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SHOCK PROCESSING OF INTERSTELLAR GRAINS

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I. INTRODUCTION

There is strong evidence for the destruction of dust grains in fast shock waves in the interstellar medium (ISM). This talk will discuss some of this evidence and will review the mechanisms by which the grains are destroyed in shocks. Grain growth in shock waves is a more controversial subject, although it is potentially as important as the destruction processes. A few comments on growth mechanisms will be made at the end of this talk.

II. IMPORTANCE OF SHOCKS

The shocks most effective at destroying grains are those with velocities in the range 30-400 km s^{-1}, propagating through diffuse interstellar clouds ($n_H \simeq 10$ cm^{-3}) or intercloud matter ($n_H \simeq 0.2$ cm^{-3}) with magnetic fields of 1-3 μG. These velocity limits are not precise; shocks slower than about 30 km s^{-1} are ineffective at destroying grains, while shocks faster than 400 km s^{-1} are too infrequent to be important. Grain destruction in shocks has been considered by many authors, including Cowie (1978), Shull (1977, 1978), Barlow (1978a,b,c), Draine and Salpeter (1979), and most recently by Seab and Shull (1983). These destruction models are relatively independent of the source of the shock wave, except insofar as the source determines the shock parameters.

The most important source for destructive shocks is probably supernova remnant (SNR) blast waves (Draine and Salpeter 1979), with cloud-cloud collisions being of lesser importance. The shock models can also be applied to stellar wind shocks (Castor, McCray, and Weaver 1975), and to Herbig-Haro

Objects (Dopita 1978; Raymond 1979; Brugel et al. 1982) and pre-main-sequence outflows in molecular clouds (Shull and Beckwith 1982). It should be noted that grain destruction within a radiative shock returns certain elements to the gas phase, where they increase the cooling and alter the structure of the post-shock region.

The importance of shock processing during the life of an interstellar grain can be estimated from the timescale for a typical grain to be hit by a fast shock, which follows from the supernova rate for the galaxy and the structure of the ISM. Consider a typical SNR with an expansion velocity of 100 km s^{-1} and a radius of 30 pc. If the mean interval between supernovae is 50 years throughout the galaxy, the shock time for a grain is approximately the supernova interval divided by the fraction of the galaxy occupied by the SNR:

$$t_{shock} = t_{SN} x (V_{gal}/V_{SNR})$$

$$= (50 \text{ yr})[(830 \text{ kpc}^2)(200 \text{ pc})/(4\ \pi/3)(30 \text{ pc})^3] = 7x10^7 \text{ yr}$$

More accurate calculations for the three-phase ISM (McKee and Ostriker 1977) give a time of 10^8 years for a grain to be hit by a shock 100 km s^{-1} or faster. This time should be compared to the several by 10^9 years calculated by Dwek and Scalo (1980) for injection of new grains into the ISM. The time for astration, or destruction by incorporation into stars, is about the same (Greenberg 1984). Therefore, a typical interstellar grain is hit by 10-20 fast shocks if it lives long enough for astration. Grains in the less dense intercloud medium will be hit even more often, on the order of every 10^7 years. Because of this high frequency of shocks, the properties of the ISM grain population will be strongly influenced and perhaps determined by the results of shock processing.

III. EVIDENCE FOR SHOCK PROCESSING

The first evidence suggesting that grains are destroyed in shocks came from the observation (Routly and Spitzer 1952; Siluk and Silk 1974) that high velocity (20 - 100 km s^{-1}) interstellar clouds exhibit a statistically higher

Ca II/Na I ratio. Shull, York, and Hobbs (1977) showed that Si and Fe abundances were also significantly greater in high velocity clouds. These observations have been interpreted as evidence for shock destruction of Ca, Fe, and Si atoms in grains by sputtering and grain-collisions (Jura 1976; Spitzer 1976; Shull 1977). These same shocks are also responsible for producing the clouds' observed velocities.

Further abundance studies with the Copernicus satellite (Fig. 1) showed that clouds with velocities greater than 100 km s^{-1} appear to have nearly cosmic abundances of Fe and Si, implying that most of the grain material has been destroyed. The cloud Doppler velocity provides a lower limit on the actual shock velocity, owing to projection effects and to cloud deceleration since the time the shock destruction began. These ultraviolet observations are significant for establishing the link between shocks and grain destruction, since silicon is commonly believed to be a major component of grain material (see Mathis review talk in this volume).

There exist two weaker pieces of evidence for grain destruction. The first is the correlation between theoretical shock-processed UV extinction curves and IUE satellite observations in lines of sight associated with supernovae (Seab and Shull 1983). These lines of sight show stronger than usual 2175 Å extinction features and enhanced far-UV extinction rises (Fig. 2). However, other explanations for these trends are possible. Second, Si or Fe abundance surveys by the Copernicus (Savage and Bohlin 1979) and IUE (Shull and Van Steenberg 1982, 1985) satellites have uncovered a correlation between depletion and mean line-of-sight density (Fig. 3). This correlation could result from preferential grain destruction in the less dense regions or from grain growth in the more dense regions. Alternatively, the apparent correlation might simply be a sampling artifact of the ISM cloud structure (Spitzer 1985).

