula varied smoothly and uniformly with increasing heliocentric distance as a result of decreasing temperatures. Any departures from simple chemical gradients in the nebular midplane must then be explained by transport of planetesimals over large heliocentric distances (>1 AU) or fractionations during giant impacts.

In this paper we review the composition of chondrites and conclude that compositions of grains and planetesimals in the central layer or midplane of the nebula did not vary simply with heliocentric distance. Instead we believe that there was considerable local chemical heterogeneity in the nebular midplane and that the extent of planetesimal transportation within the midplane may have been overestimated. We infer that evidence for these chemical heterogeneities in the midplane may be preserved in the planets, and that local chemical heterogeneities were just as important as any nebula-wide chemical gradients produced by condensation. We conclude that the asteroids may have preserved rather faithfully a record of the chemical heterogeneities in the nebular midplane between the formation locations of Mars and Jupiter and that this record may offer our best hope of understanding the nature and cause of primordial chemical variations.

Chondrites

Chondrites are composed of diverse kinds of components that probably formed in a variety of nebular environments. They have bulk compositions that resemble that of the solar photosphere, except for H, C,

N, O and the noble gases [10]. Eight groups of chondrites are recognized: each is relatively homogeneous and is probably derived from one asteroid, or perhaps several asteroids. The H, L and LL groups are closely related and form the ordinary chondrite class; the EH and EL groups are analogously related and compose the enstatite chondrite class; and the CI, CM, CO and CV groups, which are more diverse chemically, compose the carbonaceous chondrite class [10].

The eight groups show approximately two-fold variations in their Si-normalized concentrations of elements such as Al (Fig. 1) that would have been refractory in the solar nebula. Normalized iron abundances vary by about 30%, and abundances of moderately volatile elements, such as Na, Ge and S, show up to five-fold variations [10, 11]. CI chondrites provide the closest match with elemental abundances in the Sun [12]. Abundances of refractories and Fe in the groups scatter about the values for CI chondrites, whereas volatile abundances in CI chondrites are, with very few exceptions, higher than those of the other groups. Except possibly for the highly volatile elements such as Bi and Tl, which show 100-fold variations within many groups, the bulk compositions of the chondrites do not appear to have been altered significantly by geological processes such as heating and aqueous alteration in asteroids. The homogeneity of each chondrite group relative to the total range of chondrite compositions suggests that each group formed by accretion of material at a specific time and place in the nebula.

The major components of chondrites are chondrules, which are millimeter-sized, ultramafic igneous spheroids, refractory inclusions, which range up to several centimeters in size and are enriched in the refractory elements Ca, Al and Ti, and matrix, which is porous, fine-grained (10 μm to submicron), relatively unfractionated material [10]. In most chondrites, the composition and mineralogy of the components have been significantly modified by heating and hydrothermal alteration in asteroids. For example, most minerals in CI chondrites probably formed during asteroidal alteration which failed to change the bulk composition of the rock significantly [13]. The approximate proportions of these components plus lithic and mineral fragments (which may be derived from chondrules and inclusions), metallic Fe,Ni and sulfides in eight chondrite groups are listed in Table 1 [14–17]. Wide but uncorrelated variations between chondrite groups are apparent. For example, matrix

abundances, which vary from <1 to 99 vol.%, are uncorrelated with the abundances of refractory inclusions, which vary from <1 to 15 vol.%. All chondritic components formed while dispersed in space prior to aggregation into chondritic material. The genetic relations between these components are not understood, but chondrules may have formed by melting of matrix-like material.

Although all of the chondrite groups are composed of broadly similar kinds of components, detailed studies of the most primitive chondrites reveal important differences that demonstrate, for example, that all chondrules were not derived from a common source. These studies also constrain the extent of mixing of materials in the solar nebula between the time the mineralogy of the components in these chondrites was fixed and the time the components accreted into planetesimals. For example, data of Clayton and coworkers show that the oxygen isotopic compositions of chondrules in the ordinary, enstatite and carbonaceous chondrite classes are quite distinct [16]; less than 1% could be foreign material from a different class. In addition, chondrules in each group of chondrites have a characteristic size range [16]. Thus, asteroids belonging to one class of chondrites probably contain less than 1% of material from another class. The asteroid or asteroids that supply the chondrites of one group may contain less than 10% of material from another group.

