Section VIII

Dust Formation and Destruction

DUST DESTRUCTION IN THE INTERSTELLAR MEDIUM

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ABSTRACT. Grains are injected into the interstellar medium (ISM) from evolved stars and supernovae; in addition, supernova ejecta may condense onto pre–existing grains before becoming well–mixed with the interstellar gas. Once in the ISM, grains can grow by accretion, but are also subject to destruction by interstellar shocks. The current status of the theory of shock destruction of interstellar grains is reviewed briefly. Small grains are destroyed by thermal sputtering in fast, non-radiative shocks; large grains are destroyed by grain–grain collisions and eroded by nonthermal sputtering in radiative shocks. The dominant shocks in the ISM are from supernova remnants (SNRs), and the mass of grains destroyed is proportional to the energy of the SNR. In a multiphase ISM, these shocks destroy the grains at a rate proportional to the volume filling factor of the phase; since the density of the hot phase is too low for efficient grain destruction, most of the destruction occurs in the warm phase. Not all SNRs are effective at destroying grains, however: some are above the gas disk, and some —Type II's in associations—are highly correlated in space and time. The galactic SN rate is observed to about 2.2 per century (van den Bergh, 1983), but the *effective supernova rate* for grain destruction is estimated to be only about 0.8 per century. As a result, the timescale for the destruction of a typical refractory grain in the ISM is inferred to be about 4×10^8 yr for either a two–phase or a three–phase ISM. Most of the refractory material in the ISM (other than carbon) is injected by supernovae, not evolved stars; the net injection timescale is estimated as about 1.5×10^9 yr. Comparison of the destruction and injection timescales indicates that the fraction of grains injected by stars which survive in the ISM is only about 20%. Most of the refractory material in interstellar grains must, therefore, have accreted onto the grains in the ISM. Nonetheless, a significant fraction of dust formed in stars survives in the ISM and may be detectable in meteorites and interplanetary dust particles.

1. INTRODUCTION

Most of the refractory elements in the interstellar medium (ISM) are tied up in dust grains, where they exert a profound effect on the energy balance and chemistry of the ISM in general, and on the process of star formation in particular. Grains must initially form in the dense environment of stellar sources, such as red giants, novae, and supernovae (Field, 1974; Salpeter, 1977), but once they enter the ISM

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they are subject to accretion, coagulation, photolysis, sputtering, and collisions with other grains. Grains contain a record of their birth and of their life in the violent ISM, a record which is difficult to interpret through remote observation but may more accessible through ground-based study of meteorites and interplanetary dust particles (Clayton, 1982; Brownlee, 1987). At present this record is obscure: we do not know to what extent grains retain a memory of their initial isotopic and chemical composition in the face of the destructive processes they face in the ISM. Refractory elements can accrete onto pre-existing grains, but the chemical structure of such accreted material is generally quite different from that produced by a stellar source. For example, refractory elements of low abundance, such as calcium and titanium, can accrete onto existing grains and form tightly bound monolayers (Barlow, 1978*c*) or compounds (Tielens and Allamandola, 1987). It is possible that carbon becomes bound into an organic polymer in the ISM (e. g., Sagan, 1972; Greenberg and Hong, 1974), and it may subsequently be processed into amorphous carbon by prolonged UV photolysis (Tielens, 1989), but it is unlikely that it forms graphite. Silicon and iron may accrete onto grains in the ISM, but at present it is not clear how they would form into silicates (but see Nuth and Moore, 1988 for a promising beginning).

There is strong observational and theoretical evidence that interstellar shock waves are the dominant destruction mechanism for interstellar grains: Observations show that clouds with line-of-sight velocities above 100 km s^{-1} typically have less than half their Si and Fe tied up in grains (Barlow and Silk, 1977; Shull, York, and Hobbs, 1977), compared to 90–99% for low velocity clouds. (Exceptions to this result have been found; for example, Gondhalekar [1985] has found large gas phase depletions for high velocity gas in Carina.) A number of theoretical studies (Spitzer, 1976; Jura, 1976; Shull, 1977; Barlow and Silk, 1977; Barlow, 1978*a*, 1978*b*; Cowie, 1978; Shull, 1978; Draine and Salpeter, 1979*a*, 1979*b*; Seab and Shull, 1983; McKee *et al.*, 1987) have shown that fast shocks should efficiently destroy grains by thermal and nonthermal sputtering in the gas behind the shock front and by grain–grain collisions. Barlow (1978*a*), Draine and Salpeter (1979*b*), and Dwek and Scalo (1980) modeled the destruction of grains in the ISM and concluded that refractory grains would be destroyed by the blast waves of supernova remnants (SNRs) in a time of only 10^8–10^9 yr. This destruction time is significantly less than the timescale over which the refractory elements are injected into the ISM ($\sim 1.5 \times 10^9$ yr: see § 5), which suggests that only a small fraction of the dust injected by stars can survive in the ISM. These authors suggested that the discrepancy with observation, which shows that most of the refractory elements are tied up in grains, could be resolved by grain growth in the ISM (see also Seab, 1987).

