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Spatial heterogeneity of $^{26}Al/^{27}Al$ and stable oxygen isotopes in the solar nebula

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Abstract–The degree of isotopic spatial heterogeneity in the solar nebula has long been a puzzle, with different isotopic systems implying either large-scale initial spatial homogeneity (e.g., ^{26}Al chronometry) or a significant amount of preserved heterogeneity (e.g., ratios of the three stable oxygen isotopes, ^{16}O, ^{17}O, and ^{18}O). We show here that in a marginally gravitationally unstable (MGU) solar nebula, the efficiency of large-scale mixing and transport is sufficient to spatially homogenize an initially highly spatially heterogeneous nebula to dispersions of ~10% about the mean value of $^{26}Al/^{27}Al$ on time scales of thousands of years. A similar dispersion would be expected for $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios produced by ultraviolet photolysis of self-shielded molecular CO gas at the surface of the outer solar nebula. In addition to preserving a chronological interpretation of initial $^{26}Al/^{27}Al$ ratios and the self-shielding explanation for the oxygen isotope ratios, these solar nebula models offer a self-consistent environment for achieving large-scale mixing and transport of thermally annealed dust grains, shock-wave processing of chondrules and refractory inclusions, and giant planet formation.

INTRODUCTION

Isotopic abundances of short-lived radionuclides such as ^{26}Al that decayed in primitive meteorites provide the most precise chronometers of events in the early solar system, provided that they were initially homogeneously distributed (Bizarro et al. 2004; Halliday 2004; Krot et al. 2005). On the other hand, the abundances of the three stable isotopes of oxygen in primitive meteorites show a mass-independent fractionation that survived homogenization in the solar nebula (Clayton 2002; Lyons and Young 2005). As a result of this and other cosmochemical evidence, the degree of spatial heterogeneity of isotopes in the solar nebula has long been a puzzle.

We show here that based on hydrodynamical models of the mixing and transport of isotopic anomalies formed at the surface of the solar nebula (Clayton 2002; Lyons and Young 2005) or injected onto the surface of the solar nebula (Vanhala and Boss 2002), initially high levels of isotopic spatial heterogeneity are expected to fall to steady state levels (~10%) low enough to validate the use of ^{26}Al for chronometry, but high enough to preserve the evidence for mass-independent fractionation of the three stable oxygen isotopes.

The solution to this puzzle relies on the mixing being accomplished by the chaotic fluid motions in a marginally gravitationally unstable (MGU) disk (Boss 2004b). MGU disks have masses of roughly 10% the mass of the central protostar, leading to Toomre Q stability values as low as ~1.5 to 2, sufficient for marginal gravitational instability and evolution toward increasingly stronger gravitational instability (Boss 2006). Observations of crystalline silicates in protostellar disks (van Boekel et al. 2005) and comets (Nuth and Johnson 2006), and the discovery of refractory materials in comets (Brownlee et al. 2006) appear to require the transport of dust grains from the hot inner solar nebula out to comet-forming distances and beyond. An MGU disk is capable of providing the mechanism for mixing and transport in the midplane of the planet-forming region of the solar nebula that has long been hypothesized in alpha accretion disk models but never successfully identified. Such a disk is also capable of driving shock fronts that appear to be responsible for much of the thermal processing of the components of primitive meteorites (Desch and Connolly 2002), creating a self-consistent picture of the basic physical processes shaping the early solar nebula (Boss and Durisen 2005).

ISOTOPIC HETEROGENEITY

Cosmochemical evidence for the decay products of short-lived radioisotopes (SLRI) in chondritic meteorites has led to spirited debates over the origin of the SLRI. For example, it has been argued that SLRI ^{10}Be formed in situ at the inner edge of the solar nebula by spallation reactions on dust grains being irradiated by energetic particles released by magnetic reconnection events on the early Sun (Chaussidon et al. 2006). Alternatively, the ^{10}Be may have originated as a result of spallation reactions involving galactic cosmic rays and the dust grains residing in the molecular cloud core that collapsed to form the solar system (Desch et al. 2004). Other SLRI, such as ^{26}Al, can be formed either by spallation close to the protosun or by nucleosynthesis in stellar sources, such as asymptotic giant branch stars and supernovae. However, the SLRI ^{60}Fe cannot have been created by spallation and must have been synthesized in a star (Tachibana and Huss 2003), with a supernova being the most likely source (Mostefaoui et al. 2005). This suggests that the bulk of the solar system's ^{26}Al originated in the supernova that also supplied the live ^{60}Fe, or perhaps in a slightly earlier phase of the same star's evolution, such as would occur in a Wolf-Rayet star (an O star with broad emission lines and a mass of ~25 $M_\odot$ or more). Satellite observations of gamma-ray lines produced by the decay of ^{60}Fe and ^{26}Al have shown these SLRI are distributed across the galactic plane where massive stars end their lives as supernovae (Prantzos 2004; Harris et al. 2005).

