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DESTRUCTION MECHANISMS FOR INTERSTELLAR DUST

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ABSTRACT

Destruction rates are estimated for interstellar dust grains as a function of size and composition of the grains, and the type of region in which the grain is located. Several idealized models of the interstellar medium are considered. The destruction mechanisms examined include sputtering and grain-grain collisions in interstellar shocks, sputtering and sublimation in H II regions, photodesorption by UV, sputtering by cosmic rays, and sublimation during a supernova radiation pulse. Sublimation by the supernova radiation pulse is found to be very important for the more volatile mantle materials (binding energy $U_0 \leq 0.2$ eV per molecule). For less volatile molecular ices (e.g., H_2O with $U_0 \approx 0.5$ eV), photodesorption and sputtering in shock waves are the principal destruction mechanisms; photodesorption rates are uncertain by several orders of magnitude, however. Sputtering in high-velocity ($v_s \geq 150$ km s^{-1}) shocks and grain-grain collisions in low-velocity ($v_s \leq 50$ km s^{-1}) shocks account for most refractory grain destruction. Polymerized "HCO-material" is almost as resistant to sputtering as refractory grains. Water ice-mantles may be marginally able to survive in low-density H II regions ($n_H \lesssim 10$ cm^{-3}), especially if the gas temperature is $T \lesssim 10^{3.8}$ K. The implications of these destruction rates for the survival of interstellar grains are briefly discussed.

Subject headings: cosmic rays: general — interstellar: matter — nebulae: general

I. INTRODUCTION

In a previous paper (Draine and Salpeter 1979*a*, hereafter Paper I) we considered the physical behavior of dust grains in hot gas ($T \gtrsim 10^5$ K), especially the forces acting, the potential attained, and the sputtering rate. In the present paper we apply the results of Paper I to a study of the various dust grain destruction mechanisms which may be important in different components of the interstellar medium (ISM). Destruction rates for grains are estimated as a function of size, composition, and type of region in which located, and the relative importance of the different destruction mechanisms is assessed. A series of three papers (Barlow 1978*a*, *b*, *c*) with similar aims has been published recently; we comment on similarities and differences and hope to make clear the remaining (sometimes large) uncertainties.

In addition to the "classical" refractory grains of silicate, graphite, and iron, we also consider grains composed of various possible "mantle" constituents: (1) To represent partially polymerized material, we consider a hypothetical "HCO-material" with an assumed binding energy per atom $U_0 = 2$ eV and a density of 1 g cm^{-3}. Polymerized H_2CO (Wickramasinghe 1975), polysaccharides (Hoyle and Wickramasinghe 1977), and less specific "oily plastics" (Sagan 1972; Salpeter 1977) or "tholins" (Sagan and Khare 1979) are likely to have even larger values of U_0, with sputtering properties closer to those of silicates. (2) We also consider two extreme examples of "ices": pure H_2O (with $U_0 = 0.53$ eV, a relatively large sublimation energy for a small molecule) and pure CH_4 (with $U_0 = 0.1$ eV, near the lower limit of plausible binding energies). If polymerization does not take place, then realistic "dirty ices" (van de Hulst 1949), consisting of a frozen mixture of small molecules, will probably fall between CH_4 and H_2O in their vulnerability to destructive processes.

Grain destruction behind steady-state shock waves is studied in some detail in § II, where attention is given to the motion of the grains in the cooling postshock gas (including the "betatron acceleration" effect first recognized by Spitzer 1976) and sputtering; grain-grain collisions (whose relative importance is estimated in § IV) are discussed in detail elsewhere (Draine and Salpeter 1979*b*). Numerical results for the fractional grain mass sputtered are given for various preshock conditions, grain types and sizes, and shock speeds from 10 to 350 km s^{-1}.

For shock speeds $v_s \gtrsim 100$ km s^{-1} the shocks generated by a supernova remnant (SNR) often may *not* be approximated as steady-state shocks since the cooling time for the gas is less than the age of the SNR, and expansion effects are important. Sputtering of grains in spherically symmetric SNRs is therefore studied in § III as a function of the SN energy E_0 and the ambient density n_H.

In § IV an attempt is made to apply the results of §§ II and III, using various idealized models of the ISM. We consider, in turn, the destruction of grains in (1) collisions between randomly moving interstellar clouds; (2) supernovae in a homogeneous ("one phase") ISM; (3) supernovae in a "two phase" ISM consisting of clouds embedded in an intercloud medium (ICM); (4) supernovae in a "three phase" ISM, as proposed by McKee and Ostriker (1977); and (5) sputtering in H II regions. Several other destruction mechanisms are considered in § V, including (6) cosmic ray sputtering, (7) photodesorption by UV, and (8) sublimation of volatile mantles from grains heated in H II regions or by SN radiation. Finally, § VI summarizes our results and discusses uncertainties.

II. GRAIN DESTRUCTION IN STEADY-STATE SHOCKS

a) *Gas Dynamics and Grain Dynamics*

The present paper makes use of a series of numerical simulations of interstellar shocks, the details of which are discussed elsewhere (Draine and Salpeter 1979*b*). The range of different preshock conditions into which shocks may propagate are represented by models A–E in Table 1, listed in order of increasing "excitation". Model A corresponds to molecular cloud material (albeit at a fairly low density), models B and C to diffuse H I clouds (without and with magnetic fields), and models D and E to material which has been partially or fully preionized.

For particular preshock conditions and specified shock speed, the evolution of the postshock gas is calculated numerically, using the basic equations given by Field *et al.* (1968) for a steady, one-dimensional shock. The ionization of hydrogen and helium (including collisional and photoionization, and radiative recombination) is followed in the "on-the-spot" approximation (Osterbrock 1974). Collisional dissociation of H_2 (if present) was included. Cooling is calculated assuming a time-dependent depletion of coolants due to grains with a specified set of compositions and sizes (chosen to roughly produce the average interstellar extinction and depletion prior to arrival of the shock); as these grains are destroyed, the gas-phase abundances increase accordingly.

The critical shock speed above which a shock driven into initially neutral gas will be preceded by an ionization front (H to H^+, He to He^+) has been estimated to be $v_I = 130$ km s^{-1} by Dopita (1977*a*) and $v_I = 110$ km s^{-1} by Shull and McKee (1979). Therefore models B and C (preshock H I) are employed only for $v_s \leq 120$ km s^{-1}. For $v_s \geq 200$ km s^{-1}, the ionization precursor probably doubly ionizes most of the He, so that model E is appropriate at the highest shock speeds. Model D (preshock H II, He II) is computed at a few intermediate shock speeds.

The motion of the dust grains is calculated assuming collisional drag and plasma drag (Paper I, eq. [4]), assuming the grains to be charged by collisional processes as well as photoemission due to the "average" interstellar UV (Paper I). In those cases with a transverse component to the preshock magnetic field (all models except B) the magnetic field is assumed to be *fully* transverse for computing the effects of the Lorentz force on the grain trajectories. Furthermore, the Lorentz force is assumed to be sufficient so that the grain motion can be calculated in the "orbiting" or small-Larmor-radius approximation. In this approximation the magnetic field contributes to grain sputtering in two ways: (1) by accelerating the grains by the "betatron" effect (Spitzer 1976; Shull 1977), and (2) by increasing the time that a given grain spends in the hot postshock region (by tying each grain to a single fluid element and forcing the grains to flow *with* the gas rather than through it). The "orbiting" approximation is usually valid, except for $v_s \gtrsim 50$ km s^{-1} shocks propagating into H I (Draine and Salpeter 1979*b*), in which case the "cooling length" becomes comparable to the gyroradius. We have therefore also considered model B, in which the transverse magnetic field is assumed to be zero, to assess the importance of magnetic effects for grain destruction.

b) *Sputtering in Steady-State Shocks*

The sputtering of spherical grains has been computed for several different initial sizes and compositions, and for various shock speeds and preshock conditions. Sputtering rates (depending on grain composition, grain velocity, grain potential, gas temperature, and gas ionization state) have been calculated as described in Paper I (§ IV), using $A = 8.3 \times 10^{-4}$ except for He → C ($A = 1.8 \times 10^{-4}$) and He → Fe ($A = 2.5 \times 10^{-3}$), and using $\xi = 0.8$ for the CH_4, NH_3 and H_2O ices.

TABLE 1

PRESHOCK CONDITIONS FOR STEADY STATE SHOCK MODELS

Parameter	Model A	Model B	Model C	Model D	Model E
n_H (cm^{-3})	20	20	20	1	1
$2n(H_2)/n_H$	0.20	1.6×10^{-5}	1.6×10^{-5}	0	0
$n(H^+)/n_H$	0.001	0.001	0.001	0.99	0.99
$n(He^+)/n_{He}$	5×10^{-4}	5×10^{-4}	5×10^{-4}	0.98	0.01
$n(He^{++})/n_{He}$	1×10^{-6}	1×10^{-6}	1×10^{-6}	0.01	0.99
T (K)	100	100	100	2×10^4	2×10^4
B (gauss)	3×10^{-6}	0	3×10^{-6}	1×10^{-6}	1×10^{-6}

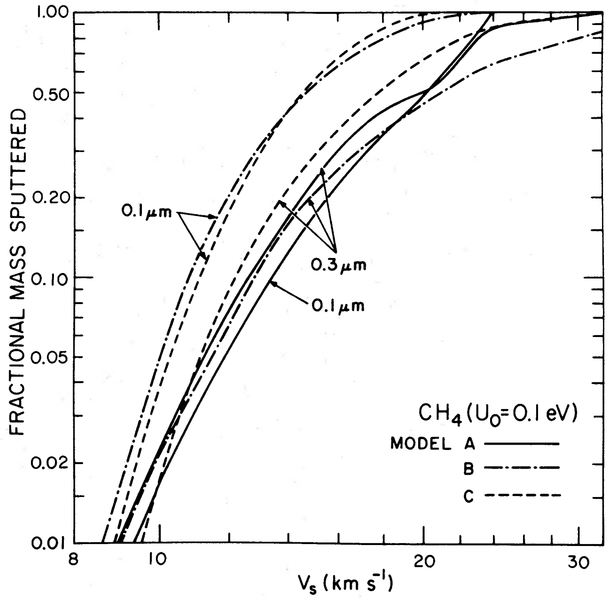

FIG. 1.—Fractional erosion of CH_4 grains (U_0 = 0.10 eV) as a function of shock speed v_s, for initial radii a_i = 0.1 μm and 0.3 μm. Models A (20% H_2 in preshock gas) and C (preshock H I) include magnetic fields, with grain dynamics computed in the small-Larmor-radius approximation, including "betatron" acceleration. Model B (preshock H I) assumes zero magnetic field.

The fractional mass sputtered, as a function of the shock speed v_s, is shown, in Figures 1–3, for "ice" grains consisting of CH_4, NH_3, and H_2O. The preshock gas is assumed to be neutral; models A, B, and C are considered for initial radii a_i = 0.1 and 0.3 μm. Our calculations include thermal sputtering, which takes place after the grain has come to rest but before the gas has cooled. For models B and C (no H_2) the gas actually cools quite slowly for $v_s \lesssim 25$ km s^{-1} and thermal sputtering dominates over the sputtering which occurs during the slowing-down of the grain for such low-velocity shocks.[1] For v_s appreciably above 25 km s^{-1}, cooling (mainly due to Lα emission)

[1] As an example, for a v_s = 16 km s^{-1} shock in model B (or C) we find that a CH_4 grain with a_i = 0.1 μm has had only 19% of its mass eroded by the time it has been slowed from a velocity (relative to the gas) of 12 km s^{-1} to 5 km s^{-1}; thermal sputtering by the hot gas continues and results in the erosion of an additional 45% (49% in model C) of the initial mass.

