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THE FORMATION OF SMALL GRAINS IN SHOCKS IN THE ISM

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ABSTRACT. Carbonaceous and silicate grains swept up, and betatron accelerated, by supernova-generated shock waves in the interstellar medium are exposed to grain destructive processing. The degree of grain destruction is determined by the differential gas-grain and grain-grain velocities, which lead to sputtering of the grain surface and grain core disruption (deformation, vaporization and shattering), respectively. The threshold pressure for grain shattering in grain-grain collisions (100 k bar) is considerably lower than that for vaporization ($\approx$ 5 M bar). Therefore, collisions between grains shatter large grains into smaller fragments (i. e., small grains and PAHs). We have used new algorithms for the destructive processes and have modeled the formation of small grain fragments in grain-grain collisions in the warm phase of the interstellar medium. We find that in one cycle through the warm medium ($\approx 3 \times 10^6$ yr) of order 1–2% of the total grain mass is shattered into particles with radii < 50Å.

1 INTRODUCTION

An important question in the study of interstellar dust is the origin of the grain size distribution; i. e., what are the processes that determine the implied size distribution (Greenberg and Hong 1974; Mathis *et al.* 1977: MRN), and how does it vary with the physical conditions of the environment? For example, is the size distribution the result of the competition between coagulation and shattering in the interstellar medium, or between stardust injection and shattering? Two models for the origin of the very small grains and PAH molecules observed in the interstellar medium have been suggested. Firstly, they may be the left over condensation nuclei from the formation of dust grains in the outflows of late type giants (Latter 1991). Secondly, the small species may result from the grinding down of large dust grains in the interstellar medium by fast shocks (Omont 1986; Tielens and Allamandola 1987). The presence of small grains in the interstellar medium can have a profound effect on the gas, through the photoelectric heating effect, and on the observed optical properties, through the ultraviolet extinction due to small grains. Additionally, if the diffuse interstellar bands have their origin in small grains or PAH molecules, then the formation of small grains in shock waves in the interstellar medium, via shattering in grain-grain collisions, will be a significant source of the DIB carriers.

2 DUST DYNAMICS IN SHOCK WAVES

Interstellar grains are swept up, and betatron accelerated, by supernova-generated shock waves in the interstellar medium, and are exposed to destructive processing (Jones *et al.* 1994 and references therein). The degree of grain destruction in a shock wave is determined by the differential gas-grain and grain-grain velocities, which lead to sputtering of the grain surface and grain core disruption (deformation, vaporization and shattering), respectively. For all destructive processes the higher the relative velocity, the greater the grain destruction. The betatron acceleration of the grains, mediated by the grain charge, occurs mostly in the cooling post-shock gas where the compressing gas produces an increasing magnetic field which accelerates the grains with respect to the gas. Figure 1 shows the graphite/carbon grain velocities with respect to the gas for several grain radii. We use the analytical grain charge scheme of McKee *et al.* 1987, and the grain destruction in shocks model of Tielens *et al.* 1994 and Jones *et al.* 1994.

3 GRAIN SHATTERING MODEL

In order to model the shattering of grains we use the algorithms derived by Tielens *et al.* 1994, and the numerical scheme of Jones *et al.* 1994. However, in these models only the vaporization in grain-grain collisions is considered. Therefore, we have adopted a threshold pressure for grain shattering in grain-grain collisions of 100 k bar (Tielens *et al.* 1994), which is considerably lower than that for vaporization ($\approx$ 5 M bar; Tielens *et al.* 1994). Otherwise, shattering is numerically treated in the same way as vaporization, but with careful attention to mass conservation and the tracking of the shattered fragment masses. Collisions between grains will shatter large grains into smaller fragments which range in mass from about one tenth of the total shattered grain mass, down to that equivalent to molecules. We use a Eulerian mass bining scheme to follow the evolution of the grain mass distribution, but do not subject the grains in the smallest mass bin to any destructive processing, which thus is a repository for the smallest shattered fragments. Figure 2 shows the initial (MRN) and final graphite/carbon size distributions for a $100\,\mathrm{km\,s^{-1}}$ shock. Note that the small grain (radii < few 100Å) abundance is enhanced at the expense of the > 500Å radius particles.