SLRI originating in a supernova must have been injected into the presolar cloud and onto the surface of the solar nebula by thin Rayleigh-Taylor (R-T) fingers that peppered the disk's surface with highly nonuniform doses of SLRI (Vanhala and Boss 2002). The initial nebular distribution of stable isotopes such as ^{27}Al was probably highly uniform, as a result of their nucleosynthesis in much earlier generations of stars and their subsequent lengthy residence times in the interstellar medium and in a molecular cloud complex prior to the collapse of the presolar cloud. The initial ratio of ^{26}Al/^{27}Al, e.g., was thus highly variable in the solar nebula during the SLRI injection process, with values ranging from zero where R-T fingers did not penetrate to the maximum dose carried by an impacting R-T finger. Because the R-T fingers carrying the live ^{26}Al would impact the disk within a short time period (~0.1 Myr) compared to the mean life of ^{26}Al (1.05 Myr), the temporal heterogeneity involved in the injection process would have been negligible for ^{26}Al.

If this spatial heterogeneity was not erased by the time that the components of primitive meteorites were forming in the solar nebula, then the variations of ^{26}Al/^{27}Al between these components could not be used to accurately date events in the solar nebula, in spite of good evidence otherwise (Amelin et al. 2002), as these variations would be largely caused by spatial heterogeneity rather than by temporal heterogeneity (i.e., by crystallization at different times, allowing for intermediate decay of the SLRI). While spatial homogeneity of ^{26}Al/^{27}Al is commonly inferred or assumed by cosmochemical studies of refractory inclusions and chondrules (Hsu et al. 2003), evidence for some level of spatial heterogeneity is also seen (Simon et al. 1998; Gounelle and Russell 2005; Young et al. 2005). The precise level of this spatial heterogeneity is crucial for assessing the true value of SLRI chronometers such as ^{26}Al/^{27}Al.

The widespread evidence for mass-independent fractionation of the three stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) in chondrules and refractory inclusions has long been recognized as a major unsolved problem in meteoritics (Clayton 1993). The solution to this problem now appears to be self-shielding of molecular CO gas exposed to a strong source of ultraviolet radiation, resulting in preferential dissociation of the C^{17}O and C^{18}O molecules and the subsequent formation of ^{17}O-, ^{18}O-rich water ice. The self-shielding process was first suggested to occur at the inner edge of the solar nebula (Clayton 2002), with the fractionated reaction products being lofted outward by the bipolar outflow of the early Sun and onto the surface of the solar nebula. Oxygen isotope fractionation in the hot inner disk runs the risk, however, of being erased by thermal processing, prompting the idea that the fractionation occurred at the cool surface of the outer solar nebula (Lyons and Young 2005) where water ice was stable. This location would require that the solar nebula was being irradiated by a nearby O or B star to receive the required ultraviolet flux (Lyons and Young 2005), a scenario that could also aid in the formation of the ice giant planets (Boss et al. 2002). This scenario would thus lead to significant oxygen anomalies at the surface of the outer solar nebula, a spatially heterogeneous starting point.

SOLAR NEBULA HETEROGENEITY

We show here that the degree of spatial heterogeneity in the solar nebula required for the use of the ^{26}Al/^{27}Al chronometer and for the survival of the oxygen isotope anomalies is consistent with the expectations for the mixing and transport of initially highly spatially heterogeneous tracers in an MGU disk. The magnetorotational instability (MRI) is often thought to be the source of the turbulent viscosity that is assumed to drive disk evolution across large distances (Gail 2002), but the presence of magnetically dead zones limits the applicability of such models to magnetically live regions, such as the disk surfaces. The midplanes of protoplanetary disks are essentially neutral in the planet-forming regions from ~1 to ~15 AU, preventing MRI from serving as a driver of midplane disk evolution in these regions (Matsumura and Pudritz 2006). MGU disk models offer a means to self-consistently calculate the mixing and transport of tracers throughout the entire planet-forming region.

