THE EVOLUTION OF DUST IN THE MULTIPHASE INTERSTELLAR MEDIUM

NASA Grant No. NAG5-11233

Final Report

For Period 15 August 2001 through 14 August 2003

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November 2003

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

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The Smithsonian Astrophysical Observatory
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Harvard-Smithsonian Center for Astrophysics

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"The Evolution of Dust in the Multiphase Interstellar Medium"

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1. Introduction

Interstellar dust has a profound effect on the structure and evolution of the interstellar medium (ISM) and on the processes by which stars form from it. Dust obscures regions of star formation from view, and the uncertain quantities of elements in dust makes it difficult to measure accurately the abundances of the elements in low density regions. Despite the central importance of dust in astrophysics, we cannot answer some of the most basic questions about it: Why is it that most of the refractory elements are in dust grains? What determines the sizes of interstellar grains? It has been the goal of our proposed theoretical investigations to address these questions by studying the destruction of interstellar grains, and to develop observational diagnostics that can test the models we develop.

2. Grain Destruction in Shocks

Large ($\gtrsim 1$ μm) grains have been thought to be very rare in the interstellar medium based on assumptions about the total mass of elements tied up in grains and the dust size distribution. Observations of dust in the Solar System, both in "pre-solar" grains found in meteorites and in direct observations of interstellar grains flowing into the Solar System from the Local Interstellar Cloud by the Ulysses and Galileo spacecrafts (Grün et al. 1994), however, have revealed the existence of such grains in unexpectedly large numbers. When shocks propatgate through gas containing such large grains their large mass and correspondingly large gyroradii lead to a large penetration depth beyond the shock front. The grains effectively decouple from the gas leading to complex grain dynamics and substantially altered grain destruction as compared to smaller grains. To carry out calculations of the processing of such large grains in shocks then required breaking from the usual assumption of a tight coupling of the gas and grains. To accomplish this we employed the codes developed by Jones et al. (1994) for the sputtering (thermal and non-thermal), vaporization and shattering of grains, as well as the charge on the grains. We used shock profiles calculated by John Raymond (private communication) for the gas properties (using some of the same profiles used by Jones et al. (1994) along with some additional profiles for a finer grid of shock velocities). To calculate the processing of the large grains, however, required the creation of a new code to numerically calculate the trajectories of the grains subject to destruction, charging, drag forces and electromagnetic forces in the shock. Examples of our results for trajectories followed by the grains are illustrated in Figure 1. An example of our results for the level of grain destruction as a function of grain size and shock speed is shown if Figure 2.

