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Donald D. Clayton
Clemson University, claydonald@gmail.com

Paul Scowen
Rice University

Kurt Liffman
NASA Ames Research Center

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AGE STRUCTURE OF REFRACTORY INTERSTELLAR DUST AND ISOTOPIC CONSEQUENCES

DONALD D. CLAYTON
Department of Physics and Astronomy, Clemson University

PAUL SCOWEN
Department of Space Physics and Astronomy, Rice University

AND

KURT LIFFMAN
NASA Ames Research Center

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ABSTRACT

We compute the mean age of dust particles using a sputtering and recycling Monte Carlo model developed by Liffman and Clayton (1988). Each particle mean age is defined not as the time it has existed but rather as the mass-weighted existence times of its parts (core plus shells) at $t = 6$ Gyr when the solar system formed in our models. We show that Galactic evolution generates a correlation between particle size and mean age. This is a mean correlation, applying to large numbers of particles binned according to size rather than to individual particles, whose mean ages fluctuate statistically. The cosmochemical consequence is that if interstellar particles can be dynamically sorted into separate size populations during the aggregation history of solar system bodies, the collections of larger grains will constitute matter that is chemically older than collections of smaller grains. This macroscopic age difference generates isotopic anomalies by virtue of the time dependence of the secondary/primary nucleosynthesis yields. The most important example is that an aggregate of refractory oxides is several percent richer in ^{16}O than is the solar gas, ranging up to 10% richer in Al_2O_3 if Al is also concentrated into larger-than-average particles. This history may explain the 5% richness of ^{16}O within meteoritic Al-rich inclusions. We compare our results with three different prescriptions for the sputtering of interstellar dust.

Subject headings: abundances — interstellar: grains — meteors and meteorites

I. INTRODUCTION

We present here a model-dependent calculation of the distribution of existence times of the matter in interstellar dust composed of refractory metals. The initial motivation was to model numerically the mechanism for isotopic anomalies introduced by Clayton (1988); namely, older dust components should be somewhat deficient in secondary-nucleosynthesis isotopes because the bulk interstellar medium (ISM) was previously deficient in those isotopes in comparison with the solar composition, which is the norm against which the isotopic anomalies are defined. To keep the clearest example of importance in mind, the reader may remember that the bulk $^{17,18}O/^{16}O$ ratios in the ISM have increased during Galactic chemical evolution, so, if metallic oxide dust mantles were formed from the bulk medium, the oldest ones would appear to be ^{16}O-rich (i.e., ^{17}O- and ^{18}O-poor by equal factors). This idea carries sufficient relevance to the question of isotopic anomalies in meteorites to warrant a numerical study, because only such studies can reveal the manner in which an isotopic anomaly in a macroscopic meteorite sample may have been assembled from microscopic dust grains and how large such an anomaly might reasonably be. We must establish means, even if only in principle, for sorting interstellar dust isotopically.

The immediate obstacle to such a program is the paucity of knowledge about interstellar dust. The question cannot be addressed without a specific description of the formation and destruction of dust, a vast area of present and future research in astronomy. Yet it does seem reasonable to begin evaluation of this isotopic mechanism by utilizing a description of refractory interstellar dust that has been developed by two of us (Liffman and Clayton 1988, 1989). Despite its idealizations, that model is capable of yielding specific answers, and may even prove to be close to the truth. It is based upon stochastic histories of individual particles as they migrate among interstellar phases and conditions. The latter are idealized as a two-phase interstellar medium: (1) a *molecular cloud phase* in which all stars are born, astrating any entrained dust; (2) a *diffuse cloud phase* in which particles are eroded by sputtering in the wakes of the supernova shocks that repeatedly traverse the medium. Sputtering reduces the particle size and mass and we continue to assume that the particle is totally destroyed (ceases to exist) if sputtered to 5 Å radius. New dust mass is created in this model in just two ways: (1) thermal condensation during ejection of both newly synthesized metals and of old metals returned from stars, both of which we place into the diffuse medium on the grounds that the starbursts have locally disrupted the molecular clouds in which they occurred; (2) mantles of accreted matter are added to diffuse-cloud dust at the moment that a diffuse-cloud volume element cools and collapses onto the molecular-cloud medium. Physical accretion in diffuse clouds appears, on average, as a reduction in the average sputtering rate, so we can suppress it. A more complete description, including attempts to justify the construction, may be found in Liffman and Clayton (1988, 1989). By generating Monte Carlo histories of a large number (10^6, say) of such particles created during the presolar evolution of the Galaxy (6×10^9 yr, say) we build a profile of the dust particles, which is stored in a computer array so so that subsequent questions may be asked of it. The two phases are taken to transmute stochastically into one another on a 10^8 yr time scale, i.e., the probability that in the next time step dt a given mass element dM_{MC} of molecular cloud matter will be disrupted by star formation to the extent of rendering it diffuse is given by $dP = dt/\tau$, where $\tau = 10^8$ yr is normally chosen for phase changes in both directions so that the molecular-cloud mass M_{MC} and the diffuse cloud mass M_{DC} are approximately equal. The stochastic selection of "transit clouds" allows each dust particle an independent history if we assume that particles and gas of each medium are continuously mixed throughout that medium. Thus the probability within dt of having a given diffuse-cloud dust particle join the molecular phase is then also $dP = dt/\tau$. But some particles reside longer than average in each phase, and some less, introducing a random walk in size (with an absorbing boundary for particles sputtered to $r < 5$ Å). For more details of this method one can read Lifman and Clayton (1988, 1989), who present not only more details but also the results of many numerical studies designed to reveal the basic properties of such systems. In particular, they distinguished the existence lifetime of particles from the mean-destruction-rate lifetime of total dust mass. What they did not study, and which we now add, is the distribution of the ages of dust components. How long has the matter within dust been residing there? Do different physical fractions of the dust have different average ages?