The components in a single primitive chondrite commonly appear to have formed under very different conditions. For example, CM chondrites contain very oxidized matrix minerals and chondrules that are mostly very reduced. This disequilibrium and the lack of correlation between the abundances of different components (Table 1) suggest that the bulk compositions of chondrite groups are unlikely to follow simple trends, even though the elemental abundances within a single group appear to be simply related to nebular volatility. However, many workers have searched for simple trends that can be understood in terms of equilibrium condensation and simple models of a hot, solar nebula to gain clues to the formation locations of the chondrites [18].

Nobody has suggested that each chondrite equilibrated with the nebula at a specific temperature, as Lewis proposed for the planets. However, some workers have explored, with some success, models for chondrites and planets in which chondritic components equilibrated with the nebula at diverse temperatures

Table 1. Approximate proportions of components (vol.%) in chondrite groups.

Components	En-statite EH	Ordi-nary H, L, LL	Carbonaceous			
			CV	CO	CM	CI
Refractory inclusions[a]	<1	<1	10	15	5	0
Ultramafic chondrules	20	70	45	40	10	0
Lithic and mineral fragments[b]	60	10	2	10	10	1
Matrix[c]	<1	10	40	30	70	99
Fe,Ni metal	10	2–10	1	2	<1	0
Sulfides	10	4	2	3	c	c

[a] Including amoeboid olivine aggregates and refractory chondrules.
[b] Some may be chondrule fragments.
[c] Magnetite and sulfides in CM and CI included in matrix.

[19, 20]. But detailed chemical and mineralogical studies of chondritic components show that these models are only gross approximations. Thus chondrule compositions are remarkably diverse and do not resemble those of equilibrium nebular solids [16]. Matrices contain heterogeneous olivines and many features of refractory inclusions cannot be explained by equilibrium between gas and solids [10].

The degree of oxidation of equilibrium nebular solids should increase with distance from the Sun as temperatures decrease, according to simple nebular models. Many workers therefore consider that the concentration of oxidized iron (FeO_x) or the $FeO_x/(FeO_x + MgO)$ ratio should increase with distance from the Sun in accordance with the spectrophotometric data for Mercury and SNC for Mars [6, 20, 21]. Thus, it is widely believed that the sequence of enstatite, ordinary and carbonaceous (E, O and C) chondrites represents one of increasing distance of formation from the Sun. FeO concentrations increase in this sequence largely because the proportion of matrix, which is FeO-rich, increases. But a monotonic increase would not be expected for a variety of reasons: 1) the mean FeO concentration of chondrules in unmetamorphosed chondrites varies in a different manner (O > C > E); 2) one unmetamorphosed chondrite, Kakangari, is known to have an FeO-poor matrix [22]; 3) the abundance of matrix in Kakangari is about 50%, much higher than suggested by its mean FeO content, which is intermediate between the matrix-poor E and O chondrites. Thus the mean FeO content of a chondrite depends on the FeO concentrations of

both chondrules and matrix and their relative proportions.

According to Wasson [21], the abundance of refractory elements may increase with increasing distance from the Sun. Refractory abundances increase in the sequence E-O-C chondrites, but the C chondrite sequence of increasing refractory abundance (CI-CO-CM-CV) does not correspond to the sequence of increasing formation distance from the Sun (CV-CO-CM-CI) that Wasson infers largely from the mean degree of oxidation. The depletions of moderately volatile elements in chondrite groups are also uncorrelated with the degree of oxidation, or any other bulk property [23].