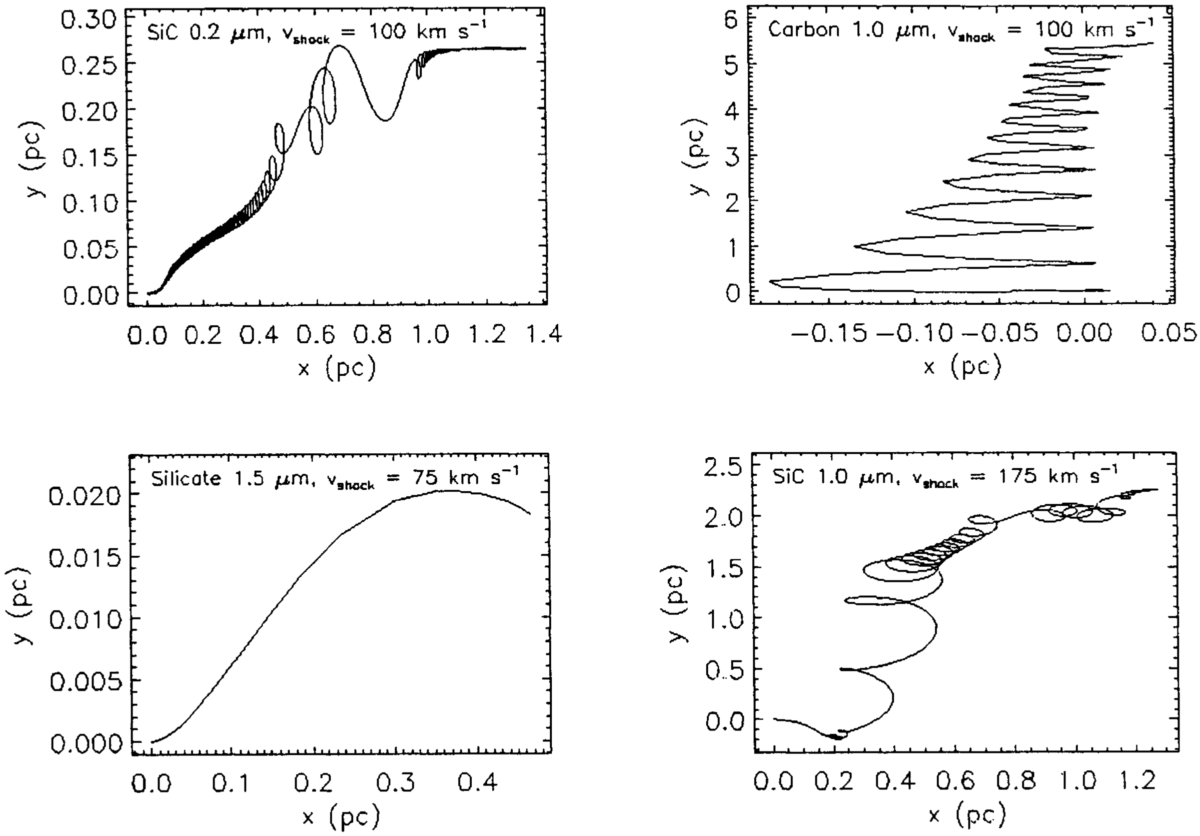

Fig. 1.— Example dust grain trajectories. The abscissa is the direction into the shock (x) while the ordinate is the direction parallel to the shock (y). The B field is assumed to be uniform in the pre-shock gas and in the z direction (perpendicular to the plane of the figure). Clockwise from the top left, the trajectories illustrate: tight coupling; multiple reflection into the pre-shock gas; decoupling/trapping leading to destruction; and complete decoupling and escape from the shock.

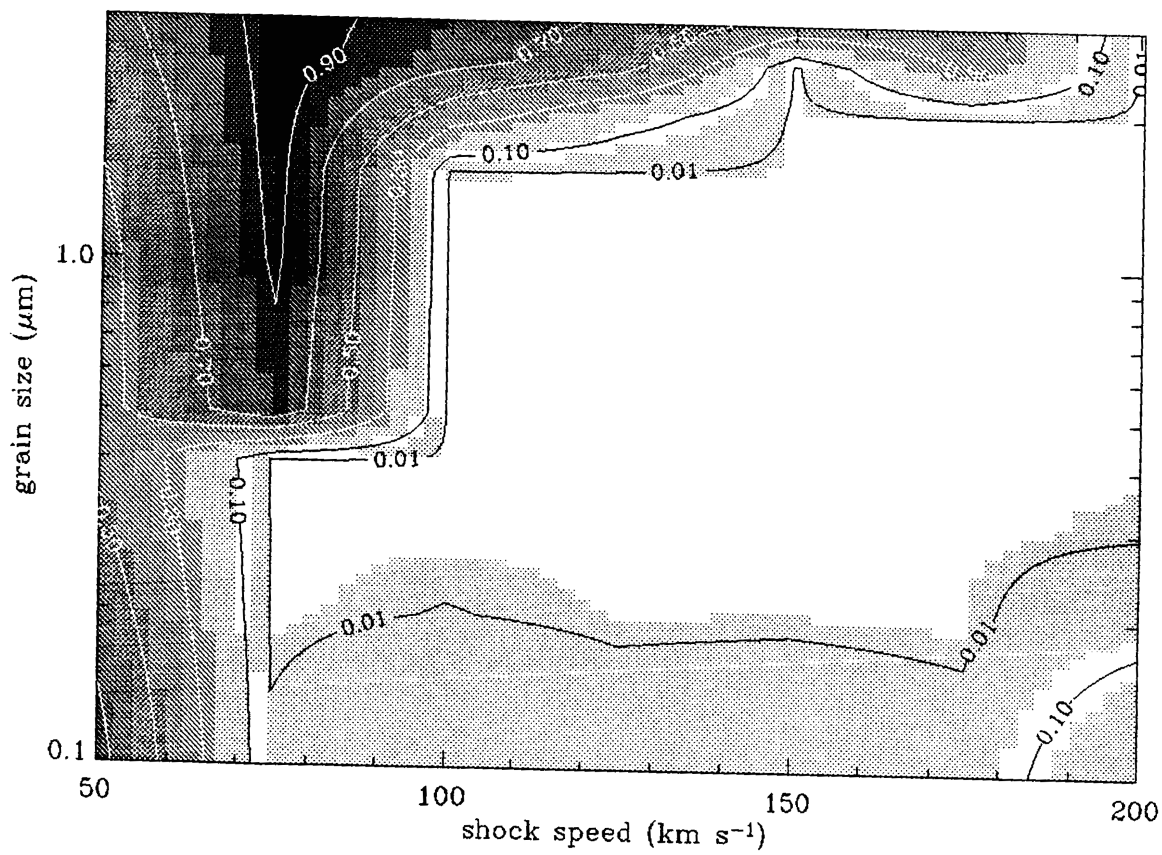

Fig. 2.— Fraction of initial silicate grain mass remaining after passage through the shock as a function of initial grain size and shock speed.