II. SPECIFYING THE CALCULATION

Liffman and Clayton (1989) coupled the Monte Carlo dust study with models of the chemical evolution of a two-phase ISM. They were also able to compute the mass of refractory gas in the diffuse phase, to treat astration correctly and return from stars of astrated material, and to follow the temporal evolution of the size of dust mantles accreted during the transfers to the molecular phase. They showed, however, that the dust structures generated differed little from those obtained by the simpler approach of Liffman and Clayton (1988). In that earlier approach, the chemical evolution was simplified to the assumption that nucleosynthesis per unit mass of ISM occurs at a constant rate, so that star-formation–related dust-particle creation can be modeled as a flat spectrum of birthdates for the particles injected; moreover, the mantle thickness Δr added during molecular cloud entries was taken as constant for every dust particle, with the constant chosen to keep the total mass of the dust system equal to the mass of unevolved dust that has been injected by star formation and evolution. Astration of dust is included, but those atoms are immediately returned as gas to keep the total mass constant. Because the profiles of dust population computed from these two approaches are so nearly equal, we use in this study the simpler computational approach (Liffman and Clayton 1988). Dust injection is at a constant rate per unit mass, and each particle follows an independent Monte Carlo history defined by a random number generator and the sets of probabilities for its fate. In this work we will not distinguish, however, between supernova condensation (SUNOCONs) and condensation during stellar return (STARDUST) or the associated condensation in cool shells outside dying stars, because we wish for the present study to suppress isotopic anomalies introduced by those specific aspects of cosmic chemical memory (Clayton 1982). To focus explicitly on the age effects in accreted mantles, to isolate Galactic chemical evolution effects as the *only* source of isotropic variations, we take each injected particle to be homogeneous in structure (i.e., no type A and type B condensates as in our earlier work). We assume only that some prompt condensation processes quickly cause all refractory atoms ejected from stars to reside in dust particles (the "injected particles"), and then follow the cyclic histories of those particles. Just as Liffman and Clayton (1988, 1989) did, we take the injection spectrum $n(a) = a^{-3}$ between initial radii 100 Å $< a <$ 1000 Å (unless stated otherwise). By taking each injected particle to be homogeneous and of identical isotopic composition (which we can even for definiteness and simplicity take to be the mean isotopic composition of the ISM at that time) we explicitly suppress the injection of isotopic anomalies. An equally valid picture of our calculation would be the condensation of *new particles* with a^{-3} spectrum at a constant rate from a well-mixed ISM subsequent to gaseous ejection from stars. So featureless is this initial construction that we reemphasize that property by remarking that if nothing further happened to these particles, no isotopic anomalies would be possible (except for the particle-by-particle differences between *individual grains* created at different times). If each particle remained forever unchanged, every size fraction of interstellar dust would be a uniform mixture of grains having identical average composition. Thus, macroscopic assemblies would of necessity be normal. By contrast, we demonstrate that the evolution of the dust system itself creates differing average isotopic compositions in collections of grains sorted according to size. Since size sorting may occur naturally, so may these isotopic anomalies. This is a nontrivial result, introduced in a general way by Clayton (1980), and reemphasized by Liffman and Clayton (1988) in their discussion of an altogether different isotopic mechanism operating in parallel to the age mechanism upon which we focus in this work.

Figure 1 summarizes key aspects of this calculation. Homogeneous particles are injected at a constant rate with a^{-3} spectrum. After a lengthy period of evolution, the particles have an evolved size spectrum that has become roughly exponential (Liffman and Clayton 1988, 1989). Most of our calculations are done by assuming that sputtering erodes all particles in the diffuse medium at a constant rate, independent of this size, as might be expected as a result of frequent reheating of the diffuse medium by supernova shock waves (every 10^6 yr or so), so that ions in the reheated Maxwellian tails strike dust grains in proportion to their surfaces areas. We call this thermal sputtering. Liffman and Clayton (1988) show why they take $dr/dt = -0.02\ \mu\mathrm{m}\ 10^{-8}$ yr to measure that thermal erosion rate, which we also adopt. With that sputtering description the evolved particle size spectrum adopts a roughly exponential distribution for 400 Å $< r <$ 3000 Å, with the largest particles having mass more than 10 times greater than the most massive injected particles. Only 8% of the injected particles survive 6×10^9 yr of evolution, and the stochastic nature of the random walk between the ISM phases has destroyed most of the smallest injected particles and created some of great mass. These results were described by Liffman and Clayton (1988) and reconfirmed with a new code written by P. S. The calculations to follow will also be carried out for "inertial sputtering," expected if supernova shocks accelerate particles to high velocity by magnetic-field compression, following which they are sputtered at a radial rate proportional to size while they are slowed. We take Liffman and Clayton's (1988) value for the inertial sputtering lifetime $dr/dt = -r(t)/\tau_{\mathrm{is}}$, namely, $\tau_{\mathrm{is}} = 2.6 \times 10^8$ yr. Because these two sputtering "laws" yield inter-