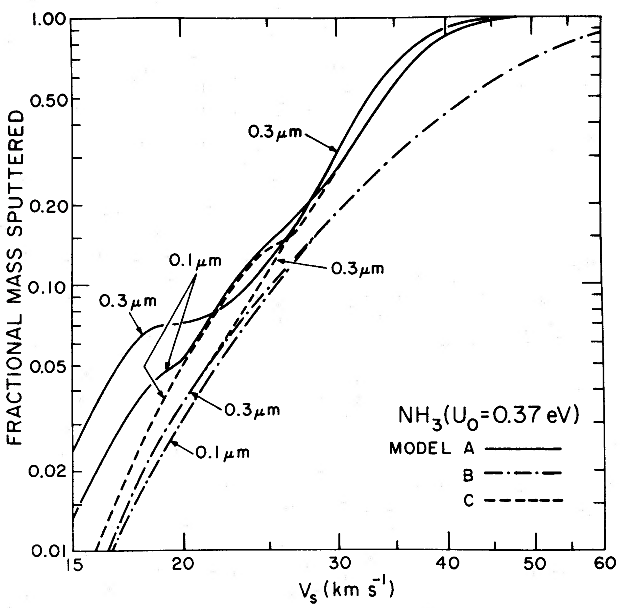

FIG. 2.—Same as Fig. 1, but for NH_3 grains (U_0 = 0.37 eV)

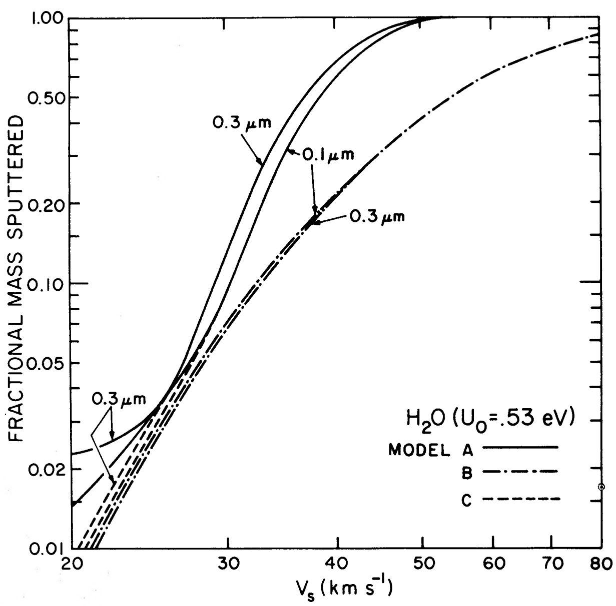

FIG. 3.—Same as Fig. 1, but for H_2O grains (U_0 = 0.53 eV)

is rapid and thermal sputtering is unimportant. For model A the initial presence of H_2 greatly enhances the cooling for $v_s \lesssim 25$ km s^{-1}, but the difference between models A and C is small for $v_s \gtrsim 25$ km s^{-1} because the H_2 is collisionally dissociated and also because the Lα cooling is rapid anyway. On the other hand, comparison of models B and C shows that magnetic effects (betatron acceleration as well as the increased time spent by the grain in hot gas) considerably enhance grain erosion for $v_s \gtrsim 25$ km s^{-1}. For very volatile grains, such as CH_4 ($U_0 =$ 0.1 eV) or CO ($U_0 = 0.087$ eV), low-velocity shocks in "diffuse clouds" (which contain little H_2) are thus sufficient for destruction (Barlow 1978*a* estimated considerably less grain erosion in low-velocity shocks, in part because the important thermal sputtering was not included, and in part because somewhat smaller sputtering yields were assumed). For NH_3 and H_2O, on the other hand, $v_s > 30$ km s^{-1} is required for appreciable erosion and magnetic effects can be important.

Figures 4–6 show the sputtering in steady-state shocks of refractory grains composed of graphite, silicate, iron, and the hypothetical "HCO-material"; results are shown for models C, D, and E. Several competing effects are present, so that the relative sputtering efficacy of the different models varies with both shock speed and grain type. Note, however, that the gross character of the curves is not highly model-dependent, but is primarily parametrized by shock speed and grain type.

Evidently iron grains are the most easily sputtered of the refractory grains, primarily because their high density makes them less susceptible to deceleration by gas drag (and therefore more susceptible to betatron acceleration). In fact, even for v_s as small as 80 km s^{-1} in model C, an iron grain with initial radius $a_i = 0.1$ μm has a final radius $a_f = 0.05$ μm, so that $\sim 90\%$ of the grain mass has been returned to the gas phase; a similar fraction of an $a_i =$ 0.01 μm iron grain is sputtered (cf. Fig. 6). Silicate grains are intermediate between grains of iron and graphite, the latter being the most resistant to sputtering of the materials considered, in part because sputtering yields are small for graphite, and in part because graphite grains are the least dense (and therefore most easily decelerated). In spite of the relatively low binding energy assumed for the "HCO-material" ($U_0 = 2$ eV), these grains are fairly resistant to sputtering (Fig. 6), partly because of their low density. Real polymers, if they exist, are probably about as resistant to sputtering in shock waves as are silicate grains.

The calculations by Shull (1978) correspond essentially to our model D, and our results are in rough agreement, except that we find much *greater* erosion of ice grains, graphite grains, and very small ($a \approx 0.01$ μm) grains. Much of the discrepancy probably arises because thermal sputtering is important but was not included by Shull. On the other hand, our sputtered fractions are comparable with or slightly *smaller* than those of Cowie (1978),

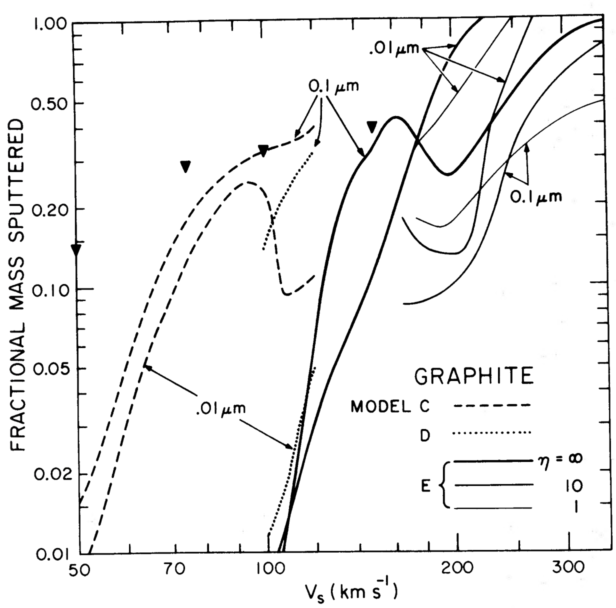

FIG. 4

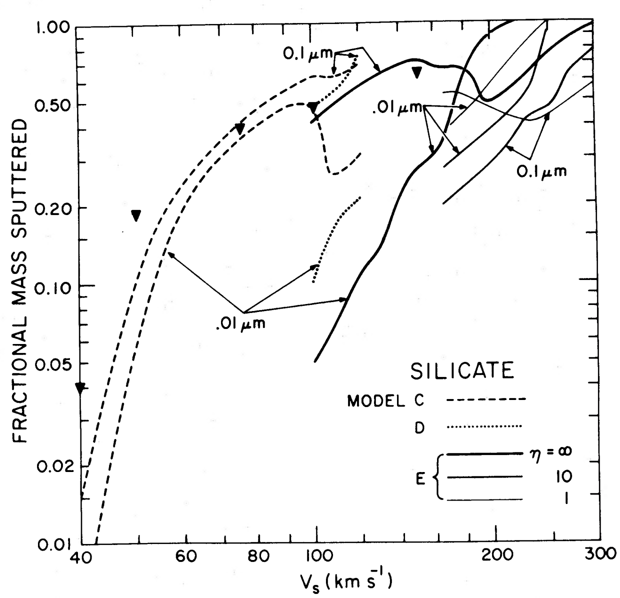

FIG. 5

FIG. 4.—Fractional erosion of graphite grains as a function of shock speed v_s, for initial radii $a_i = 0.01$ μm and 0.1 μm. All models include magnetic fields, and grain dynamics are computed in the small-Larmor-radius approximation, including "betatron" acceleration. The broken, dotted, and heavy solid curves are steady-state ($\eta = \infty$) shock calculations for Models C (preshock H I), D (preshock H II, He II), and E (preshock H II, He III). The model E calculations for $\eta = 1$ and $\eta = 10$ are for spherical blast waves (see text). The filled triangles are estimates by Cowie (1978) based on sputtering yields of Draine (1977); for He $\rightarrow$ graphite, the sputtering yields assumed in the present work are smaller by a factor 4.6.

FIG. 5.—Same as Fig. 4, but for silicate grains. The filled triangles are estimates by Cowie using the same sputtering yield as the present work.

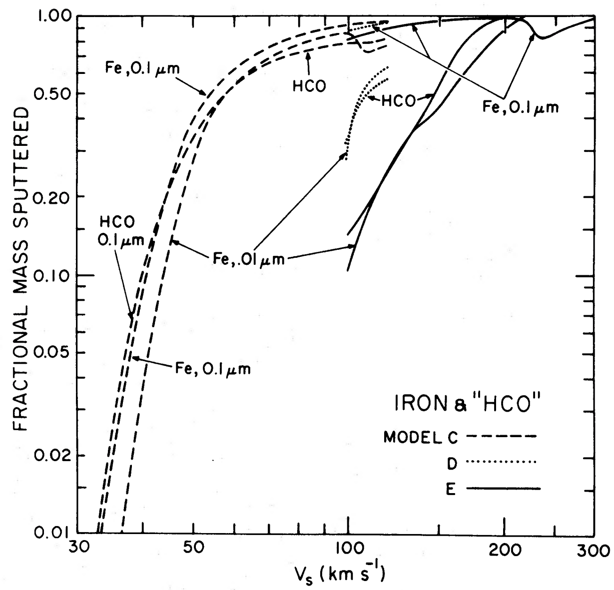

FIG. 6.—Similar to Figs. 4 and 5, except showing results for Fe grains (a_i = 0.01, 0.1 μm), and a_i = 0.1 μm grains composed of a hypothetical "HCO" material, with a density $\rho = 1\ \mathrm{g\ cm^{-3}}$, mass per atom = 7.5 amu, and binding energy per atom U_0 = 2 eV.

shown in Figures 4 and 5; in the case of graphite, much of the discrepancy is due to different assumed sputtering yields (for He, Cowie used $A = 8.3 \times 10^{-4}$, while we assumed $A = 1.8 \times 10^{-4}$ in eq. [31] of Paper I).

Barlow (1978*c*) has discussed the sputtering of chemisorbed monolayers on interstellar grains, and has given values of the threshold velocity above which an adsorbed monolayer will be completely removed from small (a = 0.01 μm) grains. As discussed in Paper I (§ IV*d*), we favor lower values for the sputtering yields for chemisorbed species, based on our general semiempirical formula for low-energy sputtering (Paper I, eqs. [31]–[33]), at least when adsorbate and substrate atomic masses are not too dissimilar. In Table 2 we give values of the critical shock velocity above which $\Delta a > 2$ Å (approximately one monolayer) of grain surface is eroded for NH_3, H_2O, Fe, silicate, and graphite grains. The silicate results, for example, would apply to any chemisorbed atom with $M = 20m_{\mathrm{H}}$ and adsorption energy E_{ads} = 5.7 eV; for this case Barlow (1978*c*, eq. [A7]) predicts sputtering of one monolayer for $v_s = 22\ \mathrm{km\ s^{-1}}$, whereas we find that $v_s = 85\ \mathrm{km\ s^{-1}}$ is required for a_i = 0.01 μm and model B preshock conditions. It is clear from Table 2 that the threshold velocity depends quite strongly on both the grain radius and the presence (model C) or absence (model B) of a magnetic field perpendicular to the shock velocity; in all cases, however, the critical shock speeds are found to be considerably larger than Barlow's estimate, except for the case of 0.1 μm Fe grains in model C (where betatron acceleration compensates for our smaller sputtering yields). All such estimates are admittedly somewhat uncertain, being based on the poorly known near-threshold sputtering yield. Unless our sputtering yields are seriously in error, however, shock speeds of $\sim 25\ \mathrm{km\ s^{-1}}$ will suffice to "clean" the grain surface only if the adsorbed atoms are very weakly bound ($E_{\mathrm{ads}} \lesssim 1$ eV).