Nevertheless, most lines of evidence point to significant grain destruction in high velocity clouds. Each piece of evidence requires a theoretical understanding of the fate of grains in interstellar shocks.

IV. GRAINS IN SHOCKS

a) Shock Structure - Radiative Shocks

The canonical grain-destroying shock modeled by Seab and Shull (1983) is a $V_s = 100$ km s^{-1}, plane-parallel, steady-state radiative shock propagating into a region of density $n_0 = 10$ cm^{-3} and magnetic field $B_0 = 1$ μG. Following a radiative precursor (Shull and McKee 1979), this gas experiences a collisionless shock layer ($N_H < 10^{14}$ cm^{-2} for electron-ion equilibration), followed by a thick ($N_H \approx 5 \times 10^{18}$ cm^{-2}, or spatial thickness 10^{15} cm) post-shock cooling region. It is in this cooling region that most of the grain destruction occurs. To 25% accuracy, the thermal gas pressure, nT, is constant in the downstream region, so that as the temperature falls, the density rises. Using the Lagrangian formulation, following a parcel of shocked gas as it flows downstream from the front, one may convert between post-shock column density and flow time, $N_H = n_0 V_s t$.

Figure 4 shows the temperature and density structure of a 100 km s^{-1} shock. Viewed in the frame in which the front is at rest, pre-shock gas of density n_0 streams toward the front at velocity V_s. Immediately behind the front, the density n jumps to about $4n_0$, and the gas velocity v relative to the shock front drops to about 0.25 V_s ($nv = n_0 V_s$ by mass conservation). The post-shock temperature T_s is determined by the shock's ram pressure, $kT_s = (3/16)(\mu V_s^2)$, and is essentially independent of the pre-shock density or ambient temperature. For a 100 km s^{-1} shock, $T_s \approx 1.4 \times 10^5$ K. Cooling in this hot post-shock gas occurs primarily by collisional excitation of resonance lines of H, He, carbon and oxygen. The ionizing radiation from this hot zone affects the shock structure in two ways: (1) for $V_s > 110$ km s^{-1}, the pre-shock medium is fully ionized by the radiative precursor; and (2) downstream absorption of the ionizing radiation extends the hydrogen recombination zone and creates a plateau in the temperature and density curves. This plateau occurs at $T \approx 5000$-10,000 K, after $N_H \approx 10^{18}$ cm^{-2}. Finally, at $N_H \approx 5 \times 10^{18}$ cm^{-2}, the ionizing radiation is nearly absorbed, and the temperature is cooled below a few hundred degrees by collisional excitation of infrared fine structure lines of C II (158 μm), O I (63 μm), and Si II (34.8 μm).

b) Grain Motion in Radiative Shocks

The large inertia of dust grains ensures that they will flow unimpeded through the thin collisionless shock and into the hot post-shock gas. Because the grains are charged, they gyrate in the magnetic field. At the shock front, a grain's pre-shock velocity of V_s relative to the front is converted into a gyromotion of $0.75V_s$ about a guiding center drift of $0.25V_s$. The details of the grain motions are determined by the electric field generated by the plasma flow through the magnetic field and by the thermal charging of the grains -- see Shull (1977, 1978). As the magnetic field is compressed downstream together with the plasma, grains are betatron accelerated to higher gyrovelocities by conservation of their magnetic moments, while their guiding center motion is locked to the gas flow. Plasma coulomb and collisional drag forces decelerate the grains; these forces are more effective on small grains, owing to their larger area-to-volume ratios.

Model results show that the large (0.25 μm radius) grains can reach gyrovelocities of about $2V_s$, or 200 km s^{-1} for the canonical shock. The gyromotions of the smallest (<0.01 μm) grains are damped out early in the post-shock layer before reaching the strong cooling zone. Small grains are thus not betatron accelerated to high velocities. Figure 5 shows representative gyrovelocities for large and small grains of different types.

c) Grain Destruction Mechanisms

Large grains gyrating at over 100 km s^{-1} bump into things frequently. Collisions with He nuclei at 100 km s^{-1} carry collision energies of 200 eV, whereas sputtering thresholds for silicates are around 23 eV. The sputtering erodes away the outer layers of large grains, but leaves the inner cores intact. This sputtering is non-thermal, since it is driven by the velocity of the grains striking the He nuclei. Sputtering by H nuclei is much less efficient, contributing only about 10% of the total. In shocks below 200 km s^{-1}, sputtering due to the thermal velocities of H and He is insignificant.