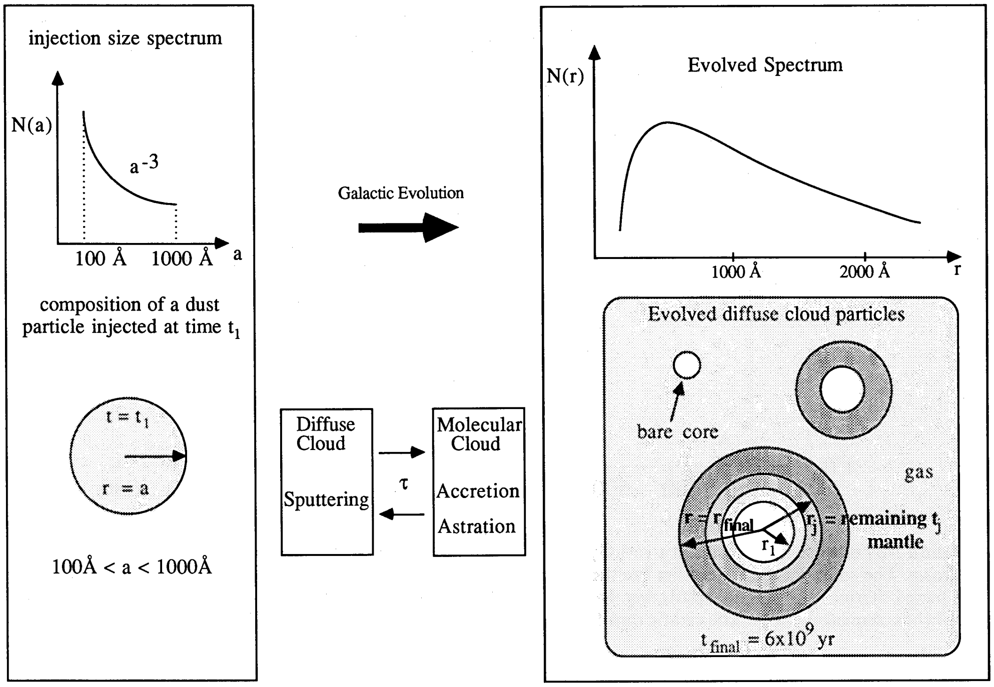

FIG. 1.—Overview of dust grain evolution in a two-phase interstellar medium. New dust grains are injected into the diffuse cloud phase with an a^{-3} size spectrum, where a is the initial value of r for each particle, $100 \text{ Å} < a < 1000 \text{ Å}$. This new grain mass is injected at a constant rate for the 6 Gyr of presolar evolution. Particles are sputtered in the diffuse clouds but accrete new mantles of refractory-element gas when their transit cloud joins the molecular-cloud phase. Each particle transfers stochastically with mean $\tau = 10^8$ yr from phase to phase, so that layered particles having successive mantles of differing ages in evolved particles, shown in right-hand panel.

estingly different results for dust structure, we will also present our first results for mixed thermal and inertial sputtering.

What we concentrate on in this work is the inner structure of the evolved particles, one of which is indicated schematically in the right half on Figure 1. The onionskin structure results from the successive $\Delta r = 160$ Å mantles of refractory material that are added each time the particle has entered a molecular cloud. This Δr value conserves dust mass for both sputtering descriptions. Because the full cycle time averages $2\tau = 2 \times 10^8$ yr, a particle living 6×10^9 yr could add some 30 shells. Most of these are, in the course of the alternating sputtering episodes, later removed. Our memory array for each particle erases a shell whenever sputtering removes it. Thus, a typical surviving particle at the end of our 6×10^9 yr evolution has but a few shells. Their masses and times of deposition are determined by the stochastic histories. But it will be clear that at the end each particle is described by the fraction of the injected particle that still remains as a central core and the thickness and times of deposition of each of the successive mantles. An *average age* for each particle can be defined as a mass-weighted average of the ages of the shells:

$$\langle \tau \rangle = \frac{\Sigma m_j \tau_j}{\Sigma m_i}, \qquad (1)$$

where m_i is the mass of the ith shell ($i = 1$ for original remaining core, 2, 3, ... surface) and τ_i is the time that shell i has been in the particle ($\tau_i = T_G - t_i$, where T_G is Galactic age, usually 6×10^9 yr at the time the sun formed in our models, and t_i is the time that shell i was accreted). Note that only a fraction of each deposited shell i remains, because some amount of it was always sputtered away during its first reemergence into the diffuse sputtering medium. The only full 160 Å shell is the last one accreted by those particles residing within the molecular clouds at the time the calculation was terminated ($t = T_G$). The shell thickness $\Delta r = 160$ Å was determined by trial to conserve mass in the sense that the evolved dust mass after 6×10^9 yr is equal to the total dust mass injected at a constant rate over that span (for the thermal sputtering case 1*b* of Table 1 of Liffman and Clayton (1988), and for the inertial sputtering case 2 of that Table 1, which we reconfirm with an independent computer code). The thermal sputtering case 3 of Liffman and Clayton (1989) is astrophysically more exact and gives $\Delta r = 151$ Å; however, its SUNOCON plus STARDUST mass is not injected at a constant rate, which we prefer to adopt for simplicity. Considering the inaccuracy of our current state of knowledge of Galactic evolution, use of the simpler constant injection rate for preliminary evaluation of this new age effect does not introduce significant physical error into the particle structures.