To be more quantitative (*cf.* Dwek and Scalo, 1980), let M be the mass of a refractory element such as Si, and let δ be the fraction of this mass contained in dust formed in stellar sources (including supernovae). Let t_{sf} be the star formation time (i. e., the timescale in which the this material is incorporated into stars), t_{in} be the injection time (the timescale in which this material is replenished by mass loss from evolved stars and by newly synthesized matter from supernovae), and t_{SNR} be the time for SNR shocks to destroy this dust. Let $\alpha\delta$ be the fraction of dust destroyed during star formation: $\alpha = 1$ corresponds to destruction of only the dust incorporated into the star, $\alpha > 1$ corresponds to a net destruction of some of the dust near the newly formed star, and $\alpha < 1$ corresponds to grain formation in the protostellar environment. Then the equations governing the rate of change of M

and $M\delta$ are:

$$\frac{dM}{dt} = -\frac{M}{t_{sf}} + \frac{M}{t_{in}}, \tag{1}$$

$$\frac{dM\delta}{dt} = -\frac{\alpha M\delta}{t_{sf}} + \frac{M\delta_{in}}{t_{in}} - \frac{M\delta}{t_{SNR}}, \tag{2}$$

where δ_{in} is the value of the dust fraction in the injected material. Together these equations imply that the dust fraction evolves as:

$$\frac{d\delta}{dt} = -(\alpha - 1)\frac{\delta}{t_{sf}} + \frac{(\delta_{in} - \delta)}{t_{in}} - \frac{\delta}{t_{SNR}}. \tag{3}$$

Note that if star formation affects only the dust in the matter which forms the star ($\alpha = 1$), then it has no effect on the dust fraction. In time, the fraction of the refractory element locked up in dust from stellar sources approaches the equilibrium value:

$$\delta_{eq} = \frac{\delta_{in}}{1 + \dfrac{t_{in}}{t_{SNR}} + (\alpha - 1)\dfrac{t_{in}}{t_{sf}}}. \tag{4}$$

This is the steady state solution of equation (3) for δ; there is no requirement that the mass M be constant, which would imply that the solutions of equations (1) and (2) were steady as well.

This simple equation is remarkable in that it ties together much of the physics of the ISM: star formation through t_{sf}, the physics of protostellar nebulae through α, stellar evolution through t_{in}, the energization of the ISM through t_{SNR}, and the nucleation of dust grains through δ_{in}. Dwek and Scalo (1980) showed that dust formation in protostellar nebulae is unimportant, particularly if δ is close to unity so that little material is available to form new dust; indeed, the high velocity flows associated with newly forming stars may destroy more dust than is created in the nebula. Hence, the equilibrium dust fraction is generally less than the injection fraction δ_{in}. Although most of the mass injected into the ISM comes from evolved stars, most of the metals (other than carbon) are injected by supernovae (see § 5 below). Supernovae are an inhospitable environment for dust grains, and the observation of large amounts of metal–enriched, hot X–ray emitting plasma in SNRs (e. g., Becker *et al.*, 1979; Hamilton, Sarazin, and Szymkowiak, 1986*a*, 1986*b*) suggests that the injection dust fraction δ_{in} is significantly less than unity. (On the other hand, after this metallic plasma cools, it may accrete onto pre–existing grain nuclei under interstellar conditions before it becomes well–mixed with the ISM.) The characteristic injection time is about 10% of the age of the Galaxy, or $t_{in} \sim 10^9$ yr, since the star formation rate has been relatively constant over the life of the Galaxy (Scalo, 1986) and the injected metals have been adequate to contaminate a stellar mass which is about 10 times the mass of the gas in the ISM.

Once a dust grain finds itself in the ISM, it is subject to destruction by SNR shocks, thereby reducing the fraction of grains which retain a memory of their stellar origin. If $\epsilon(v_s)$ is the efficiency of grain destruction by a shock of velocity v_s, and $M_s(v_s)$ is the mass of gas shocked to a velocity of at least v_s by a SNR, then the timescale t_{SNR} for grain destruction by shocks is given by:

$$\frac{M_{ISM}}{t_{SNR}} = \frac{1}{\tau'_{SN}} \int \epsilon(v_s) dM_s(v_s) \equiv \frac{\bar{\epsilon} M_s(1)}{\tau'_{SN}}, \tag{5}$$

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where M_{ISM} is the mass of interstellar gas and dust in the Galaxy, τ'_{SN}, the *effective* interval between supernovae, will be defined in § 4, and $M_s(1)$ is the mass a SNR shocks to a velocity of at least 100 km s^{-1}(corresponding to $v_{s7} \equiv v_s/[10^7 \text{ cm s}^{-1}] > 1$). The determination of the rate of grain destruction in the ISM thus falls into three parts: determining the grain destruction efficiency ϵ (§ 2), the shocked mass per SNR, $M_s(v_s)$ (§ 3), and the effective supernova frequency $\tau_{SN}'^{-1}$ (§ 4). The structure of the ISM affects the latter two quantities, particularly $M_s(v_s)$.