A collision between two grains of comparable size at 100 km s^{-1} velocities will probably vaporize both grains, including their cores. Some fragmentation might occur, but the importance of the fragmentation process is limited by the requirement of matching the observed gas-phase abundances in Fig. 1. Vaporization in grain-grain collisions is dominated by large grains striking medium-sized grains, which are favored because they are more abundant (Mathis, Rumpl, and Nordsieck 1977 -- hereafter MRN). The threshold energies in the center-of-mass frame prevent collisions with the smallest grains from vaporizing large grains.

Shock models (Seab and Shull 1983) show that about 50% of the grain material can be returned to the gas phase in a 100 km s^{-1} diffuse cloud shock, in general agreement with Draine and Salpeter (1979) and Shull (1978). The Seab-Shull results are an improvement over the earlier work since they use a full MRN size and composition distribution to calculate grain-grain collision effects, and because their code allows the shock's cooling structure to be affected by the heavy elements released by grain destruction.

The principal destruction mechanisms in steady-state radiative shocks depend primarily on the betatron acceleration of the grains, and are therefore more effective for large grains. Small grains survive these shocks, but they are preferentially destroyed by thermal sputtering in fast adiabatic shocks.

d) Grain Destruction in Adiabatic Shocks

Shocks with $V_s > 200$ km s^{-1} cannot be treated with the steady-state radiative shock models discussed above. The cooling time for these shocks usually exceeds the expansion time, R_s/V_s, of the generating SNR, so that the time-dependent pressure drop of the expanding remnant must be considered. The effect of the pressure drop is to partially suppress the betatron acceleration of grains. Instead, thermal sputtering in the $>10^6$ K post-shock gas becomes the dominant grain destruction mechanism, as the thermal energy of the shocked gas increases above the sputtering threshold. Grains up to several 100 Å size that survive slower shocks will be destroyed in these fast shocks.

e) Timescales for Grain Destruction

Calculating galactic averages for shock destruction rates is a formidable problem. It involves modeling the occurrence and evolution of supernova blast waves and cloud-cloud collisions in the galaxy, together with models for the ISM structure and grain destruction fractions in shocks. Several authors have attempted this sort of modeling. Dwek and Scalo (1980) find grain lifetimes of 10^9 years, somewhat less than their injection rates of new grains into the ISM. They conclude that heavy element depletions greater than 30% can only explained by grain accretion processes in the ISM. Draine and Salpeter (1979) obtain lifetimes nearer 10^8 years, which makes the requirement of in situ grain growth even stronger. Greenberg (1984) suggests a scenario for grain evolution in the galaxy, but he underestimates the effectiveness of shock destruction.

Seab, Hollenbach, McKee, and Tielens (see abstract, this volume) have undertaken a thorough analysis of the grain history and life cycle in the galaxy. Their preliminary results indicate grain lifetimes slightly over 5×10^8 years, nearly independent of size. Further work may modify this figure, particularly for the large grains.

These grain lifetimes present a problem for silicon depletion, since Si is a major grain constituent which is about 90% depleted in the diffuse ISM (Fig. 3). Since grain injection times are about 10^9 years, such large depletions would seem to require grain lifetimes of 10^{10} years. Three possible explanations for the discrepancy are: (1) grain injection rates are an order of magnitude larger, contrary to observations of the occurrence of supernovae and mass-loss in red giant winds; (2) grain destruction rates are an order of magnitude lower, which seems unlikely at this time; or (3) much of the observed grain mass is formed by some process in the ISM itself. As an example of the last process, we will next discuss grain growth in shocks.

V. GRAIN GROWTH IN SHOCKS

The standard sources for new grains in the ISM are: red giant winds, planetary nebulae, novae, and possibly protostellar nebulae or supernova ejecta. If grains form efficiently in supernova ejecta, then this source dominates red giant winds by a factor of three, with the other sources being less important (Dwek and Scalo 1980). As discussed above, the total injection rates from these sources are inadequate to explain the 90% depletion of Si in the diffuse ISM, given the current best estimate for destruction rates.

Grain growth behind shocks is a speculative field, since there is little data supporting such growth. It is difficult observationally to distinguish newly-grown grain material in a shock from grains swept up from the ambient medium (Dwek et al. 1983). Meyers et al. (1985) present data suggesting that some grain growth has occurred behind a 10 km s^{-1} shock towards ζ Oph; however the difficulty of the observation prevents their conclusions from being compelling.

Grain growth is more likely in low velocity ($V_s < 30$ km s^{-1}) shocks that are inefficient at grain destruction. In fast shocks, the grain velocities are well over sputtering thresholds, and the net effect will be to sputter away rather than add to grain surfaces. It is unlikely that the grains will sweep up much new material after they slow below sputtering thresholds. The plasma coulomb drag peaks when the grain velocity is comparable to the proton thermal velocity, and the gyration of the grain slows rapidly once it drops below its betatron-accelerated peak. However, even in fast shocks, grain growth may occur in the cool dense regions far downstream from the front.

