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Survival of Carbon Grains in Shocks

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I. INTRODUCTION

The diffuse interstellar medium (ISM) is a hostile environment for all types of interstellar grains; it offers a variety of ways to destroy the grains. In the very hot (10^6 K) phase, thermal sputtering will erode away grain material. In the warm (10^4 K) phase, fast radiative shocks ($30 < v_s < 150$ km s^{-1}) can vaporize or shatter grains (Seab and Shull, ref. 1). Other destructive processes include astration, or incorporation into new formed stars; thermal sputtering in the galactic halo (Seab and Edgar, ref. 2) , thermal evaporation in hot dense environments, and chemical sputtering of carbon grains (Barlow, ref. 3). Of all the grain destruction mechanism, grain destruction is supernova-driven shocks dominates (Draine and Salpeter, ref. 4; Dwek and Scalo, ref. 5). It is the purpose of this review to examine the processing of interstellar grains (carbon grain and other types) in interstellar supernova shock waves.

A typical interstellar grain will experience frequent shocks while it resides in the ISM. Seab (ref. 6) calculates the average shock time to be

$$\tau_{sn} = 10^8 \ v_7^2 \ \text{years} \tag{1}$$

for a given grain being hit by a shock with velocity greater than $v_7 = v/10^7$ cm s^{-1}. This average explicitly accounts for the different phases of the ISM in the McKee and Ostriker (ref. 7) model. For this shock frequency, the lifetime of a typical grain is approximately

$$\tau = \tau_{sn}/\epsilon \tag{2}$$

where ϵ is the efficiency of grain destruction in a shock of a given velocity.

Section II briefly reviews the mechanisms of grain destruction in shocks; Section III describes the results of evaluating ϵ for carbon grains specifically, while Section IV considers the possibility of producing small diamond particles from graphite grains subjected to grain-grain collisions. The final section summarizes these results and conclusions.

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II. GRAIN DESTRUCTION IN SHOCKS

The calculation of grain destruction in shocks divides into two parts depending primarily on the velocity. Shocks with v_s less than about 150 to 200 km s^{-1} are radiative; the cooling time for the shocked gas is less than the evolution time of the shock. This evolution time is approximately given by the age of the supernova remnant (SNR) driving the shock. Shocks with velocity greater than 150 to 200 km s^{-1} can be treated as adiabatic shocks, since the SNR expands significantly before the hot post-shock gas has a chance to cool by radiation. In the intermediate regime, and in some cases for slower shocks, at least a first-order time dependence correction to the shock structure must be done (McKee et al., ref. 8).

In radiative shocks, a cooling layer is established in the immediate postshock region. The shock layer itself can be treated as a thin discontinuity in which the gas temperature jumps from the ambient temperature up to 10^4 to 5×10^5 K, depending on the velocity, and the density jumps by about a factor of four in a strong shock. The gas is abruptly accelerated to about $0.75v_s$ in this layer. The grains, however, are sufficiently massive to go straight through the thin shock layer. In the shock frame, they are effectively injected into the gas with velocity $0.75v_s$ at the shock front. In addition to this initial velocity, the grains are also betatron accelerated (Spitzer, ref. 9). As the gas cools, it compresses; the frozen-in magnetic field is compressed along with the gas. Since the grains will normally be charged by up to several volts (McKee et al., ref. 8), they will gyrate around the magnetic field lines. As the field is compressed, the grains will spin up, attempting to conserve the magnetic moment $\mu = qB/m$. Calculations by Seab and Shull (ref. 1) show that they can reach velocities up to about twice the shock velocity before drag forces slow them to a halt. In radiative shocks, it is this velocity of the grains through the gas that powers the grain destruction.

As the grains move through the gas, they are gradually destroyed by non-thermal sputtering and by grain-grain collisions. Non-thermal sputtering is the erosion of surface layers of the grain by collision of the fast-moving grain with relatively stationary He atoms in the gas. Hydrogen, CNO group, and heavier elements contribute less than 10% of the He sputtering amount. Occasionally, the grains will collide violently with one another. The largest velocities are carried by the larger, more dense grains because they have greater mass per unit surface area than do the smaller, less dense grains. Collisional and plasma drag forces are less effective in decelerating these grains. Therefore the large grains are able to accelerate to higher gyration velocities and consequently suffer more destruction in radiative shocks, both from non-thermal sputtering and from grain-grain collisions. Note that the small grains continue to be destroyed in collisions as long as any of the grains are moving with high velocity.