TABLE 2

CRITICAL SHOCK SPEED (km s^{-1}) FOR SPUTTERING OF ONE MONOLAYER

		MODEL B		MODEL C		
MATERIAL	U_0 (eV)	a_i = 0.01 μm	0.1 μm	0.01 μm	0.1 μm	BARLOW*
NH_3	0.35	...	15	...	15	...
H_2O	0.53	...	20	...	19	...
Fe	4.13	65	40	41	32	28
Silicate	5.7	85	51	50	37	22
Graphite	7.35	>120	75	65	44	22

* Barlow 1978*c*, eq. (A7).

III. SUPERNOVAE IN HOMOGENEOUS MEDIA

During the early stages of the evolution of a SNR (Chevalier 1977), the age of the SNR is comparable to or less than the (radiative) cooling time for the shocked gas, and the shocked gas evolves in a manner very different from the flow through a steady-state shock. Spherically symmetric blast waves of energy E_0 in homogeneous media of ambient density n_H obey simple scaling relations (Mansfield and Salpeter 1974) and, if no magnetic field is present, can be reduced to a one-parameter family of solutions parametrized by $\eta \equiv (n_H/\text{cm}^{-3})^{2/3}(E_0/3 \times 10^{50} \text{ ergs})^{1/3}$. The relationship between shock speed v_s and radius R is shown in Figure 7 for three models calculated by W. I. Newman (private communication), assuming cosmic coolant abundances and a preionized ambient medium with $T = 1.5 \times 10^4$ K. At early times, all models conform closely to the Sedov similarity solution, but for each value of η there comes a time when radiative cooling becomes important, a cool dense shell begins to form, and the shock speed drops rapidly. The shock speed at the onset of shell formation (Appendix A) is close to

$$v_A \approx 200\eta^{1/5} \text{ km s}^{-1}; \tag{1}$$

a reasonable fit to the numerical results is to assume the Sedov solution when $v_s > v_A$, followed by a discontinuous drop in v_s from v_A to $v_b = 140$ km s^{-1}, followed by "snowplow" evolution with $v_s \propto R^{-3}$.

Sputtering of a grain (of given composition and size) is fully determined by η and the combination $n_H R^3 E_0{}^{-1}$, where R is the distance of the grain from the SN. Since, for given η, the shock speed v_s is an (almost) monotonic function of $n_H R^3 E_0{}^{-1}$, the final grain size may be regarded as being determined by η and the shock speed v_s when the blast wave overtakes the grain. Numerical calculations were carried out for the sputtering of several types of refractory grains in SNRs with $\eta = 1$, 3, and 10. The hydrodynamics were calculated numerically by W. I. Newman (private communication); the shock front was later fitted by hand to the results of the hydrodynamic code (in which "artificial viscosity" smeared the front out over several Lagrangian zones). The grain dynamics were calculated in the orbiting approximation, with each dust grain permanently coupled to the fluid element in which it was initially at rest. Prior to the formation of a dense shell, adiabatic cooling is more rapid than radiative cooling; one then has betatron *deceleration* of grains (assuming the validity of the orbiting approximation) as the postshock gas expands, rather than the betatron acceleration always encountered in one-dimensional steady-state shocks.

The results of the numerical calculations for $\eta = 1$ and 10 are shown in Figures 4 and 5 for graphite and silicate grains. At low shock speeds the sputtering of a grain overtaken by a spherical blast wave is essentially identical to that resulting from a one-dimensional steady-state shock, since the expansion time scale $\sim R/v_s$ is long compared to the radiative cooling time. At higher velocities, however, this is no longer the case, and grain destruction depends upon the value of η as well as v_s.

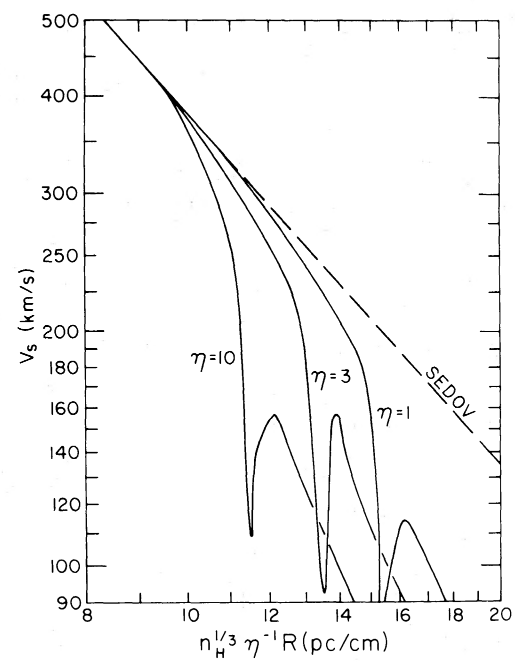

FIG. 7.—Supernova remnant expansion speed v_s as a function of the reduced radius $n_H{}^{1/3}R/\eta$, where R is the radius, n_H is the preshock proton density, and $\eta = (n_H/\text{cm}^{-3})^{2/3}(E_0/3 \times 10^{50} \text{ ergs})^{1/3}$, where E_0 is the total initial energy. The expansion speed v_s is shown for SNR models with $\eta = 1$, 3, and 10 (W. I. Newman, private communication) as well as the adiabatic Sedov solution.

The present results may be compared with the estimates of Barlow and Silk (1977*a*), who compared sputtering lifetimes, radiative cooling times, and adiabatic expansion times for SNRs (note that postshock density $n_H = 1$ cm^{-3} and $E_0 = 10^{51}$ ergs corresponds to $\eta = 0.59$). The minimum shock speed for destruction of $a_i = 0.03$ μm silicate grains, estimated using their Figure 1, is $v_{crit} = 260$ km s^{-1} for $\eta > 1$; for graphite grains, $v_{crit} = 500$ km s^{-1} and 300 km s^{-1} for $\eta = 3$ and 10, respectively (for $\eta = 1$ the SN expansion time is shorter than the sputtering time). Our results are in reasonable agreement; the differences arise from use of different sputtering rates, as well as the fact that Barlow and Silk did not follow the detailed dynamics of the grains.

IV. SPUTTERING IN THE INTERSTELLAR MEDIUM

a) Cloud-Cloud Collisions

Omitting SNRs temporarily, we adopt a picture of the ISM consisting of isolated spherical clouds moving with random velocities and occasionally colliding. Consider two identical clouds colliding with zero impact parameter and relative speed v_{cc}. In the center-of-mass frame, the two clouds meet at a stationary plane of symmetry, where compressed gas begins to accumulate. If transverse motion of the shocked gas is neglected, then, after each cloud has traveled about 0.01 pc, the first-shocked gas has reached a final density equal to, say, γ times its preshock density; normally $\gamma \gg 1$ and the shock front attains a steady velocity (relative to the unshocked gas) $v_s = \gamma(\gamma - 1)^{-1}v_{cc}/2 \approx v_{cc}/2$. If clouds collide with nonzero impact parameter, we crudely estimate the "overlap" region to be shocked with $v_s \approx v_{cc}/2$, and the nonoverlapping regions to remain unshocked; thus a given fluid element "sees" the geometric cross section of other clouds as the effective collision cross section. Consider identical clouds of radius R distributed randomly with density n_{cl}, moving isotropically with the line-of-sight velocity v_r (relative to the local standard of rest) having a distribution $P(v_r) = P(-v_r)$, with normalization

$$\int_{-\infty}^{\infty} P(v_r)dv_r = 1 \, .$$

Let $\phi(v)dv$ be the probability per time that a given cloud will participate in a cloud-cloud collision with relative speed $v_{cc} > 0$ in $[v, v + dv]$. Let $\psi(v_s)dv_s$ be the probability per time that a given cloud element will be shocked with shock speed in $[v_s, v_s + dv_s]$. Assuming $v_s = \frac{1}{2}v_{cc}$, we find (Appendix B)

$$\psi_i(v_s) = \tfrac{1}{2}\phi_i(2v_s) = \frac{12f}{R} v_s^2 \int_0^{\infty} du \frac{dP_i(u)}{du} [P_i(2v_s + u) - P_i(|2v_s - u|)] \, , \tag{2}$$

where $f = 4\pi R^3 n_{cl}/3$ is the volume filling factor.

For the "standard," low-velocity clouds with appreciable optical depth in the 21 cm line (Mast and Goldstein 1970) the distribution of radial velocities v_r can be represented by

$$P_1(v_r) = 2b^{-1} \exp(-|v_r|/b) \, , \qquad b = 5.0 \text{ km s}^{-1} \, . \tag{3}$$

For $|v_r| > 25$ km s^{-1} is dealing with intermediate- or high-velocity clouds. The velocity distribution depends somewhat on the optical depth of the cloud (cf. Fig. 45 of Dickey, Salpeter, and Terzian 1978). Following the analysis by Siluk and Silk (1974) of Ca K absorption lines (Adams 1949), a simple representation of both low- and intermediate-velocity clouds is

$$P_2(v_r) = b^2(b + |v_r|)^{-3} \, , \qquad b = 7.0 \text{ km s}^{-1} \, . \tag{4}$$

The statistics are poor for high-velocity clouds ($|v_r| > 60$ km s^{-1}, say), but we shall still use equation (4). Neglecting any velocity correlations for nearby clouds and adopting a filling factor $f = 0.05$ and cloud radius $R = 5$ pc (with $n_H = 20$ cm^{-3} in the clouds, these give $E(B - V) = 0.07$ mag per cloud, with 7.5 clouds per kpc; cf. Spitzer 1978, p. 156), we may evaluate $\psi_i(v)$ and the "cumulative shock frequency function"

$$\Psi_i(v) \equiv \int_v^{\infty} \psi_i(u)du \, ;$$

the results for Ψ_i using both P_1 and P_2 appear in Figure 8, labeled as Ψ_1 and Ψ_2.

We shall arbitrarily consider as "cloud-cloud collisions" only those collision events having $v_s \leq 60$ km s^{-1} (i.e., relative speed ≤ 120 km s^{-1}); shocks with $v_s > 60$ km s^{-1} will be regarded as due to SN blast waves. For cloud-cloud collisions we therefore define

$$\Psi_i{}^*(v) \equiv \int_v^{60 \text{ km/s}} \psi_i(u)du \, ; \tag{5}$$

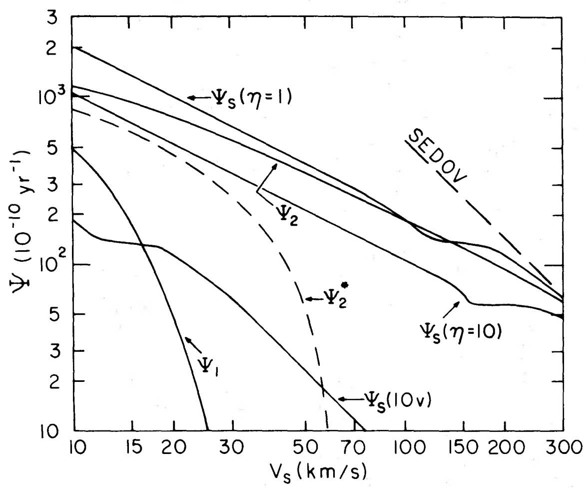

FIG. 8.—The shock frequency function $\Psi(v_s)$, the probability per unit time of being shocked with a shock speed exceeding v_s, for various shock mechanisms. Ψ_1 and Ψ_2 are due to cloud-cloud collisions, for the two cloud velocity distributions P_1 and P_2 (see eqs. [3] and [4]); Ψ_2^* is the shock frequency computed from P_2 but with $v_s > 60$ km s^{-1} shocks omitted. Ψ_s is due to supernova blast waves, for two different choices of η (see text); Ψ_s obtained from the adiabatic Sedov solution is also shown. $\Psi_s(10v_s)$ is one-third of the estimated shock frequency within clouds due to SN blast waves propagating through the intercloud medium and "crushing" the clouds, for an assumed cloud/ICM density contrast of 100.

