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Stochastic Models of Refractory Insterstellar Dust

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STOCHASTIC MODELS OF REFRACTORY INTERSTELLAR DUST;

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This is a first report of studies that we are making of the evolution of properties of interstellar dust. Our initial interest lies in mathematical properties of the migration of grain populations subjected to interstellar sputtering during residence in a diffuse medium and to mantle accretion during transition to molecular cloud phase. Initially we idealize the description to avoid numerous complications and uncertainties in order to focus on specific physical affects having realistic counterparts.

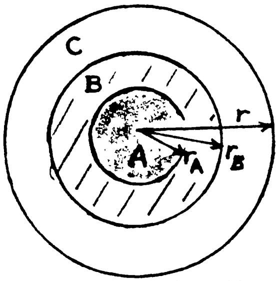
This problem finds application to the cosmic chemical memory of interstellar dust and therefore to isotopic anomalies generated by its occurrences. To this end we model the history of a highly refractory component, because that is the chemical component that condenses with high efficiency during the expansion of the supernova interiors that synthesized the abundant refractory elements and that is thereby capable of storing isotopic memory of the source - the SUNOCON component [1]. For this study we will take it that all such material appears initially in condensed form, the SUNOCONs. We will then follow numerically the evolution of those initial particle memories by constructing a large number of Monte Carlo histories of individual particles.

This this first study we take sputtering in the diffuse medium to be the only destructive process and we ignore reaccretion of refractory atoms in the diffuse medium where the sputtering occurs. Designating the particle radius by a, we take sputtering to erode that radius at the constant rate $(da/dt)_{sputter} = -0.02\ \mu m/10^8$ yr. This sputtering rate lies in the range of published calculations [2], which have considerable average uncertainty in application owing to uncertainty in the frequency with which various interstellar media are impacted by supernova shock waves. But it will be evident that with this average erosion rate, a characteristic particle having $a = 0.1\ \mu m$ will have half its mass sputtered away in 10^8 yr, so that if the sputtering lifetime τ_S is defined as $m\ (dm/dt)^{-1}$, the rate adopted corresponds to $\tau_S = 2 \times 10^8$ yr. We omit grain-grain collisions until a later study.

We construct a two phase model of the ISM having equal masses in the diffuse sputtering phase and in the molecular cloud phase, and between which material is continuously cycled with timescale $\tau_d = 1 \times 10^8$ yr being defined as the mean time for a diffuse-cloud particle to be transported into a molecular cloud. Thus the probability e^{-t/τ_d} that a given particle still reside after time t in the diffuse medium can be set equal to random number in a Monte Carlo code. The diffuse phase is assumed to be well mixed both in its dust components and in the gaseous refractory atoms that have been sputtered away from the initial dust, with two consequences for our models: (1) each particle has equal probability per unit time for being included within a parcel of matter added to a molecular cloud, independent of its history; (2) when each particle does join a molecular cloud it accretes a shell of refractory atoms whose thickness Δr is independent of the current size of that particle. These features introduce a random walk on the particle sizes as they shuttle back and forth between the sputtering medium and the molecular clouds. As a simplification for this study we consider only the atoms of the refractory elements in the added shell Δr, ignoring volatiles and carbonaceous material. The thickness Δr could be set by a complete model, but it is initially unknown in our approach, which treats particles one at a time in the construction of a large number of Monte Carlo histories. We redress this uncertainty by seeking that time independent interstellar medium in which the death rate of particles equals the rate of creation of new SUNOCONs and in which the rate of mass loss by sputtering in the diffuse phase is balanced by the rate of reaccretion when particles enter molecular clouds. This balance is established by numerically adjusting Δr until conservation of the total mass of condensible refractories is achieved. Particles are destroyed when they are sputtered to a size smaller than a recorded minimum ($a_{min} = 5$ A) or, within the molecular cloud, when they are incorporated into newly forming stars. We take the astration mean lifetime of dust to be $\tau_* = 3 \times 10^9$ yr. We let the *a priori* age spectrum of particles be uniform by injecting new SUNOCONs at a uniform rate into the ensemble of histories.

With these prescriptions it is possible to construct a Monte Carlo code that creates particles of random size, random core-mantle structure, and follows their evolution through their random walks through the interstellar processes described, until particle death or until the model galactic history ends. Our calculations to date normally are set up to track 6×10^5 dust particles over a 6×10^9 yr history (aiming toward the formation of the solar system at the end of that time). We here report on one such prototypical calculation and on the nature of its application to meteoritic science, which can of course be no more reasonable than the assumptions used.

