Dust Destruction Processes

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Observed Distribution of Dust

- Dust is injected into the ISM on timescales of a few 10^9 years by stellar winds and SN.
- Observations are well-matched by assuming grain size distribution is a power law (MRN).

$$dn_{\mathrm{gr}} = Ca^{-3.5} n_{\mathrm{H}}\, da, \quad a_{\min} < a < a_{\max}$$

- How do dust destruction processes affect the distribution?

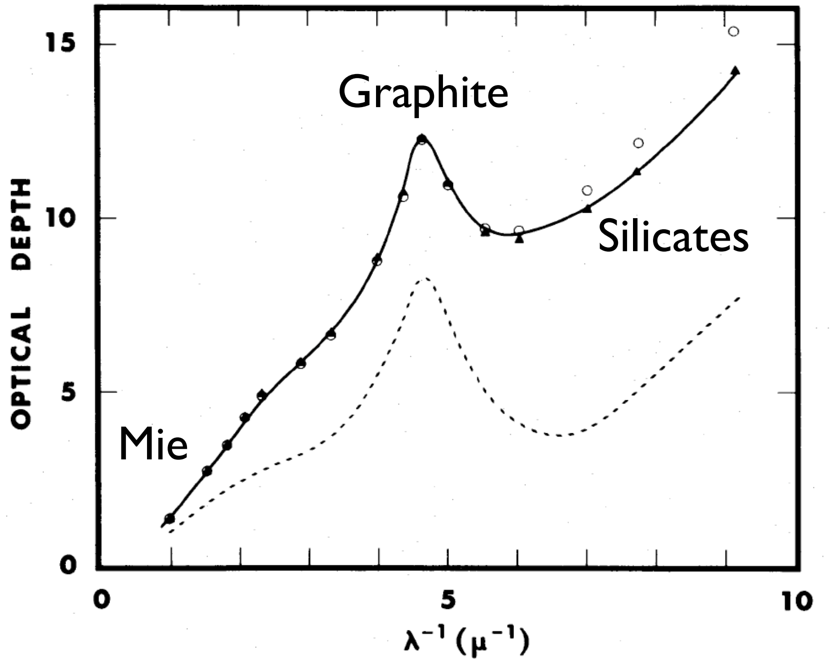


FIG. 4.—Optical depths, for column densities of 10^{22} H atoms cm^{-2}, versus inverse wavelength. *Solid line:* observed by OAO. *Triangles:* the extinction of (C + Ol) mixture of Fig. 2. *Dashed line:* the contribution of graphite to the extinction. *Dots:* a mixture of graphite and olivine, $n(a) \propto a^{-3.5}$, $0.005\ \mu\mathrm{m} < a < 0.25\ \mu\mathrm{m}$, forced to fit at the maximum of the "bump" at 4.6 $\mu\mathrm{m}^{-1}$.

Mathis, Rumpl, & Nordsieck 1977

How is Dust Destroyed?

- Photon-Grain Interactions
- Gas-Grain Collisions (Sputtering)
  - Thermal
  - Non-thermal
  - Primary mechanism for converting dust back into gas.
- Grain-Grain Collisions
  - Vaporization
  - Shattering
- Cosmic Rays
  - Low-energy only (Rutherford scattering)

Photon-Grain Interactions

- Low-energy photons (radio and IR) are weakly absorbed by dust (wavelength > dust size).
- Medium-energy photons (visible to UV)
  - Below work function energy: Absorbed readily by dust, radiation is reprocessed to lower wavelengths.
  - Above work function: Free electrons are ejected by dust grains and heat the ambient gas.
  - Does not destroy dust.
    - Exception: Volatile materials like H_2O.
- High-energy photons (extreme UV and up)
  - Direct heating → ejection of surface atoms.
  - Fast removal of electrons can result in coloumb explusion of ions.

Gas-Grain Collisions (Sputtering)

- Dust grains are reduced in size by the removal of surface atoms/molecules by the impacts of individual gas atoms.
- This directly converts matter from the dust phase to the gas phase.
- Gas must be hot enough and dense enough for this process to destroy dust.
- These conditions are mostly seen in the wakes of SN blast waves, although any dense environment with $\mathrm{T} > 10^6$ suffices.