In Figs. 1–3 we show compositional plots for the nine chondrite groups; Figs. 1 and 3 show mean group compositions, whereas Fig. 2 shows compositions for individual chondrites. Plots of abundances of refractory lithophile elements [21] or refractory lithophile and siderophile elements (Fig. 1) show rather smooth variations through the nine chondrite groups, but many other compositional plots do not. Figures 2 and 3 are typical of many elemental ratio plots that show no systematic trends for the nine chondrite groups. The large compositional gaps between the nine groups on these plots, the overall lack of systematic trends among their abundances of chondritic components (Table 1) and the compositions inferred for the chondritic precursors of differentiated meteorites suggest that many other kinds of chondrites formed of which we have no samples. The conclusion that our set of chondrites is "grossly incomplete" [24] is also supported by compositional data for the few ungrouped chondrites (Figure 3). Regardless of the formation locations of chondrites, their compositions provide strong evidence that chemical trends in the inner part of the nebular midplane were not simple.

In view of the close match between the compositions of CI chondrites and the Sun [12], it might be expected that, except for the elements H, C, N and O, nebular solids that formed farther from the Sun than CI chondrites would have solar elemental abundances. However, there are significant differences between the normalized abundances of Fe, Mn, Ge and Pb in CI chondrites and the Sun, though these differences are not readily understandable in terms of cosmochemical fractionations [12]. In addition there appear to be significant differences between the abundances of non-volatile elements in CI chondrites, interplanetary dust [31] and Comet P/Halley [32]
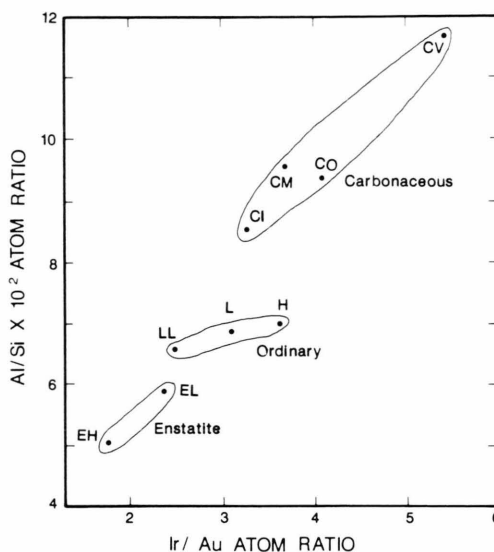

Fig. 1. Plot showing the mean Al/Si and Ir/Au atomic ratios of the 9 groups of chondrites; data from [24]. The approximately three-fold variations in these ratios in chondrites probably results from physical separation of refractory phases in the nebula and not from nebular equilibration of chondrites at high temperatures. In this plot, the nine chondrite groups define a simple, fairly complete, chemical sequence, but in most other plots this is not the case.
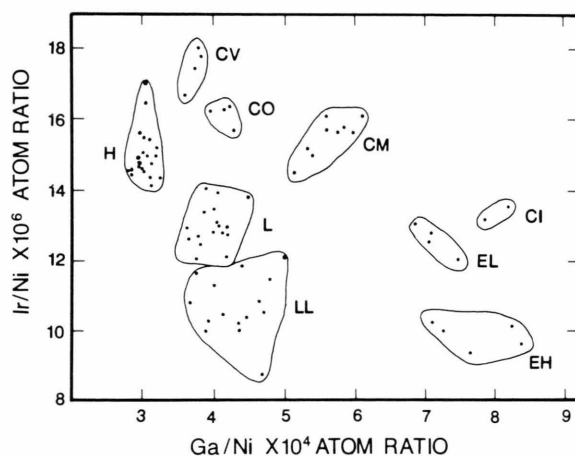