III. RESULTS

Figure 2 shows the size spectrum $N(r)$ of the particles remaining at the end of 6×10^9 Gyr of galactic history in the molecular cloud phase. The solid curve, for thermal sputtering, reproduces Liffman and Clayton's (1988) result. No particles having $r < 160$ Å exist in the molecular clouds because each preexisting particle accreted $\Delta r = 160$ Å upon its last entry to it. For larger sizes the numbers decrease exponentially, showing no discontinuity at the maximum injection size $a_{\max} = 1000$ Å. A significant percentage of dust mass is put into large particles. By contrast, the inertial sputtering prescription, shown as the dashed curve, allows survival of very few particles above $r = 1200$ Å, because it is very destructive of large particles. These two distributions confirm cases 1*b* and 2 from Table 1 of Liffman and Clayton (1988), but note (see caption)

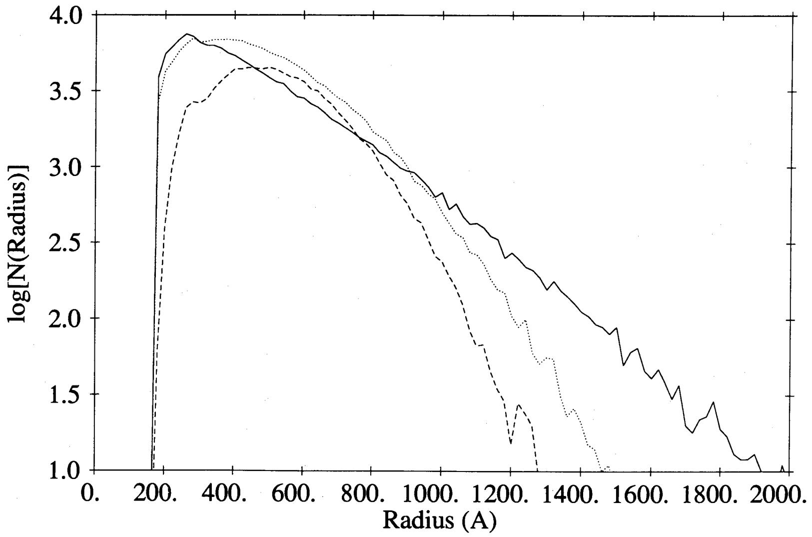

FIG. 2.—The size distribution $N(r)$ of existing particles at $t = 6$ Gyr in the molecular-cloud phase. All particles in this phase have $r > 160$ Å owing to the final accreted mantle of that thickness. The solid curve results from the thermal sputtering prescription, whereas the dashed and dotted curves result, respectively, from inertial sputtering and from mixed thermal and inertial sputtering. Inertial sputtering is destructive to large particles and thermal sputtering is destructive to small ones. The actual ISM probably has elements of both. The erratic results for the largest sizes reflect the statistics of few particles in the largest 20 Å bins.

that because a higher percentage of particles survive under inertial sputtering (which is ineffective in destroying the abundant small particles) the dashed inertial case reflects fewer total injected particles (5×10^5 vs. 4×10^6 for the thermal-sputtering case).

The intermediate dotted curve in Figure 2 shows our first results for a mixed sputtering law. Its Monte Carlo construction was as follows. A random number determines as before the residence time in the diffuse-cloud sputtering phase, usually of order 10^8 yr. Whatever the residence time, it is divided into 10^7 yr segments plus a remainder, and additional random numbers determine whether the sputtering is thermal or inertial during each segment. Not surprisingly, the results on particle number $N(r)$ are intermediate to those of thermal and inertial separately. The inertial component holds down the number of large particles, and the thermal component rapidly destroys the smallest ones. (Compare from the caption the total numbers injected in the comparison displayed.) These results establish contact with and confirm our earlier results, and they set the stage for the main question of this investiation: How old are the mean mass components of the dust, and do isotopic differences exist between particles of differing size? The affirmative answer to the second question is what gives urgency to our results, because many chemical-memory applications to meteoritic science may follow.

a) *Mean Age according to Size*

We take our memory array for the surviving particles and sort those particles according to their total radius into size bins. These bins are 20 Å wide. We could place more particles in each bin by making them wider, which would reduce the statistical fluctuations that will be evident. Then the mean age of each particle is calculated by the mass-weighted average over its shells according to equation (1). Figures 3, 4, and 5 show these mean age results averaged over all particles in a given bin size for thermal, mixed, and inertial sputtering descriptions, respectively. The diffuse-cloud phase is solid and the molecular-cloud phase is dotted.