Ψ_1^* is indistinguishable from Ψ_1, but Ψ_2^* is plotted (*dashed line*) in Figure 8. The rate for volume erosion τ_e^{-1} and the "annihilation" rate τ_a^{-1} due to cloud-cloud collisions are therefore

$$\tau_e^{-1} = \int_0^{60\ \mathrm{km/s}} [1 - (a_f/a_i)^3]\psi_i(v_s)dv_s\,, \tag{6}$$

$$\tau_a^{-1} = \int_{v_d}^{60\ \mathrm{km/s}} \psi_i(v_s)dv_s\,, \tag{7}$$

where v_d is the shock speed above which the grain is completely destroyed. The final grain radii a_f are taken to be the results of steady-state shock calculations for model C preshock conditions. The resulting destruction rates τ_e^{-1} and τ_a^{-1} are given in Tables 3–5. For CH_4 and H_2O, both Ψ_1^* and Ψ_2^* are considered. For silicate grains, Ψ_1^* gives negligible destruction rates and is omitted but, in addition to sputtering, grain destruction by grain-grain collisions is also estimated for Ψ_2^*.

TABLE 3

DESTRUCTION RATES (10^{-10} yr^{-1}) FOR CH_4 GRAINS ($U_0 = 0.10$ eV)

MECHANISM	τ_e^{-1}		τ_a^{-1}	
	$a_i = 0.1\ \mu$m	$a_i = 0.3\ \mu$m	$a_i = 0.1\ \mu$m	$a_i = 0.3\ \mu$m
a) Sputtering in cloud-cloud collisions,† Ψ_1^*	220	130	35	< 1
b) Sputtering in cloud-cloud collisions,† Ψ_2^*	650	540	450	140
c) Sputtering in one-phase SNR,§ $\eta = 1$	1900	1600	1500	1200
d) Sputtering in one-phase SNR,§ $\eta = 3$	1400	1200	1100	930
e) Sputtering in one-phase SNR,§ $\eta = 10$	1000	890	830	670
f) Sputtering in two-phase SNR, ICM	5700	4800	4500	3600
g) Sputtering in two-phase SNR, cloud-crushing	500	450	410	390
h) SN sublimation	2×10^5	2×10^5	2×10^5	2×10^5
i) Photodesorption (if $\sigma_{pd} = 10^{-20}$ cm^2)	450	150	150	50
j) Sputtering in H II regions	75	75	75	75
k) Star formation	> 8	> 8	> 8	> 8
l) Cosmic rays	< 15	< 5	< 5	< 2
Total for ICM ($f + h + i + l$)	2×10^5	2×10^5	2×10^5	2×10^5
Total for diffuse cloud ($b + g + h + i + l$)	2×10^5	2×10^5	2×10^5	2×10^5
Total for molecular cloud [$0.1 \times (h + i) + k + l$]	10^4	10^4	10^4	10^4

† $v_s < 60$ km s^{-1} shocks only.

§ $v_s > 60$ km s^{-1} shocks only.

TABLE 4

DESTRUCTION RATES (10^{-10} yr^{-1}) FOR H_2O GRAINS ($U_0 = 0.53$ eV)

Mechanism	τ_e^{-1} $a_i = 0.1$ μm	τ_e^{-1} $a_i = 0.3$ μm	τ_a^{-1} $a_i = 0.1$ μm	τ_a^{-1} $a_i = 0.3$ μm
a) Sputtering in cloud-cloud collisions,† Ψ_1^*	2	2	0	0
b) Sputtering in cloud-cloud collisions,† Ψ_2^*	160	170	0	0
c) Sputtering in one-phase SNR,§ $\eta = 1$	550	560	320	320
d) Sputtering in one-phase SNR,§ $\eta = 3$	420	430	250	250
e) Sputtering in one-phase SNR,§ $\eta = 10$	300	310	180	180
f) Sputtering in two-phase SNR, ICM	1700	1700	960	960
g) Sputtering in two-phase SNR, cloud-crushing	140	140	50	50
h) SN sublimation	0.1	0.1	0.1	0.1
i) Photodesorption (if $\sigma_{pd} = 10^{-20}$ cm²)	450	150	150	50
j) Sputtering in H II regions	30	10	20	10
k) Star formation	> 8	> 8	> 8	> 8
l) Cosmic rays	< 3	< 1	< 1	< 0.3
Total for ICM ($f + h + i + l$)	2200	1900	1100	1000
Total for diffuse cloud ($b + g + h + i + l$)	750	460	200	100
Total for molecular cloud [$0.1 \times (h + i) + k + l$]	50	20	20	15

† $v_s < 60$ km s^{-1} shocks only.
§ $v_s > 60$ km s^{-1} shocks only.

Barlow (1978*a*) obtained rates for grain destruction in cloud-cloud collisions which are appreciably smaller than our results, partly because he did not include thermal sputtering; in large part the discrepancy is only apparent, however, because Barlow included shocks with v_s between 10 and 60 km s^{-1} under the heading of SN blast waves.

Disruptive grain-grain collisions are potentially important for grain destruction (Jura 1976; Shull 1977, 1978). For $v_s = 20$ km s^{-1}, Shull (1977) estimated that ~4% of the refractory grains may be destroyed by grain-grain collisions; for $v_s = 100$ km s^{-1}, Shull (1978) again found ~4% destruction for silicate grains. For $v_s \gtrsim 50$ km s^{-1}, shocks propagating into H I, sputtering removes more than 5% of the initial mass of silicate grains (Fig. 5, model C), so grain-grain collisions are expected to be important for refractory grain destruction only in $v_s \lesssim 50$ kms^{-1} shocks. Grain-grain collisions in shocked gas will be reexamined in a future paper (Draine and Salpeter 1979*b*), but we give in Table 5 (line *b*) a preliminary estimate of the integrated rate in cloud-cloud collisions (corresponding, for the shock distribution Ψ_2^*, to an average of 1.5% destruction of $a_i = 0.1$ μm silicate grains per $v_s < 50$ km s^{-1} shock, somewhat less than earlier estimates).

TABLE 5

DESTRUCTION RATES (10^{-10} yr^{-1}) FOR SILICATE GRAINS ($U_0 = 5.7$ eV)

Mechanism	τ_e^{-1} $a_i = 0.01$ μm	τ_e^{-1} $a_i = 0.1$ μm	τ_a^{-1} $a_i = 0.01$ μm	τ_a^{-1} $a_i = 0.1$ μm
a) Cloud-cloud collisions,† sputtering	10	18	0	0
b) Cloud-cloud collisions,† grain-grain collisions	12	14	12	14
c) Sputtering in one-phase SNR,§ $\eta = 1$	120	150	84	0
d) Sputtering in one-phase SNR,§ $\eta = 3$	95	120	77	31
e) Sputtering in one-phase SNR,§ $\eta = 10$	63	99	53	39
f) Two-phase SNR, ICM sputtering	360	450	250	0.5
g) Two-phase SNR, cloud-crushing, sputtering	24	34	3	0.2
h) Two-phase SNR, cloud-crushing, grain-grain collisions	9	11	9	11
i) Three-phase SNR, cloud-crushing, sputtering	15	22	2.4	1.6
j) Three-phase SNR, cloud-crushing, grain-grain collisions	11	11	11	11
k) Three-phase SNR, cloud evaporation, sputtering	44	14	12	0
l) Star formation (molecular clouds)	> 8	> 8	> 8	> 8
m) Cosmic rays	< 0.1	< 0.01	< 0.04	< 0.004
Total for ICM ($f + m$)	360	450	250	0.5
Total for diffuse cloud ($a + b + g + h + m$)	55	77	24	25
Total for molecular cloud ($l + m$)	> 8	> 8	> 8	> 8

† Ψ_2^*, $v_s < 60$ km s^{-1} shocks only.
§ $v_s > 60$ km s^{-1} shocks only.

b) *Supernovae in a One-Phase Medium*

We have seen in § III that the sputtering of a given grain in a spherically symmetric blast wave in a uniform medium depends on the speed v_s of the blast wave as it engulfs the grain, and on a parameter η. To estimate $\Psi_s(v) \equiv \int_v^\infty \psi_s u)du$, where $\psi_s(v)dv$ is the probability per time of being shocked by a blast wave with shock speed v_s in $[v, v + dv]$, we assume that supernovae deposit energy into the ISM at a rate $(SE_0/M_{\rm gas})$, where $E_0 = 10^{51}$ ergs is the energy per SN, S is the rate for supernovae in the galactic disk, and $M_{\rm gas}$ is the gas mass in the disk. From the work of Tamman (1977) we estimate $S = 0.04\ {\rm yr}^{-1}$ as the rate within the disk. Assuming a 15 kpc radius disk of mean full-thickness H column density $N_{\rm H} = 6 \times 10^{20}\ {\rm cm}^{-2}$ (Falgarone and Lequeux 1973) gives $M_{\rm gas} = 5 \times 10^9\ M_\odot$. Adopting these values and the $v_s(R)$ relations from Figure 7, $\Psi_s(v)$ may be computed and is plotted in Figure 8 for $\eta = 1$ and $\eta = 10$.

A SN of energy $E_0 = 10^{51}$ ergs would have $\eta = 0.5$ in the ICM ($n_{\rm H} = 0.2\ {\rm cm}^{-3}$), $\eta = 11$ in a diffuse cloud ($n_{\rm H} = 20\ {\rm cm}^{-3}$), and $\eta = 150$ in a molecular cloud ($n_{\rm H} = 10^3\ {\rm cm}^{-3}$). For the cases $\eta = 1$, 3, and 10 for which models are available we have computed the volume erosion rate τ_e^{-1} and the annihilation rate τ_a^{-1}, using equations (6) and (7) but with the upper limit replaced by ∞ and the lower limit replaced by 60 km s^{-1} in equation (6) and max (60 km s^{-1}, v_d) in equation (7). The resulting destruction rates for CH_4, H_2O, and silicate grains appear in Tables 3–5; destruction rates for graphite and iron grains were found to be quite similar to the results for silicates. The coincidence between Ψ_2, estimated from the cloud velocity distribution (4), and $\Psi_s(\eta = 1)$, estimated for spherical SNRs in a homogeneous medium, is reassuring, and it is reasonably consistent to use ψ_s for $v_s > 60$ km s^{-1} and ψ_2 for $v_s < 60$ km s^{-1}. Thus the destruction rates computed using $\Psi_2{}^*$ for cloud-cloud collisions may be *added* to the destruction rates computed using Ψ_s for $v_s > 60$ km s^{-1}.

