

# **Planetary Accretion, Oxygen Isotopes and the Central Limit Theorem**

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### Abstract

The accumulation of presolar dust into increasingly larger aggregates (CAIs and Chondrules, Asteroids, Planets) should result in a very drastic reduction in the numerical spread in oxygen isotopic composition between bodies of similar size, in accord with the Central Limit Theorem. Observed variations in oxygen isotopic composition are many orders of magnitude larger than would be predicted by a simple, random accumulation model that begins in a well-mixed nebula - no matter which size-scale objects are used as the beginning or end points of the calculation. This discrepancy implies either that some as yet unspecified process acted on the solids in the Solar Nebula to increase the spread in oxygen isotopic composition during each and every stage of accumulation or that the nebula was heterogeneous and maintained this heterogeneity throughout most of nebular history. Large-scale nebular heterogeneity would have significant consequences for many areas of cosmochemistry, including the application of some well-known isotopic systems to the dating of nebular events or the prediction of bulk compositions of planetary bodies on the basis of a uniform cosmic abundance.

## I. Introduction

The central limit theorem is a very basic and well-tested element of Statistics that relates the properties of an underlying population of smaller components to larger aggregates. These aggregates are made up by randomly choosing  $N$  of the smaller components and combining them into the larger bodies. If many such large bodies are assembled from the set of smaller components then the mean composition and standard deviation of the larger components can be derived from the properties of the smaller bodies. In particular, the mean of both populations will be identical. However, the standard deviation about the mean of the larger bodies will be less than the standard deviation of the original population according to the formula (Boas, 1966)

$$D' = D (N)^{-1/2} \quad (1)$$

where  $D'$  is the standard deviation of the larger, aggregate population,  $D$  is the original standard deviation of the smaller, underlying population and  $N$  is the number of smaller bodies that must be put together in order to make one of the larger aggregates.

Any application of the central limit theorem to processes in the Primitive Solar Nebula must assume that the nebula was well mixed over reasonably large spatial scales. When considering the application of the central limit theorem to the formation of chondrules and CAIs from a dusty nebula, such scales might range to as large as a fraction of an AU. However, when considering the formation of the terrestrial planets we might reasonably require spatial homogeneity out to several AU, depending upon the widths and degree of overlap of the various “feeding zones” providing the required numbers of planetesimals

(Wetherill, 1986). In a similar vein, the composition of the nebula must remain constant throughout the time necessary to form the body in question. For CAIs and chondrules this might imply homogeneity for a relatively short time span when compared to that required for the accumulation of the terrestrial planets. Planetary formation timescales range anywhere from  $10^5$  to  $10^8$  years, depending upon the various assumptions put into the individual models (Alexander, et al., 2001). However, a homogeneous, well-mixed nebula has been a standard assumption of most models of solar system formation for many decades and is the basis for a number of techniques for dating major events in nebular history (Tilton, 1988). If the nebula were not homogeneous, in either space, time or even in both, then many cherished assumptions, models and techniques require serious re-consideration.

Approximately one third of all of the atoms making up the terrestrial planets, the moon and asteroids are oxygen (Press & Siever, 1974). The remarkable discovery that this gigantic atomic reservoir is fractionated in a non-mass-dependent fashion (Clayton, Grossman and Mayeda, 1973) must tell us something about the manner in which the planets and asteroids within this region were assembled from the original dust in the nebula. In what follows, we will first apply the central limit theorem to the oxygen isotopic data available for several levels of planetary aggregates: presolar dust, chondrule and CAI-sized aggregates, meteorite parent bodies (asteroids) and planets. As a first approximation we will assume that the average isotopic composition of the starting material in question was a homogeneous mixture throughout the nebula. This material ranges from pre-solar dust in discussions of the formation of chondrules and CAIs, to the

population of planetesimals that served as a starting point in the accumulation of planets. When we find that the prediction of the central limit theorem has been violated, we will then examine potential reasons for the discrepancy.