In addition to finding, as we expected, that large grains do decouple from the gas, in some cases reducing their destruction, we found a number of surprising and important results:

- the level of decoupling is very shock speed dependent,
- for a wide range of shock speeds and grain sizes, the grains are reflected back into the pre-shock gas leading to multiple reflection and acceleration to high speeds before being destroyed, possibly acting as a seed population for cosmic rays,
- for some of the largest grains studied ($> 1\mu$m), the decoupling protects them from destruction and they pass through the shock and "escape" into the hot, low density supernova or superbubble gas behind the shock suffering little destruction.

With a significant fraction of the dust mass contained in grains larger than 0.1 μm, it is critically important that grain trajectories be calculated in order to assess accurately the level of destruction in interstellar shocks, which is critical to understanding the life cycle of dust in the ISM.

3. Related Studies

Other studies that we have carried out that are relevant to the evolution of dust in the ISM include our work on the ionization of the diffuse ISM due to radiation from old, cooling supernova remnants (Slavin, McKee, & Hollenbach 2000) and work on the ionization and abundances in the Local Interstellar Cloud (Slavin & Frisch 2002; Frisch & Slavin 2003). The main destruction mechanism for dust in the ISM is SNR shocks propagating in warm phase gas (McKee 1989). The reason is straightforward: the destruction is dominated by the phase the occupies the largest volume, subject to the constraint that the density be high enough that substantial dust destruction can occur. In a two-phase ISM, the warm gas fills the space and dominates the destruction; in a three-phase ISM, the hot gas fills space, but is at too low a density for significant dust destruction, so once again shocks in the warm gas dominate destruction. The heating mechanisms for the warm phase are not well understood, but may be due to photoelectric heating from dust. In any case the gas phase abundances of the elements such as C, O and Fe that are incorporated into dust play an important role in its thermal balance. For this reason studies of the ionization and thus heating of the warm phase are directly relevant to the evolution of dust.

In our studies of the Local Interstellar Cloud, we have constrained the gas phase abundances of several elements by using models of the interstellar radiation field and calculations of the ionization and thermal balance in the cloud. These calculations in combination with absorption line observations toward nearby stars, *in situ* observations of neutral H and He flowing into the Solar System and anomolous cosmic rays and pickup ions provide tight constraints on the constituents of dust grains. The apparent conflict of the dust-to-gas ratio determined under the assumption of solar abundances for the reference (i.e. gas+dust) abundances versus direct observation of interstellar dust in the Solar System (Grün et al. 1994) provides perhaps the first direct evidence of decoupling of gas and dust on at least the several 100 AU scale.

4. Summary

We have undertaken studies of the ISM in order to understand dust evolution. We have completed the modeling of the destruction and dynamics of large grains in shocks, have presented our results (Slavin 2003, see also http://www.mpi-hd.mpg.de/galileo/~gruen/DUNE/Slavin_DUNE_workshop.pdf) and will soon submit an article for publication summarizing our results (Slavin, Jones & Tielens 2003). These investigations suggest that many large grains and even smaller grains may survive shock passage with relatively little destruction. Our results suggest several new avenues for further studies of grain evolution as well as presenting a possible solution to the "overdestruction" problem for interstellar dust. In addition we find evidence that dust evolution and cosmic ray generation may be closely related, as previously suggested by Epstein (1980)

Our completed investigations have given us insight into the nature and evolution of dust in the diffuse ISM. Interstellar dust is intimately linked to the structure and evolution of the ISM and our ongoing modeling efforts will have significant implications for the ISM as a whole. Our models will have direct applications for the interpretation of the spectral characteristics of the ISM, in particular SNR shocks, and the Local Cloud. While we have yet to complete other projects in our (perhaps somewhat overambitious) proposal, we now have a solid foundation for carrying out future work on dust evolution in supernova remnants, stellar wind bubbles and other interstellar environments.

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