2. GRAIN DESTRUCTION IN SHOCKS

The processes by which grains are destroyed in shocks have been reviewed recently by Seab (1987), so the discussion here will be brief. Shocks abruptly compress and heat the gas overtaken by the shock. For a strong nonradiative shock, the density jumps by a factor 4; if the shock decelerates, this density will decline subsequently. On the other hand, if radiative losses are important behind the shock front, the gas undergoes further compression until limited by the pressure of the magnetic field.

In nonradiative shocks, thermal sputtering dominates the grain destruction. Since the rate of sputtering is proportional to the grain area, the rate of change of grain radius a is independent of the size of the grain. The rate scales linearly with the gas density, so the total amount of grain destruction depends on the density of the medium in which the shock is propagating. Seab (1987) finds that a blast wave propagating in a medium of density 0.25 cm^{-3} erodes grains by about 200 Å at $v_s = 300$ km s^{-1}, and by about 300 Å at $v_s = 500$ km s^{-1}. Thermal sputtering thus annihilates sufficiently small grains, but it leaves the cores of larger grains intact.

Radiative shocks offer a far richer range of behavior. For a steady radiative shock, the structure depends on the shock velocity and is almost independent of the density. Grains enter the shocked gas at a velocity $3/4v_s$, and, being charged, commence spiraling in the magnetic field. If the Larmor radius is smaller than the cooling length (as is generally the case for $n_0 \lesssim$ 1–10 cm^{-3} [Shull, 1978]) the grains will undergo betatron acceleration as the magnetic field is compressed in the cooling gas (Spitzer, 1976). If the upstream magnetic field is parameterized by $b \equiv (B_0/1\ \mu\text{G})n_0^{-1/2}$, so that the upstream Alfvén velocity is $1.84b$ km s^{-1}, then the maximum compression in the shock is $77v_{s7}/b$ (Hollenbach and McKee, 1979) and the maximum grain velocity behind the shock is $3.3(v_{s7}/b)^{1/2}v_s$ (McKee *et al.*, 1987). Collisional drag and plasma drag prevent the grains from attaining this maximum possible velocity; since the deceleration due to drag scales as a^{-1}, the larger grains reach higher velocities and therefore experience more destruction. Because of betatron acceleration, the grains are subject to erosion by nonthermal sputtering as they gyrate at highly supersonic velocities in the shocked gas, and they are also subject to collisions with other grains. Grain–grain collisions are particularly important because they can annihilate grains, eliminating the protection afforded to cores by protective mantles; less violent collisions can shatter grains, leaving the resulting fragments exposed to erosion by sputtering. Grain–grain collisions can also transform the structure of the grains, and have been suggested as the origin of the small diamonds observed in some meteorites (Tielens *et al.*, 1987). Calculations of grain destruction to date (Seab and Shull, 1983; McKee *et al.*, 1987) have ignored shattering and partial vaporization, but more refined calculations are currently underway (Tielens *et al.*, 1989). The grain destruction efficiency ϵ includes both erosion and annihilation (Draine and Salpeter, 1979*b*), and a proper understanding of their relative importance awaits the outcome of these calculations. We anticipate that shattering will be relatively efficient, however, making it difficult to preserve refractory cores inside protective mantles.

Most of the grain destruction in the ISM occurs in the warm intercloud medium, with a density ~ 0.25 cm^{-3}(Draine and Salpeter, 1979*b*). Shocks in this gas are cushioned by the interstellar magnetic field, substantially reducing the amount of grain destruction. For $B_0 = 3\mu$G, which corresponds to $b = 6$ at this density, the silicate destruction fraction is $\epsilon \simeq 0.10$—0.16 at $v_s = 100$ km s^{-1}(McKee *et al.*, 1987), where the range of values corresponds to different models for the blast wave. By contrast, Seab and Shull (1983), who considered a cloud density of 10 cm^{-3} and a magnetic field of 1 μG, corresponding to $b = 0.3$, found $\epsilon \simeq 0.5$ at this shock velocity. Despite this cushioning, however, interstellar shocks remain effective at destroying grains.

3. THE GRAIN DESTRUCTION PER SNR

3.1. HOMOGENEOUS ISM

The explosion of a supernova releases an energy $E \sim 10^{51}$ erg into the surrounding medium. Once the ejecta from the supernova have swept up a significant amount of interstellar matter, the remnant enters the Sedov–Taylor stage; energy is conserved in this stage so that $M_s v_s^2 \propto E$ is constant. Eventually, radiative losses become important, and the SNR is said to enter the radiative stage; for a blast wave with energy $E = 10^{51} E_{51}$ erg propagating in a medium of density n_0, the transition to a radiative shock occurs when v_s drops to $200(n_0^2 E_{51})^{1/14}$ km s^{-1}(McKee *et al.*, 1987). Finally, when the expansion velocity drops to the effective sound speed of the surrounding medium, the remnant merges with the ISM.