A chemical question arises in this context. Approximately 10^4 hydrogen atoms will strike the grain surface for each atom of a refractory element. It is possible that this much H could inhibit grain growth by occupying all the available binding sites before a heavy element could stick. On the other hand, H_2 formation on grain surfaces could provide a "safety valve", or the ionization state of the heavy elements (C II, Si II, Fe II) and the grain charge could complicate the gas-grain interactions. Evidently further laboratory and theoretical work is needed on these questions.

Two scenarios have been proposed in which grains could form or grow behind fast shocks. The first occurs when a fast shock impinges on a dense cloud. The shock will decelerate quickly, so that the steady state shock destruction rates do not apply. Elmegreen (1981) calculates that the relative forward drift of grains can equilibrate with the deceleration of the shock to maintain part of the grain population at a fixed position behind the shock front where growth is possible. He suggests that centimeter sized grains can grow behind SNR shocks and potentially accumulate enough of the ejecta material to explain the isotopic anomalies observed in connection with interplanetary grains (see Kerridge review in this volume). Alternatively, Dwek has suggested that grains can nucleate and grow in dense clumps of supernova ejecta plowing through a less dense ambient medium. Such newly formed grains will be protected by the density of the clump from destruction by the initial SNR blast wave or from reverse shocks.

These two growth mechanisms can potentially explain the observed isotopic anomalies in meteorites, provided that at least some grains survive long enough in the ISM for incorporation into the solar system. However, none of these growth mechanisms is likely to compensate for the large destruction rates calculated for radiative and adiabatic shocks. Unless substantial changes are made in the grain injection or destruction rates, then a new grain growth mechanism must be found. The best candidate may be grain growth in dark interstellar clouds (Draine 1984).

VI. CONCLUSION

Shock processing plays an important role in the life of a typical interstellar grain. Shocks of 100 km s^{-1} or greater can destroy about 50% of the grain material under appropriate pre-shock conditions of density and magnetic field. The destruction occurs by grain-grain collisions and non-thermal sputtering for steady-state radiative shocks ($30 < V_S < 200$ km s^{-1}) and by thermal sputtering for fast adiabatic shocks ($V_S > 200$ km s^{-1}).

The evaluation of the lifetime of grains against shock destruction depends on models of the ISM structure and on SNR evolution. Results from various authors give lifetimes between 10^8 and 10^9 years, compared to typical injection times for new grains of a few times 10^9 years. These numbers require that a major portion of the interstellar silicon bearing grain material must be formed by grain growth in the ISM. At the same time, the presence of isotopic anomalies in some meteorites implies that at least some grains must survive from their formation in SNRs or red giant winds through incorporation into the solar system. These requirements are not necessarily incompatible.

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FIGURE CAPTIONS

Fig. 1. Depletion of Si as a function of cloud radial velocity, compiled by Cowie (1978). The solid, dashed, and dotted curves show theoretical depletion curves from various authors.

Fig. 2. Normalized $E(\lambda-V)/E(B-V)$ selective extinction curves towards stars associated with SNRs (Seab and Shull 1983), compared to the "standard" interstellar curve of Savage and Mathis (1979). The stars HD 48099 and HD 48434 are near the Mon Loop SNR, while HD 72350 and HD 75821 are in the Vela SNR.

Fig. 3. Depletion correlations of interstellar Si and Fe from a preliminary sample of an IUE abundance survey (Shull and Van Steenberg 1982, 1985). Note the increased depletion, log δ, in lines of sight with higher mean density, $N(H_{tot})/r$.

Fig. 4. Temperature and density structure for a shock with $V_s = 100$ km s^{-1}, pre-shock density $n_o = 10$ cm^{-3}, and magnetic field $B_o = 1$ μG. Behind this shock, the thermal pressure, nT, is nearly constant, and the column density $N_H = n_o V_s t$ in cm^{-2} is a factor of 10^8 greater than the time t in seconds.

Fig. 5. Grain velocities behind a 100 km s^{-1} shock (Seab and Shull 1983) for two grain sizes and for both silicate and graphite composition. The large grains (0.25 μm) experience betatron acceleration and reach large velocities, while the small grains (0.01 μm) slow down rapidly by collisional and plasma coulomb drag.