Consider these results from Figure 3 for the choice of thermal sputtering: (1) The mean age increases with particle size, i.e., larger particles carry, statistically, a larger number of mass shells that have been there for a long time; (2) molecular-cloud dust is much younger than diffuse dust of the same size, a result of the final, young $\Delta r = 160$ Å shell that was the last change to have occurred in every particle in the molecular medium. Although very small diffuse particles exist (which are mostly on their road to sputtering destruction), only particles having $r > 160$ Å exist in the molecular phase. One notes that statistical fluctuations associated with the small numbers of particles per bin become stronger in the larger size bins, but the continuing upward trend is clear. In principle the two curves would asymptotically converge to a single curve for particles so large that the last 160 Å shell would be insignificant. But no such particles exist. The caption to Figure 3 notes that the almost exactly linear increase of mean age with particle size can be summarized as 5.6×10^5 yr Å^{-1}. Analogous characterizations are given for mixed thermal and inertial sputtering in Figure 4 and for inertial sputtering in Figure 5. For pure inertial sputtering (Fig. 5), the inefficiency for destroying small particles results in the high average age of small particles in the diffuse (solid) phase. Those small old cores are swamped in mass by the last 160 Å young mantles in the molecular phase.

Figure 6 illustrates a sharp bifurcation of core/mantle structure between the final particles in molecular and diffuse media (shown for the choice of thermal sputtering only). Let the core be defined as that central part of the particle composed of the remainder of the initially injected particle. The mantle is the sum of the accreted shells overlying the core. This distinction is not only isotopic but could also be structural if the cores are mineralized owing to thermal condensation initially and the mantles are amorphous. Whether that be so or not, Figure 6 reveals that the cores dominate the masses of the small (<200 Å) particles in the diffuse medium whereas they are only several percent by mass of molecular cloud particles. For comparison's sake it must be borne in mind that this core is the same as the sum of remaining phases A and B defined by Liffman and Clayton (1988). They emphasized the specific isotopic anomalies in these cores if they have been injected as SUNOCONs

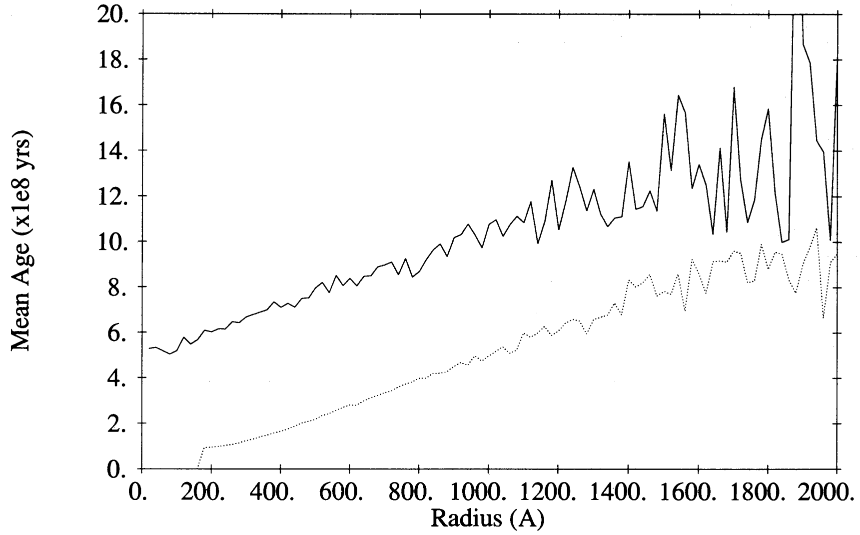

FIG. 3.—The correlation of mean age with particle size for the thermal sputtering prescription. The diffuse cloud phase is solid, and the molecular phase is dotted. Molecular cloud particles are younger because they have just added a young $\Delta r = 160$ Å mantle during their last entry to the molecular clouds. The almost linear correlation of mean age with size has slope 0.56 Myr Å^{-1}. Statistics of small numbers make results erratic in the largest bins. The larger older particles will also be ^{16}O-rich.

recording the supernova shell compositions, whereas we here make no explicit construction for core compositions.

Although the mean age of molecular cloud particles increases with total size, there exists wide and interesting diversity among particules of a given size. Figure 7 shows, for molecular-cloud particles of fixed total size, the distribution of number of particles per 20 Å bin according to mean particle age (for the choice of thermal sputtering). Each size fraction shows declining numbers with increasing age, but larger size fractions are increasingly deficient in young particles and more abundant in old particles.