To determine the mass shocked to a velocity of at least v_s in the Sedov–Taylor stage, we exploit the constancy of $M_s v_s^2$ and write:

$$M_s(v_s) = \frac{E}{\sigma v_s^2} = 6800 \frac{E_{51}}{v_{s7}^2} \ M_\odot, \tag{6}$$

where the constant $\sigma = 0.736$ (Ostriker and McKee, 1988). To evaluate the grain destruction parameter $\bar{\epsilon}$, we adopt the Case D (Sedov–Taylor), $B_0 = 3$ μG results of McKee *et al.* (1987), namely $\epsilon(0.5) = 0.016$, $\epsilon(1) = 0.1$, and $\epsilon(1.5) = 0.14$; we assume $\epsilon(v_s) = 0.5$ for $v_{s7} > 2$. Equations (5) and (6) then give $\bar{\epsilon} \simeq 0.4$. This estimate should be regarded as illustrative, since the grain collision model used by McKee *et al.* was known to be oversimplified. With this value for $\bar{\epsilon}$, a SNR in a homogeneous medium would destroy an amount of dust equivalent to that in $2700 E_{51}$ $M_\odot$ of interstellar gas, were the SNR to expand as a nonradiative blast wave.

In fact, SNRs in homogeneous media do become radiative unless the ambient density is extremely low. Once the remnant enters the radiative stage, it slows down, so that $M_s(v_s)$ is smaller. Cioffi *et al.* (1988) have studied SNR evolution in

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this case, and their results imply:

$$M_s(v_s) = 2460 \frac{E_{51}^{0.95}}{n_0^{0.1} v_{s7}^{9/7}} \ M_\odot. \tag{7}$$

The grain destruction parameter $\bar{\epsilon}$ is again about 0.4. Thus we expect SNRs in homogeneous media to destroy an amount of dust equivalent to that in about $1000E_{51}$ $M_\odot$ of interstellar gas (neglecting the factor $[E_{51}n_0^2]^{0.05} \sim 1$) . The results for both the adiabatic and radiative stages give grain destruction rates in reasonable agreement with those of Draine and Salpeter (1979*b*).

3.2. MULTIPHASE ISM

The ISM is observed to be highly inhomogeneous, with cold clouds, both atomic and molecular, occupying a small fraction of the volume and the warm medium ($T \sim 10^4$ K) and hot gas ($T \sim 5 \times 10^5$ K) filling the rest. In the three–phase model of the ISM (McKee and Ostriker, 1977), the hot gas has the largest volume filling factor ($f_h \sim 0.7$), and the warm medium is treated as consisting of low density clouds; we shall follow that convention here. The blast wave propagates primarily in the hot gas, so that equation (6) becomes:

$$M_{sh}(v_{sh}) \equiv f_h \rho_h \left(\frac{4}{3\pi R^3}\right) = \frac{E}{\sigma v_{sh}^2}, \tag{8}$$

where ρ_h is the mass density of the hot gas, v_{sh} is the velocity of the shock in the hot gas, etc., and R is the radius of the blast wave. The shocked cloud is at about the same pressure as the shocked hot gas (McKee and Cowie, 1975), so that $\rho_c v_{sc}^2 \simeq \rho_h v_{sh}^2$, where ρ_c is the initial density of the cloud and v_{sc} is the velocity of the cloud shock. Although the cloud shocks are often radiative, the blast wave in the hot gas is not. Hence, with the aid of equation (6), we find that the mass of the shocked cloud material is:

$$M_{sc} \equiv f_c \rho_c \left(\frac{4}{3\pi R^3}\right) \simeq 6800 \left(\frac{f_c}{f_h}\right) \frac{E_{51}}{v_{sc7}^2} \ M_\odot. \tag{9}$$

The important conclusion which follows from this result is that the mass of a phase j shocked to a given velocity is proportional to its filling factor f_j; since the cold clouds have a small filling factor, they make only a small contribution to $M_s(v_s)$. Equation (9) is based on the assumption that the clouds are small so that they are shocked quickly. In reality, some cold clouds are sufficiently large that the shock decelerates as it traverses the cloud, thereby reducing the mass shocked to a given velocity. The cloud shock will be radiative (in the sense that the cooling is sufficiently rapid that the shocked gas will be compressed despite the deceleration of the shock) provided $v_{sc} > 220(n_0^3 n_c E_{51}^2)^{1/28}$ km s^{-1} (*cf.* McKee *et al.*, 1987).