## **II. The Central Limit Theorem and Planetary Accretion**

Oxygen isotopic data is currently available on four levels of aggregates. Presolar oxide grains have only recently been measured (Huss, et al., 1992; Nittler, 1997) and span a remarkable range in oxygen isotopic composition. Chondrules and CAIs (Clayton, 1993) span a more restricted range in oxygen isotopic composition and are largely confined to a line in a 3-isotope plot known as the CAI Fractionation line, though several parallel lines have now been discovered. Large planetesimals, asteroids or meteorite parent bodies have oxygen isotopic compositions that lie within a relatively small “box” near the conjunction of the CAI Fractionation and Terrestrial Fractionation lines. Finally, oxygen isotopic compositions are only available for three planetary-scale bodies, Earth, Mars and the Moon: the isotopic compositions of the Earth and Moon are identical, yet significantly different from that of Mars.

Comparison of any of these data sets presents us with an interesting problem if we view planetary accretion as a relatively linear process whereby dust aggregates into pebbles, these combine with more dust to form parent bodies and these larger bodies accrete to form the planets (e.g. Wetherill, 1986). In what follows below, we will purposely “rig” the input population distribution to yield the maximum possible standard deviation in the

aggregate: the results are quite insensitive to such assumptions. We will show that in no case can the standard deviation about the mean oxygen isotopic composition measured in the larger population be reconciled with that measured in the starting material, assuming only the operation of a simple aggregation process. In the first two rows of Table 1 we list the nominal size and “observed” standard deviation about the mean oxygen isotopic composition (see below) of the four building blocks discussed above: dust, pebbles, planetesimals and planets. In each succeeding calculation, we list the number of small building blocks required to form one of the larger planetary units, and the predicted standard deviation about the mean for those units if the aggregate obeyed the central limit theorem. Note that in this calculation we use the “standard deviation about the mean” in the broadest possible sense; nominally in units of per mil that apply to similar deviations in both  $^{17}\text{O}/^{16}\text{O}$  and  $^{18}\text{O}/^{16}\text{O}$ . If we applied the appropriate statistical criteria rigorously, the deviations between the predictions of the central limit theorem and “observation” noted below would only increase.

The large range in the oxygen isotopic diversity of the presolar oxide population is clearly shown in the review by Nittler (see his Figure 1, 1997). We can (over) estimate the standard deviation about the mean of this population to be on the order of ~3000 per mil (maximum). In Table 1 we can see what happens if this dust population is used by nature to build pebbles, asteroids and planets, respectively. Approximately one trillion dust grains are required to form a chondrule or CAI. The predicted standard deviation about the mean for chondrules or CAIs formed from pre-solar dust grains should therefore be on the order of  $10^{-3}$  per mil, as compared to the “observed” value of about

100 per mil. Again using “dust” as the starting material, we can calculate the number of grains (N) required to form a typical asteroid or planet and the predicted standard deviation about the mean oxygen isotopic composition (D’‰). These numbers are listed in the third and fourth columns of Table 1 in the rows labeled “Required Dust (‘N’)” and “Predicted D’‰”. Comparison of the calculated D’ values with those listed in the second row of Table 1, “Observed D’‰,” reveal differences of  $\sim 10^{13}$  and  $10^{17}$  for asteroids and planets, respectively.

As a second exercise, suppose we were to ignore presolar dust altogether and try to go directly from pebble-sized aggregates to asteroids and planets. We might generously assume that the end of the known CAI and chondrule fractionation line ( $\sim 100$  per mil) represents one standard deviation about the mean (an obvious overestimate). We then require the accumulation of  $\sim 10^{18}$  pebbles to make an asteroid and predict that the standard deviation about the mean asteroidal oxygen isotopic composition would be  $\sim 10^{-7}$  per mil. To build a planet requires the accumulation of  $\sim 10^{27}$  pebbles and predicts that the standard deviation about the mean planetary oxygen isotopic composition should be on the order of  $10^{-12}$ . Neither prediction comes anywhere close to the “observed” value.