Stellar winds from OB stars may inject a substantial amount of kinetic energy into the ISM, producing around each such star a "bubble" which in many respects resembles a SNR (Weaver *et al.* 1977). The question arises whether these expanding bubbles will contribute significantly to the destruction of interstellar grains. Once radiative cooling has produced a dense shell at the outer edge of the bubble, the bubble radius is given by (Weaver *et al.* 1977)

$$R = \left(\frac{125}{154\pi}\right)^{1/5}\left(\frac{\dot{M}V_w{}^2t^3}{2\rho_0}\right)^{1/5}, \tag{8}$$

where $\dot{M}$ is the mass loss rate, V_w is the stellar wind velocity, and ρ_0 is the density of the ambient medium. Thus the mass of swept-up material is related to $v_s = dR/dt$ by

$$M_s = 1.1\ M_\odot\left(\frac{\dot{M}}{10^{-5}\ M_\odot\ {\rm yr}^{-1}}\right)^{3/2}\left(\frac{V_w}{2000\ {\rm km\ s}^{-1}}\right)^3\left(\frac{n_{\rm H}}{{\rm cm}^{-3}}\right)^{-1/2}\left(\frac{v_s}{200\ {\rm km\ s}^{-1}}\right)^{-9/2}. \tag{9}$$

We have seen in § II that $v_s \approx 200$ km s^{-1} is required for destruction of refractory grains. Even for $\dot{M} = 10^{-5}\ M_\odot$ yr^{-1} and $V_w = 2000$ km s^{-1}, which is a more powerful wind than normally observed (Snow and Morton 1976; Lamers and Morton 1976), equation (9) gives $\lesssim 1\ M_\odot$ shocked at $v_s \geq 200$ km s^{-1} (for $n_{\rm H} \geq 1$ cm^{-3}). This is small compared to the corresponding quantity for a SNR in the Sedov phase, $\sim 10^3\ M_\odot$. Since every OB star is thought to evolve to a SN, stellar winds apparently make only a minor contribution to interstellar grain destruction.

c) *SNR in a Two-Phase Medium*

Consider now the effects of a SNR in a two-phase medium consisting of "clouds" ($n_{\rm H} = 20\ {\rm cm}^{-3}$, $T = 80$ K) embedded in an "intercloud medium" (ICM; $n_{\rm H} = 0.2\ {\rm cm}^{-3}$, $T = 8000$ K), with cloud radii small compared to the SNR radius and occupying a small fraction f (say, $f = 0.05$) of the total volume (McKee and Cowie 1975). If v_s is the shock speed in the ICM as the blast wave passes the cloud, then a shock of velocity $v_{s,\rm cloud} \approx (\rho_{\rm ICM}/\rho_C)^{1/2}v_s = 0.1v_s$ will propagate into the cloud. If thermal conduction and cloud evaporation (Cowie and McKee 1977; McKee and Cowie 1977) are neglected, then the blast wave will be largely unaffected by the presence of clouds. If $n_{\rm H} = 0.2\ {\rm cm}^{-2}$ and $E_0 = 10^{51}$ ergs, then $\eta = 0.5$ and the SNR sputtering results for $\eta = 1$ may be employed without serious error. The shock frequency Ψ_s was calculated for a medium with (full thickness) column density $N_{\rm H} = 6 \times 10^{20}\ {\rm cm}^{-2}$; if the ICM has a scale height $h = 150$ pc, then $N_{\rm H}({\rm ICM}) = 2 \times 10^{20}\ {\rm cm}^{-2}$ and the ICM shock frequency is $\Psi_{\rm ICM}(v_s) = 3\Psi_s(v_s, \eta = 1)$. Thus the ICM grains will have destruction rates approximately 3 times those listed in Tables 4–6 for the one-phase model with $\eta = 1$. "Cloud" grains, on the other hand, have a shock frequency function $\Psi_{\rm cloud}(v_s) \approx \Psi_{\rm ICM}[(\rho_C/\rho_{\rm ICM})^{1/2}v_s] \approx 3\Psi_s(10v_s)$. It is evident from $\Psi_2{}^*$ and $\Psi_s(10v_s)$ in Figure 8 that shocks due to "cloud-crushing" [with frequency $\Psi_c \approx 3\Psi_s(10v_s)$] are about as frequent as those due to cloud-cloud collisions if P_2 (eq. [4]) is the correct cloud velocity distribution. Entry *g* in Tables 3–5 is the estimated destruction rate due to sputtering in "cloud-crushing" shocks alone; entry *h* in Table 5 is a preliminary estimate of the destruction rate due to grain-grain collisions in cloud-crushing shocks.

d) *SNR in a Three-Phase Medium*

We turn now to the three-phase model of the ISM proposed by McKee and Ostriker (1977, hereafter MO) in which clouds (consisting of a "cold" core and a "warm" boundary) are assumed to be immersed in a hot, low-density medium. Following MO, supernovae are assumed to be "evaporation-dominated" in their early phases. We consider the "standard" model of MO, in which the SN rate per gas mass is $S/M_{\rm gas} = 2.9 \times 10^{-12}\ {\rm yr}^{-1}\ M_\odot{}^{-1}$ (about half of the SN rate assumed in §§ IV*b* and IV*c*). We estimate only the rate of destruction of refractory grains during the early evolution of the SNR.

The proton density within the hot interior of the expanding SNR of radius R is

$$n_h = n_0(1 + x^{-5/3})\,, \qquad x = 10^{-2.53}R\ {\rm pc}^{-1}\,, \tag{10}$$

where $n_0 = 10^{-2.80}\ {\rm cm}^{-3}$ is the density of ambient hot gas before the arrival of the SNR. A shock will be driven into the cloud with shock speed $v_s \approx (n_h/n_c)^{1/2}(dR/dt)$, where n_c is the density of the cloud core and $R(t)$ is obtained from equations (5a) and (6) of MO. For $v_s < 200\ {\rm km\ s}^{-1}$ and $n_c > 20\ {\rm cm}^{-3}$, ${\rm cm}^{-3}$, the cooling time for the shocked cloud gas is short compared to the expansion "age" $R(dR/dt)^{-1}$, and it is reasonable to employ the results of steady-state shock calculations (§ II) to estimate the grain destruction occurring within the shocked cloud. According to MO, the cloud material begins to evaporate after being engulfed by the SNR, and grains initially present near the cloud surface will be injected into the hot plasma where thermal sputtering will ensue. The destruction rates $\tau_e{}^{-1}$ and $\tau_a{}^{-1}$ associated with sputtering in the initial shock are

$$\tau_e{}^{-1} = \left(\frac{S}{M_{\rm gas}}\right)\langle\rho\rangle \int_0^{R_{\rm max}} 4\pi R^2[1 - (a_f/a_i)^3]dR\,, \tag{11}$$

$$\tau_a{}^{-1} = \left(\frac{S}{M_{\rm gas}}\right)\langle\rho\rangle \int' 4\pi R^2\left|\frac{dR}{dv_s}\right|dv_s\,, \tag{12}$$

where $\langle\rho\rangle = 2.4 \times 10^{-24}\ {\rm g\ cm}^{-3}$ is the mean density of interstellar gas, and $\int'$ is taken only over shock speeds for which $a_f = 0$. For sputtering in such shocks during the evaporative phase, the destruction rates $\tau_e{}^{-1}$ and $\tau_a{}^{-1}$ both vary as $n_c{}^{-1}$. In Table 5, $\tau_e{}^{-1}$ and $\tau_a{}^{-1}$ are both given for the standard MO cloud density $n_c = 42\ {\rm cm}^{-3}$. The numerical values in line *j* of Table 5 are based on preliminary estimates of the probability of disruptive grain-grain collisions.

The effects of thermal sputtering *following* evaporation from the cloud are estimated by adopting the thermal sputtering rates from Figure 7 of Paper I, and calculating the final radius $a_f(R)$ of a grain, of initial radius a_i, which is injected into the hot phase when the SNR radius is R (since the hot phase in the SNR interior is assumed by MO to be isothermal and of uniform density n_h, a_f is a function only of a_i and R). Making use of the fact that the number of evaporated protons is

$$N_{\rm evap} = \tfrac{4}{3}\pi R^3(n_h - n_0) = \tfrac{4}{3}\pi(10^{2.53}\ {\rm pc})^3x^3n_0{}^{-5/3}\,, \tag{13}$$

the volume erosion rate $\tau_e{}^{-1}$ and annihilation rate $\tau_a{}^{-1}$ are

$$\tau_e{}^{-1} = \left(\frac{S}{M_{\rm gas}}\right)\frac{16\pi}{9}(10^{2.53}\ {\rm pc})^{5/3}1.4n_0m_{\rm H}\int_0^{R_{\rm max}}[1 - (a_f/a_i)^3]R^{1/3}dR\,, \tag{14}$$

$$\tau_a{}^{-1} = \left(\frac{S}{M_{\rm gas}}\right)\frac{16\pi}{9}(10^{2.53}\ {\rm pc})^{5/3}1.4n_0m_{\rm H}\int_0^{R_d}R^{1/3}dR\,, \tag{15}$$

where R_d is the SNR radius for which $a_f(R) = 0$. These destruction rates are evaluated and given in Tables 3–5.

e) H II *Regions*

Young massive stars generate H II regions within which volatile mantles may be either evaporated or sputtered. Osterbrock (1974) estimates the H II mass within the galactic disk to be at least $M_{\rm H\,II} = 4 \times 10^7\ M_\odot$. However, evidence has been accumulating (Mezger 1978) for additional, extended H II regions of lower density, and we adopt (in total) $M_{\rm H\,II} = 1.5 \times 10^8\ M_\odot$. If the lifetime of the "typical" H II region is $\tau_{\rm ms} = 5 \times 10^6$ yr, then the rate at which interstellar grains enter H II regions is

$$\tau_{\rm H\,II}{}^{-1} = \frac{M_{\rm H\,II}}{M_{\rm gas}}\tau_{\rm ms}{}^{-1} = 60 \times 10^{-10}\ {\rm yr}^{-1}\,. \tag{16}$$

The effect of stellar motion relative to the gas would be important for the mass-fluxing rate if R_s/v were smaller than $\tau_{\rm ms}$, where R_s is the Strömgren radius and $v \approx 20\ {\rm km\ s}^{-1}$ is the typical relative velocity between star and gas. The extended low-density H II regions (Mezger 1978) are mainly ionized by O stars, for which R_s is large and $\tau_{\rm ms}$

TABLE 6

THERMAL SPUTTERING RATES (Å cm^3 yr^{-1}) FOR VOLATILE GRAINS

		PRESENT WORK			BARLOW†
COMPOSITION	$\varphi = eU/kT$	$T = 10^{3.8}$ K	$T = 10^{4.0}$ K	$T = 10^{4.2}$ K	$T = 10^{4.0}$ K
CH_4 ($U_0 = 0.10$ eV)	0	3.6(−4)*	1.4(−3)	5.0(−3)	4.2(−5)
	−2	1.4(−3)	4.6(−3)	1.4(−2)	2.6(−4)
NH_3 ($U_0 = 0.37$ eV)	0	3.0(−6)	2.5(−5)	1.4(−4)	...
	−2	2.2(−5)	1.8(−4)	7.0(−4)	...
H_2O ($U_0 = 0.53$ eV)	0	1.3(−7)	2.3(−6)	2.1(−5)	...
	−2	1.0(−6)	1.7(−5)	1.4(−4)	...

* e.g., 3.6(−4) = 3.6×10^{-4}.

† Barlow 1978*a*.

is small; the effect of relative motion is unimportant (except for high-density H II regions ionized by B stars). For the total rate we adopt $\tau_{\rm H\,II}{}^{-1} = 75 \times 10^{-10}$ yr^{-1}.

Sputtering rates for spherical grains at rest in plasma with $T = 10^4$ K are given in Table 6 for CH_4, NH_3, and H_2O grains, either neutral ($\varphi = 0$) or collisionally charged ($\varphi = -2$). Hydrogen and helium ($n_{\rm He} = 0.1 n_{\rm H}$) are assumed to be singly ionized, and heavy elements are collectively represented by O III with n(O III) $= 10^{-3} n_{\rm H}$. Note that, especially for H_2O, the sputtering is occurring near threshold and the rates are quite sensitive to both gas temperature and grain potential. Thermal sputtering rates for refractory grains are completely negligible at $T = 10^4$ K (cf. Paper I, Fig. 7). Also given in Table 6 are sputtering rates obtained by Barlow (1978*a*, Table 5) for grains with $U_0 = 0.1$ eV. The yield function $Y(E)$ used here (Paper I, eqs. [31]–[33]) gives a significantly different sputtering rate for CH_4 in this environment.