The total rate at which grains are destroyed in the ISM is the sum of the rates at which they are destroyed in the individual phases:

$$\frac{M_{ISM}}{t_{SNR}} = \Sigma_j \frac{M_{ISM,j}}{t_{SNR,j}} = \frac{1}{\tau'_{SN}} \Sigma_j \bar{\epsilon}_j M_{sj}(1), \tag{10}$$

where we have assumed that the dust fraction δ is essentially the same for all the phases (see § 3.3 below). In a *two-phase* ISM, most of the grain destruction occurs in the intercloud medium. Since its filling factor is nearly unity, the mass of grains destroyed is the same as in a homogeneous medium, which we have seen is equivalent to that in about $1000E_{51}\ M_{\odot}$ of gas. If the cold clouds have a filling factor $f_{cold} \sim 0.02$, then equation (9), together with the estimate $\bar{\epsilon} \simeq 0.4$ made above, imply that only about $50E_{51}M_{\odot}$ of cloud gas has its complement of dust destroyed; indeed, since the shocks may decelerate substantially while crossing the clouds, this is an upper limit. The *three phase* ISM model has $f_h \simeq 0.7$ and two types of clouds, the warm medium with $f_{warm} \simeq 0.3$ and the cold clouds with $f_{cold} \simeq 0.02$. In this case, equation (9) implies that a SNR destroys all the dust in $1160E_{51}\ M_{\odot}$ of warm medium, and in at most $80E_{51}\ M_{\odot}$ of cloud gas. The hot gas has the largest filling factor, but its density is too low for any significant grain destruction to occur in the lifetime of the remnant ($\bar{\epsilon}_h \ll 0.4$); I estimate that only about $70E_{51}\ M_{\odot}$ of hot gas is cleansed of dust. Altogether, a SNR in a three phase ISM destroys the refractory grains in about $1300E_{51}\ M_{\odot}$ of ISM, which is about the same as in a two-phase ISM. In either case, the prediction that grain destruction in the warm medium is much greater than in the clouds is compatible with the observation that the gas phase depletions are significantly greater in the clouds than in the warm medium, corresponding to the dust fractions being somewhat lower in the warm medium than in the clouds (Jenkins, Savage, and Spitzer, 1986).

3.3. MIXING AMONG THE PHASES

Since the destruction of the dust is dominated by shocks in the intercloud medium, one might imagine that grains could be preserved in clouds. From equation (10), one infers that the timescale for dust destruction in the warm medium is about:

$$t_{SNR,warm} \simeq \frac{M_{ISM,warm}}{M_{ISM}} t_{SNR} \sim 0.1 t_{SNR}, \tag{11}$$

whereas in the cold clouds it is:

$$t_{SNR,cold} \simeq \frac{f_{warm}}{f_{cold}} t_{SNR} \sim 10 t_{SNR}. \tag{12}$$

Thus, if the warm medium comprises about 10% of the mass of the ISM, the grain destruction time in clouds is about 100 times that in the warm medium. Despite this, mixing among the phases is too rapid to allow significant variations in the injected dust fraction between the phases.

Consider a two phase ISM, and let $t_{i \to j}$ be the timescale for gas in phase i to be converted into phase j. The equation for the rate of change of the dust fraction in phase i may be derived in the same fashion as equation (3):

$$\frac{d\delta_i}{dt} = \frac{(\delta_{in} - \delta_i)}{t_{in}} - \frac{\delta_i}{t_{SNR,i}} + \frac{(\delta_j - \delta_i) M_{ISM,j}}{t_{j \to i} M_{ISM,i}}, \tag{13}$$

where we have set $\alpha = 1$ (so that the effects of star formation drop out), and where we have taken δ_{in} and t_{in} to be the same for both phases. The effect of the mixing between the phases is contained in the last term. In equilibrium the mixing rates between the phases are equal, so that $M_{ISM,j}/t_{j\to i} = M_{ISM,i}/t_{i\to j}$. Solving equation (13) together with the analogous equation for δ_j gives:

$$\frac{(\delta_{j,eq} - \delta_{i,eq})}{\delta_{j,eq}} = \frac{\dfrac{1}{t_{SNR,i}} - \dfrac{1}{t_{SNR,j}}}{\dfrac{1}{t_{i\to j}} + \dfrac{1}{t_{j\to i}} + \dfrac{1}{t_{in}} + \dfrac{1}{t_{SNR,i}}} \tag{14}$$

for the relative difference in the dust fractions in the two phases in equilibrium. To apply this result to the ISM, let phase i be the warm phase and j be the cold phase. Larson (1987) estimates that molecular clouds are photoionized by massive stars in a time of order $1\text{–}2\times10^7$ yr; we shall adopt $10^{7.5}$ yr as a more conservative estimate. Diffuse clouds are converted to warm medium by photoionization in a similar timescale. If 10% of the ISM is in the warm phase, then in a steady state the time for the warm gas to be transformed into cold clouds is only $t_{warm\to cold} \sim 10^{6.5}$ yr, which is short compared to other timescales in the problem. Since the dust destruction timescale in the warm medium is small compared to that in clouds, equation (14) reduces to:

$$\frac{(\delta_{cold,eq} - \delta_{warm,eq})}{\delta_{cold,eq}} \simeq \frac{t_{warm\to cold}}{t_{SNR,warm}} \simeq \frac{t_{cold\to warm}}{t_{SNR}} \sim 0.07, \tag{15}$$

where the numerical estimate is based on the result for t_{SNR} obtained below, $\sim 4\times10^8$ yr. In other words, the difference in dust fractions between the phases is simply the ratio of the time for the dust to escape from the warm phase to the time for shocks to destroy it there. Mixing thus maintains close equality in the mean injected dust fractions in the different phases.