In adiabatic shocks, in contrast, the primary destruction mechanism for grains is thermal sputtering in the hot postshock gas. The postshock tempera-

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ture behind a 250 km s^{-1} shock, for example is about 5 x 10^5 K. Thermal sputtering erodes away the outer layers of the grains in the same manner as non-thermal sputtering, except that here the collision velocities are due to the thermal motion of the gas rather than the gyration velocity of the grains. Figure 1 shows the thermal sputtering rates of silicate and graphite grains from Seab (ref. 6). Note that sputtering turns on rather steeply near 3 x 10^5 K. Thermal sputtering in radiative shocks is not significant because the postshock temperatures are not high enough and because the gas quickly cools below the thermal sputtering threshold. In adiabatic shocks, the high temperatures persist in the SNR cavity roughly until the expanding SN bubble reaches pressure equilibrium with the general ISM. The smallest grains can be totally vaporized in this time, while the larger grains are merely pared down to a smaller radius. Preliminary calculations show that a 250 km s^{-1} shock removes about 300 Å from each grain. Slower shocks hit more frequently according to equation (2) but destroy less grain material. We find that 250 km s^{-1} shock tend to dominate the grain destruction by thermal sputtering in adiabatic shocks.

McKee et al. (ref. 7) use a first order time dependent numerical hydrodynamic shock code to find the destruction efficiencies for silicate grains in radiative shocks from 50 to 150 km s^{-1}. The typical of destruction efficiency shocks in this range is on the order of 10%, down from the 50% typical efficiency found by Seab and Shull (ref. 1). With ϵ — 0.10, the grain lifetime from equation (2) is on the order of 10^9 years for silicate grains.

This calculated lifetime for silicates poses a fundamental problem for grain evolution models. The formation time for new silicate grains in red giant winds is a few times 10^9 years. Since the destruction time is less than this, we would expect most of the silicon in the ISM to be in the gas phase. Instead, Si is found to be 90% or more depleted in most lines of sight (Shull and van Steenberg, ref. 10). Moreover, most of the depleted silicon must be in the form of silicates to give the observed strength of the 10μ feature (Tielens and Allamandola, ref. 11). The difficulty can be resolved if either the destruction rates are actually much lower than calculated, or if the grain formation rates are much higher than expected. The latter possibility would hold if a large fraction of the grain material is formed in the cloud phases of ISM itself, rather than exclusively in red giant atmospheres. At least some refractory grain material must necessarily form in the ISM to account for lines of sight with 99% or greater depletion of elements such as Si, Fe, and Ca. Greenberg and coworkers (Greenberg, ref. 12, 13) propose a mechanism for forming an organic refractory material in dark clouds. It therefore seems more likely that the classical formation rates are too low, rather than that the destructions rates are too high. It is not clear, however, just how a silicate material would form rather than an organic refractory material. Until this question is settled, some level of doubt must be attached to the whole issue of grain destruction.

III. CARBON GRAINS

Carbon grains do not present the same problems as do silicate grains. The depletion of carbon in the ISM is on the order of 50% (Jenkins, ref. 14), much less than the depletion of silicon. These depletions can be reasonably explained with destruction rates approximately the same as the formation rates. Calculations of the destruction rates of graphite are in fact somewhat lower than for silicon because of the higher binding energy of graphite (7.5 ev for graphite versus about 5.35 ev for silicates). Graphite grains are accordingly expected to live longer than silicate grains. Unlike interstellar silicon, which must be in the form of silicates in order to produce the observed 10 and 20 μ features, carbon is not constrained to be in the form of graphite. Some or all of the carbon in grains might be in the form of amorphous carbon, glassy carbon, or an organic refractory material without violating the observations. The last form is easily grown in dark clouds in the interstellar medium. The primary question on carbon in grains is in what form the carbonaceous material exists. Whatever the form, shock processing of carbonaceous grains must still play a primary role in determining the structure of the grains.