Finally, if we assume that a 10‰ standard deviation has been “observed” among the meteorite parent bodies (Clayton, 1993) we can predict the size of the standard deviation about the mean of the oxygen isotopic composition of a planet accumulated via the mechanisms discussed by Wetherill (1986). In this case, we require the accumulation of  $10^9$  asteroids and calculate that the standard deviation about the mean oxygen isotopic

composition should be  $\sim 10^{-4}\%$ . The observed difference between the oxygen isotopic composition of the Earth-Moon system and that of Mars is nearly 1000 times the predicted standard deviation about the mean composition of “planetary oxygen.” In fact, a quick glance at Table 1 reveals that the predicted standard deviation about the mean of any aggregate population is much smaller than the deviation actually measured in the natural samples.

The conclusion one should draw from Table 1 is quite clear: no aggregate component was built directly by the accumulation of any combination of smaller components from a homogenized nebula. This statement is as true for the processes that made chondrules or CAIs from pre-existing dust as it is for the processes that made planets from asteroid-sized bodies; e.g. Wetherill (1986). During each stage of the accumulation process “something else” must have occurred in order to broaden the standard deviation about the mean oxygen isotopic composition beyond the value predicted by the central limit theorem. Alternatively, one of the basic assumptions of the theorem might have been violated. Identification of the process or processes that were responsible for this isotopic diversification, or the nature of the violated assumption, could yield significant insight into the conditions or processes experienced by solids in the solar nebula.

### **III. Discussion**

Robert Clayton et al. (1973) originally suggested that there must have been at least three distinct isotopic reservoirs of oxygen in the solar nebula: a population of  $^{16}\text{O}$ -rich solids,



a population of  $^{16}\text{O}$ -poor solids and a population of  $^{16}\text{O}$ -poor gas. The latter reservoirs may have differed in their ratio of  $^{17}\text{O}$  to  $^{18}\text{O}$ . The population of  $^{16}\text{O}$ -rich grains could have been formed in a nearby supernova that might have triggered the collapse of the solar nebula itself (Cameron and Truran, 1977). Donald Clayton (1988) has suggested that older solids might be richer in  $^{16}\text{O}$  than solids formed in more recent stellar outflows due to processes in the interstellar medium and to the action of Galactic Chemical Evolution. Wasson (2000) has argued that the solar nebula may have been formed from spatially distinct parcels of gas that were neither homogenized within the Giant Molecular Cloud from which the nebula collapsed, nor in the nebula itself. It may therefore be possible that incomplete mixing between various reservoirs was responsible for the diversity of oxygen isotopic compositions observed in nebular solids. We will examine this possibility in more detail below after we outline a second mechanism that might also explain the observed discrepancy.

Nuth et al. (1999) suggested that the oxygen isotopic composition of solids in the solar nebula would increase with time as a result of the repeated evaporation and re-condensation of refractory grains such as silicates. This would result in a large drift in the average oxygen isotopic composition of the nebula with time, and possibly with distance from the sun (assuming that evaporation/condensation processes occurred more frequently closer to the sun). We note that several other studies have also indicated a possible drift in the oxygen isotopic composition of the solar nebula with time and all seem to be in the same general direction. Choi et al. (1998) observed a drift toward heavier oxygen isotopes with time in solids during the formation of the ordinary

chondrites. Wasson et al. (2000b) studied chondrule isotopic compositions in the chondrite LEW 85332, and reached the same conclusion. Wasson et al. (2000a) recently argued that the oxidation state of iron in chondrules might serve as a rough proxy for time in a cooling nebula given that iron is reduced at high temperatures and oxidized at low temperatures. Based partly on this hypothesis and partly on a new study of oxygen isotopes in the CO3.0 chondrite Y81020, they again find evidence for a drift in the oxygen isotopic composition of the solids toward heavier isotopes with time. These results are consistent with a similar study of the CO3.0 chondrite ALH77307 recently published by Jones et al. (2000) where they found more negative  $\delta^{17}\text{O}$  values in low-FeO chondrules than in high-FeO chondrules. These studies all seem to suggest that CAIs, chondrules, asteroids and planets might have formed throughout a significant timespan in nebular history. In this case materials formed at different times could have sampled precursors of different oxygen isotopic composition.