Accretion onto grains can cause the observed difference in dust fractions to differ from that in equation (15); since accretion is more important in the clouds than in the lower density warm medium, accretion will tend to make the observed difference larger than that estimated above. Observations of the depletion of iron have been interpreted as indicating a gas phase abundance that is 1% of the cosmic abundance in clouds and 4% of cosmic in the warm medium (Jenkins *et al.*, 1986). This gives an observed difference in dust fractions of $(\delta_{cold} - \delta_{warm})/\delta_{cold} \simeq 0.03$, which is within a factor 2 of the estimate in equation (15); this is satisfactory given the uncertainties in the timescales. As this example shows, the near equality of the dust fractions in the different phases implied by equation (15) does not imply that the gas phase abundances are about the same. For the other elements studied by Jenkins *et al.* (Mn, Mg, Cl, and P) the differences in dust fractions between the phases are significantly larger than for iron, indicating that these elements are more readily returned to the gas phase by shock destruction than is iron.

3.4. THE ENERGY OF SUPERNOVA REMNANTS

We have seen that the amount of dust destroyed by a SNR is proportional to its energy E, whether the remnant is adiabatic or radiative, in a homogeneous medium or in a cloudy medium. Unfortunately, there is considerable dispersion in the estimates of this energy. Measurements of the SNR energy come from detailed studies of individual remnants and from surveys of extragalactic remnants, where the known distances reduce the uncertainties. The most careful modeling of the Type I remnants SN 1006 and Tycho, to date, gives $E_{51} = 1.0$ and 0.7, respectively (Hamilton *et al.*, 1986*a*, 1986*b*), although Hamilton (private communication) has emphasized that these values are quite uncertain. For the Cygnus Loop, which is believed to be a Type II remnant, McKee and Cowie (1975) estimated an energy $E_{51} = 0.75$ from the optical emission, whereas Ku *et al.* (1984) found $E_{51} = 0.3$ from an analysis of the X-ray emission. Braun and Strom (1986) have estimated the energy from IRAS data and found $E_{51} = 0.75$. All three estimates assume that the remnant can be described as a Sedov–Taylor blast wave, whereas in fact it appears that the supernova exploded in a cavity evacuated by the progenitor star (e. g., Charles *et al.*, 1985); hence these estimates may be inaccurate. (Indeed, Braun and Strom presented a second estimate allowing for this cavity, but erred in assuming that the ratio of kinetic to total energy would be the same for the cavity case as for the Sedov–Taylor case.)

Estimates of SNR energetics based on optical emission from extragalactic SNRs reveal a remarkable trend (Dopita, 1979; Blair, Kirshner, and Chevalier, 1981): the energy appears to increase with SNR radius, going from less than 10^{50} erg for small remnants (radius $\lesssim 5$ pc) to about 10^{51} erg for large remnants (radius $\gtrsim 20$ pc). The most natural interpretation of this trend is that much of the energy of the smaller, and therefore younger, remnants is stored in kinetic energy of the ejecta. The fact that Hamilton *et al.* (1986*a*, 1986*b*) found that proper inclusion of the ejecta increased the inferred SNR energy by about an order of magnitude for both SN 1006 and Tycho is consistent with this interpretation. Nonetheless, until a quantitative understanding of this energy vs radius relation is developed, some uncertainty will hang over the energetics of SNRs.

4. THE EFFECTIVE SUPERNOVA RATE

Conflicting estimates of the galactic supernova rate have bedeviled efforts to quantitatively determine the rate at which the resulting SNRs heat the ISM and destroy interstellar grains. Several lines of evidence suggest that van den Bergh's (1983) estimate $\tau_{SN}^{-1} = 0.022 \pm 0.013$ yr^{-1} is a good one: It is consistent with the most recent determination of the pulsar birthrate of 0.013 yr^{-1} (Narayan, 1987, rescaled to a galactocentric radius of 8.5 kpc), if about half the supernovae (i. e., most of the Type IIs) produce pulsars. Similarly, a reanalysis of Güsten and Mezger's (1982) determination of the birthrate of massive stars based on thermal radio emission from HII regions gives 0.013 Type II progenitors per year (McKee, 1989). Tammann's (1982) higher estimate of the galactic supernova rate, 0.05 SN yr^{-1}, has been called into question because his analysis gives a substantially higher extragalactic supernova rate than observed (van den Bergh, McClure, and Evans, 1987). On the other hand, the rate cannot be too much less than 0.022 yr^{-1} because the six known galactic supernovae in the last thousand years are all relatively close to the Sun.