While it has long been recognized that protostellar disks (i.e., relatively massive disks orbiting protostars that are still in the process of accreting the bulk of their final mass from the infalling envelope and circumstellar disk) are likely to be gravitationally unstable (e.g., Cassen et al. 1981), only recently has it become appreciated that an MGU disk is also likely to have characterized much later phases of disk evolution. In particular, it now appears that an MGU or nearly MGU disk is necessary to explain the formation of the gas giant planets (Jupiter and Saturn) by either the core accretion (Inaba et al. 2003) or the disk instability (Boss 2002) mechanisms. This need not mean that the solar nebula was continually in an MGU state, but that the nebula was probably never far from being MGU during the time when the first phases of planetary accretion were taking place (i.e., growth of submicron-size dust grains to kilometer-size planetesimals). Continued infall of presolar cloud gas and dust onto the disk, as well as MRI instabilities in the ionized outer disk, may have triggered phases of MGU evolution in the inner disk. MGU disks lead to strongly time-variable mass accretion rates onto the central protostar, with fluctuations of several orders of magnitude about mean values of order 10^{-6} to 10^{-5} $M_\odot$ yr^{-1} (Boss 2002). Such mass accretion rates are consistent with disks being in an MGU state for times of about ~10^5 yr, during which time most of the disk's gas will be accreted by the growing central protostar.

Previous work has shown that an MGU disk is able to transport tracers over distances of ~10 AU in ~1000 yr (Boss 2004b), implying a similar time scale for mixing and an approach to spatial homogeneity. Here we quantify for the first time the evolution of the level of spatial heterogeneity using these same hydrodynamical models. MGU disks have the added attraction of providing a robust source of shock fronts capable of thermally processing solids into the chondrules and other components found in the most primitive meteorites (Desch and Connolly 2002; Boss and Durisen 2005).

NUMERICAL METHODS

The models presented here were calculated with a three-dimensional, radiative, gravitational hydrodynamics code that has been subjected to a wide range of tests (Boss and Myhill 1992). The code has been shown to be second-order accurate in space and time. A spherical coordinate grid is used with $N_r = 100$, $N_\theta = 23$ in $\pi/2 \geq \theta \geq 0$, and $N_\phi = 256$ grid points, for a total of over 10^6 grid points counting both hemispheres. The radial grid is uniformly spaced between 4 and 20 AU, with boundary conditions chosen to absorb radial velocity perturbations. The θ grid is compressed into the midplane, where $\Delta\theta = 0.3°$. The ϕ grid is uniformly spaced. A spherical harmonic expansion with $N_{Ylm} = 32$ is used to solve for the gravitational potential of the disk. Radiative transfer is handled in the diffusion approximation, and a complete thermodynamical description of the disk gas and dust grain opacity is included.

The MGU disk model is the same as that presented by Boss (2004b), where a disk with a mass of 0.091 $M_\odot$ between 4 and 20 AU orbits a solar-mass (1 $M_\odot$) protostar. If the disk was extended in radius to ~100 AU with the same assumptions about its radial structure, the disk's mass would increase to ~0.15 $M_\odot$. The models begin with a total (gas plus dust) disk surface density of $\approx 2 \times 10^3$ g cm^{-2} at 4 AU and $\approx 3 \times 10^2$ g cm^{-2} at 20 AU. The Toomre Q stability value ranges from ≈ 9 to ≈ 1.6 at 4 AU and 20 AU, respectively (see Fig. 1 in Boss 2002), dropping to a minimum of 1.5 across a broad range of radii between ~8 and 20 AU.

A tracer field representing SLRI or oxygen anomalies is sprayed onto the outer surface of an already evolving disk at a radial distance of 15 AU, into a 90 degree (in the azimuthal direction) sector of a ring of width of 1 AU, simulating the arrival of an R-T finger. The models include the effects of the diffusion of the tracer field with respect to the gaseous disk by a generic turbulent viscosity characterized by an alpha disk parameter of $\alpha = 0.0001$, which is small enough to have a negligible effect on the tracer field (Boss 2004b). Instead, the tracer field is transported and mixed by a combination of the global actions of gravitational torques in the MGU disk and the local actions of convection-like motions (Boss 2004a). SLRI or oxygen anomalies that reside in the gas or in particles with sizes of centimeters to millimeters or smaller will remain tied to the gas over time scales of ~1000 yr or so, because the relative motions caused by gas drag result in differential migration by distances of less than 0.1 AU in 1000 yr, which is negligible compared to the distances they are transported by the gas in that time, justifying their representation by the tracer field.