Sputtering Yields

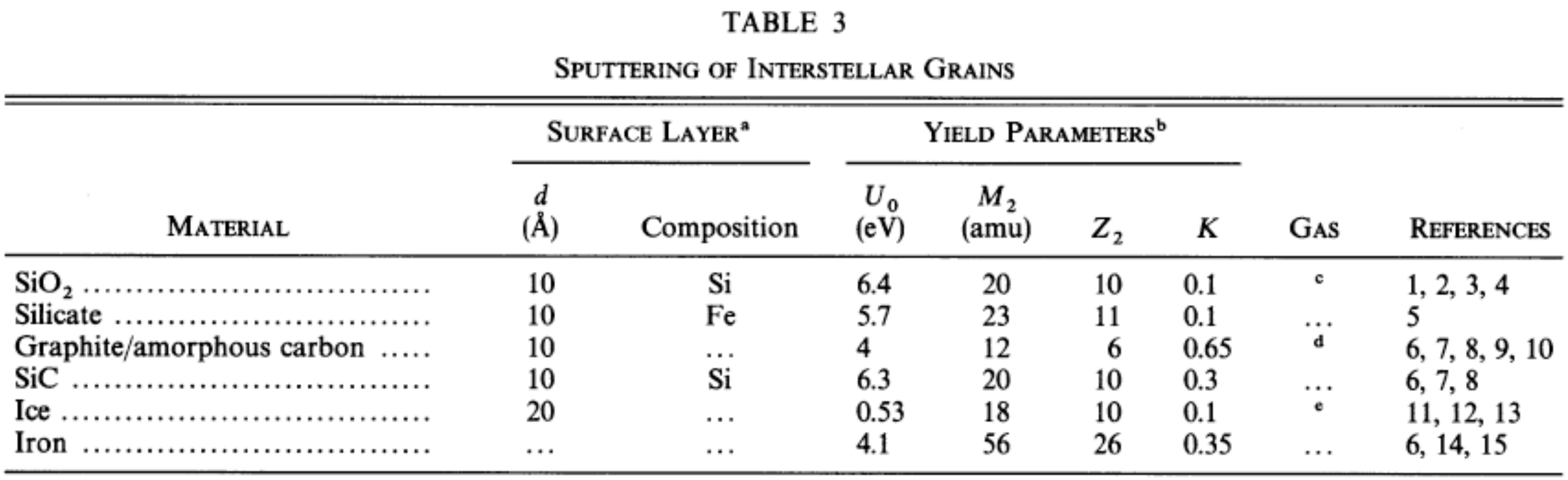


TABLE 3

SPUTTERING OF INTERSTELLAR GRAINS

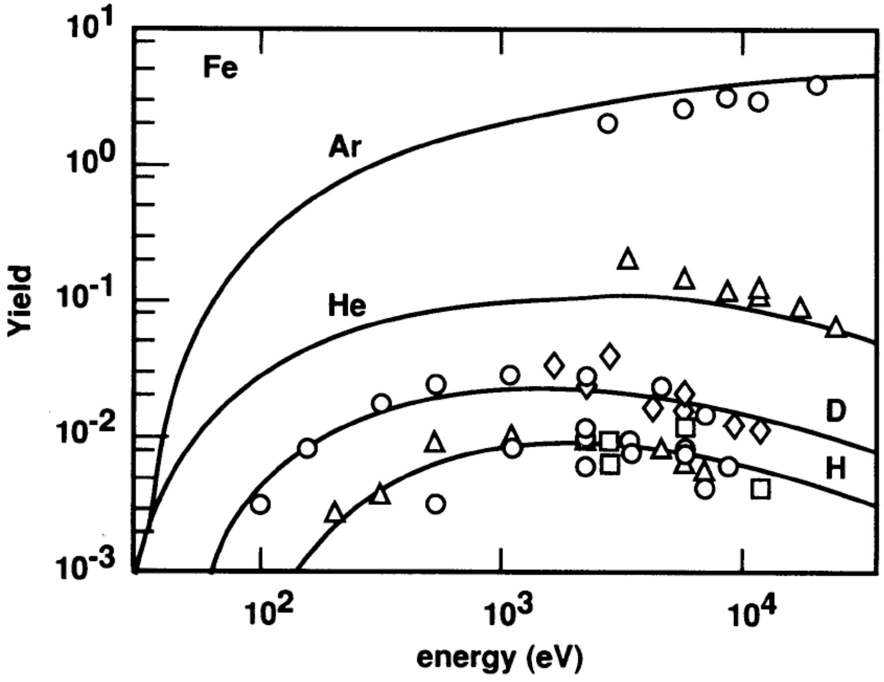
	SURFACE LAYER[a]		YIELD PARAMETERS[b]					
MATERIAL	d (Å)	Composition	U_0 (eV)	M_2 (amu)	Z_2	K	GAS	REFERENCES
SiO_2	10	Si	6.4	20	10	0.1	[c]	1, 2, 3, 4
Silicate	10	Fe	5.7	23	11	0.1	...	5
Graphite/amorphous carbon	10	...	4	12	6	0.65	[d]	6, 7, 8, 9, 10
SiC	10	Si	6.3	20	10	0.3	...	6, 7, 8
Ice	20	...	0.53	18	10	0.1	[e]	11, 12, 13
Iron	...	...	4.1	56	26	0.35	...	6, 14, 15