Not all galactic SNRs interact with the ISM, however, so the *effective* supernova rate $(\tau'_{SN})^{-1}$ for grain destruction is less than the observed rate. Supernovae from low mass progenitors (Type I, or perhaps only Type Ia) are associated with an old stellar population, and hence should have a larger scale height than the interstellar gas. Indeed, the three galactic Type I SNRs in the last 1000 years (SN 1006, Tycho,

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and Kepler) are all well away from the galactic plane. Heiles (1987) concludes that only about 38% of the Type I supernovae can interact effectively with the gas disk, so that $(\tau'_{SN})^{-1} \simeq 0.38\tau_{SNI}^{-1}$.

For the Type II's the situation is more complicated because some of their progenitors are in associations. The stars in an association homogenize the surrounding gas through their intense ionizing radiation, so from the discussion below equation (7) we infer that the first supernova destroys the dust in $1000E_{51}$ $M_\odot$ of gas. This SNR forms a dense radiative shell at a radius of $20E_{51}^{2/7}/n_0^{3/7}$ pc, and this shell is driven out to a radius of order 70 pc before it merges with the ambient medium (Cioffi *et al.*, 1988). Subsequent supernovae repeatedly hammer the gas inside the shell, destroying all its dust; this accounts for perhaps another $500E_{51}$ $M_\odot$ of gas, for a total of $1500E_{51}$ $M_\odot$. The expansion of the supershell created by the association is too slow to add to the dust destruction (*cf.* McCray and Kafatos, 1987). This estimate suggests that an entire association destroys only slightly more dust than an isolated SNR. Heiles (1987) has estimated that there are about 40 Type II supernovae per association. Even if we allow for a factor 3 uncertainty in the estimate of the dust destruction per association, we find that each SNR in an association destroys at most 10% as much dust as an isolated SNR.

Next, consider the isolated Type II SNRs, which arise from field stars and runaway stars. With Scalo's (1986) Initial Mass Function, the median mass of a Type II progenitor is about 13 $M_\odot$, under the assumption that stars above 8 $M_\odot$ explode as supernovae. The HII region around such a star is small, about 15 pc after it expands into pressure equilibrium with the ambient medium. Similarly, the size of the stellar wind bubble around the star is governed by the evolution of the HII region and remains less than the radius of the HII region (McKee, Van Buren, and Lazareff, 1984). The configuration of the ISM around such a star is thus not unlike that inferred for the Cygnus Loop, whose progenitor must have been about 15 $M_\odot$ (Charles *et al.*, 1985). When the star explodes as a supernova, the cavity is sufficiently small that it does not significantly alter the amount of dust destroyed. Thus, provided the SNR occurs in the gas disk of the Galaxy, it should destroy the dust in about $1300E_{51}$ $M_\odot$ of gas.

In a survey of over 5000 massive stars, Humphreys and McElroy (1984) found that they are nearly evenly divided between those in associations and those in the field. In a smaller survey which focused on O stars, Gies (1987) found a smaller proportion of stars in the field (including runaways), $\sim$ 30%; we shall adopt 50% based on the larger Humphreys and McElroy survey, however. Of the field O stars in Gies's survey, 58% are within 185 pc of the galactic plane, the value of the scaleheight of the warm medium adopted by Heiles (1987). Hence, the total effective Type II SNR rate is:

$$(\tau'_{SN})^{-1} = (0.5 \times 0.1 + 0.5 \times 0.58)\tau_{SNII}^{-1} = 0.34\tau_{SNII}^{-1}, \qquad (16)$$

where the two terms account for SNRs in associations and in the field, respectively. Exploiting the fact that the effective rate for Type II SNRs is reduced by about the same factor as that for the Type I's, we find that the effective rate for all SNRs is

$$(\tau'_{SN})^{-1} = 0.38\tau_{SNI}^{-1} + 0.34\tau_{SNII}^{-1} \simeq 0.36\tau_{SN}^{-1} \simeq 8 \times 10^{-3} \quad \text{yr}, \qquad (17)$$

or one per 125 yr.

It is interesting to note that this effective SNR rate is comparable to that inferred from radio SNRs a number of years ago by Clark and Caswell (1976), one per 150 yr. This coincidence is not entirely fortuitous: SNRs which are effective at destroying dust interact sufficiently strongly with the ISM that they produce luminous radio remnants.