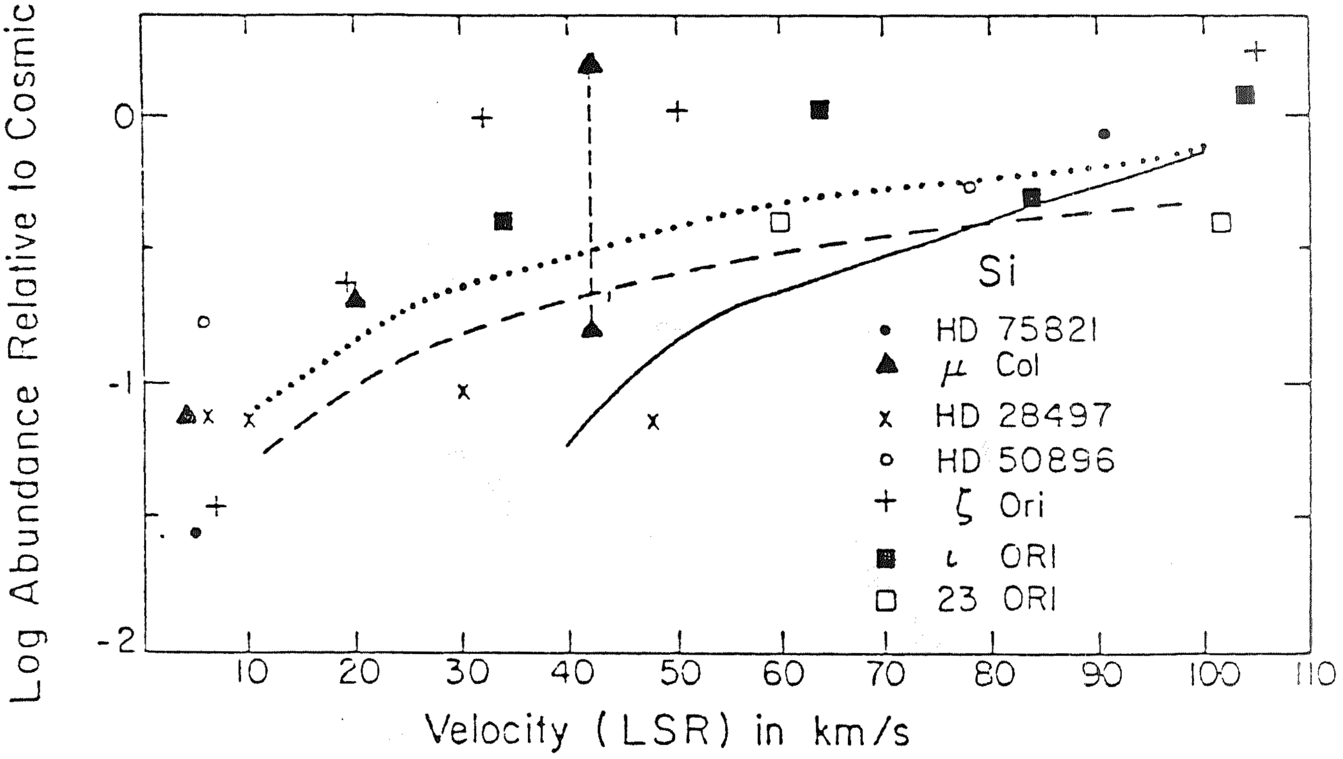
Log Abundance Relative to Cosmic
0
-1
-2
10
20
30
40
50
60
70
80
90
100
110
Velocity (LSR) in km/s
Si
● HD 75821
▲ μ Col
x HD 28497
○ HD 50896
+ ζ Ori
■ ι ORI
□ 23 ORI