IV. DISCUSSION

Probably the clearest and potentially most important application of these results to the chemical memory of meteorites lies in oxygen isotopes. Superrefractory calcium-aluminum-rich inclusions (CAI) within carbonaceous meteorites apparently formed from refractory oxides having ^{17}O/^{16}O and ^{18}O/^{16}O ~ 5% less than terrestrial values (R. N. Clayton *et al.* 1977). Several possible reasons for this fact exist in the literature (and our results evaluate yet another as first described in general terms by Clayton 1988). Figures 3, 4, and 5 show that any dynamic process of aggregation of molecular cloud dust that favors larger than average particles, will produce an aggregate that is older in the sense of this paper, i.e., the mean average age of the dust particle structures making up the aggregate. One may envision gravitational sedimentation as the simplest example of such a physical sorting process. Just to be specific, Figure 3 shows that a collection of 1400 Å particles has a mean age 4.5×10^8 yr greater than the mean age of a

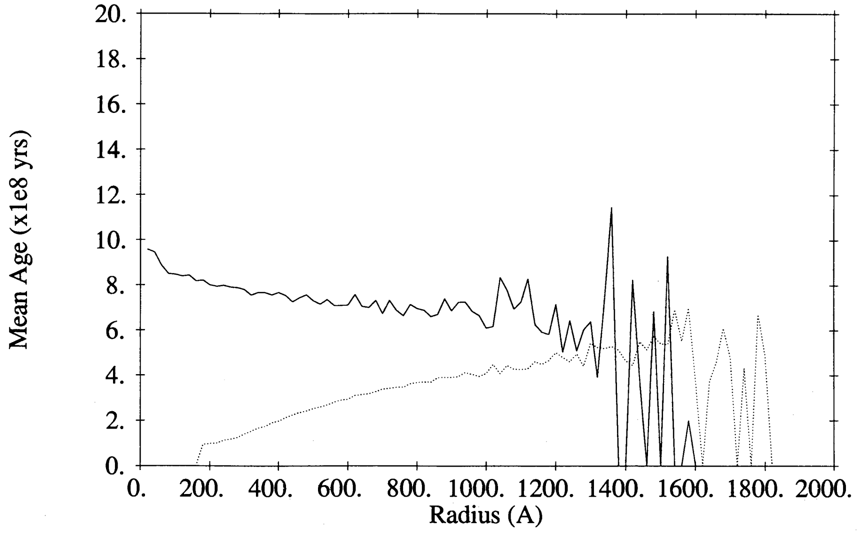

FIG. 4.—The correlation of mean age with particle size for the sputtering prescription that is mixed (alternately thermal and inertial) during diffuse-cloud residence. The diffuse phase is solid and the molecular phase is dotted, as in Fig. 3. The positive correlation in the molecular phase has slope 0.57 Myr Å^{-1} for 200 Å $< r <$ 600 Å, almost equal to that in Fig. 3, but the shallower slope 0.27 Myr Å^{-1} for 600 Å $< r <$ 1600 Å, above which the statistics of small numbers obscures the situation. In the diffuse cloud, on the other hand, the correlation is *negative*. The oldest particles, the small bare cores, have become more numerous with this sputtering prescription.

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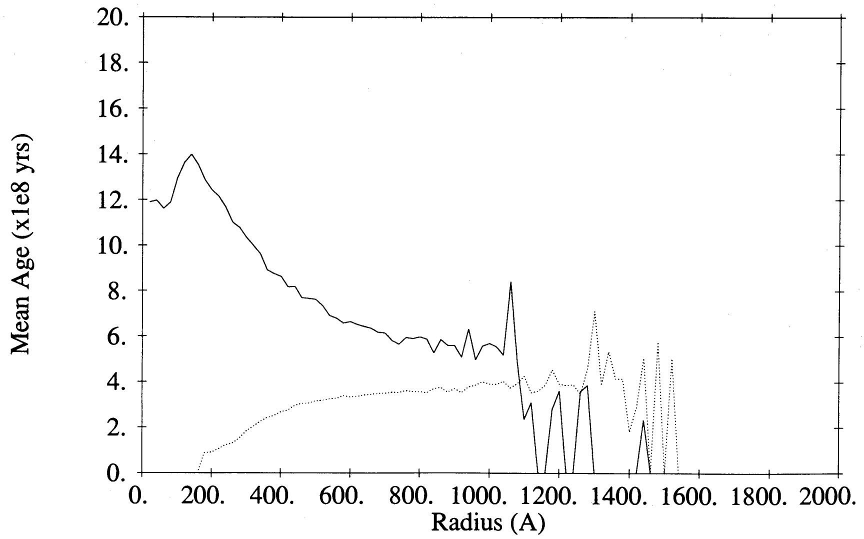

FIG. 5.—The correlation of mean age with particle size for the inertial sputtering prescription, which is the one most severely limiting the numbers of large particles (see Fig. 2). The molecular-cloud correlation (*dotted curve*) is even steeper, 1.0 Myr Å^{-1}, for 200 Å $< r <$ 400 Å, but is shallower, 0.12 Myr Å^{-1}, for 400 Å $< r <$ 1400 Å. The diffuse-cloud (*dotted curve*) correlation is again negative (as in Fig. 4). Because small bare old cores accumulate with this sputtering prescription, there exists a large age peak at small sizes. But these are swamped by young mantles in the molecular cloud.

collection of 600 Å particles. That extra age might be as much as 10% of the age of the Galactic disk at the time of solar birth. Clayton's (1988) argument concerning the mean isotopic evolution of the Galactic disk points to a corresponding 10% deficiency in the ^{17}O and ^{18}O isotopes in the older larger aggregates. In this way, mean Galactic chemical evolution couples with the evolution of interstellar dust under sputtering and accretion cycles to produce two macroscopic dust aggregates differing by several percent in bulk-oxygen isotopic composition. The larger-particle aggregate appears to have excess ^{16}O.