We noted above that the oxygen isotopic content of increasingly larger aggregates of primitive solar system material is completely inconsistent with a simple picture of planetesimal accretion at any stage of development. In this simple scenario smaller grains aggregate into chondrule- and CAI-mass precursors, these pebble-sized objects accrete more primitive dust and fresh condensate during aggregation to form meteorite parent bodies and these asteroid-sized objects then accrete to form the terrestrial planets. It may be possible that the nebula was not homogeneous in either time, space or both, during the accumulation of pebbles, asteroids and/or planets. However, such

inhomogeneities should have observable consequences and may apply differently to each stage of accretion. We will examine these possibilities in more detail below.

**Spatial inhomogeneities:** These homogeneities might take several forms, ranging from Jupiter-mass parcels of gas and dust originating in individual stellar outflows (Wasson, 2000) to separate populations of old and new grains (Clayton, 1988). Alternatively, a relatively homogeneous mass of gas and dust might have been hit suddenly by a population of supernova produced material (Clayton et al., 1973). Each of these suggestions has observable consequences. If the nebula is found to be heterogeneous, then we must reconsider one of the most fundamental assumptions underlying nebular models and must seriously question many nebular chronometers.

Don Clayton's (1988) suggestion that older dust would be more  $^{16}\text{O}$ -rich is based on models of galactic chemical evolution, and in some sense, underlies parts of both the Wasson (2000) and the Clayton et al. (1973) suggestion that the nebular dust and gas might have different isotopic compositions. However, only if one can keep the old and new dust in physically separate reservoirs does this lead to violation of the central limit theorem; two, well mixed dust populations would simply increase the standard deviation of the underlying dust population. In the Clayton et al. (1973) case, the outer (and potentially younger) parts of the grains constantly exchange with the gas through various sputtering mechanisms, while the older cores retain their  $^{16}\text{O}$ -rich identity. The gas might therefore be  $^{16}\text{O}$ -poor relative to the dust in an old molecular cloud. Grains produced in supernovae would be  $^{16}\text{O}$ -rich because supernovae are sources of  $^{16}\text{O}$ . In this instance we

have three separate reservoirs. As each star processes its complement of  $^{16}\text{O}$ , it produces varying quantities of  $^{17}\text{O}$  and  $^{18}\text{O}$ . If the stellar outflows from individual stars are not well mixed within molecular clouds, then the spatial inhomogeneities postulated by Wasson (2000) can be produced. In principle, there is no limit to the number of separate reservoirs that might thereby be present in the nebula, depending upon the scale of the initial inhomogeneities in the molecular cloud core that produced the sun.

Clayton et al. (1973) and Clayton (1993) propose that CAIs and chondrules form as  $^{16}\text{O}$ -rich supernova grains mix intimately with the  $^{16}\text{O}$ -poor dust in the molecular cloud. The oxygen isotopic composition of the resulting solids is a mixture that lies between the compositions of these two reservoirs, tempered by back reaction with the  $^{16}\text{O}$ -poor nebular gas. Wasson (2000) proposes that chondrules form within separate parcels of gas and dust originating in individual stellar outflows that had not yet been homogenized by the action of the nebula. Both the Wasson (2000) and Clayton (1993) scenarios can adequately explain the observed variation in the oxygen isotopic composition of pebble-sized objects such as CAIs and chondrules. However, if Wasson is correct, then many chronometers, such as Iodine-Xenon or Rubidium-Strontium, can not be applied to the small-scale inclusions seen in meteorites as there would not be a uniform initial nebular concentration of the unstable parent.

One should also note that the Wasson (2000) scenario becomes increasingly improbable as the time between the arrival of an individual parcel of gas and dust in the nebula, and the formation of chondrules within that parcel, increases. This is due to the dynamic

nature of the nebula itself. Differential rotation of individual parcels of gas of significant radius would smear the parcels out around the disk, while turbulent eddies within the disk would act to mix adjacent parcels. Chondrules must therefore form very quickly after the infalling material arrives at the nebular accretion disk. It is highly doubtful that separate parcels of dust and gas could survive several orbital periods and almost certain that they could not survive hundreds. This, of course, is one basis for the widespread belief that material in the solar nebula was at least spatially homogeneous.