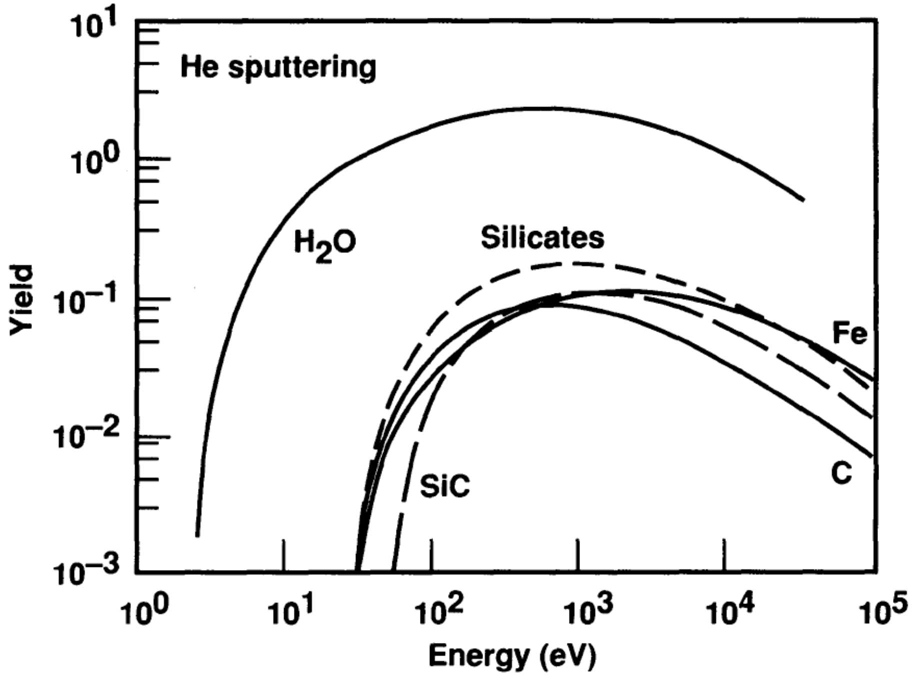
$$Y(E) = 4.2 \times 10^{14} \frac{\alpha S_n(E)}{U_0} \text{ atoms per ion}$$

$$< Y_\mathrm{i}(E) > \equiv 2 \int_0^{\pi/2} Y_\mathrm{i}(E,\theta) \sin(\theta) \cos(\theta) d\theta$$

(Tielens 1994)

Sputtering Yields (cont.)

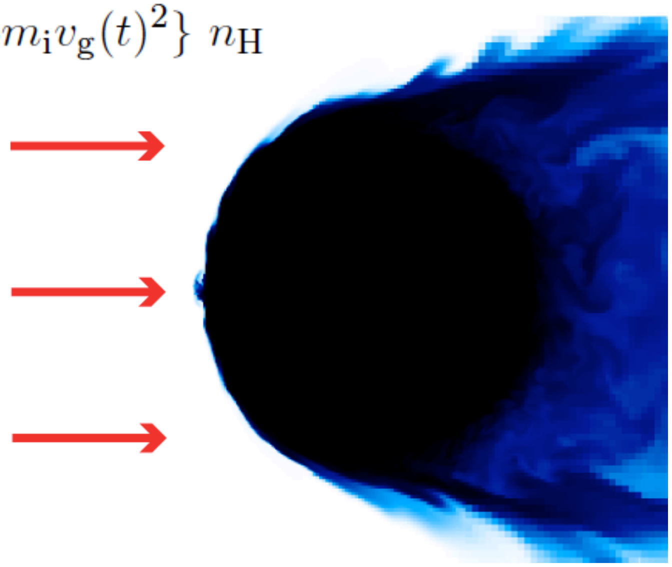




Non-Thermal Sputtering

- Happens when $v_{\rm dust} > v_{\rm gas}$.
- Dust can essentially be treated as moving w/ respect to a fixed background of gas.
- Does the amount of non-thermal sputtering depend on grain size?

$$\frac{da}{dt} = \frac{m_{\rm sp}}{2\rho}\, v_{\rm g}(t) \sum_{\rm i} A_{\rm i} < Y_{\rm i} > \{E = 0.5 m_{\rm i} v_{\rm g}(t)^2\}\; n_{\rm H}$$



SN Blast Waves

(Shu: Gas Dyn.)