The remainder of the observed meteoritic correlation of excess ^{16}O with aluminum depends at the present time on a plausibility argument given as mechanism 3 by Clayton (1988); viz., because superrefractory Al (the element most correlated with ^{16}O excesses) is observed to be more depleted from diffuse-cloud gas than are other elements, it must reside for longer times in grains undergoing sputtering. The largest and oldest ISM particles therefore become enriched in the very refractory elements, including Al. Their Al_2O_3 is more ^{16}O-rich than are most interstellar oxides because it was incorporated into grains earlier than other oxides. This plausibility argument in conjunction with the age/size results presented here calls for a careful modeling of the aluminum content of interstellar dust.

The increase of mean age with size is more modest with the choice of inertial sputtering (Fig. 5), but even there, one sees a sufficiently large age difference between small and large par-

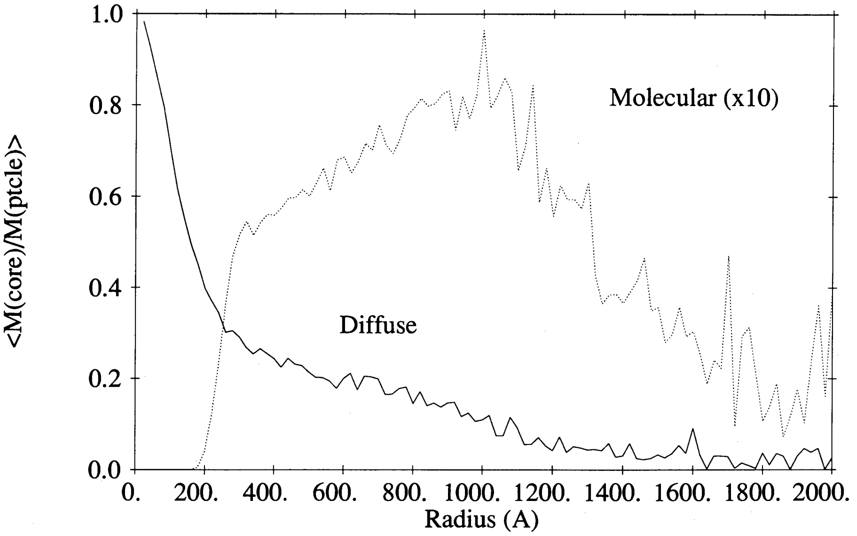

FIG. 6.—The average mass fraction of core (initial particle) mass in particles of radius r in both phases with the thermal sputtering prescription. The molecular-cloud particles (*dotted curve*) have been multipled by 10 for easy viewing, but are physically less core than in the diffuse clouds, where the average small particle is almost pure core. This result is consistent with Figs. 4 and 5 of Liffman and Clayton (1988), although those figures are differently formatted. The largest core fraction in the molecular cloud is near 1000 Å, the maximum size of the injected cores. This figure assumes importance if one considers specific isotopic anomalies in the supernova-dust cores, and, because the core is the oldest part of every particle, it also explains in part the positive age correlation of Fig. 3.

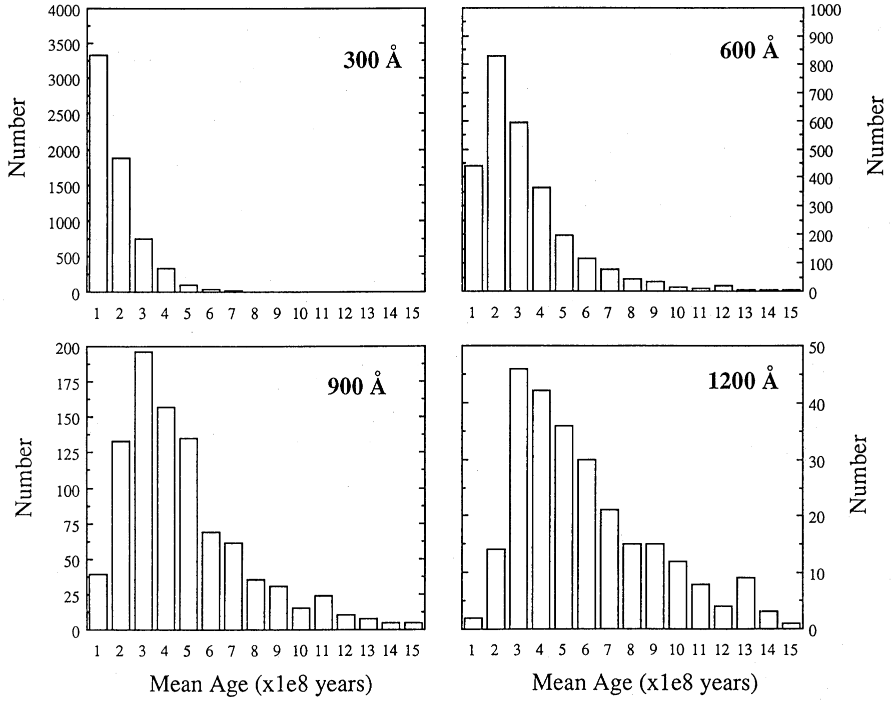

FIG. 7.—Histogram of the mean-age distribution of molecular-cloud particles of specific sizes. As one considers groups of larger particles, the fraction having low age declines and the number having mean age $\langle\tau\rangle > 5 \times 10^8$ yr increases greatly. This is for the thermal sputtering prescription.

ticles to find that difference potentially significant for the oxygen problem. The mixed sputtering case (Fig. 4) is intermediate to the other two, and therefore also interesting. We emphasize the molecular-cloud particles as being most relevant to the early solar system.