Weidenschilling (1997) has modeled the formation of comets in a minimum mass solar nebula and his results have some very interesting implications for the formation of planetesimals in general. Ice grain aggregates that formed at 40 – 50 AU, aided by gas drag, slowly drift inward, picking up additional ice and dust grains, colliding with and accreting other cometesimals as they grow larger. Comets were fully formed once they had reached roughly 10 – 15 AU, approximately  $10^5$  years later. In a higher mass nebula, comets could have formed somewhat faster, though they might still have drifted similar distances through the nebula. There is as yet no widely accepted model for the accretion of asteroidal bodies; however, it may be plausible to postulate a scenario similar to that suggested for the formation of comets albeit through a somewhat hotter and denser annulus in the nebula. Ice and dust aggregates that formed closer to the sun (10 AU?) might drift to only a few AU before they had grown sufficiently large to ignore gas drag, thus forming planetesimals containing variable quantities of dust and ice or water. Formation of such planetesimals might be complete within a timescale of hundreds, to tens of thousands of years due to the higher density of dust within the inner solar system.

The most important points to note in this scenario are the very large feeding zones traversed by the planetesimals as they grow, and the relatively long times required for growth. Both points argue against spatial heterogeneities in the nebula as the basis for explaining the range in the oxygen isotopic compositions observed in asteroids. If the average dust grain were richer in  $^{16}\text{O}$  than the average (water) ice grain, then Clayton's (1993) reservoir mixing model might still explain the widely divergent oxygen isotopic composition of asteroids. However, such an explanation should predict a correlation between the oxygen isotopic composition of the asteroid and its initial water/rock ratio: this has not yet been observed.

Wetherill's (1986) model for the formation of the terrestrial planets from a population of ten-kilometer scale planetesimals is widely accepted in the planetary science community. Although the planetesimals themselves might span a wide range in isotopic composition, the model proceeds by driving up the orbital eccentricity of this population in such a way as to thoroughly mix planetesimals throughout the feeding zones of all of the terrestrial planets. This model of planetary formation appears to be completely consistent with the postulated assumptions of the central limit theorem, yet the oxygen isotopic compositions of the only two planets measured differ by approximately 1000 standard deviations. This comparison does assume that both the Earth and Mars were randomly assembled from the present-day asteroid population, as inferred from the meteorite collection and assumed to be representative of the primitive planetesimal population. Each of the foregoing assumptions is made routinely by the planetary science community and would be very difficult to abandon.

**Operation of Two (or more) Chemically Separate, Unchanging Reservoirs:** Clayton

(1993) postulated the existence of isotopically distinct dust and gas reservoirs that partially exchange to produce solids lying along the chondrule fractionation line. If the CAIs and chondrules were the only materials that required some mechanism to broaden their underlying isotopic heterogeneity, then isotopic exchange might be a viable mechanism. However, as noted above and in Table 1, each stage of planetary growth requires similar processing. Yet mixing between simple reservoirs appears to be a less probable process to explain the isotopic spread observed in latter stages of accretion. To effect planetary or even asteroidal-scale bodies, mixing must become increasingly efficient as the volume of the aggregate increases, while the separate identities of the reservoirs themselves must be maintained throughout the entire process (Going from CAIs to fully-formed terrestrial planets may have required as much as  $10^8$  years). Increased efficiency is required to produce the isotopic heterogeneity seen in large aggregates such as asteroids and planets since considerable mass exchange is required to move the isotopic composition of such large bodies to any appreciable extent. However, if isotopic equilibration were too efficient then it would be impossible to preserve the isotopic spread seen in CAIs and chondrules, as they exchange with the gas more efficiently due to their vastly larger surface to volume ratios. In a worst case-scenario, isotopic exchange might be so efficient that the separate isotopic identities of the gas and solid reservoirs themselves would have been lost.