The most popular candidate material has been graphite. Graphite has an absorption feature at about the right place and the right strength to explain the 2200 Å feature in the ultraviolet interstellar grain extinction curve (Savage and Mathis, ref. 15). Objections have been raised to this identification of the carbon grain material on the grounds that there is little correlation observed between the 2200 Å bump strength and the far-UV extinction rise (Greenberg and Chlewicki, ref. 16), and because the peak wavelength of the bump does not show any of the shifts that would be expected from variations in grain size (Massa and Fitzpatrick, ref. 17). For the present, graphite is still being used in destruction calculations because it remains a possible candidate for interstellar grain material (cf. Draine and Lee, ref. 18) and because at least some measured sputtering data is available.

The experimental data on graphite sputtering has been used to get a best fit sputtering curve (Seab, ref. 6; Tielens et al., in preparation) based on an empirical formula by Anderson and Bay (ref. 19). Agreement between experimenters is not good, even for supposedly similar samples of material. The worst case is for sputtering yield measurements of graphite by hydrogen, where there is nearly a factor of ten discrepancy between measurements by different groups (Anderson and Bay, ref. 19). Fortunately, hydrogen contributes less than 10% of the total sputtering rate. Agreement is better for sputtering by He, which contributes about 90% of the total. Overall, the adopted best fit sputtering parameters are uncertain by a factor of 2 to 3, only mildly worse than the uncertainties for silicate sputtering. It is reasonable that graphite should be harder to sputter than silicates since the binding energy per atom is 50% larger. The thermal sputtering curves shown in figure 1 reflect this conclusion.

In addition to being harder to sputter, graphite grains may also have a

very different size distribution than silicate grains. Basic information on the sizes of interstellar grains is deduced from the observed extinction curve, which measures the wavelength dependence of the attenuation of starlight due to the dust in the line of sight to a star. Mathis, Rumpl, and Nordsieck (ref. 20; hereinafter MRN) fit the average extinction curve very well with a combination of graphite grains and silicate grains, each with a power law size distributions of dex -3.5 and a range from 2500 Å to 50 Å grain radii. Graphite grain destruction calculations by Tielens et al. (ref. 21) use this sort of size distribution. However, the objections mentioned previously may restrict the sizes of graphite grains to less than about 200 Å in radius. Other types of carbonaceous grains may still exist in larger sizes.

Changing the size distribution of the carbon grains will have only a minor effect on the total destruction rate results. The non-thermal sputtering rates will be significantly decreased if smaller grains are used, since drag forces are more effective on small grains and consequently the betatron acceleration mechanism will be less effective. The effect of grain-grain collisions might be lessened by a factor of not more than 2 or 3. The decrease is not more because the large silicate grains will still be betatron accelerated to high velocities and will continue to collide energetically with smaller carbon grains. Smaller graphite grains will be more vulnerable to destruction by thermal sputtering behind adiabatic shocks since small grains have more surface area for their volume. Thus the total carbon grain destruction rate in the galaxy is not very sensitive to the size distribution chosen.

The results of a series of calculations on graphite grain destruction by Tielens et al. (ref. 21) are shown in figure 2. The sputtering process has a threshold just above 50 km s^{-1} shock velocity, but increases steeply from there. The vaporization of material in grain-grain collisions has a lower threshold velocity than sputtering, but increases more slowly. The dominant process shown in Figure 2 is the shattering of grains in grain-grain collisions. Shattering has a lower threshold than both sputtering and vaporization since it must break atomic bonds only along the surfaces of the fragments, instead of having to break every bond in the solid.

If the carbon exists in forms other than graphite, as seems likely, then these results will be modified. Non-graphitic forms (other than diamond) are likely to be less tightly bound than graphite. The sputtering threshold for these materials will be correspondingly lower, so that the destruction rates will be higher. On the other hand, if the grain densities are also lower, then drag forces in radiative shocks will be more effective, so that grain velocities will be less and the destruction rates lower. Duley (ref. 22) proposes that the carbonaceous material is in the form of a thin layer covering a silicate type grain. In this case, the grain velocity will be determined by the bulk density of the grain, and the carbon material, being on the outside of the grain, will again be more readily destroyed. The resolution of this admittedly confusing situation depends on the careful evaluation of the destruction rates for the different grain models. Tielens et al. (in preparation) will present a more thorough analysis of the grain destruction rates and mechanisms. For the present, the calculations based on

an MRN graphite grain/ silicate grain model will be used as a guide to grain destruction rates.