Boss (2004a) and more recently Mayer et al. (Forthcoming) have shown that MGU disks naturally lead to convective-like motions as a result of the formation of dense spiral arms and clumps in an otherwise convectively stable (i.e., vertically isothermal) disk. This is a result of the compressional heating of the disk gas associated with the formation of the arms and clumps in the midplane of the disk. This leads to a vertical temperature gradient steeper than the adiabatic gradient, which is the standard Schwarzschild criterion for convection in a stellar atmosphere. Because MGU disks undergo strong dynamical evolution, these motions are not "convection" in the sense of the classic, stable stellar atmosphere, but they do resemble convective cells in that they have transient upwellings in regions where the Schwarzschild criterion is met and downwellings (toward the midplane) in regions where it is not. These convective-like motions are efficient at transporting mass in the vertical direction, but less so in the radial direction, because of the need to transfer angular momentum to achieve radial motions. The gravitational torques associated with the nonaxisymmetric arms and clumps are quite strong and lead to angular momentum transfer rates and hence radial motions that are much larger than those associated with these convective-like motions.

RESULTS

The tracer field shown in Fig. 1 represents the number density of SLRI such as ^{26}Al in a disk 2377 yr after an R-T

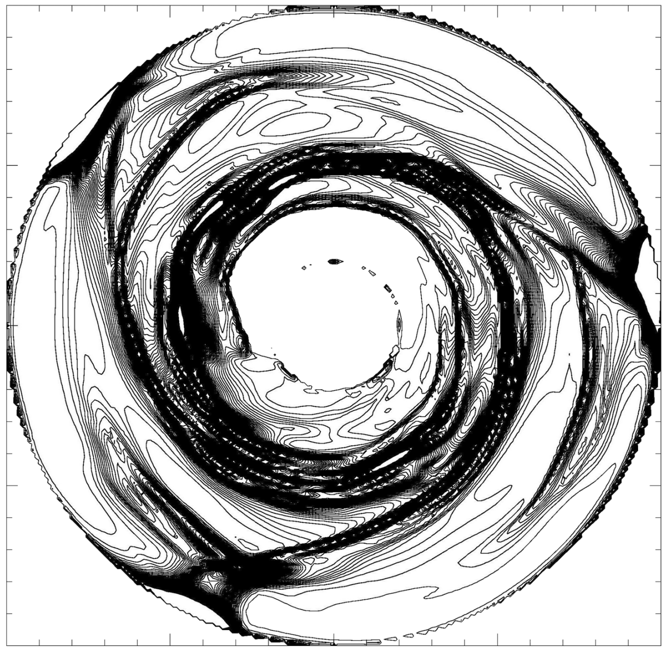

Fig. 1. The linear contours of the tracer field density (i.e., number of atoms of ^{26}Al cm^{-3}) in the midplane of a solar nebula model 2377 yr after the tracer field was sprayed onto the disk's surface in a 90 degree azimuthal sector between 14.5 and 15.5 AU. The region shown is 20 AU in radius with a 4 AU radius inner boundary. Contours represent changes in the tracer field density by 0.001 units on a scale normalized by the initial tracer density, up to a maximum value of 0.1. While the tracers have spread throughout the disk, their spatial distribution is highly heterogeneous, with the highest concentrations residing inside the spiral arms of the marginally gravitationally unstable (MGU) disk.

injection event. During this time, about 0.04 $M_\odot$ of disk mass is transported to within 4 AU of the central protostar. Given the strong gradients evident in Fig. 1, it is clear that the tracer field is still spatially heterogeneous 2377 yr after injection. However, Fig. 2 shows that in terms of the abundance ratios of $^{26}Al/^{27}Al$, i.e., abundance ratios of the injected SLRI divided by the stable isotope already present in the disk, spatial homogeneity has been rapidly approached in this same time period. By way of comparison, at the moment of injection, the ratio of tracer to gas density was highly spatially heterogeneous, being equal to zero everywhere except at the surface of the disk in an azimuthal sector between 14.5 and 15.5 AU from the protosun.

Figure 3 shows how the level of spatial heterogeneity of SLRI abundance ratios such as $^{26}Al/^{27}Al$ evolves as a function of time after a single SLRI injection event. Figure 3 gives the dispersion (in a "root of the sum of the squares" sense) of the abundance ratio from its mean value at each time. The injection event at 200 yr leads to a high initial level of dispersion that decreases over a time scale of ~1000 yr and appears to settle into a steady state level of ~10% by ~2000 yr in this dynamically evolving, chaotic MGU disk. This steady state value appears to be a naturally chosen level for an MGU disk after ~1000 yr of evolution, unrelated to any of the specific parameters chosen for the disk model (e.g., α = 0.0001).