5. CONCLUSIONS

Although there has been substantial progress in our understanding of the ISM and of grain destruction in shocks since the work of Barlow (1978*a*), Draine and Salpeter (1979*b*), and Dwek and Scalo (1980) almost a decade ago, the basic conclusion reached by these authors remains unchanged: Refractory grains are efficiently destroyed by shocks associated with supernova remnants. Adopting $M_{ISM} = 4.5 \times 10^9\, M_\odot$ (Scoville and Sanders, 1987) and a three–phase model for the ISM, we find that the time for SNR shocks to destroy a typical refractory grain is:

$$t_{SNR} = \frac{M_{ISM}\tau'_{SN}}{\bar{\epsilon} M_s(1)} = \frac{4.5 \times 10^9\, M_\odot \times 125\text{yr}}{1300 E_{51}\, M_\odot} = \frac{4.3 \times 10^8}{E_{51}} \quad \text{yr.} \tag{18}$$

The result for a two–phase ISM is very nearly the same (§ 3.2). This estimate should be accurate to within a factor 2. As discussed in § 3.4, the SNR energy E_{51} is believed to be of order unity, although some uncertainty remains. Equation (18) is comparable to Barlow's (1978*a*) estimate, if his smaller SNR energy is used, and comparable to Draine and Salpeter's (1979*b*), if their higher SNR rate is used.

The clear implication of this small value for t_{SNR} is that most of the dust formed in stars does not survive in the ISM. Equation (4) shows that, neglecting the effects of star formation ($\alpha = 1$), the fraction of the injected dust which survives in the ISM is $(1 + t_{in}/t_{SNR})^{-1}$. In § 1 we estimated that the injection time in the ISM is of order 10^9 yr since nucleosynthesis is adequate to supply the ISM, which is about 10% of the mass of the Galaxy, with its complement of metals in 10% of the life of the Galaxy. A more refined estimate for t_{in} can be made by considering the sources for a refractory element such as silicon. Red giants inject about 0.3–1 $M_\odot$ of gas into the ISM each year, corresponding to about $10^{-3.5}$—10^{-3} $M_\odot$ of silicon. With Scalo's (1986) IMF ($\propto m_*^{-1.5}$) and a mass range for Type II SN progenitors of 8–100 $M_\odot$, the average Type II SN injects a mass of 16 $M_\odot$ into the ISM (including mass lost in a wind by its progenitor). According to Woosley and Weaver (1986), the abundances of the intermediate mass elements, including silicon, can be accounted for by nucleosynthesis in Type II SNe with a mean metallicity 9 times cosmic, so that the average Type II SN injects about 0.14 $M_\odot$ of silicon into the ISM. Type I SNe also inject silicon into the ISM: Hamilton *et al.* (1986*a*, 1986*b*) estimate that 0.04 $M_\odot$ and 0.1 $M_\odot$ of silicon (all of which is hot enough to emit X–rays) is present in SN 1006 and Tycho, respectively. If the rates of Type I and Type II SNe are comparable, then the average SN injects about 0.1 $M_\odot$ of silicon. With a galactic supernova rate of 0.022 yr^{-1} (§ 4), this gives a silicon injection rate of about 2×10^{-3} $M_\odot$ yr^{-1}, which is 2–6 times greater than that from red giants. The same argument applies to the other intermediate mass elements, such as magnesium and iron. Hence, *the bulk of the refractory elements (with the exception of carbon) are injected into the ISM by supernovae, not red giants.* For a red giant mass injection of 1 $M_\odot$ yr^{-1}, the resulting injection time for silicon is:

$$t_{in} \simeq \frac{4.5 \times 10^9 M_\odot \times 10^{-3}}{3 \times 10^{-3} M_\odot \mathrm{yr}^{-1}} = 1.5 \times 10^9 \quad \mathrm{yr}. \tag{19}$$

This result is insensitive to the precise value of the cosmic abundance of silicon, which is taken here as 10^{-3} by mass. The surviving dust fraction is then $\delta_{eq} \simeq 0.22\delta_{in}$. Liffman and Clayton (1988) have carried out detailed Monte Carlo calculations with considerably different assumptions and reach a similar conclusion: most of the dust injected by stars, including supernovae, is destroyed in the ISM.

Two important conclusions follow from this result: First, *most of the material in refractory grains accreted onto the grains in the ISM.* As shown above, most of the refractory elements are injected into the ISM at high velocity and high temperature in supernova ejecta, not in the cool winds of red giants, which strengthens the conclusion that refractory grain growth must occur in the ISM. For silicon, this grain growth must lead to silicates, since most of the interstellar silicon is tied up in silicates with an absorption spectrum that is observed (Roche and Aitken, 1984) to be essentially the same as that of circumstellar silicates observed in cool stars. Note that the grain growth may occur under unusual conditions, since after the SN ejecta cool they may condense onto grains before becoming well–mixed with the interstellar gas.

The second conclusion is the converse of the first: *A significant fraction (~ 20%) of the refractory dust injected by stars can survive the harsh environment of the ISM, thereby providing a record of its creation.* This record can be interpreted through studies of interstellar inclusions in meteorites and interplanetary dust particles, as discussed by Anders (1989) and Sandford (1989).

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