**Temporal Inhomogeneities:** As with the spatial heterogeneities discussed above, temporal heterogeneities come in at least two varieties. The suggestion by Clayton et al. (1973) that the  $^{16}\text{O}$ -rich grains may have originated in a supernova spawned the hypothesis by Cameron and Truran (1977) that the collapse of the nebula itself may have been triggered by a nearby supernova. This supernova may have also injected short-lived radioactive materials together with  $^{16}\text{O}$ -rich grains into the cold molecular cloud material. This scenario could lead to both spatial and temporal heterogeneities as the wave of injected material mixed into the interior of the collapsing cloud and/or tapered off with time. As with the previous scenarios, this wave of supernova produced material, and the resulting heterogeneities in the source materials used to build chondrules, asteroids and planets, will play havoc with our assumption of a homogenized nebula that is intrinsic to many cosmochemical chronometers.

Unlike the previously discussed heterogeneities, these are not easily averaged throughout the nebula, as the supernova-produced component may be in continuous flux. It may be that the supernova-produced component is chemically stratified as materials in the outer layers of the star were ejected with the highest velocity. This leading wave of material would also be most effected by the intervening interstellar gas and dust and might therefore be considerably diluted even before mixing into the collapsing nebula. Gas and dust arriving significantly after the collapse begins could represent a much purer sample of the supernova's interior layers than the wave that triggered the collapse. A shock speed from about 10 - 50km/s is quite efficient in triggering collapse (Foster and Boss, 1997; Vanhalla and Boss, 2000). However, one must remember that some of the initial



supernova actually collapses back onto the star, thus implying a significant spread in the velocity of the ejected material. This suggests that there may be a significant mass of even slower moving material that could continue to arrive and mix into the nebula throughout its entire active history. Indeed, if such material is responsible for the spread in oxygen isotopic composition seen in each stage of planetary accumulation, then this material may have dribbled into the nebula for as long as  $10^8$  years (the time required in some models to accrete the terrestrial planets). Under such circumstances, the material in the nebula may never have had the chance to completely homogenize, either isotopically or chemically.

It is now known that oxygen isotopes can become non-mass-dependently fractionated via chemical means (Thiemens, 1996). Such processes have been studied in the laboratory and observed in the natural environment (Thiemens, 1999). The chemical processes underlying the non-mass-dependent fractionation of oxygen isotopes are quite complex (Hathorn and Marcus, 1999; 2000). We can not yet predict the degree of fractionation expected as a silicate grain evaporates, then nucleates – isotopically exchanging with the gas phase oxygen reservoir - and grows into one of the many condensates observed in meteoritic materials. Nuth et al. (1999) postulated that repeated evaporation and condensation of silicates would gradually increase the  $^{16}\text{O}$  content of the gas phase at the expense of the condensing solids. Note that because the gas-phase reservoir contains up to 20 times more oxygen than found in solids, such isotopic exchange processes have a much larger effect on the composition of the solids than on the gas. Upon examination of the oxygen isotopic composition of nebular solids of varying size, Nuth et al. (1999)

noted that smaller aggregates extended to more  $^{16}\text{O}$ -rich compositions whereas larger bodies tended to be  $^{16}\text{O}$ -poor. Nuth et al. (1999) proposed that aggregate size could serve as a proxy for time, noting that many smaller aggregates must have formed – on average – prior to the accumulation of larger bodies such as planets. One might therefore conclude that the average oxygen isotopic composition of nebular solids gradually evolved from  $^{16}\text{O}$ -rich to  $^{16}\text{O}$ -poor over the time span required to form chondrules, CAIs, asteroids and planets. As noted above, similar conclusions were reached by a number of other researchers based on the correlation of oxygen isotopic composition and the oxidation state of iron in chondrules (e.g. Wasson, 2000a).