The occasional upward spikes seen in Fig. 3 at times of, e.g., 2200 and 2500 yr are associated with the transport of the color field into the extremely gas-depleted inner disk (Fig. 2), resulting in equally extremely large ratios of the color field to the gas density in a few numerical grid cells. Given that this strong inner disk depletion appears to be a result of the inner disk boundary conditions, rather than a physically realistic effect, the upward spikes in Fig. 3 do not appear to be particularly significant. Regardless, variations in the dispersion from the mean of the ratio of $^{26}Al/^{27}Al$ ranging from ~7% to ~15% (as seen in Fig. 3 after 2000 yr) correspond to chronological uncertainties of only ~0.1 Myr for the $^{26}Al/^{27}Al$ system, insufficient to invalidate the use of this system for chronometry over ~1 Myr time intervals.

DISCUSSION

Short-Lived Radioisotopes

Supernovae result in outflowing shells of gas and dust with initial speeds of about 10^3 km s^{-1} or more. Were it to strike the cloud unimpeded, such a high-speed shock would shred the presolar cloud to pieces rather than induce its collapse. Instead, detailed models of supernova-induced collapse assume that the supernova shock has been slowed down to speeds of 10 km s^{-1} before striking the presolar

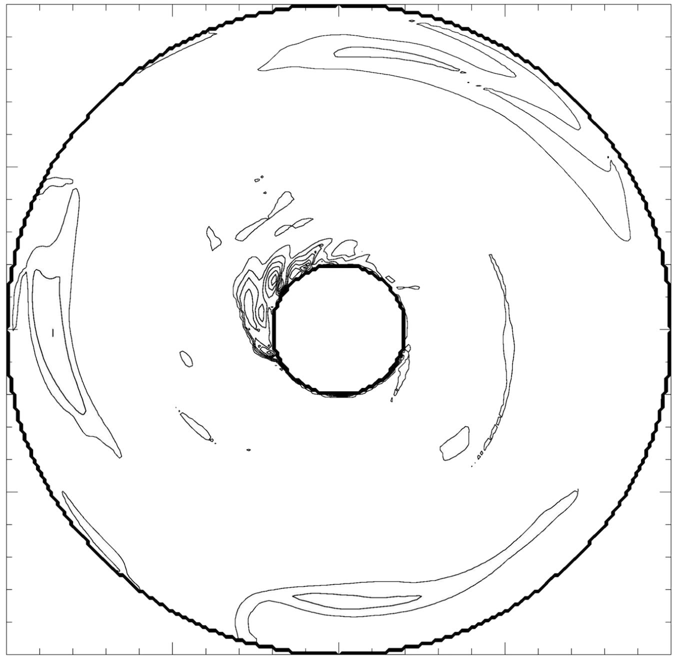

Fig. 2. The logarithmic contours of the tracer field density divided by the disk gas density i.e., log of the abundance ratio $^{26}Al/^{27}Al$ for the model shown in Fig. 1, plotted in the same manner. Contours represent changes by factors of 1.26 up to a maximum value of 9.3, on a scale defined by the gas disk density ~10^{-11} g cm^{-3}. The abundances of SLRI injected by a supernova are rapidly homogenized to within ~25%, except for inside a very low density region adjoining the inner boundary (cf. Fig. 1).

cloud. These speeds are sufficiently slow to permit the target cloud to be imploded into self-gravitational collapse and to inject the supernova's SLRI (Boss 1995). The supernova's shock is slowed to these much lower speeds by the "snowplow" effect—the supernova shock traverses a distance on the order of 10 pc before striking the target cloud, diluting its dose of SLRI and slowing down as a result of the sweeping up of intervening interstellar cloud material. As a result of this slowing down of the leading edge of the supernova shock front, the SLRIs lagging far (i.e., several pc) behind the leading edge have sufficient time to catch up and join the leading edge (Boss and Foster 1998). At 10^3 km s^{-1}, supernova ejecta can traverse 10 pc in ~10^4 yr. As a result, the R-T fingers responsible for the injection of the SLRI into the presolar cloud and the solar nebula should arrive more or less simultaneously, at least on the time scale of the cloud collapse process (i.e., within 10^5 yr). This near-simultaneity helps to preserve the use of SLRI as chronometers.