Fig. 2. Plot or Ir/Ni and Ga/Ni ratios of chondrite falls belonging to the nine groups [25–27]. On this plot the nine groups do not define a simple compositional sequence. However, each of the three classs (H-L-LL, CV-CO-CM-CI, EL-EH) defines or is consistent with a negative correlation between Ir/Ni and Ga/Ni. Irrespective of where the nine groups formed, concentrations of Ir, Ga and Ni in chondritic materials could not have varied monotonically with heliocentric distance in the solar nebula.
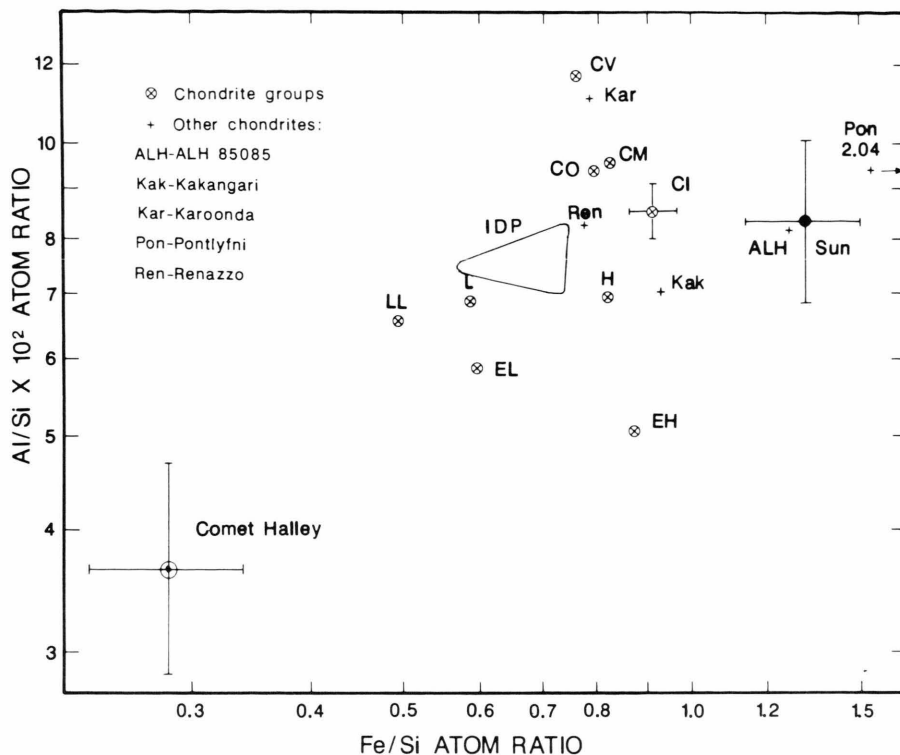
Fig. 3. Logarithmic plot of Al/Si and Fe/Si ratios for the nine chondrite groups [12, 14], five ungrouped chondrites [28–30], the Sun [12], mean compositions of three kinds of interplanetary dust particles [31] and Comet Halley [32]. Al/Si and Fe/Si ratios are not correlated within the nine chondrite groups, nor is there any systematic change in Fe/Si through the sequence EH-EL, H-L-LL, CO-CV-CM, CI, which is believed to be the order of increasing formation distance from the Sun [21]. Data for the five ungrouped chondrites scatter within and outside the fields of chondrite groups suggesting that Fe/Si and Al/Si ratios varied at least three-fold in a complex manner in chondritic asteroids. There are large differences between data for the Sun, CI chondrites, interplanetary dust and Comet Halley suggesting that relative abundance of rock-forming elements were also diverse in bodies in the outer solar system. Since chondrules and other products of heating events were probably absent in the outer solar system, differences in the concentrations of rock-forming elements in planetesimals may result from chemical heterogeneities that were produced during settling of interstellar grains to the central layer of the nebula.

(Figure 3). Thus the close match between CI chondrites and the Sun may be partly fortuitous. Rietmeijer [33] infers from these data that the solar photosphere and the primordial solar nebula may not have been identical chemically. He suggests that there were monotonic chemical changes in the composition of primordial silicate particles beyond 2 AU.

Wood [34, 35] suggests that the nature of planetesimal formation was such that there never was a smoothly varying spectrum of compositions among planetesimals and asteroids. He envisages that periodically, in rather limited zones of the nebula, chondritic components were rapidly aggregated into small planetesimals. Although small discontinuities must have existed, the similarities, for example, between EH and EL chondrites and between H, L and LL chon-

drites (Figs. 1–3) suggest that there were distinct trends in chemical and mineralogical properties on at least a local scale (perhaps 0.1 to 0.2 AU). We infer that the trends on larger scales must have been quite different.