Except in compact ($n_{\rm H} > 10^3$ cm^{-3}) H II regions, collisional charging will dominate throughout most of the volume of the H II region (Moorwood and Feuerbacher 1975; Draine 1979), so $\varphi = -2$ is assumed. For "normal" H II regions within a molecular cloud complex, one may estimate $\int n_{\rm H} dt \approx 1 \times 10^8$ cm^{-3} yr (Draine 1979), while $\int n_{\rm H} dt \approx 1 \times 10^7$ cm^{-3} yr for the low-density H II regions which comprise about 75% of the ionized mass (Mezger 1978). Applying the $\varphi = -2$, $T = 10^4$ K sputtering rates from Table 6, we estimate the decrease in grain radius to be

$$\Delta a = 0.02\ \mu{\rm m}\left(\int n_{\rm H} dt / 10^7\ {\rm cm^{-3}\ yr}\right) \qquad (17)$$

for H_2O, 10 times larger for NH_3, and 250 times larger for CH_4. These rates are uncertain by about a factor of 10, but H_2O ice is the borderline case: substances with binding energies U_0 less than half that of H_2O will be easily sputtered in even a low-density H II region, while those with binding energies more than twice that of H_2O will be unaffected by physical sputtering in H II regions. If, as found by Stasinska (1978), the gas temperature T is closer to $10^{3.8}$ K, then H_2O grains will escape significant sputtering in H II regions if $\int n_{\rm H} dt < 10^8$ cm^{-3} yr, and NH_3 becomes the borderline case.

Barlow and Silk (1977*b*) and Barlow (1978*b*) have argued that graphite grains will be "chemically sputtered" by H, N, and O atoms and ions in H I and H II regions if the grains are heated to temperatures $T \gtrsim 100$ K. However, a recent reexamination of this question (Draine 1979) concludes that chemisputtering of graphite grains is negligible except in extremely compact H II regions ($n_{\rm H} \gtrsim 10^5$ cm^{-3}), which means that relatively little gas is affected.

V. OTHER DESTRUCTION MECHANISMS

a) Radiation-Pressure–driven Drift

We estimate the anisotropic component of the interstellar radiation field to have an energy density of order

$$\delta u_{\rm rad} \approx 1 \times 10^{-13}\ {\rm ergs\ cm^{-3}}\,, \qquad (18)$$

which is the value which would result from a 10^{10} $L_\odot$ source at a distance of 10 kpc. The terminal velocity of a grain subject only to radiation pressure and collisional drag with hydrogen is $v_t = s_t(2kT/m_{\rm H})^{1/2}$, where s_t is a solution to (Paper I, eq. 4)

$$s_t\left(1 + \frac{9\pi}{64} s_t^2\right)^{1/2} \approx \langle Q_{\rm pr}\rangle \frac{3\pi^{1/2}}{16} \frac{\delta u_{\rm rad}}{n_{\rm H} kT}\,. \qquad (19)$$

A typical pressure in the ISM is $n_{\rm H} kT \approx 2000k$ cm^{-3} K $\approx 3 \times 10^{-13}$ ergs cm^{-3} $\approx 3\delta u_{\rm rad}$, so that $s_t \approx 0.1\langle Q_{\rm pr}\rangle$.

With $\langle Q_{pr} \rangle \approx 0.3$ (for $a \approx 0.03$ μm grains and $T \approx 10^4$ K blackbody radiation; Gilman 1974), radiation pressure will lead to drift speeds $v_t \approx 0.03$ km s^{-1} in H I clouds ($T \approx 10^2$ K), $v_t \approx 0.3$ km s^{-1} in the intercloud medium, and $v_t \approx 1$ km s^{-1} in "coronal" gas ($T \approx 10^6$ K and $n_{\rm H}T \approx 10^4$ cm^{-3} K; McKee and Ostriker 1977). Except perhaps in coronal gas, these drift speeds are too small to produce disruption of grains in grain-grain collisions, although grain coalescence is a possibility (Simons and Williams 1976). The lifetime against grain-grain collisions $\tau_{\rm ggc}$ is given by

$$\tau_{\rm ggc}{}^{-1} = 4n_{\rm H}\Delta v_t \sigma \,, \tag{20}$$

where $\sigma \approx 1.5 \times 10^{-21}$ cm^2 is the grain geometric cross section per H atom, and $\Delta v_t \approx v_t/2$ is the spread in terminal velocities due to the spread in $\langle Q_{pr} \rangle$ values. Thus in an H I region with $n_{\rm H} \approx 20$ cm^{-3} and $v_t \approx 0.03$ km s^{-1}, we find $\tau_{\rm ggc}{}^{-1} \approx 60 \times 10^{-10}$ yr^{-1}; if collisions result in coalescence, then clusters of grains may form in clouds before disruptive events (e.g., SN shocks) occur.

b) *Cosmic Rays*

The erosion of grains by cosmic rays was discussed in Paper I. For cosmic ray intensities expected in the ISM (hydrogen primary ionization rate $\zeta \lesssim 10^{-15}$ s^{-1}) the rate of erosion of refractory grains by cosmic rays is negligible. For H_2O grains the erosion rate, assuming the large sputtering yield reported for H_2O ice by Brown *et al.* (1978) is only of order $|da/dt| \approx 10^{-11}(\zeta/10^{-15}\ {\rm s}^{-1})$ μm yr^{-1}, again negligible. Evidently cosmic rays are unimportant since other destruction mechanisms limit the lifetimes of volatile grains to $\lesssim 10^8$ yr.

c) *Photodesorption*

i) *Theory*

Ultraviolet photons are capable of photodesorbing molecules from the surface of a grain. Outside of H II regions and dark clouds, the flux of UV photons between, say, 6 and 13.6 eV is about $F = 1.5 \times 10^7$ cm^{-2} s^{-1} sr^{-1} (Draine 1978). Let $\sigma_{\rm pd}$ be the effective cross section (per adsorbed surface molecule) for photodesorption, averaged over the appropriate energy range. The rate of desorption, per individual adsorbed molecule, is then at least

$$r_{\rm des} = \pi F \sigma_{\rm pd} \approx 2 \times 10^{-5}(\sigma_{\rm pd}/10^{-20}\ {\rm cm}^2)\ {\rm yr}^{-1}\,; \tag{21}$$

for very small grains the rate would be 4 times larger. The rate at which atoms x (with $m_x \approx 20m_{\rm H}$) impinge upon a surface site (of area $A \approx 5 \times 10^{-16}$ cm^2) is $n_x(kT/2\pi m_x)^{1/2}A = 3 \times 10^{-7}(n_x/10^{-4}n_{\rm H})(n_{\rm H}/20\ {\rm cm}^{-3})(T/100\ {\rm K})^{1/2}$ yr^{-1}; thus if $r_{\rm des} \gtrsim 10^{-6}$ yr^{-1}, then photodesorption can keep a grain surface in a diffuse cloud (or the intercloud medium) "clean" during periods when the cloud has not been subjected to a shock.

There are two distinct mechanisms which can lead to photodesorption of a physisorbed or chemisorbed molecule. The "direct" mechanism begins with absorption of a photon by the adsorbed molecule, leaving it in an excited electronic state. If the excited state has a sufficiently repulsive interaction with the substrate, and a lifetime $\gtrsim 10^{-12}$ s, then the electronically excited molecule may be ejected from the surface. If the molecule has resonance absorptions with total oscillator strength Δf within the energy range ΔE of the photon flux, then the average photodesorption cross section due to the "direct" mechanism is

$$\sigma_{\rm pd} = 1.8 \times 10^{-18}\epsilon\left(\frac{\Delta f}{0.1}\right)\left(\frac{6\ {\rm eV}}{\Delta E}\right)\ {\rm cm}^2\,, \tag{22}$$

where ϵ is the probability that photoexcitation of the molecule will be followed by desorption. Watson and Salpeter (1972) and Barlow (1978*b*) have argued for cross sections close to the upper limit given by $\epsilon = 1$ (provided adsorbate and substrate are dissimilar). In addition to the "direct" process, photodesorption may proceed "indirectly": the photon is absorbed by the *substrate*, creating a substrate excitation (e.g., a hole) which may then interact with the adsorbed molecule, possibly resulting in desorption. For indirect mechanisms equation (22) is obviously not applicable.

ii) *Experimental Evidence*

Photodesorption of molecules adsorbed on metallic (oxide-free) surfaces is extremely inefficient, if it occurs at all: Lichtman and Shapira (1978) found all published experiments to be consistent with $\sigma_{\rm pd} < 10^{-22}$ cm^2. Much larger yields are observed for insulators. Greenberg (1973) measured photodesorption of physisorbed molecules from a SiO_2 substrate at $T = 77$ K using 4.5–6.2 eV photons, and found $\sigma_{\rm pd} \approx 2 \times 10^{-20}$ cm^2 for CS_2, but $\sigma_{\rm pd} \approx 10^{-22}$ to 10^{-21} cm^2 for a number of other substances. Unfortunately, no molecules with strong absorption in this energy range were included (so the "direct" model would predict small $\sigma_{\rm pd}$ even if ϵ were large) and the SiO_2 substrate is transparent at these energies, so the "indirect" process should not be operative. However, gas-phase C_6H_6 absorbs in this range with $\Delta f \approx 0.003$, and the measured $\sigma_{\rm pd} \approx 6 \times 10^{-22}$ cm^2 gives $\epsilon \approx 0.003$ if the "direct" model applies. The efficiency ϵ is expected to be larger for smaller molecules and more energetic photons (where the electron excitation increases the molecule size by a larger percentage), but there is no experimental evidence to confirm this expectation.

Lichtman and Shapira (1978) claim that (1) all observed photodesorption of *chemisorbed* molecules from semiconductors and insulators occurs via the "indirect" process, and that (2) after the chemisorption bond is broken the molecule is left in a *physisorbed* state, from which it may be desorbed by *thermal* desorption. Experiments by Ryabchuk *et al.* (1973) and Shapira, Cox, and Lichtman (1975, 1976) indicate that, at least in the cases studied (NO/Al_2O_3, CO_2/ZnO), photodesorption is indeed thermally activated [$\sigma_{pd} \propto \exp(-\theta/T)$, with $k\theta = 0.25$ eV for CO_2/ZnO].

iii) *Conclusions*

From the limited experimental evidence we draw the following (*very* tentative) conclusions: (1) The "indirect" photodesorption mechanism, because it requires thermal desorption, will lead to negligible desorption rates at interstellar grain temperatures ($T \approx 30$ K), assuming that the intermediate physisorbed state has a binding energy $\gtrsim 0.1$ eV. (2) For the "direct" process we provisionally adopt $\epsilon \approx 0.005$ and $\sigma_{pd} \approx 10^{-20}$ cm^2, provided adsorbate and substrate are dissimilar. With $\sigma_{pd} \approx 10^{-20}$ cm^2, the interstellar flux of 6–13 eV photons should suffice to keep grain surfaces in diffuse clouds or the intercloud medium "clean" between shocks, but photodesorption is probably less important that sputtering in shocks as regards the destruction of intact grain mantles. We emphasize that the values of σ_{pd} appropriate for various plausible interstellar adsorbates and substrates remain uncertain by several orders of magnitude: laboratory experiments (with 6–14 eV photons and realistic materials at low temperatures) to resolve this uncertainty are feasible and are badly needed.

d) *Molecular Clouds, Protostars, and* H II *Regions*

Prior to star formation, a large mass of gas is processed through a dense molecular cloud phase. Scalo (1977) has discussed the possibility of shattering or coagulation of grains in dense clouds, and concluded that the largest grains ($a > 0.3$ μm?) are likely to shatter due to turbulence-driven grain-grain collisions, while the very smallest grains ($a < 0.002$ μm?) will be removed by Brownian coagulation. If ϵ_* is the fraction of the molecular cloud mass which is formed into stars, then the rate at which interstellar gas is processed through molecular clouds is

$$\tau_{mc}^{-1} = \epsilon_*^{-1}(1\ M_\odot\ \mathrm{yr}^{-1})(5 \times 10^9\ M_\odot)^{-1} = 2 \times 10^{-10}\epsilon_*^{-1}\ \mathrm{yr}^{-1}\ , \tag{23}$$

where the current rate of star formation is taken to be 1 $M_\odot$ yr^{-1}, and we assume that the molecular cloud is dispersed upon completion of star formation in it. Assuming a star formation efficiency $\epsilon_* \approx 0.01$ leads to a destruction rate $\tau_a^{-1} \approx 2 \times 10^{-8}$ yr^{-1} for very small or very large grains. Comparison with Tables 3–5 shows that this rate is marginally significant.