The width of individual R-T fingers is of about 0.005 pc (~1000 AU) when they first appear following the impact of the supernova shock front (see Fig. 1 of Vanhala and Boss 2002), with a spacing of about 0.01 pc (~2000 AU). Perhaps 10 such R-T fingers would be expected to inject SLRIs into the solar nebula. The R-T fingers appear to become narrower and better defined as the injection process proceeds. Given that these fingers must all converge down onto a disk with a maximum dimension of perhaps 30 AU in radius (given the radial extent of the giant planets in our solar system), one would expect that the R-T fingers might have a radial extent of no more than ~1 or 2 AU at the time that they strike the surface of the disk. A fully three-dimensional calculation of R-T finger injection into the solar nebula is necessary to refine these crude estimates, but the assumption made here of R-T fingers hitting the disk with spatial extents on the order of 1 AU appears to be a reasonable one, given the present state of knowledge.

As shown in Fig. 3, within ~200 yr after the R-T finger injection event, variations in SLRI abundances are predicted to be substantial (of order unity). If these variations could be captured by solids that formed within ~200 yr of injection, then the variations in their SLRI ratios caused by spatial heterogeneity would be expected to be so large as to make the SLRI useless as chronometers. However, the time scale for the growth of dust grains in the solar nebula is not thought to be that rapid. Growth to centimeter-size particles is expected to require at least ~1000 yr (Weidenschilling 1988). By the time that newly formed dust grains have grown to that size, the level of spatial heterogeneity is expected to have decreased to ~10%, as shown in Fig. 3. This level of spatial heterogeneity is consistent with using ^{26}Al as a chronometer with an accuracy of about 0.1 Myr—grains formed in the most SLRI-depleted regions of the disk will appear to be ~0.1 Myr too old, while grains formed in the most SLRI-enriched regions will appear to be ~0.1 Myr too young,

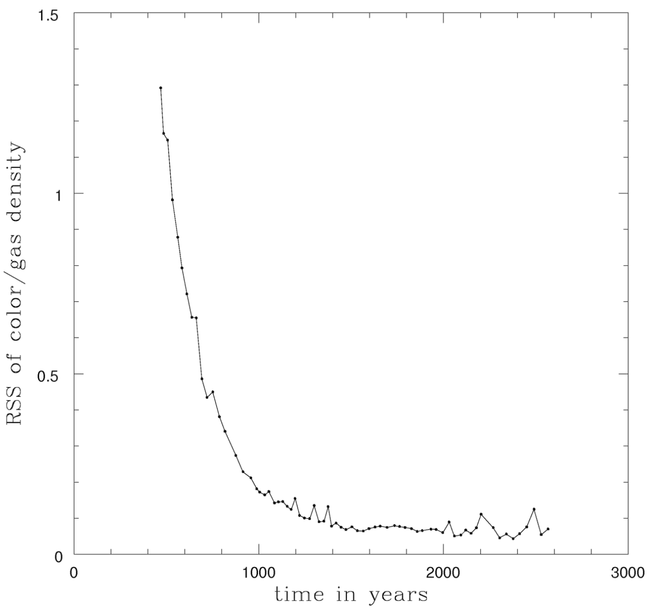

Fig. 3. The time evolution of the dispersion from the mean of the $^{26}Al/^{27}Al$ abundance ratio in the disk midplane from 5.5 to 19 AU following an R-T surface injection event that occurred at 200 yr. The quantity plotted is the square root of the sum of the squares (RSS) of the tracer color field density divided by the gas density subtracted from the mean value of this ratio, then normalized by the mean value, for the disk shown in Figs. 1 and 2. Starting from high values (RSS at 200 yr is >>1), the dispersion decreases on a time scale of ~1000 yr, then approaches a steady state value of ~10%. The occasional small spikes evident in the steady state phase are caused by localized, transient variations in the innermost disk as seen in Fig. 2.

compared to grains formed simultaneously with the mean abundance of SLRI. These abundance variations limit somewhat the usefulness of SLRI chronometry, but preserve most of their power as tools to probe the earliest phases of solar system formation and evolution.