In addition to shattering graphite grains, grain-grain collisions in radiative shocks can convert the shatter products into the high-pressure form of carbon: diamond. The diamond conversion process will be discussed in the next section.

IV. DIAMONDS IN THE SKY

Lewis et al. (ref. 23) found small ($\simeq$ 50 Å) diamonds in the Cδ phase of the Allende meteorite. These diamonds were associated with isotopic anomalies, indicative of an interstellar origin of the diamonds. They propose that the diamonds were formed by condensation in the outer atmosphere of a red giant which subsequently went supernova, thereby implanting additional isotopic anomalies in the circumstellar carbon grains.

Tielens et al. (ref. 21) propose that these small interstellar diamonds were produced by grain-grain collisions of graphitic or other carbonaceous grains in supernova-driven shocks.

When two grains collide at high velocities, they drive shock waves into the solid material of each grain. The shock wave heats and pressurizes the grain material. This high temperature and pressure can convert graphite into diamond. The process has been shown experimentally (cf. Tielens, this volume) to give high yields of small diamond particles when the shock pressure is greater than a threshold of about 0.7 eV per atom. This threshold is nearly the same as the shattering threshold, and both are a factor of ten less than the vaporization threshold of 7.5 eV per atom. Thus, the grain-grain collision will not only shatter part or all of the grain, but will convert the shatter products into diamond. The characteristic size of diamond produced by this process will be on the order of 30 Å, in reasonable agreement with the Allende diamond sizes. The microphysics of the diamond conversion is discussed more thoroughly by Tielens (this volume).

We can estimate the population of interstellar diamonds by balancing the formation and destruction rates to get

$$f_d = \frac{\epsilon_d/\epsilon_v}{\left[1 + \dfrac{\tau_{sn}}{\epsilon_v \tau_{sf}}\right] \left[1 + \left(\dfrac{\epsilon_v \tau_{sf}}{\tau_{sn}}\right)\left(1 + \dfrac{\epsilon_d}{\epsilon_v}\right)\right]} f_i \qquad (3)$$

$$\simeq 0.1 f_i$$

where f_d is the fraction of interstellar carbon in diamond form; f_i is the fraction of carbon injected into the ISM as graphite; ϵ_d is the diamond-ization efficiency and ϵ_v the vaporization efficiency including sputtering, both averaged over a distribution of shock velocities; τ_{sf} is the star formation timescale, here taken to be the same as the destruction time for graphite grains; and τ_{sn} is the time for a grain to be hit by a supernova shock with a velocity greater than the diamondization threshold. Figure 2 shows that the shock velocity corresponding to significant diamond conversion is about 35 km s^{-1}. Although ϵ_d is larger than ϵ_v for the radiative shocks shown in figure 2, it will drop to zero for shocks fast enough to be adiabatic (v > 200 km s^{-1}). The ϵ_v efficiency also drops off as shock velocity approaches the adiabatic case, but then increases strongly as thermal sputtering turns on. Averaged over all shock velocities, we find $\epsilon_d \simeq \epsilon_v$ (Tielens et al., ref. 21).

Equation (3) is not very sensitive to the ϵ_v, τ_{sf}, or τ_{sn} parameters, since these appear both as ($\epsilon_v \tau_{sf}/\tau_{sn}$) and as its inverse in the denominator. A wide range of values for these parameters yield values of about 0.1f_i for equation (3). Unfortunately f_i is not known. If we take an optimistic 50% of the fresh carbon injected into the ISM is in the form of graphite or amorphous carbon, then $f_d \approx 0.05$, or 5% of the interstellar carbon in the form of diamond.

This number is probably an upper limit to the actual diamond fraction of the ISM since we do not know the efficiency of diamondization of submicron-sized grains in shocks. The timescale for grain-grain collisions in the ISM is on the order of 10^{-9} seconds, much shorter than the time for shocking graphite in the laboratory. The time required for conversion to diamond is not known; an upper limit has been set at 10^{-6} seconds. It is not unreasonable to assume that diamond conversion can occur on the nanosecond timescale required for interstellar grain-grain collisions.