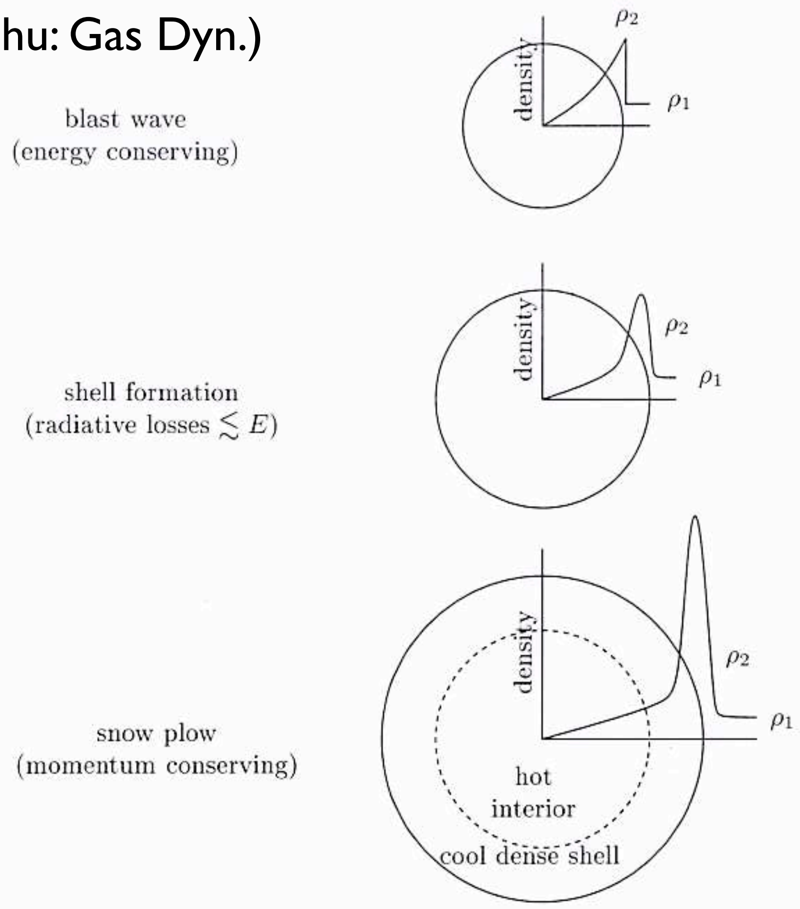


FIGURE 17.4
The transition from the blast-wave phase (energy conserving) to the snow-plow phase (momentum conserving) phase in the evolution of a supernova remnant.

- Sedov-Taylor blast wave solution.
    - Free-expansion phase.
    - Adiabatic phase.
    - Isothermal phase.