Morfill [36, 37] has discussed how turbulence, intermittent coagulation of dust and other phenomena may have introduced complexity into chemical variations in the composition of solids condensing from a hot solar nebula. However, the mineralogical properties of chondrules, refractory inclusions and matrices show that much nebular material was heated through 1000 K in periods of minutes or hours due to unknown sources of energy. Because the minimum time to transport material from close to the Sun out to large heliocentric distances is 10^3 to 10^5 times longer

than these heating periods, this heating must have been localized. Astronomical evidence for unexpected energetic behavior in protostars also suggests that the solar nebula was not the simple, quiescent object pictured by current models, but that there were episodic, large deviations from local equilibrium in the nebula [38].

To understand the origin of variations in the bulk composition of chondrites it is clearly necessary to know more about the composition of the components in unmetamorphosed and unaltered chondrites. Such data are difficult to obtain because all chondrites have been modified to some extent by geological processing, and because it is difficult to separate the components cleanly. However, we do have, for example, chemical data for chondrules in a primitive LL chondrite which show that the chondrules accreting into a single chondrite may have been as heterogeneous as the eight chondrite groups (Figure 4). Thus a major part of chondrite variability could be due to the process responsible for chondrule heterogeneity.
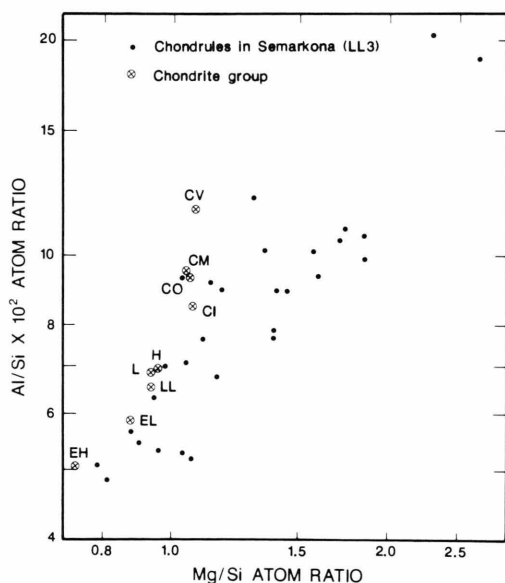

Fig. 4. A logarithmic plot of Al/Si and Mg/Si ratios in the nine chondrite groups [24] and 29 chondrules in the Semarkona chondrite [39]. Except for two chondrules, the chondrite groups and chondrules have broadly similar compositional ranges. Although chondrules in the nine groups were not derived from a common reservoir, the processes that established diverse chondrule compositions, viz., physical mixing of diverse solids in the nebula, may have been largely responsible for the two-fold variations in Mg/Si and Al/Si ratios in bulk chondrites. Grossman and Wasson [39] believe these diverse solids were solar nebular condensates, but some may be annealed interstellar grains.

Wood [35] proposes that recycling of compositionally uniform aggregates of interstellar dust grains through the brief high temperature events that formed chondrules may be solely responsible for the chemical variations observed in chondrules and chondrites. Wood et al. [40] suggest that chondrules may even be equilibrium nebular products that formed in environments which were non-classic in terms of composition and total pressure. However, there is little evidence that chondrules equilibrated significantly with the nebula while they were molten: loss of volatiles and metal, for example, were relatively minor [41, 42]. Thus it is more plausible that the dust aggregates from which the chondrules formed were almost as heterogeneous as the chondrules.

The heterogeneity of chondrule precursors may be due to prior high-temperature processing [39], but we believe that other low-temperature processes may have been responsible. Differential transport and preferential agglomeration of nebular grains were probably responsible for the diverse contents of metallic Fe,Ni grains in chondrites. Such processes may also have produced chemically diverse silicate-rich aggregates.

Differential transport of grains and aggregates to produce chemical fractionations may have resulted from differences in the density, size, morphology and magnetic properties of the particles [9, 43, 44]. Fractionation of grains during agglomeration of particles could have been caused by differences in the magnetic, mechanical, chemical or surface properties that caused different sticking efficiencies of particles [45, 46]. Ionization of nebular gas as a result of ^{26}Al and ^{40}K decay in the presence of a strong magnetic field can result in separation of charged and neutral species [47] and possibly lead to chemical fractionations in the gas and solids. Thus differential transport and preferential agglomeration of diverse types of solar and presolar grains and aggregates probably operated throughout the collapse of the dense molecular cloud to the nebula and the formation of the nebular midplane. The scale of compositional variations could have been multiplied many times from the sub-micron dimension of interstellar dust, through the millimeter and centimeter sizes of chondrules and refractory inclusions to the 10^3 to 10^6 kilometer width of asteroidal accretion zones.