There is a major difference between the gradual evolution in the oxygen isotopic composition of solids in the nebula due to chemical processes and all of the other heterogeneities discussed above. Whereas each model requiring the separation or admixture of materials in the nebula potentially effects every other chemical and isotopic species, the gradual evolution in oxygen isotopic composition effects oxygen alone. At any given instant, the solar nebula could have been completely homogeneous and well mixed in every element and isotope, including oxygen. However, within the timescale necessary for the accumulation of chondrules/CAIs, asteroids or planets, the oxygen isotopic composition of nebular solids may have changed significantly. Because in this scenario the nebula is both well-mixed and homogeneous, we might be able to track the evolution of the oxygen isotopic composition of nebular solids using one or more cosmochemical chronometers.

## Conclusions

Careful examination of the oxygen isotopic distributions in increasingly larger objects, ranging from pre-solar grains, through CAIs and chondrules, to asteroids and finally to planets, indicate that one or more processes were acting to increase the isotopic spread in these objects over that predicted for simple hierarchical accumulation. This clearly violates a basic assumption of the central limit theorem. If the processes involved were mixing and partial equilibration of two or more spatially or chemically distinct reservoirs, then the nebula may have been heterogeneous on a fairly massive scale, thus invalidating the use of many cosmochemical chronometers. Because the nebula must remain heterogeneous from the time CAIs formed through to the end of planetary accumulation, and because the time required for hierarchical accretion of planetary-scale bodies might have been as long as  $10^8$  years, one might assume that such equilibration processes were extremely inefficient. However, in order to effect planetary-scale bodies one requires the action of a highly efficient reservoir mixing process that should also imply the presence of additional correlated anomalies.

We can evaluate the hypothesis that a supernova injected material into the solar nebula as either a spatial or a temporal heterogeneity. In either case, injection invalidates the use of most cosmochronometers for as long as the nebula remained heterogeneous. As an alternative, we might postulate that a chemical process gradually shifted the oxygen isotopic composition of solids in the nebula. It is easy to imagine that grain processing could have occurred near the sun throughout much of nebular history, provided that some mechanism exists to circulate processed materials back out to the region of planetesimal

accumulation (e.g. Shu et al., 1996; Nuth et al., 2000; Hill et al., 2001). In this paper we will not consider the specific chemical reaction mechanism involved in changing the oxygen isotopic ratio of nebular solids. If such a mechanism does exist however, then this hypothesis has the advantage that only the distribution of the oxygen isotopes changes: all other chemical and isotopic systems remain homogeneous. Thus all cosmochronometers as well as many other barometric, thermal and oxygen fugacity indicators remain valid.

The Genesis Mission may help to resolve this controversy by measuring the oxygen isotopic composition of the largest single oxygen reservoir in the solar system, the sun. Once we know the average bulk composition of the oxygen once contained in all reservoirs, both solid and gaseous, it should be easier to decide how the individual reservoirs we see today were established.

**Acknowledgments:** The authors thank Drs. Larry Nittler and John Wasson for careful readings of the original manuscript and for many helpful suggestions. JAN thanks Washington University for its support in the preparation of this manuscript.

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Table 1.

<b><u>The Formation of Larger Bodies by the Accretion of Smaller Objects Should Significantly Reduce the Spread in the Oxygen Isotopic Composition of the Larger Bodies</u></b>				
	<b><u>Dust</u></b>	<b><u>Pebbles</u></b>	<b><u>Asteroids</u></b>	<b><u>Planets</u></b>
<b>Typical Size</b>	100nm	1mm	1km	$10^3$ km
<b>Observed D‰</b>	3000	100	10	0.3
<b>Required "N" Dust →</b>		$10^{12}$	$10^{30}$	$10^{40}$
<b>Predicted D' ‰ →</b>		$3 \times 10^{-3}$	$3 \times 10^{-12}$	$3 \times 10^{-17}$
<b>Required "N" Pebbles →</b>			$10^{18}$	$10^{27}$
<b>Predicted D' ‰ →</b>			$10^{-7}$	$3 \times 10^{-12}$
<b>Required "N" Asteroids →</b>				$10^9$
<b>Predicted D' ‰ →</b>				$3 \times 10^{-4}$