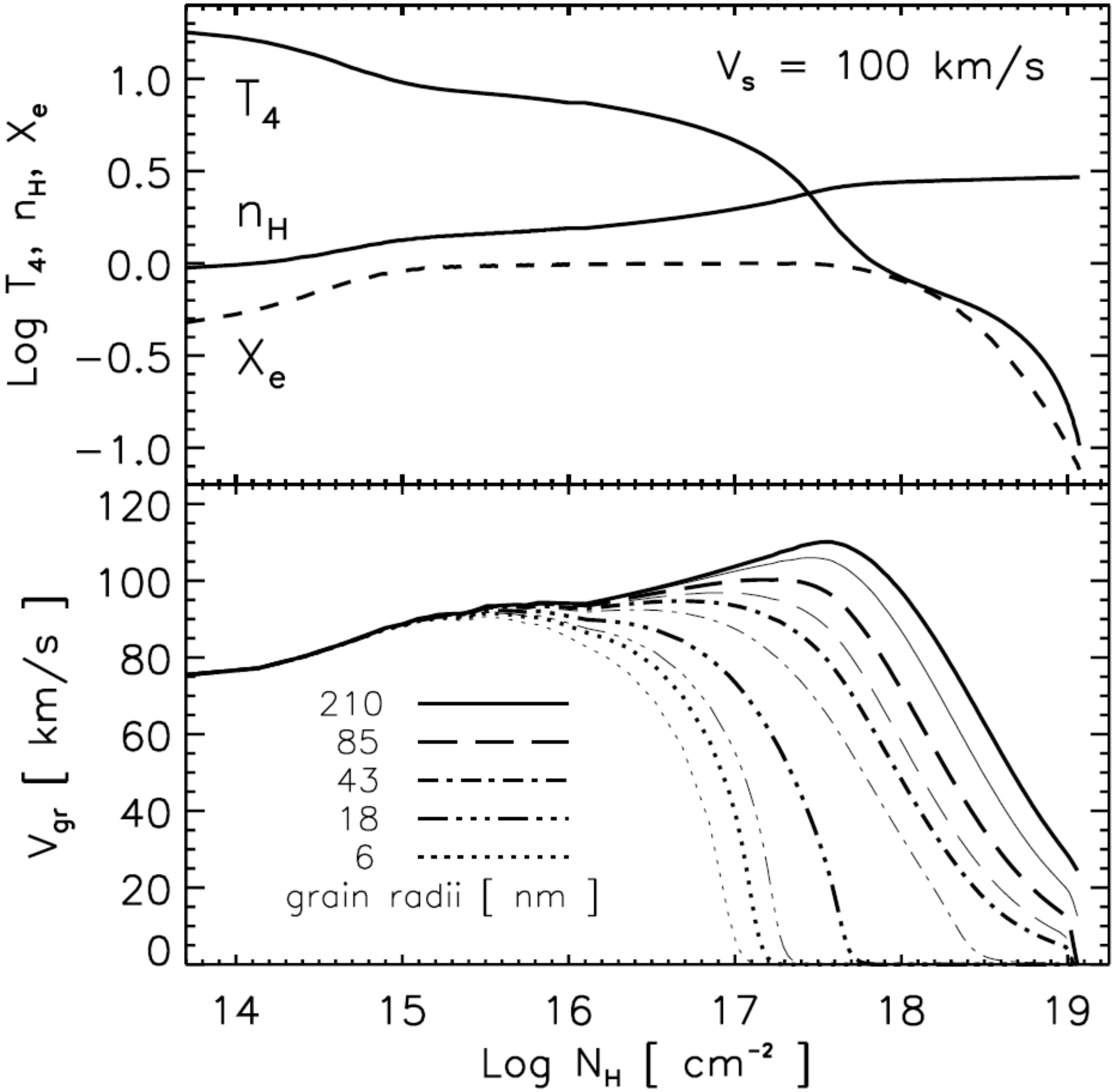
Betatron Accleration

- Shocked gas behind a SN blast wave in isothermal phase quickly cools via radiation.
- As the gas cools, it compresses.
- The magnetic energy density increases.
- The resulting $\partial B/\partial t$ leads to the acceleration of particles, this is known as "betatron" acceleration.
- Grains energy scales with magnetic energy density (McKee 1987).

Drag Forces on Accelerated Grains

- Grains are decelerated primarily by collisional forces.
- These forces are proportional to grain size and inversely proportional to grain mass, $F_D \propto (a\rho)^{-1}$.
- Therefore, larger dust grains are harder to slow down and will have greater average velocities.
- Non-thermal sputtering will destroy these grains preferentially.