The diamond conversion process must start with something close to pure carbon. Some impurities can be tolerated, and will just add color to the diamond. The limit on the amount of impurities that can be tolerated and still yield a substantial conversion to diamond is not known; diamond conversion has been obtained with 10% oxygen impurity in glassy carbon (cf. Tielens this volume). The organic refractory material probably cannot be converted to diamond. Polycyclical aromatic hydrocarbons (PAHs) (Allamandola and Tielens, ref. 24) are too small for the conversion to work; the PAH will break apart before a shock front has time to fully develop. Graphite and amorphous or glassy carbon grains are likely candidates for conversion to diamond in the interstellar shocks. It is not known how much of the inter-stellar solid carbon is in these forms; the 50% figure used for f_i may be too high. The 5% figure derived above is again an upper limit to the expected amount of interstellar diamond.

Hecht (ref. 25) places an observational upper limit of 1% on the amount of carbon in diamond form, based on the absence of a diamond absorption edge starting at 7 ev (1430 Å in the far-UV extinction curve. This is not a hard upper limit because the absorption edge could be smoothed out by size effects in a distribution of diamond particle sizes. The small fraction of diamond

found in meteorites (Lewis et al., ref. 23) does not set an effective upper limit on the interstellar population because of the unknown amount of processing of the meteoritic material through the presolar nebula. Thus the 5% theoretical figure, regarded as a generous upper limit, is consistent with the little data available.

V. SUMMARY AND CONCLUSIONS

Supernova shocks play a significant part in the life of an interstellar grain. In a typical 10^9 year lifetime, a grain will be hit by an average of 10 shocks of 100 km s^{-1} or greater velocity, and even more shocks of lower velocity. Evaluation of the results of this frequent shock processing is complicated by a number of uncertainties, but seems to give about 10% destruction of silicate grains and about half that for graphite grains. Because of the frequency of shocking, the mineralogy and sizes of the grain population is predominately determined by shock processing effects, and not by the initial grain nucleation and growth environment.

One consequence of the significant role played by interstellar shocks is that a certain fraction (up to 5%) of the carbon should be transformed into the diamond phase. Diamond transformation is observed in the laboratory at threshold shock pressures easily obtainable in grain-grain collisions in supernova shocks. Yields for transforming graphite, amorphous carbon, glassy carbon, and other nearly pure carbon solids into diamond are quite high. Impurities up to at least the 10% level (for oxygen) are tolerated in the process. The typical size diamond expected from shock transformation agrees well with the observed sizes in the Lewis et al. (ref. 23) findings in meteoritic material. Isotopic anomalies already contained in the grain are likely to be retained through the conversion process (Tielens, this volume), while others may be implanted by the shock if the grain is close to the supernova. The meteoritic diamonds are likely to be the results of transformation of carbon grains in grain-grain collisions in supernova shock waves.