4 GRAIN LIFETIME AGAINST SHATTERING

We determine the grain lifetime against shattering , $t_{SNR,sh}$, after the method of McKee (1989), and Jones *et al.* 1994, using the following formulation;

$$t_{SNR,sh} = \frac{\tau'_{SN} M_{ISM}}{\int \epsilon_{sh}(v_s)\, dM(v_s)}, \tag{1}$$

where $M_{ISM} = 4.5 \times 10^9\,\mathrm{M_\odot}$ is the mass of the interstellar medium (gas and dust); $\tau'_{SN} =$ 125 yr is the effective interval between supernovae (McKee 1989); $\epsilon_{sh}(v_s)$ is the efficiency for the complete shattering of a grain into sub 50Å fragments by a shock of velocity v_s; and M_s is the mass of gas shocked to at least v_s by a supernova remnant. For grain shattering

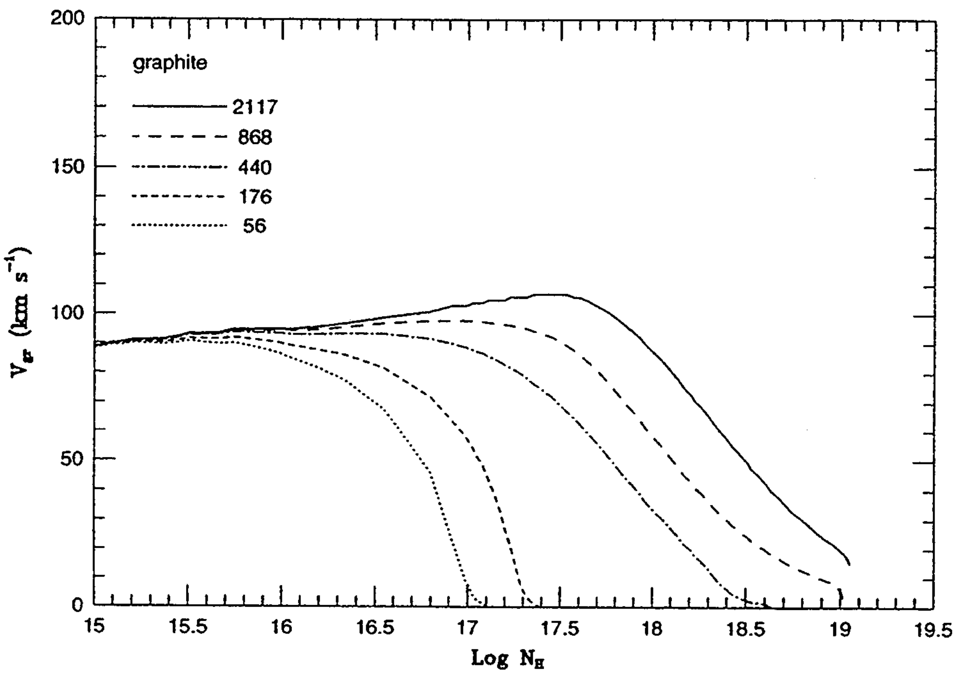

Figure 1 The carbon/graphite grain velocities with respect to the gas for five grain radii (56Å, 176Å, 440Å, 868Å, and 2117Å), for a 100 $\mathrm{km\,s^{-1}}$ shock in the warm intercloud medium.