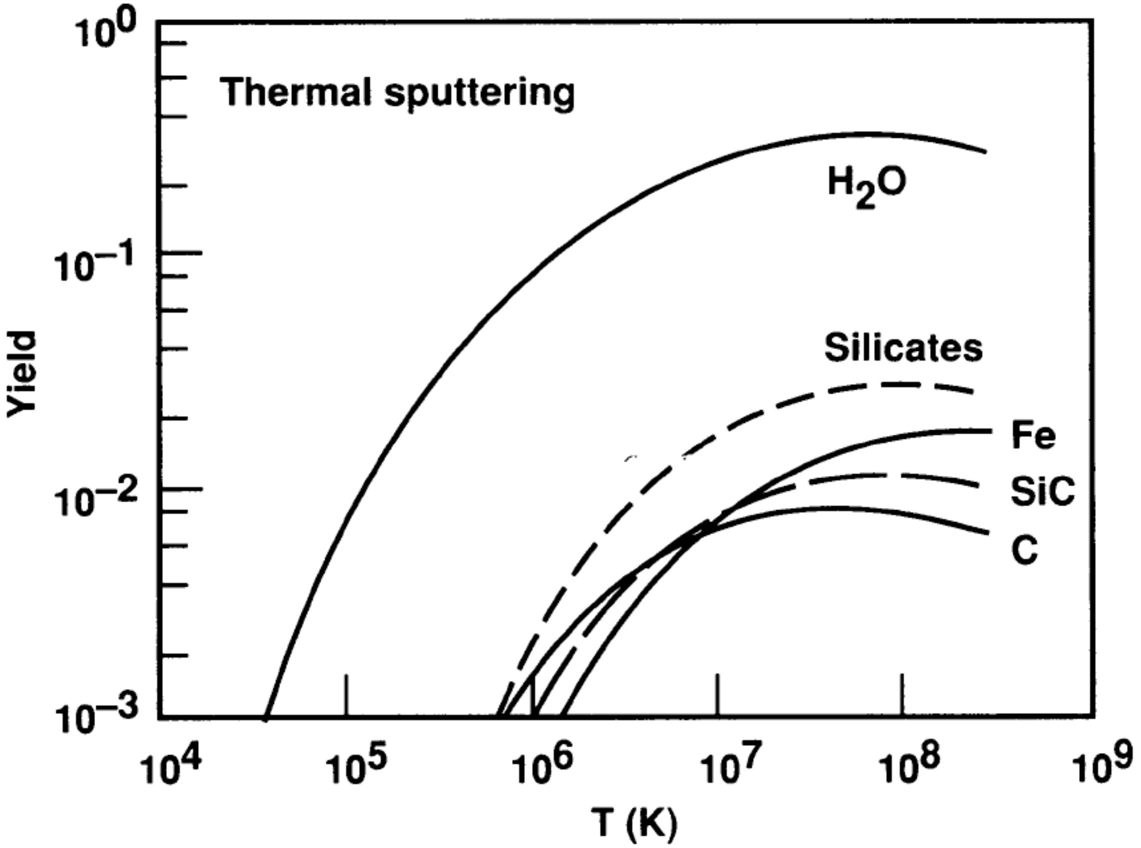
Resulting Velocity Distribution



Thermal Sputtering

- Happens when $v_{\rm gas} > v_{\rm dust}$.
- Dust velocity relative to background gas is irrelevant; therefore this process affects grains of all sizes equally.
- Since dust moves at the shock speed, $v_{\rm gas} > v_{\rm shock}$ which corresponds to $T_{\rm gas} > 10^6$ K.
- Only effective at large shock velocities (>150 km/s).

Thermal Sputtering Yields



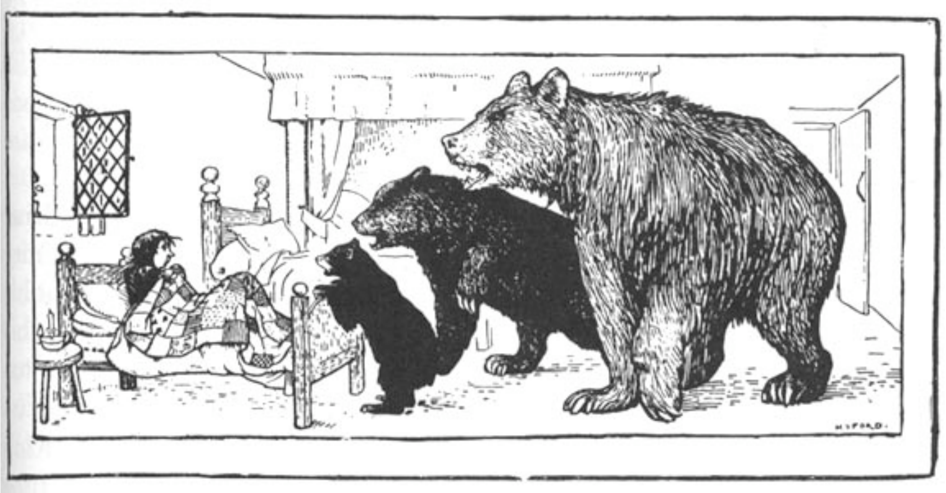
$$\frac{da}{dt} = \frac{m_{\rm sp}}{2\rho} \sum_{\rm i} A_{\rm i} \; < Y_{\rm i} v_{\rm i} > \; n_{\rm H}$$

Where Do We Sputter?

- ISM is modeled as a three-phase medium.
  - Hot Intercloud Medium (HIM)
    - 5×10^5 K, 0.003 cm^{-3}
    - 70-80% filling factor
  - Warm Intercloud Medium (WIM)
    - 10^4 K, 0.25 cm^{-3}
    - 30% filling factor
  - Cold Neutral Medium (CNM)
    - 80 K, 40 cm^{-3}
    - 2-4% filling factor
- In which phase is the dust primarily destroyed?

Goldilocks and the Three ISM Phases

- HIM is too barren, gas-grain interaction is rare.
- CNM is too cold, gas cannot liberate surface atoms.
  - SN shocks propagate very slowly through this medium, minimal Betatron and post-shock $T \propto v_{\rm sh}^2$.
  - Also, very small covering fraction.
- WIM: Juuuuust right…
  - SN shocks propagate quickly and heat gas significantly.
  - Gas is dense enough to destroy dust quickly.



Can the cold phase protect dust?

- 90% of the mass in the ISM is in the cold phase.
- And since we've established that dust destruction is difficult in the CNM, most of the dust should safe, right? NO!
- O star formation will reionize cold clouds on timescales of a 3×10^7 years (McKee 1989).
  - This cycles dust from CNM → WIM!
  - Timescale is much shorter than dust production timescale.

Grain-Grain Collisions

Colliding dust grains
(not to scale)

- Dust grains can be vaporized by collisions with other grains.
- Grain vaporization is a dust destruction process since dust is converted into gas.
- Grain shattering is NOT a destruction process since only the size distribution of grains is altered.
- Grain-grain collisions are only important for large shock velocities (>50 km/s).