Fig. 1

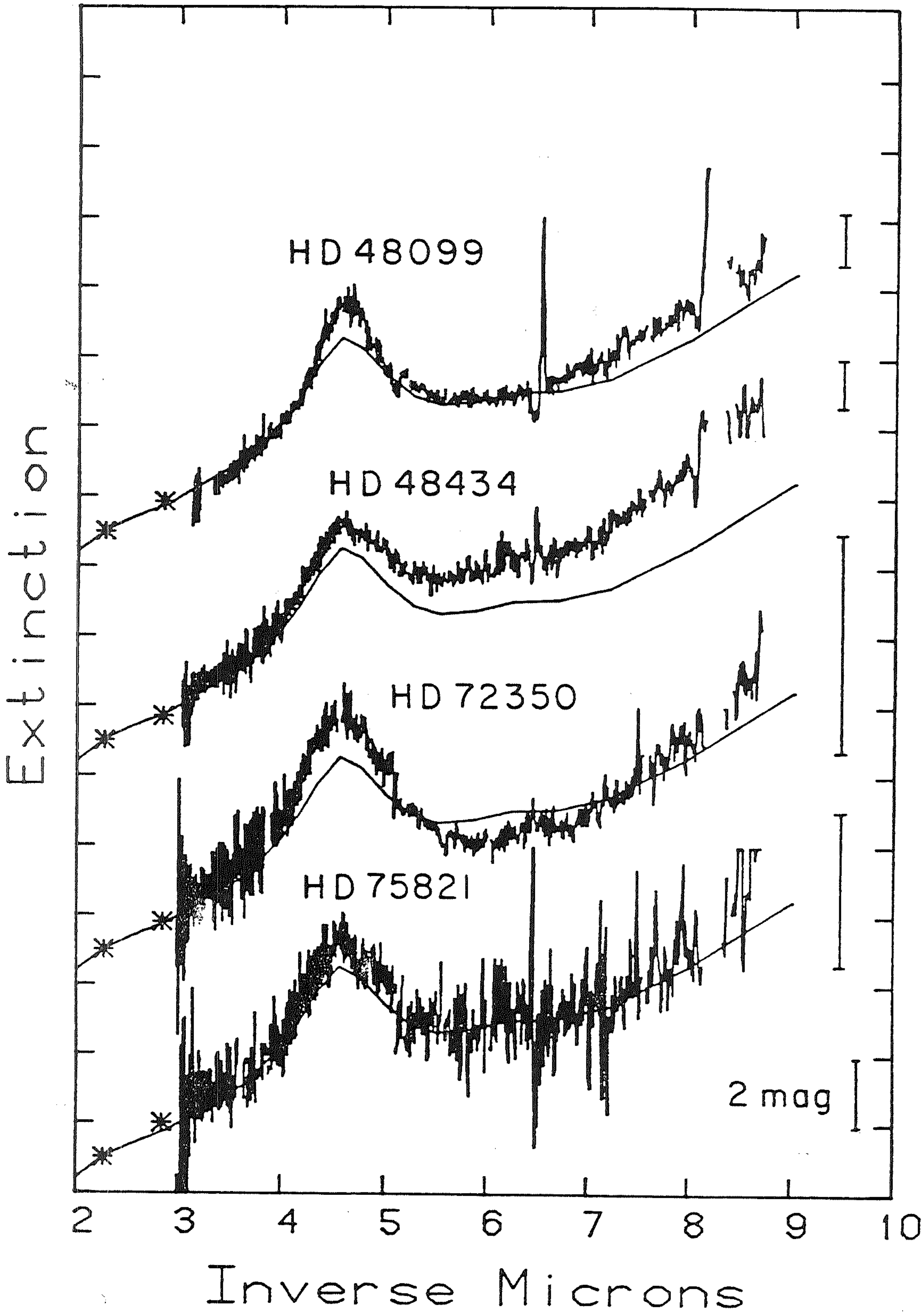
HD 48099
HD 48434
HD 72350
HD 75821
2 mag
Extinction
2
3
4
5
6
7
8
9
10
Inverse Microns

Fig. 2

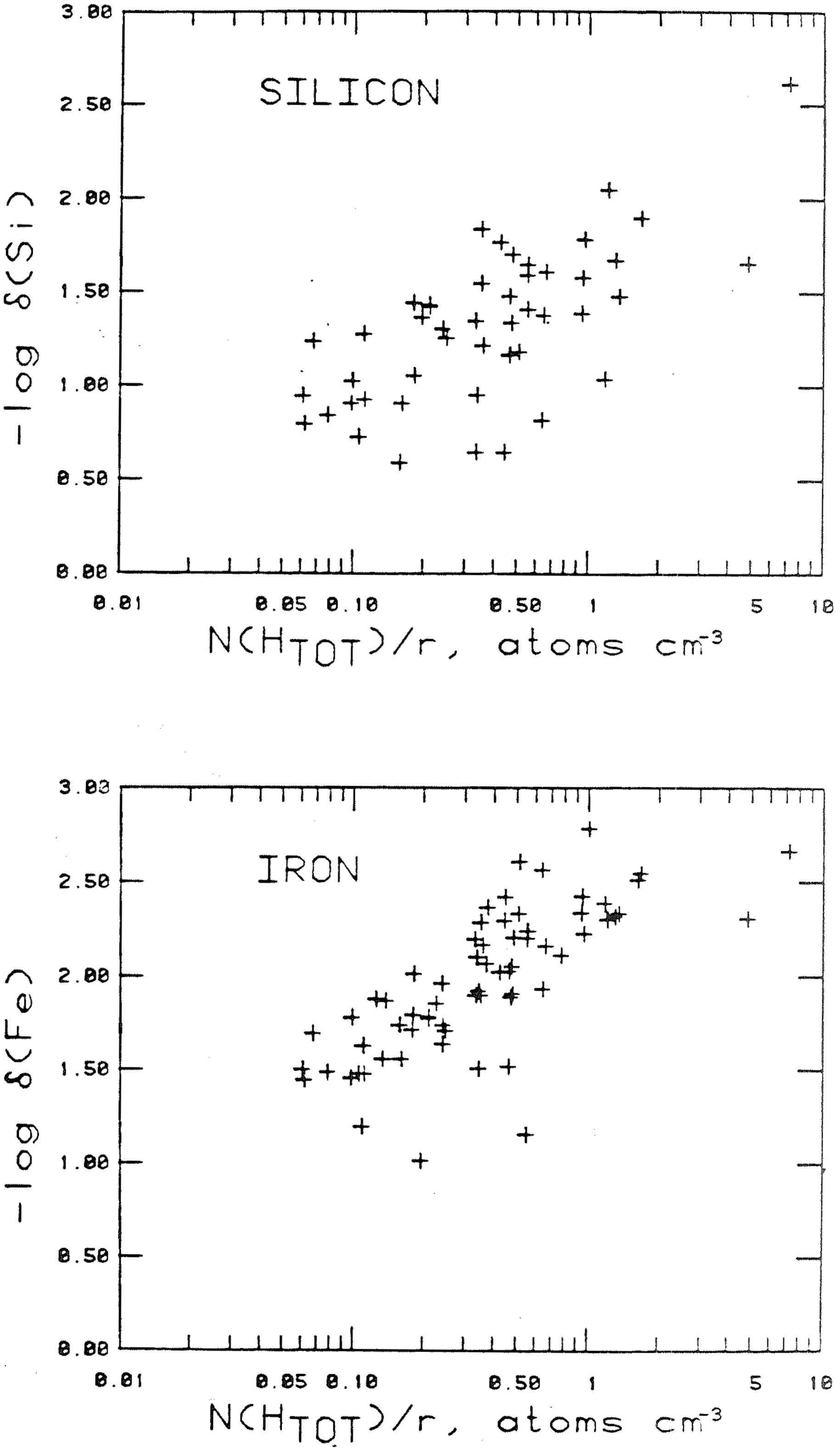
SILICON
-log δ(Si)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.01
0.05
0.10
0.50
1
5
10
N(H$_{TOT}$)/r, atoms cm^{-3}
IRON
-log δ(Fe)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.01
0.05
0.10
0.50
1
5
10
N(H$_{TOT}$)/r, atoms cm^{-3}