For the case of oxygen it is evident that even without age sorting the bulk of dust is ^{16}O-rich. From Figures 3, 4, and 5 and the size spectrum of particles one can calculate that the totality of dust is 3–5 $\times 10^8$ yr old, and is therefore several percent richer in ^{16}O than is the gaseous oxygen at the time the solar system formed (Clayton 1988). The ordinate in Figures 3, 4, and 5 could be relabeled as a percentage excess of ^{16}O. Liffman and Clayton (1988) showed in their Figure 4 that the mass-average particle in the case shown in our Figure 3 is about $r = 1000$ Å, so that its mean age can be seen to be 5×10^8 yr from Figure 3. Clayton (1988) showed this to imply that mean dust has δ^{16}O = 5%–10%, depending on the Galactic age and chemical evolution model. The ^{16}O-rich CAI could be merely a dust aggregate formed thermally in the solar system without exchanging its oxygen with the ^{16}O-poor gaseous component, whereas the normal bulk oxygen would be interpreted as gaseous oxygen exchanged with the particulate matter. This is indeed the interpretation that has normally been assumed in the large body of work from R. N. Clayton's laboratory documenting these compositions (e.g., Thiemens 1988). That argument has been more explicitly detailed by Wood (1981). Whether sorting of particles is involved will be a difficult issue to pin down with CAI alone. But the different chondritic classes have both differing bulk oxygen composition and bulk chemical composition. Parent bodies of differing mean particle size (and density) remain a good possibility for accounting for these differences. One can at least anticipate from our work a continuum of initial oxygen isotopic reservoirs, ranging from ^{16}O-poor gas and final-mantle dominated particles of smallest size to the largest most ^{16}O-rich particles, the latter probably being also refractory-element rich.

Another example of considerable possible significance occurs in magnesium (Clayton 1988), which has a rich measured spectrum of isotopic anomalies in meteorites. A difference from the oxygen case is that oxygen is mostly in the gas at all times, because it is too abundant to be condensed in refractory oxides, whereas magnesium is largely in the dust. For oxygen it is therefore more nearly correct to assume that the isotopic composition of accreted mantles is approximately equal to that of the bulk ISM. For magnesium, however, a detailed mass-balance and isotopic-balance calculation is needed. We do not provide this because it exceeds our purpose of documenting only the age distribution of a carefully calculated dust ecology.

The reader should be reminded of the physical consequences of our choice (for it *is* a choice at the present time) of a value of the accretion increment Δr that conserves dust mass, conserving it in the sense that the total mass of refractory dust remains equal to the time-integrated injection rate of new dust mass. This constraint is plausible only if newly synthesized metals are completely condensed as they are ejected for the first time from the synthesizing supernova, which was in fact our mental picture guiding the construction initially. This assumption will seem implausible to many who prefer to expect gaseous ejection from supernovae (while we await the answer from SN 1987A). If supernova ejection is mostly gaseous but is nonetheless the source of the new cores that are injected, it is clear that Δr will be larger as the particle pool accretes in molecular clouds the refractory metals that were initially ejected in gaseous form. We would model this by instead choosing Δr larger so that the refractory-dust mass grows at a rate greater than its injection rate, as discussed by Liffman and Clayton (1988). The net effect will be cores that are more protected from sputtering but that are a somewhat smaller fraction of total particle mass. Figure 6 displayed the core refraction for the mass conserving $\Delta r = 160$ Å only. Once 100% condensation efficiency for new nuclei is challenged, exciting new possibilities for isotopic anomalies also appear. Liffman and Clayton (1988) described, for example, a solution to the observed $^{48}\mathrm{Ca} - {}^{50}\mathrm{Ti} - {}^{54}\mathrm{Cr}$ correlation in meteorites that is based on Clayton's (1981) argument that those isotopes cannot condense as efficiently as others because they are so near the neutron-star mass cut that they are more radiation impacted and have no oxygen or sulfur around to condense with. This would, as those isotopes are later accreted with the Δr material, cause them to be entirely in the mantles and again be sortable by particle size. Thus, we remind the reader of the rich world of astrophysical complications with isotopes that we have intentionally suppressed in an effort to concentrate on the first numerical results of the age distribution of matter in dust. Our assumptions are too simple, but the range of age variations and their basic causes may be more robust.

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DONALD D. CLAYTON: Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-1911

KURT LIFFMAN: NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035

PAUL SCOWEN: Department of Space Physics and Astronomy, Rice University, Houston, TX 77251