Since all grains are certainly destroyed when incorporated into stars, a lower bound on the destruction rate associated with star formation is just $(1\ M_\odot\ \mathrm{yr}^{-1})(5 \times 10^9\ M_\odot)^{-1} = 2 \times 10^{-10}$ yr^{-1}. It is also likely that a comparable mass of gas is processed sufficiently violently (Burke and Silk 1976; Draine 1979) in the protostellar nebula so that the resident grains are at least severaly modified (e.g., melted, shattered, or evaporated and renucleated). Thus $\tau_a^{-1} = 4 \times 10^{-10}$ yr^{-1} is a reasonable estimate for the minimum annihilation rate associated with star formation. Since $\sim 50\%$ of the gas mass is in molecular clouds, the destruction rates τ_e^{-1}, τ_a^{-1} for those grains in molecular clouds are about twice this number, whence entry *k* in Tables 3 and 4, and entry *l* in Table 5.

e) *Sublimation by OB Stars and Supernovae*

The temperature of a dust grain heated by a point source of luminosity *L* at distance *r* is (assuming only radiative cooling)

$$T = \left(\frac{LQ_*}{16\pi r^2 Q_{ir}\sigma}\right)^{1/4}\ , \tag{24}$$

where Q_* is the effective absorption efficiency for the *source* spectrum, Q_{ir} is the Planck-averaged emissivity at temperature *T*, and σ is the Stefan-Boltzmann constant. The grain temperature T_{sub} required to sublime *N* monolayers in a time τ is

$$T_{sub} = U_0[k \ln(\nu\tau/N)]^{-1}\ , \tag{25}$$

where $\nu \approx 10^{12}$ s^{-1} is a molecular vibration frequency and U_0 is the binding energy (plus activation energy, if any) of the molecule. Aannestad (1975) has calculated $Q_{abs}(\lambda)$ for silicate core-mantle grains; $Q_{abs}(\lambda) \approx 1 \times 10^3$ $(a/\mu\mathrm{m})(\lambda/\mu\mathrm{m})^{-2.6}$ approximates his results for lunar rock core/H_2O mantle grains with $a \lesssim 1$ μm, $\lambda \gtrsim 20$ μm. The Planck-averaged emissivity is then

$$Q_{ir}(T) = 8 \times 10^{-7}(a/\mu\mathrm{m})T^{2.6}\ . \tag{26}$$

Assuming $\tau = 5 \times 10^6$ yr (a typical OB stellar lifetime), equation (25) requires a grain temperature $T_{sub} \approx (U_0/56k)$ to sublime 10^2 monolayers, and sublimation occurs out to a distance

$$r_{sub} \approx 20(L/10^5\ L_\odot)^{1/2}(U_0/0.1\ \mathrm{eV})^{-3.3}\ \mathrm{pc}\ . \tag{27}$$

It is evident that mantle constituents with $U_0 \geq 0.2$ eV (e.g., NH_3, H_2O) will be sublimed in only a small fraction of the volume of the lower-density ($n_H \lesssim 10\ cm^{-3}$) H II which contributes most of the ionized mass. Having seen above (§ IV*e*) that even NH_3 grains ($U_0 = 0.37$ eV) grains may be destroyed by sputtering in an H II region with $n_H \gtrsim 10\ cm^{-3}$, we conclude that sublimation in an H II region is of secondary importance compared to sputtering, except for those grains very close to the luminous star.

Dopita (1977*b*) has suggested that ice grains may be heated by the optical emission from a SN and sublimed out to a distance $r_{sub} = 40$ pc. With a decay time $\tau = 20$ days for the light curve (Tammann 1977), grains must be heated to $T_{sub} \approx (U_0/37k)$ for sublimation of 10^2 monolayers. Assuming a peak bolometric magnitude $M_{bol} = -18$ (Tammann 1977) as typical (and ignoring extinction) we find that sublimation occurs out to a distance

$$r_{sub} = 570(U_0/0.1\ \text{eV})^{-3.3}\ \text{pc}\,. \tag{28}$$

Extinction may be corrected for by multiplying the value of r_{sub} given by equation (35) by a correction factor $\beta < 1$, where β is a solution to $(\beta\tau_0 + 2\ln\beta) = 0$, with τ_0 the optical depth out to the uncorrected value of r_{sub}. For $U_0 = 0.1$ eV, assuming an effective extinction of 3 mag kpc^{-1}, we find $\beta = 0.617$. Cooling of the grain by the sublimation itself has been neglected, because the total sublimation energy is small compared with the total energy absorbed and reradiated by the grain.

With supernovae occurring at a rate $\sim 0.04\ yr^{-1}$ in a volume $\pi(15\ kpc)^2(200\ pc)$, sublimation results in a mantle destruction rate

$$\tau_{sub}^{-1} = 6.2 \times 10^{-6}\beta^2(U_0/0.14\ \text{eV})^{-6.6}\ \text{yr}^{-1} \quad \text{for} \quad U_0 < 0.14\ \text{eV} \tag{29a}$$

$$= 7.7 \times 10^{-6}\beta^3(U_0/0.14\ \text{eV})^{-9.9}\ \text{yr}^{-1} \quad \text{for} \quad U_0 > 0.14\ \text{eV}\,, \tag{29b}$$

where equation (29b) represents the disk as infinitely thin (appropriate for $\beta r_{sub} > 150$ pc), while equation (29b) assumes that βr_{sub} is small compared to the scale height, ~ 100 pc. The destruction rate (29) is uninterestingly small for H_2O ($U_0 = 0.53$ eV) but *very* significant ($\tau_{sub}^{-1} > 10^{-7}\ yr^{-1}$) for $U_0 \leq 0.2$ eV. Evidently sublimation by supernovae is very effective in removing the more volatile of possible mantle materials, and we conclude that grain mantles outside molecular clouds are unlikely to consist of materials with $U_0 \leq 0.2$ eV.

VI. DISCUSSION

a) *Modeling the Interstellar Medium*

In this paper we have attempted to survey the variety of mechanisms which are thought to contribute to grain destruction in the Galaxy. Predicted lifetimes for both volatile grain mantles (CH_4 and H_2O) and refractory grains (silicate is representative) are given in Tables 3–5, with various destruction mechanisms and environments considered. Lifetimes are given both against erosion (τ_e, the "turnover" time for the mass in grains to be returned to the gas) and complete destruction or "annihilation" (τ_a).

Predicted destruction rates depend considerably on the model adopted for the ISM, especially for sputtering in shock waves. Three highly idealized models for SNR evolution are examined: (1) SN explosions in a homogeneous medium (three different densities are compared), (2) SN explosions in a two-phase medium ($n_H = 20\ cm^{-3}$ clouds embedded in an intercloud medium of density $n_H = 0.2\ cm^{-3}$), and (3) the evolution of an "evaporation-dominated" SNR (McKee and Ostriker 1977) with clouds embedded in "coronal gas." In addition to sputtering and grain-grain collisions in shocked gas, refractory grains are also destroyed by processes associated with star formation; volatile grains are in addition subject to destruction by thermal sublimation and photodesorption throughout the ISM, and by sputtering in H II regions. Low-velocity grain-grain collisions can lead to either shattering or coalescence of grains.

About half (by mass) of the interstellar gas in the galactic disk is in molecular clouds ($n_H > 10^3\ cm^{-3}$), about one-quarter in "standard diffuse clouds" ($n_H \approx 20\ cm^{-3}$), and about 5% in H II regions (Mezger 1978). The remaining quarter is mainly neutral and at lower densities than the "standard clouds," but most of it is probably not at densities as low as those we assume for the "classical" intercloud medium (Salpeter 1978). Besides this uncertainty in the ratio of "substandard clouds" to intercloud medium, the biggest uncertainty at the moment concerns the typical time scale t_m for matter to go into molecular clouds (since these clouds contain half the mass, the time scale for leaving molecular clouds is also $\sim t_m$): Arguments about galactic spiral shocks and about star formation both suggest $t_m \approx 10^8$ yr, although theoretical estimates of gravitational collapse would give shorter time scales.

This uncertainty in t_m is important for the inverse of the processes considered in this paper, namely the forming of new grains and the growth of existing grains: small grain cores of silicate or carbon can form in outflows from cool, late-type stars and planetary nebulae (Salpeter 1977), but the overall "throughput" per atom (of gas) is only about $10^{-10}\ yr^{-1}$. On the other hand, a heavy atom in a molecular cloud is likely to condense out on a grain on time scales of order 10^6 yr, so the overall average condensation rate per heavy atom is $\sim t_m^{-1} \gtrsim 10^{-8}\ yr^{-1}$. Another uncertainty concerns the material of "typical" grains: Only a small fraction of the condensable atoms form the "standard" refractory grains of silicate, iron, and graphite. The bulk of the condensable atoms can easily form the volatile "dirty ices" (including CO); but since the turnover rate $t_m{}^{-1}$ is large, even a small probability of polymerization per cycle (into and out of molecular clouds) could lead to an appreciable amount of moderately refractory "HCO-material" or "oily plastics" (Sagan 1972; Wickramasinghe 1975; Hoyle and Wickramasinghe 1977; Salpeter 1977; Sagan and Khare 1979).

b) *Volatile Mantles*

Photodesorption due to interstellar UV in diffuse clouds is controversial at the moment and is also likely to suffer "hysteresis": photodesorption probably prevents the formation of a new grain mantle on a bare refractory grain core in diffuse clouds (even more so in the intercloud medium), but probably does not destroy a fully formed grain mantle which has been injected into a diffuse cloud from a molecular cloud (unless the cross sections are as large as adopted by Barlow 1978*b*). The optical pulse from a supernova (§ V*e*) is very effective at subliming very volatile mantle material with binding energy per molecule $U_0 < 0.2$ eV, such as CH_4 and CO (and probably amorphous "ices" of various mixtures). This sublimation process is very sensitive to the value of U_0 and is unimportant for material with $U_0 > 0.35$ eV, such as pure crystals of NH_3 or H_2O and for most polymers. Sublimation by SN radiation probably ensures that grains outside of molecular clouds are free of mantles with $U_0 \lesssim 0.2$ eV, but (if "nonlinear" effects are important in photolysis) this radiation may also help polymerize material.

Mantles of moderate volatility ($U_0 \approx 0.35$–0.6 eV—e.g., pure H_2O with $U_0 = 0.53$ eV) are mainly destroyed by sputtering due to shocks (in cloud-cloud collisions and in SN blast waves), as seen in Table 4. Thermal sputtering in H II regions is not a very important destruction mechanism: material with $U_0 \lesssim 0.4$ eV is destroyed in an H II region, but is destroyed more often in other regions; material with $U_0 \gtrsim 0.5$ eV may even survive in an H II region if the gas temperature $T \lesssim 10^{3.8}$ K, since near-threshold sputtering yields are small and the lifetime of an H II region is only a few million years.

c) *Refractory Cores*

Although cumulative destruction rates are given here only for silicate grains (Table 5), the corresponding rates for iron or graphite (or other refractory) grains are not very different. For the two-phase model of the intercloud medium (see total rates at bottom of Table 5), we find that the bulk of refractory grain erosion and destruction is due to sputtering in SN blast waves, these being responsible for most high-velocity ($v_s > 150$ km s^{-1}) shocks (stellar winds from OB stars and their associated "bubbles" apparently make only a minor contribution to refractory grain destruction). Our estimates give a large mass turnover rate to the gas for a silicate grain in the intercloud medium, even though a small core may remain. For the models in Table 5 the erosion rate is appreciably smaller for grains in diffuse clouds, although grain-grain collisions in shocks also contribute to destruction there.