Asteroids

Our arguments above for substantial, complex variations in the composition of accreting solids do not

depend on where the chondrites were formed or where they were stored for 4.5 billion years. Nevertheless it would be helpful in interpreting their record for clues to planet formation and chemical gradients in the nebular midplane to know their formation locations, whether at 0.4–6 AU or 2.0–2.6 AU from the Sun.

There are currently two contradictory views concerning the formation locations of asteroids. One considers the asteroid belt to be "a kind of zoo where planetesimals from all parts of the solar system have been preserved (in a unique, dynamically safe refuge)" (Shoemaker, quoted in [48]). Workers who believe that all or most of the asteroids formed outside the belt can point to certain chemical and isotopic similarities between the Earth and E chondrites [21, 49] and the ease with which a few planetesimals from the Earth region could have been perturbed into the asteroid belt during accretion, given certain assumptions [2, 50]. The opposite view, which we and others [51] favor, is that the asteroid belt is not a zoo but a wilderness area, where asteroids are preserved in their native habitat. If nearly all the asteroids formed between Mars and Jupiter, we must then determine he extent of intermixing. Have asteroids been shifted relative to each other by distances of <0.1 AU [52] or 0.5–1 AU [53]?

Evidence that asteroids formed in situ is provided by the spectral and albedo data indicating mineralogical stratification of the asteroid belt. Asteroids with similar surface mineralogies are concentrated in relatively narrow zones [54], and as the resolution of spectral features improves, these zones become narrower [55, 56]. The weakness in this argument is that some or many of these spectral features may be controlled by heating and alteration processes that could have postdated changes of asteroidal semi-major axes.

Another line of evidence that argues against the derivation of asteroids from outside the asteroid belt, is the chemical information about planetesimals that struck the Moon early in its history, as represented by the "ancient meteorite groups" of Anders and co-workers [57]. Eight groups have been delineated on the basis of the siderophile element signatures in lunar highland breccias. The projectiles are roughly chondritic in composition and undifferentiated and their siderophile and volatile compositions do not match those of the Earth, Moon or known meteorite classes [58]. An alternative explanation for the different siderophile element signatures is that redistribution of volatile siderophile elements, such as Au and As, from within the parent body coincidentally produced the observed groupings [59]. If the ancient meteorite groups are real, however, the planetesimals that struck the Moon were different from the asteroids that are presently supplying meteorites, suggesting that asteroids were not derived from the vicinity of the Earth. Another possible weakness in this argument is that meteorites are probably a very poor sample of the asteroids.

The asteroid belt is a unique part of the solar system probably because Jupiter prevented a planet from forming, but the nature of this process is poorly understood. Jupiter probably formed early and may have scattered large planetesimals into the belt which pumped up velocities and halted accretion [60]. A more plausible explanation is that Jupiter prevented planetesimal fragments (or even small planetesimals) from spiraling into the belt because of gas drag [61]. Even though the accretion processes are poorly understood, we do not know of any process whereby Jupiter could have caused the rich chemical and mineralogical diversity of the chondrite asteroids.

Since the cause of the 1000-fold depletion of mass in the asteroid belt is not known, and the accretion process is very poorly understood, the formation location of asteroids is still poorly constrained. Detailed chemical and mineralogical maps of the asteroid belt are needed to search for traces of primordial chemical gradients.