Grain Collisions at Different Velocities

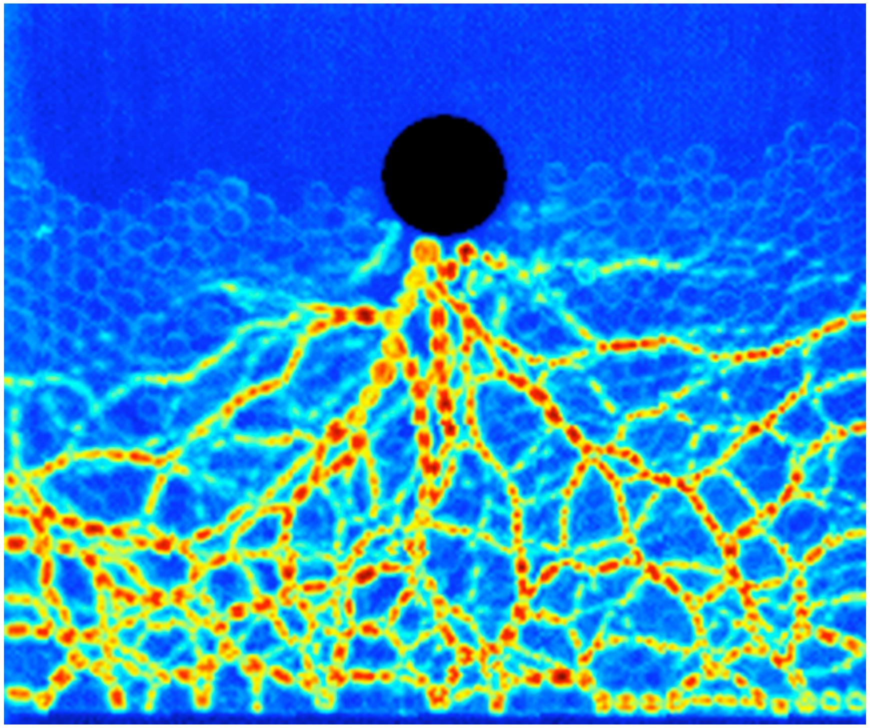
- At velocities of ~m/s grains can stick together (grain growth process).
- ~20m/s grains bounce off of each other.
- ~100m/s aggregate grains can be disassociated.
- ~1km/s homogenous grains can be shattered.
- ~20km/s grains can be vaporized.
  - Only the smaller body is vaporized unless the masses are comparable.

Grain Vaporization

- Grain vaporization is less effective than sputtering for all but the largest grains.
- Gas yield from a collision is maximized when the colliding grains are similar in size.
- For large grains, these events are rare since the number density of large grains is small.