Fig. 3

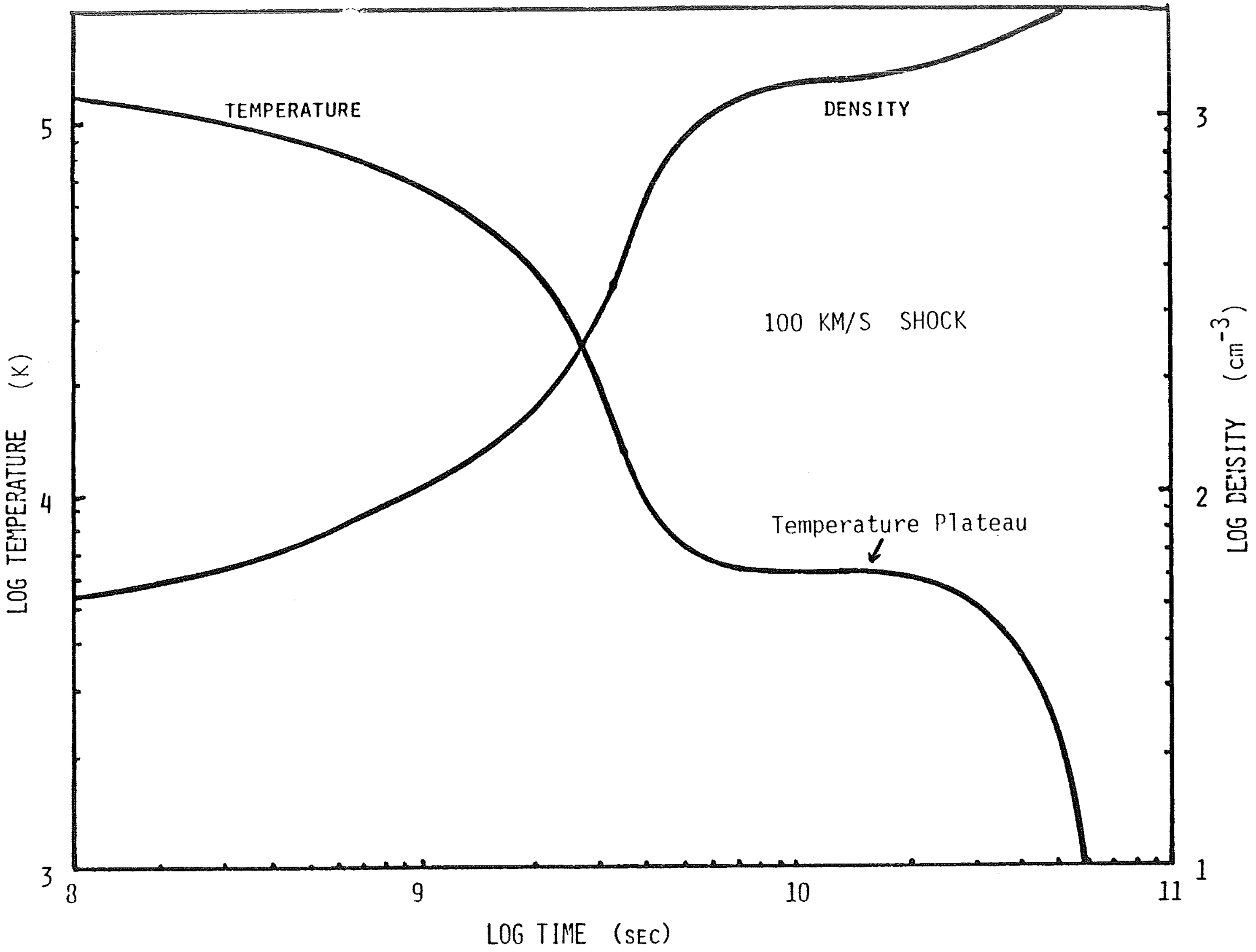
TEMPERATURE
DENSITY
100 KM/S SHOCK
Temperature Plateau
LOG TEMPERATURE (K)
LOG DENSITY (cm^{-3})
LOG TIME (SEC)
3
4
5
1
2
3
8
9
10
11