Accretion of Asteroids and Planets

Before we can judge whether the heterogeneity of chondritic asteroids has any bearing on the chemical differences between planets, we must know more about the accretion of asteroids and planets. If asteroids grew by accreting silicate particles, metal grains and chondrules, then it is possible that chondrules were selectively enriched relative to smaller particles by aerodynamic forces [62] or that metal grains were selectively accreted because of magnetic effects [4, 5]. Lewis [4, 5] and Whipple [62] suggest that effects due to selective accretion of particles onto planets would be different thus invalidating any conclusion about planets drawn from chondritic compositions. However, asteroids probably grew by collision of planetesimals formed from gravitational instabilities in the nebular midplane or, more plausibly, by coagulation of successively larger aggregates [60]. In this case, selective accretional effects were probably

subtle [60]. Even if planetesimals were not accreted quantitatively from the midplane material, it is possible that the effects on asteroidal and planetary compositions were similar.

Evidence from the hundreds of analyzed ordinary chondrites suggests that their parent asteroids were remarkably homogeneous. Half-gram samples from a wide variety of depths are quite uniform in composition (Fig. 2) and texture. This shows that selective accumulation of fine-grained matrix or metal grains generally ceased after aggregates reached millimeter size, and that either all solids were quantitatively accreted in the midplane, or the efficiency of accretion of each component was uniform throughout each asteroidal accretion zone in the nebular midplane. If particles accreted onto planetesimals from the nebula, then their minimum size would increase as the planetesimal grew due to aerodynamic sorting [62]. Since chondrites within a group have a rather uniform size of chondrules, it seems unlikely that planetesimals grew significantly in this way [63]. Therefore chondritic components were probably not selectively accreted during agglomeration after particle sizes exceeded a millimeter.

The next issue that must be considered is the width of a planetary accretion zone. If planets are largely accreted from zones that overlap considerably, as Wetherill's model [2] implies, then it is possible, but not inevitable, that many heterogeneities in the nebular midplane will not cause chemical differences between planets. However, Wetherill's model has at least one unrealistic assumption, viz., all of the planetesimals that form the terrestrial planets at 0.4 to 1.5 AU initially have semi-major axes of 0.7–1.1 AU, and there are still uncertainties in the modelling of accretion processes [64]. In Patterson's model of resonance accretion [65], planetary accretion zones do not overlap.

Two other arguments can be advanced to suggest that planets accreted material from wide zones (>3 AU). If the late heavy bombardment on the Moon occurred simultaneously on inner and outer planets, this might suggest that the late stages of accretion were highly chaotic. However, it is doubtful whether a single population of impactors affected inner and outer planets [66], and possible that the lunar projectiles were unique to the Earth-Moon system [67]. Another argument for chaos during accretion is that if comets were flung from the outer solar system to the Oort cloud during accretion, then perturbations

of planetesimal orbits must have been considerable throughout the solar system. However, the origin of comets is certainly not well established [68].

Even if planets formed by chaotic movements across overlapping accretion zones [2] rather than orderly accretion from narrow zones [69], it is unlikely that the record of local primordial chemical heterogeneities of the kind discussed above was completely erased.

Chemical Differences Between Planets

In this section we discuss some of the evidence for chemical differences between planets that cannot be explained by models involving orderly accretion in a solar nebula that has simple, chemical gradients. Since most authors have assumed such gradients, explanation for the "anomalous" planetary compositions have relied on giant impacts or transport of planetesimals over large heliocentric distances. An example is the suggestion that the Earth's primitive atmosphere was removed by a large impact [70]. We suggest that some of these chemical differences may have resulted from local primordial chemical heterogeneities in the nebular midplane.

The metal contents of the terrestrial planets range widely: Mercury has 66 wt% metal, Venus and Earth approximately 30%, Mars approximately 19% and the Moon less than 5%. This range and other evidence have led to suggestions that large impacts are responsible for both the large metal content of Mercury [3] and the small metal content of the Moon [71]. Metal contents of known chondrites range from 0 to 35 wt% [30], suggesting that primordial variations should not be completely ruled out.

Information is now available from siderophile elements regarding accretion and core formation events for the Earth and Mars (probably the parent body of the SNC meteorites) that provides additional clues to the nature of components which formed the planets. These data suggest, for example, that the Earth accreted sequentially from material with different oxidation states while Mars did not [1].