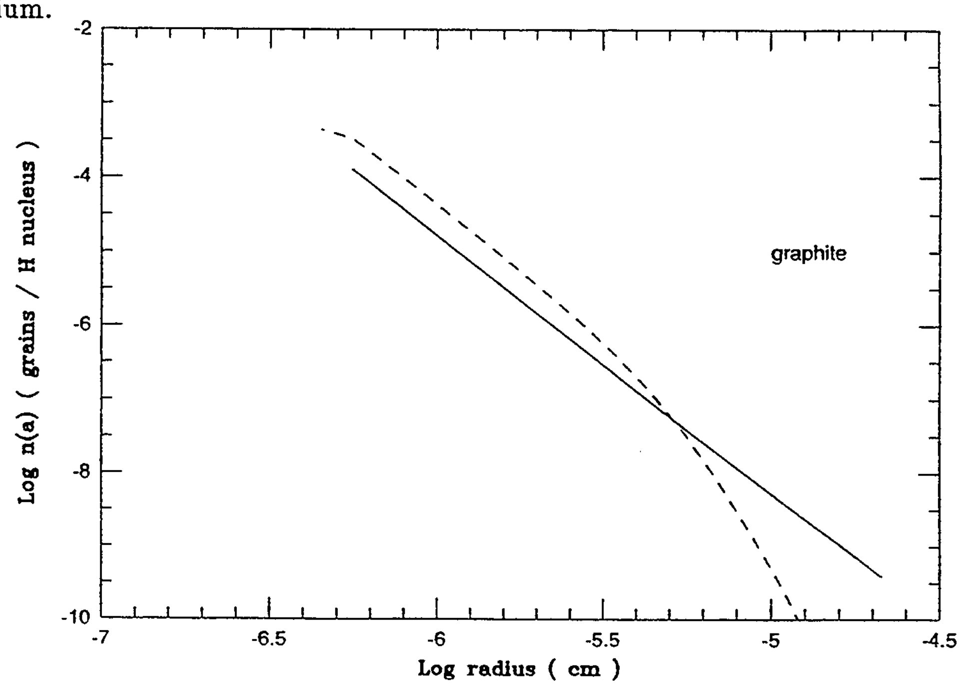

Figure 2 The initial MRN size distribution (solid line), and the final size distribution (dashed line) for carbon/graphite grains that have experienced a 100 $\mathrm{km\,s^{-1}}$ shock in the warm intercloud medium.

in the warm medium we then have;

$$t_{SNR,sh} = \frac{9.7 \times 10^7}{\int \epsilon_{sh}(v_{s7})/v_{s7}^3 \, dv_{s7}} \, yr \,, \tag{2}$$

where $v_{s7} = v_s/(10^7 \mathrm{cm\,s^{-1}})$. Using the above expressions, and our results for carbon and silicate grain shattering in shocks of velocities 50, 100, 150, and 200 $\mathrm{km\,s^{-1}}$ (2–4% of the total grain mass is shattered into grains with radii < 50Å for a given shock), we derive grain lifetimes against shattering of $\approx 2 \times 10^8$ yr. Therefore, for one sojourn in the warm medium of 3×10^6 yr, of order 1–2% of the total carbon or silicate grain mass is shattered into small particles of radius < 50Å.

5 DISCUSSION

Interstellar shocks permeate all phases of the interstellar medium, and play a major role in regulating the structure of clouds and the intercloud media. In the study reported here we have considered the effects of shocks in the warm medium, the environment in which most grain destruction occurs (McKee 1989), and find that in one cycle through the warm medium ($\approx 3 \times 10^6$ yr) of order 1–2% of the total grain mass is shattered into particles with radii < 50Å. We conclude that the shattering of grains in grain-grain collisions will be the major mass re-distribution process acting on the grains in interstellar shock waves. Thus, shattering will dominate vaporization in grain-grain collisions, and is likely to be a viable source of small grains in the interstellar medium. This, however, does not preclude the possibility that some of the small grains may be the left over grain condensation nuclei from late type giant outflows. Indeed, it is likely that both processes contribute to the small grain population in the interstellar medium.

We are presently further investigating the grain shattering process in interstellar shock waves, in order to determine the grain lifetimes and the abundances of the grain-forming elements depleted into dust in the different phases of the interstellar medium.

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