Oxygen Isotopes

A line with a slope of ~1 in a plot of $\delta^{17}O$ versus $\delta^{18}O$ appears to represent the primitive oxygen isotope reservoir of the solar nebula (Clayton et al. 1973; Young and Russell 1998). This CCAM (carbonaceous chondrite anhydrous mineral) line covers a range in $\delta^{17}O$ and $\delta^{18}O$ values of about 6% (i.e., from ~−50 per mil to ~+10 per mil with respect to standard mean ocean water) for CAIs and ordinary chondrites. In addition, some rare chondrules have extreme values of $\delta^{17}O$ and $\delta^{18}O$ of ~−80 per mil (Kobayashi et al. 2003; Yin 2004). Relatively small deviations from a slope ~1 line can be explained by mass-dependent fractionations starting from the primitive oxygen isotope reservoir (Young and Russell 1998). We suggest here that the complete range in $\delta^{17}O$ and $\delta^{18}O$ values of ~10% is related to the efficiency of mixing in an MGU disk, as follows.

In the disk self-shielding model of Lyons and Young (2005), the solar nebula is assumed to have started as a disk with oxygen isotopes of solar composition, i.e., ^{16}O-rich gas and dust ($\delta^{17}O$ and $\delta^{18}O$ of ~−50 per mil). This same solar composition is predicted in the molecular cloud self-shielding model of Yurimoto and Kuramoto (2004). An O star then forms nearby and begins to photodissociate CO molecules at the surface of the disk at distances of about 30 AU. The O star's UV light photodissociates the rare $C^{17}O$ and $C^{18}O$ molecules to much greater depths in the disk than the common $C^{16}O$ molecules, producing a higher abundance of ^{17}O and ^{18}O atoms that recombine with the dominant hydrogen gas of the disk to form ^{17}O-, ^{18}O-rich water molecules. Given the low disk temperatures at these distances, the ^{17}O-, ^{18}O-rich water molecules form ice particles or icy mantles on silicate grains, both of which settle down toward the midplane of the disk, leaving behind ^{16}O-rich CO gas near the surface of the outer disk.

The expected positive values of $\delta^{17}O$ and $\delta^{18}O$ for the ice grains may be considerably higher than the values recorded in carbonaceous chondrites (Lyons and Young 2005), allowing for the CCAM line to result from mixing between the initial ^{16}O-rich solar composition and the ^{16}O-poor ice grain end members. Yurimoto and Kuramoto (2004) predicted that comets would still retain the signature of UV self-shielding in their water ice and CO gas with a much larger range of $\delta^{17}O$ and $\delta^{18}O$ values than has been found to date in meteoritical components. We suggest here that the fact that meteorites seem to be limited to variations in $\delta^{17}O$ and $\delta^{18}O$ of about 10% (rather than to the even larger range that might be found in comets) is related to this range of 10% being the expected level of isotopic heterogeneity in an MGU disk.

Krot et al. (2005) suggested that refractory inclusions formed in the inner disk when the disk was ^{16}O-rich, i.e., before the O star formed and began to photodissociate CO gas. Roughly ~1 Myr later, the inner disk gas became ^{16}O-poor, and persisted in that state for several Myr, as most chondrites formed. This transition in oxygen isotope abundances is thought to have been caused by the migration of ^{16}O-poor icy boulders formed in the outer disk inward to distances where the ice sublimated and led to ^{16}O-poor disk gas.

Lyons and Young (2005) similarly suggested that rapid inward orbital migration of meter-size, ^{16}O-poor icy boulders with respect to the outer disk gas (presumably even more ^{16}O-rich than the inner disk gas) was the means by which these oxygen isotopic anomalies were preserved from loss by isotopic exchange in the hot inner disk. If both the ^{16}O-poor ices and the ^{16}O-rich outer disk gas were simultaneously transported to the inner disk, then isotopic exchange would erase the oxygen anomalies created by UV photodissociation, resulting once again in solar composition gas and dust. The key point is that once the UV photodissociation process occurs, a means must be found to physically separate the water ice and the CO gas for the anomalies to survive.

We propose an alternative to the ice/gas separation mechanism suggested by Krot et al. (2005) and Lyons and Young (2005). The models presented here suggest that large-scale mixing in an MGU disk could have transported the ^{16}O-poor ice-rich grains formed in the outer disk ~20 AU inward on time scales of ~10^3 yr, comparable to the inward orbital migration times expected for meter-size boulders (Weidenschilling 1988). This alternative would not require the rapid formation of meter-size boulders that would later have to be sublimated inside the ice condensation front. Provided that the ice particles are small enough (i.e., centimeter-size or smaller), they will be transported along with the gas on the same time scale, and can more readily be sublimated and mixed with the warm inner disk gas. Meteoritical components forming around 2.5 AU would thereafter be expected to be more likely to be ^{16}O-poor than ^{16}O-rich, as seems to be the case for most chondrites.