Fig. 4

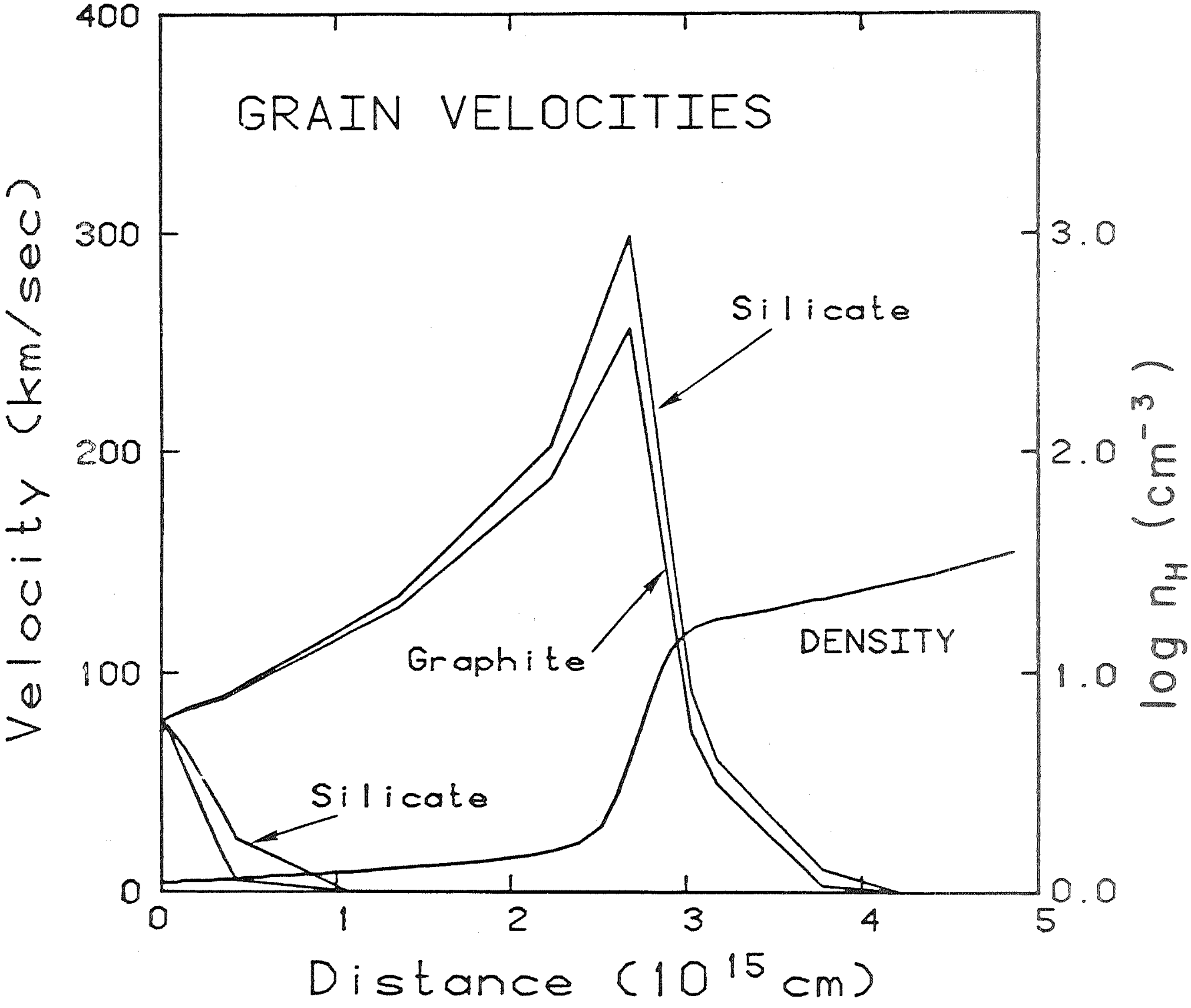
GRAIN VELOCITIES
Silicate
Graphite
DENSITY
Silicate
Velocity (km/sec)
400
300
200
100
0
log n_H (cm^{-3})
3.0
2.0
1.0
0.0
0
1
2
3
4
5
Distance (10^{15} cm)

Fig. 5