The present estimates for refractory grain destruction rates are somewhat greater than earlier estimates (Salpeter 1977), largely because the most recent estimates for SN frequency (Tammann 1977) and energy are larger. Barlow (1978*a*) pointed out that such high SN frequencies lead to rather large destruction rates, but the evidence (mainly from external galaxies) for these frequencies seems to be fairly good. The large destruction rates in the intercloud medium seem particularly embarrassing but, as mentioned above, the mass fraction in the intercloud medium may be small. The erosion rate from Table 5 for silicate grains in a diffuse cloud is smaller but still appreciable: much of the Mg, Ca, and Si are in grains but the depletion factor in the gas phase for these atoms would not be expected to be very severe, at least if the molecular cloud turnover rate is $t_m{}^{-1} \lesssim 10^{-8}$ yr^{-1}. This discrepancy with the observed very severe depletion factors might be due to a combination of various (highly conjectural) factors: (1) The turnover rate $t_m{}^{-1}$ may be larger, so that heavy atoms condense out on grains more often. (2) Metal and Si atoms may (or may not) migrate through a grain-mantle to a silicate core. (3) Grain mantles may grow large and become polymerized, so that an inner part of the mantle is usually present to "shield" the silicate core where Mg, Fe, Ca, Si, etc. are locked up. (4) The many dynamical complexities which have been omitted in our treatment (e.g., the effect of coronal tunnels on the utilization of supernova energy) may lead to significantly less grain destruction than the simple models considered here. We plan to return to such conjectures and to more realistic models of the ISM in a later paper, but hope that the basic results of the present paper will be applicable to different models.

We wish to thank J. Raymond for making available to us cooling rates due to various ions (used in the shock calculations), W. I. Newman for permitting us to use the results of his SNR models, and M. J. Barlow for helpful comments.

APPENDIX A

SHOCK SPEED AT THE ONSET OF SHELL FORMATION

If n_0 is the preshock H density, the time t_c when a fraction α of the initial energy E_0 has been radiated away is given by

$$\alpha E_0 \approx \frac{4\pi}{3} n_0{}^2 \beta \int_0^{t_c} R^3 \lambda(T_s) dt \,, \tag{A1}$$

where the cooling rate per volume is $n_H^2\lambda(T)$ and

$$\beta \equiv 3R^{-3}\int_0^R (n_H/n_0)^2 r^2 dr$$

allows for the nonuniform density. The cooling rate may be approximated by (Raymond, Cox, and Smith 1976)

$$\lambda(T) = AT^{-2/3}\,, \qquad A = 1.8\times 10^{-18}\ \mathrm{erg\ K^{2/3}\ cm^3\ s^{-1}}\,. \tag{A2}$$

The early SNR may be modeled by the Sedov similarity solution, for which $\beta = 2.29$ and $R = \xi(E_0t^2/n_0\mu)^{1/5}$, where μ is the mass per H atom and $\xi = 1.15167$ (Newman 1977). The shock temperature is $T_s = 3\mu v_s^2(16\nu k)^{-1}$, where ν is the number of free particles per H nucleus. Thus (A1) can be written

$$\alpha E_0 \approx \frac{2^{25/3}\xi^{20/3}\nu^{2/3}\pi\beta}{3^{8/3}5^{8/3}}\,\frac{E_0^{4/3}n_0^{2/3}k^{2/3}A}{\mu^2}\int_{v_c}^{\infty} v^{-6}dv\,, \tag{A3}$$

where $v = (2R/5t)$ is the shock speed. Thus v_c, the shock speed when a fraction α of the energy has been radiated away, is

$$\begin{aligned} v_c &\approx \frac{2^{5/3}\xi^{4/3}\nu^{2/15}}{3^{8/15}5^{11/15}}\left(\frac{\pi\beta}{\alpha}\right)^{1/5}\frac{k^{2/15}A^{1/5}(E_0^{1/3}n_0^{2/3})^{1/5}}{\mu^{2/5}} \\ &= 205\eta^{1/5}\ \mathrm{km\ s^{-1}}\,, \qquad \eta \equiv (n_0/cm^{-3})^{2/3}(E_0/3\times 10^{50}\ \mathrm{ergs})^{1/3}\,, \end{aligned} \tag{A4}$$

where $\alpha = \frac{1}{4}$, $\nu = 2.3$, and $\mu = 1.4m_H$ have been assumed.

APPENDIX B

CLOUD-CLOUD COLLISION KINETICS

Let $P(v_x)dv_x$ be the probability that a cloud has x-component of velocity (relative to the local standard of rest) in $(v_x, v_x + dv_x)$, and let $p(v)dv$ be the probability that the cloud speed ($v \geq 0$) is in $(v, v + dv)$. Let $\cos\theta \equiv v_x/v$. Then, for an isotropic velocity distribution, it is easily seen that

$$\begin{aligned} P(v_x)dv_x &= dv_x\int_0^{\infty} 2\pi v\sin\theta d(v\sin\theta)\frac{p(v)}{4\pi v^2} \\ &= \frac{dv_x}{2}\int_0^{\pi/2} d\theta\tan\theta p\left(\frac{v_x}{\cos\theta}\right) = \frac{dv_x}{2}\int_{v_x}^{\infty} du\frac{p(u)}{u}\,. \end{aligned} \tag{B1}$$

Thus, $p(v) = -2v[dP(v)/dv]$.

Consider now a cloud with velocity $\boldsymbol{v}_1$. If n_c is the number density of clouds and σ is the collision cross section, then the rate at which the cloud undergoes collisions with relative speed in $(u, u + du)$ is $\xi(v_1, u)du$, with

$$\xi(v_1, u) = n_c\sigma u\int_0^{2\pi}(2\pi u\sin\theta)ud\theta\frac{p(v_2)}{4\pi v_2^2}\,, \tag{B2}$$

where θ is the angle between $\boldsymbol{v}_1$ and $\boldsymbol{u} = \boldsymbol{v}_2 - \boldsymbol{v}_1$, so that

$$\xi(v_1, u) = \frac{n_c\sigma u^2}{2v_1}\int_{|u-v_1|}^{u+v_1} dv_2\frac{p(v_2)}{v_2} = \frac{n_c\sigma u^2}{v_1}[P(|u-v_1|) - P(u+v_1)]\,. \tag{B3}$$

Thus, the average collision rate for a cloud [with relative speed in $(u, u + du)$] is $\phi(u)du$, with $\phi(u)$ given by

$$\begin{aligned} \phi(u) &= n_c\sigma u^2\int_0^{\infty}\frac{dv_1}{v_1}[P(|u-v_1|) - P(u+v_1)]p(v_1) \\ &= 2n_c\sigma u^2\int_0^{\infty} dv_1\frac{dP(v_1)}{dv_1}[P(u+v_1) - P(|u-v_1|)]\,. \end{aligned} \tag{B4}$$

REFERENCES

Aannestad, P. A. 1975, *Ap. J.*, **200**, 30.
Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Barlow, M. J. 1978*a*, *M.N.R.A.S.*, **183**, 367.
———. 1978*b*, *M.N.R.A.S.*, **183**, 397.
———. 1978*c*, *M.N.R.A.S.*, **183**, 417.
Barlow, M. J., and Silk, J. 1977*a*, *Ap. J.* (*Letters*), **211**, L87.
———. 1977*b*, *Ap. J.*, **215**, 800.
Brown, W. L., Lanzerotti, L. J., Poate, J. M., and Augustyniak, W. M. 1978, *Phys. Rev. Letters*, **40**, 1027.
Burke, J. R., and Silk, J. 1976, *Ap. J.*, **210**, 341.
Chevalier, R. A. 1977, *Ann. Rev. Astr. Ap.*, **15**, 175.
Cowie, L. L. 1978, *Ap. J.*, **225**, 887.
Cowie, L. L., and McKee, C. 1977, *Ap. J.*, **211**, 135.
Dickey, J. M., Salpeter, E. E., and Terzian, Y. 1978, *Ap. J. Suppl.*, **36**, 77.
Dopita, M. A. 1977*a*, *Ap. J. Suppl.*, **33**, 437.
———. 1977*b*, *Astr. Ap.*, **56**, 303.
Draine, B. T. 1977, CRSR Report, No. 669, Cornell University.
———. 1978, *Ap. J. Suppl.*, **36**, 595.
———. 1979, *Ap. J.*, **230**, 106.
Draine, B. T., and Salpeter, E. E. 1979*a*, *Ap. J.*, **231**, 77 (Paper I).
———. 1979*b*, in preparation.
Falgarone, E., and Lequeux, J. 1973, *Astr. Ap.*, **25**, 253.
Field, G. B., Rather, J. D. G., Aannestad, P. A., and Orszag S. A. 1968, *Ap. J.*, **151**, 953.
Gilman, R. C. 1974, *Ap. J. Suppl.*, **28**, 397.
Greenberg, L. T. 1973, in *IAU Symposium 52, Interstellar Dust and Related Topics*, ed. J. M. Greenberg (Dordrecht: Reidel), p. 413.
Hoyle, F., and Wickramasinghe, N. C. 1977, *Nature*, **268**, 610.
Jura, M. 1976, *Ap. J.*, **206**, 691.
Lamers, H. J., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 715.
Lichtman, D., and Shapira, Y. 1978, *CRC Critical Reviews in Solid State and Materials Sciences*, **8**, 93.
Mansfield, V. N., and Salpeter, E. E. 1974, *Ap. J.*, **190**, 305.
Mast, J. W., and Goldstein, S. J. 1970, *Ap. J.*, **159**, 319.
McKee, C. F., and Cowie, L. L. 1975, *Ap. J.*, **195**, 712.
———. 1977, *Ap. J.*, **215**, 213.
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148 (MO).
Mezger, P. G. 1978, *Astr. Ap.*, **70**, 565.
Moorwood, A. F. M., and Feuerbacher, B. 1975, *Ap. Space Sci.*, **34**, 137.
Newman, W. I. 1977, *Ap. Space Sci.*, **47**, 99.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976, *Ap. J.*, **204**, 290.
Ryabchuk, V. K., Basov, L. L., Lisachenko, A. A., and Vilesov, F. I. 1973, *Zh. Tekh. Fiz.*, **43**, 2148 (English transl. *Soviet Phys. Tech. Phys.*, **18**, 1349).
Sagan, C. 1972, *Nature*, **238**, 77.
Sagan, C., and Khare, B. N. 1979, *Nature*, **277**, 102.
Salpeter, E. E. 1977, *Ann. Rev. Astr. Ap.*, **15**, 267.
———. 1978, in *IAU Symposium 84, The Large-Scale Characteristics of the Galaxy*, in press.
Scalo, J. M. 1977, *Astr. Ap.* **55**, 253.
Shapira, Y., Cox, S. M., and Lichtman, D. 1975, *Surface Sci.*, **50**, 503.
———. 1976, *Surface Sci.*, **54**, 43.
Shull, J. M. 1977, *Ap. J.*, **215**, 805.
———. 1978, *Ap. J.*, **226**, 858.
Shull, J. M., and McKee, C. F. 1979, *Ap. J.*, **227**, 131.
Siluk, R. S., and Silk, J. 1974, *Ap. J.*, **192**, 51.
Simons, S., and Williams, I. P. 1976, *Nature*, **262**, 273.
Snow, T. P., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 429.
Spitzer, L. 1976, *Comments Ap.*, **6**, 177.
———. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley).
Stasinska, G. 1978, *Astr. Ap. Suppl.*, **32**, 429.
Tammann, G. A. 1977, in *Supernovae*, ed. D. N. Schramm (Dordrecht: Reidel), p. 95.
van de Hulst, H. C. 1949, *Rech. Astr. Obs. Utrecht*, Vol. **11**, part 2.
Watson, W. D., and Salpeter, E. E. 1972, *Ap. J.*, **174**, 321.
Weaver, R., McCray, R., Castor, J., Shapiro, P., and Moore, R. 1977, *Ap. J.*, **218**, 377.
Wickramasinghe, N. C. 1975, *M.N.R.A.S.*, **170**, 11P.

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