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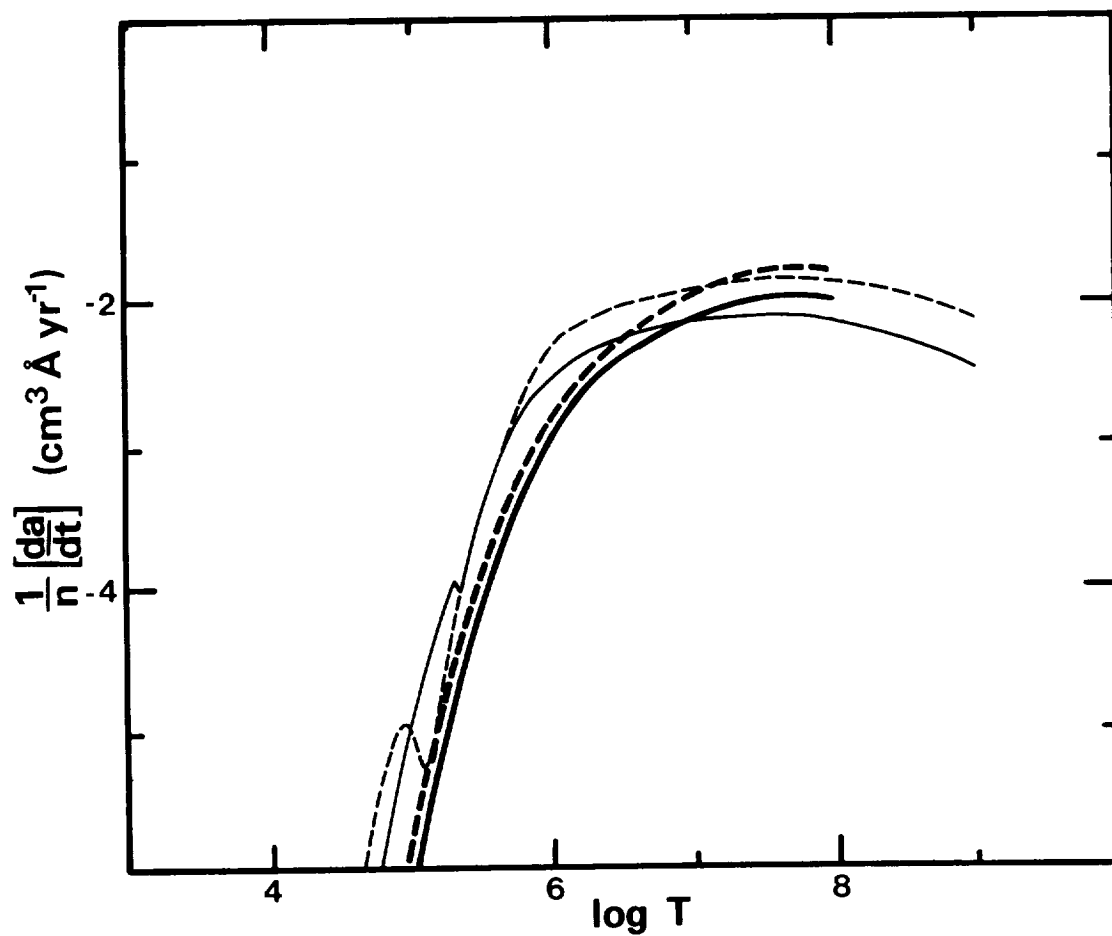26. Hecht, J. H.: Observations on Constraints on Interstellar Diamonds. Nature, vol. 326, 1988, p.765.

Figure 1.– Thermal sputtering rates for silicates (dashed curves) and graphite (solid curves). The thick lines represent the best fit to data from Seab (ref. 6), while the thin lines are from Draine and Salpeter (ref. 4).
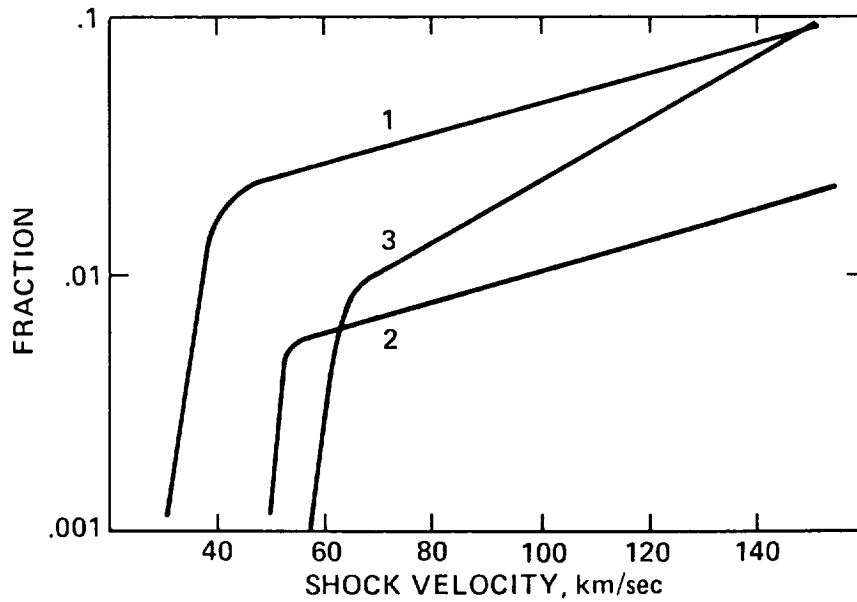
Figure 2.– Shock processing of graphite grains as a function of shock velocity. Curve (1) gives the fraction of total graphite grain material transformed into diamond; curve (2) gives the amount vaporized into gaseous carbon by grain-grain collisions, and curve (3) the amount sputtered off the grains. These curves are for radiative shocks only; for adiabatic shocks, thermal sputtering dominates the destruction, while the other processes are negligible.