One such calculation takes the newly injected particles to have a power-law initial size spectrum $n(a) = a^{-2}$ between $0.01\ \mu m < a < 0.1\ \mu m$, injecting 6×10^5 such particles over 6 Gyr. For more fingerprinting of cosmochemical memory, we endow each particle with a superrefractory core (phase A) of initial radius 0.5 a. These cores therefore constitute 1/8 of the mass of the injected particle spectrum. As motivation we think of them as being Al_2O_3 or spinel, whereas we think of the more massive phase B SUNOCON mantles as MgO and/or magnesium silicate [1,3]. If this particle still exists after 6 × 10^9 yr of stochastic evolution, its structure will now have in general three portions, as shown in Figure 1; the core of radius r_A, which may still equal a/2 if it has not yet been exposed to sputtering; a core-mantle of radius r_B containing unsputtered initial SUNOCON; a mantle of radius r (phase C), consisting of probably amorphous atoms reaccreted during repeated molecular cloud entries. The core-mantle B is entirely missing in some final particles. The percentages of the final condensed mass are also shown for each phase. In bulk it is dominated by the accretion of previously sputtered matter; but that fact obscures others of equal cosmochemical significance. That m_A was reduced from 1/8 in the injection spectrum to 2.48% after 6 Gyr shows that 20% of the super-refractory core A has survived, confirming the conclusion of a previous analytic treatment [4] and also confirming its conclusion that astration is the major destroyer of phase A material even though sputtering dominates the destruction of grain mass. Applications to isotopic anomalies are discussed in a companion paper [5].



final mass
m_A= 2.48%
m_B= 6.09%
m_C=91.43%

Figure 2 shows the grain-size distribution of the particles in the diffuse phase after 6 Gyr, along with the spectrum n(a) ∝ a^{-2} of the particles injected over that 6 Gyr and its associated spectrum of phase A cores. For 10^{-8} m < a < 10^{-7} m, the injection size range, the source n(a) is considerably more numerous than the final distribution, showing that most of the 600,000 particles have been destroyed by sputtering. Only 88,178 particles remain after 6 Gyr, with 87% of the deaths due to sputtering, primarily of the more abundant particles injected at the small-a end of the spectrum, whereas 13% of the deaths were by astration in the molecular clouds. Because the total condensed mass is conserved, it is evident that the remaining 88,178 particles necessarily have much greater mass than the average mass of the injected particles. This final mass is born by the particles having r > 10^{-7} m in Figure 2, for those particles are absent at injection and can only be built up by multiple accretion epochs with Δr = 1.7 × 10^{-8} m per molecular cloud entry. Particles up to 3 × 10^{-7} m are evident in Figure 2. For the precondensed matter in the initial solar system the conclusion to be drawn, if our calculation here were totally realistic, would be that most of the refractory mass is isotopically normal reaccreted atoms comprising the bulk of the most massive particles, but 8.57% of initial SUNOCONs and 20% of their cores do survive.

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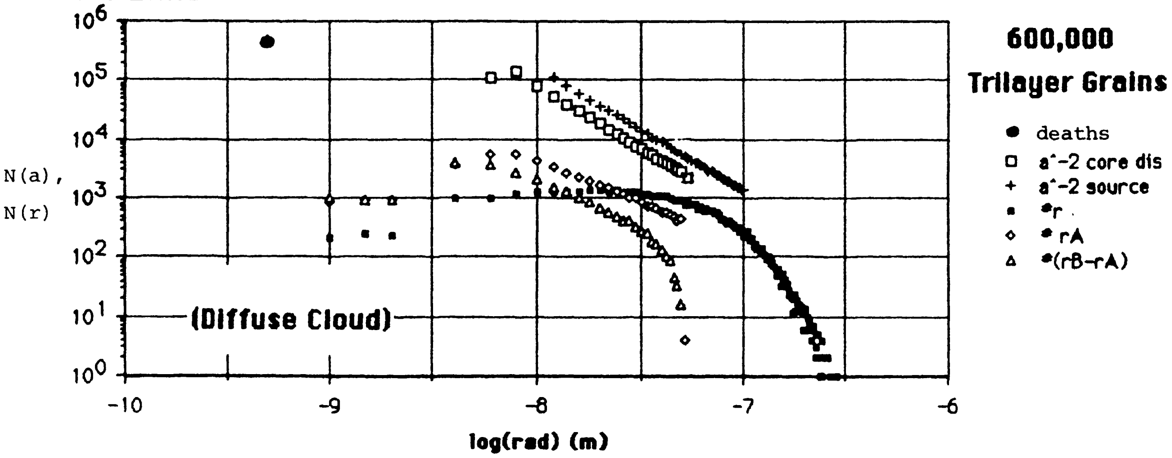

Figure 2. The total number of source particles injected over 6 Gyr and the shape distribution of the survivors is shown.The large number of deaths is by sputtering in this diffuse medium. The radii $r=r_C$,r_B and r_A are those shown in Figure 1.Note particles grown to r>0.1μm.