This alternative mechanism can only work, however, if a means exists to transport the ice grains inward, but not the complementary CO gas. A possible agent for achieving this separation is the same UV flux that led to the photodissociation of the CO molecules in the first place. The far UV (FUV) and extreme UV (EUV) photons from a nearby massive star will heat the molecular hydrogen gas at the disk surface to temperatures of 2000 K to 10,000 K, sufficient to drive a strong photoevaporative loss of the hydrogen and CO gas from the disk (Boss et al. 2002). Considering that the ^{16}O-rich CO gas is produced only near the surface of the disk (based on the dense cloud models of van Dishoeck and Black 1988), and assuming that the ^{16}O-poor ice grains can settle rapidly to the disk midplane, the photoevaporation process will preferentially remove the ^{16}O-rich CO gas from the disk, leaving behind the ^{16}O-poor ice grains.

Ireland et al. (2006) presented evidence from lunar regolith samples that the Sun's oxygen isotopic composition is considerably more ^{16}O-poor than is assumed in the UV photodissociation scenario, with δ^{17}O and δ^{18}O values of ~+50 per mil. Such a ^{16}O-poor solar composition would presumably require that ^{16}O-rich CO gas be transported into the inner disk to explain the CCAM line, without the inward transport of the ^{16}O-poor ices, in a UV photodissociation scenario. The inward transport of the ^{16}O-poor ices might be avoided if the ^{16}O-poor ice grains in the outer disk were able to grow to meter-size bodies faster than they could be transported inward by the MGU disk. The meter-size ice bodies might then be prevented from migrating to the inner disk by the presence of spiral arms in an MGU disk, which act as collection points for meter-size bodies because of the effects of gas drag (Haghighipour and Boss 2003). This scenario would also require, however, that the ^{16}O-rich CO gas not be lost from the disk's surface by photoevaporation, which seems unlikely. In fact, growth of the ^{16}O-poor ice grains to meter-size on a time scale faster than that of transport in an MGU disk also seems unlikely. Hence the conclusion of Ireland et al. (2006) that their lunar regolith measurements appear to be inconsistent with a UV photodissociative origin of the oxygen isotopic anomalies appears to be correct.

Krot et al. (2002) suggested that amoeboid olivine aggregates (AOA) and accretionary rims on CAIs formed in ^{16}O-rich regions of the nebula, compared to the ^{16}O-poor regions where most chondrites formed. These could correspond to solids formed before and after UV photodissociation began in earnest, respectively. However, Fagan et al. (2001) found evidence for CAIs with both ^{16}O-poor and ^{16}O-rich compositions in carbonaceous and enstatite chondrites, implying either some overlap in CAI and chondrite formation epochs, or else the persistence of isotopic oxygen heterogeneity at levels sufficiently large to lead to these differing values for solids formed at the same epoch. The models presented here lend support to this latter idea as a possibility.

While many details remain to be considered, it appears likely that a MGU disk is capable of rapidly transporting inward and mixing the ^{16}O-poor ice grains produced by UV self-shielding in the outer disk in a manner consistent with an overall spread in oxygen isotope values for meteoritical components of ~10%.

CONCLUSIONS

Components of primitive meteorites have a scatter in initial ^{26}Al/^{27}Al ratios ranging from values of ~0 to ~4.5 × 10^{-5} or to even higher values (~7 × 10^{-5}; Young et al. 2005). The scatter around the peak value (MacPherson et al. 1995) of ^{26}Al/^{27}Al ratios of ~4.5 × 10^{-5} is about 10%. We have shown that this scatter is entirely consistent with the dispersion expected from spatial heterogeneity in the solar nebula. Such a low level of spatial heterogeneity implies that larger variations in initial ^{26}Al/^{27}Al ratios must be due primarily to temporal heterogeneity, preserving a role of SLRI as accurate chronometers for the solar nebula. This 10% level of heterogeneity is also roughly consistent with the preservation of oxygen isotope anomalies in water ice produced by self-shielding at the outer disk surface (Lyons and Young 2005) followed by transport inward to regions of the disk where such anomalies could not have been sustained because disk surface temperatures were too high for stability of water ice. These MGU disk models thus appear to be capable of solving the puzzle of nebular spatial heterogeneity presented by SLRI ratios and by oxygen isotope anomalies in primitive meteorites.

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