The Earth's mantle is apparently not in equilibrium with the core, based on enriched levels of siderophile elements [72]. The siderophile elements in the Earth's primitive mantle (i.e. the Earth's silicate portion) fall into two groups. Moderately siderophile elements have abundances that are 0.1 to 0.01 times those of known chondrites, while the highly siderophile ele-

ments, which have equilibrium metal-silicate distribution ratios of $> 10^5$, have concentrations that are approximately 0.002 times chondritic [72, 73]. Although other explanations such as incomplete core formation have been suggested [74], heterogeneous accretion is preferred by most workers. Wänke [72] explained the depletion of the siderophile elements in terms of heterogeneous accretion of two components, with the Earth accreting initially from a highly reduced volatile-free component. After about two-thirds of the Earth's mass had accreted, more and more of a volatile-rich oxidized component was added. During this second phase of accretion, the concentrations of the moderately siderophile elements built up to their present levels, but the abundances of the highly siderophile elements must have remained below their present levels due to a small amount of metal or sulfide segregation into the core [73]. During the third and final stage of accretion, less than 1% of the Earth's mass was added after core formation had ceased: this established the observed chondritic relative abundances of the highly siderophile elements. This third-stage material was believed by Wänke [72] to be highly oxidized material, but it may have resembled enstatite chondrites according to some models that attempt to account for the isotopic composition of the Earth's atmosphere [75].

What is the origin of the diverse reservoirs of material that accreted to form the Earth? The oxidized material may have formed in the asteroid belt or beyond [73], but we suggest that the Earth accreted from planetesimals with diverse compositions that formed in the vicinity of the proto-Earth.

Concentrations of siderophile elements in the SNC meteorites suggest that the mantle of Mars is in equilibrium with a sulfur-rich metal core, consistent with accretion from a single kind of material [1, 76], but not necessarily ruling out simultaneous accretion of different types of material. The inferred sulfur-content of Mars is higher than that inferred for the parent body of the eucrites and that observed in iron meteorites. This evidence and the high abundance of sulfur in carbonaceous chondrites indicates a highly heterogeneous sulfur distribution in the solar system.

The Moon and Earth have identical oxygen isotopic compositions but diverse concentrations of oxidized iron [77]. Thus, whatever the origin of the Moon, it is likely that it was derived from material in the vicinity of the Earth that had a much higher concentration of oxidized iron.

The compositions of planetary atmospheres may also provide evidence of different types of components involved in accretion. As an example, Pepin [70] and Prinn and Fegley [78] have called upon enstatite-chondrite-type components to explain certain characteristics of the atmospheres of the terrestrial planets. Other models involving multiple components for planetary atmospheres, including impacts of icy planetesimals from the outer solar system are discussed by Hunten et al. [79].

Summary

1. Chemical and mineralogical data for chondrites strongly suggest that planetesimals in the inner solar system did not show simple correlations between chemical composition and heliocentric distances; we infer that the nebular midplane had highly complex chemical zoning.

2. Asteroids largely formed in the asteroid belt. The degree of chemical zoning in the asteroid formation zone of the nebula midplane was probably much larger than our very biased sample of meteorites would suggest. Although Jupiter probably prevented a planet from forming in the asteroid belt, it is unlikely to be responsible for the rich chemical and mineralogical diversity of chondritic asteroids.

3. Concentrations of non-volatile elements in the asteroid belt were not controlled by any systematic decrease in ambient nebular temperatures with increasing distance from the Sun, as the equilibrium condensation theory of Lewis [4, 5] suggests. Instead, chemical differences were very largely controlled by differential sorting of interstellar grains during formation of the nebular midplane, brief localized heating events that formed chondrules and refractory inclusions, and differential movement of these and other chondritic components during formation of the nebular midplane.

4. Planetary compositions may reflect accretion of planetesimals of local origin that were as chemically diverse as those that formed the asteroids.

5. Differences between the Fe/Si ratios of the Sun, CI chondrites, interplanetary dust particles and Comet P/Halley suggest that planetesimals in the outer as well as the inner solar system may have had diverse relative concentrations of the common rock-forming elements. This contradicts Lewis' condensation theory, which predicts constant relative concentrations of these elements beyond Mars.

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