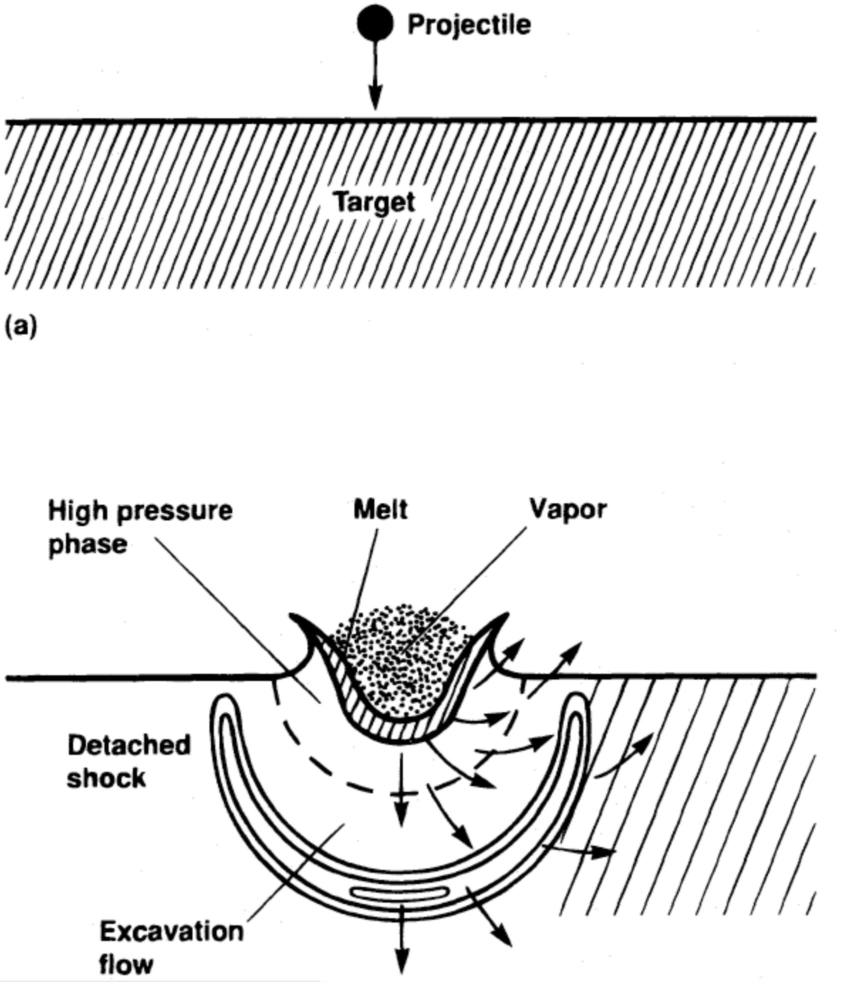
Grain Shattering

- Threshold pressure required to shatter a dust grain is roughly $1/10^{\text{th}}$ the critical vaporization pressure.
- Large grains can therefore be shattered by small grains; these events are much more common than large-large collisions.



Crater Formation

- Small projectile on large grain.



What happens to the large grain?

- A shock wave travels through the large grain
  - At first, the response of shocked material is “elastic”, stress and strain are linearly related.
  - The Hugoniot shock jump conditions increase the pressure beyond a critical value, the response of the material is now “plastic,” stress and strain are independent.
- An excavation flow form behind the shock wave as rarefaction waves propagate from the free surfaces.

Dust to Dust

- If the shock pressure exceeds the tensile strength of the material, dust fragments are ejected from the excavation flow region.
- Half of the crater volume is ejected.
- The size of range of these fragments is

$$a_{f+} = \frac{R_c(\pi/2)}{2z} \qquad a_{f-} = a_{f+}\left[\frac{R_v}{R_c(\pi/2)}\right]^{z+1}$$

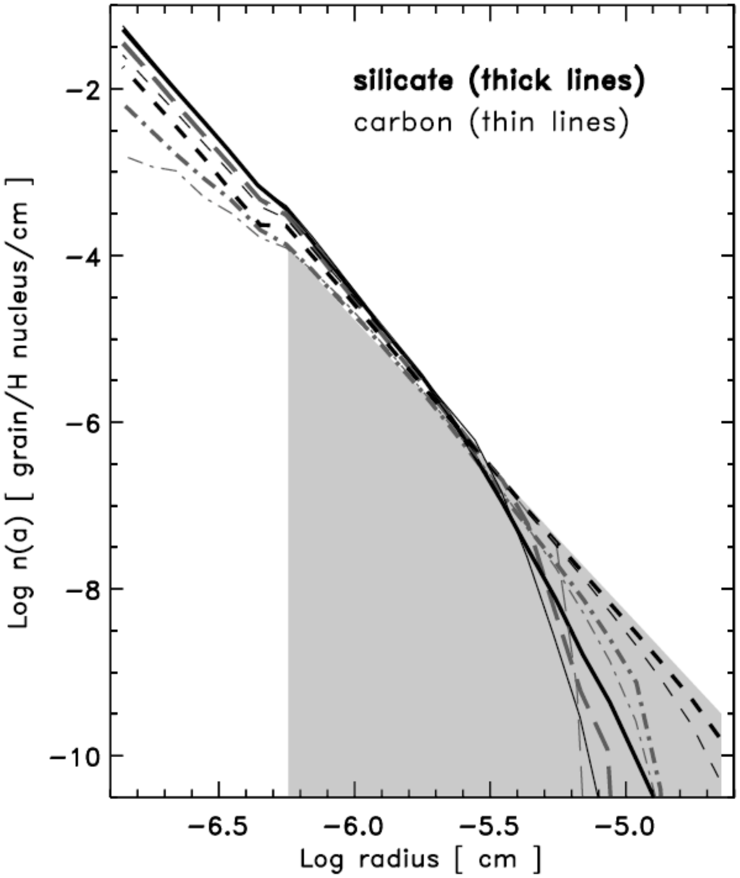
- $z = 3.4$, $a_{f+} = 0.15\ R_c$, $a_{f-} = 0.0045\ R_c$
- Size distribution of fragments $n(a)da \propto a^{-3.3}da$.

Catastrophic Destruction

- Happens when the post-shock pressure is comparable to the tensile strength of the material.
- As the shock wave reaches the backside of the target grain, "spallation" occurs.
- Since shattering is easy, the largest grains (~500 Å) only have lifetimes of 10^7 years!

Resultant Distribution

- Power law has a very similar slope (-3.3), but the distribution has been shifted to smaller grains.
- Notable depletion of large grains.



Timescale of Destruction

- Including the effects of sputtering and vaporization only, the time scale for dust destruction is ~3 × 10^8 years.
- If we include shattering, this time scale is increased to ~5 × 10^8 years.
- Remember that dust creation rate is ~3 × 10^9 years!
- Therefore, there must be some process that allows the observed dust depletion to be maintained.

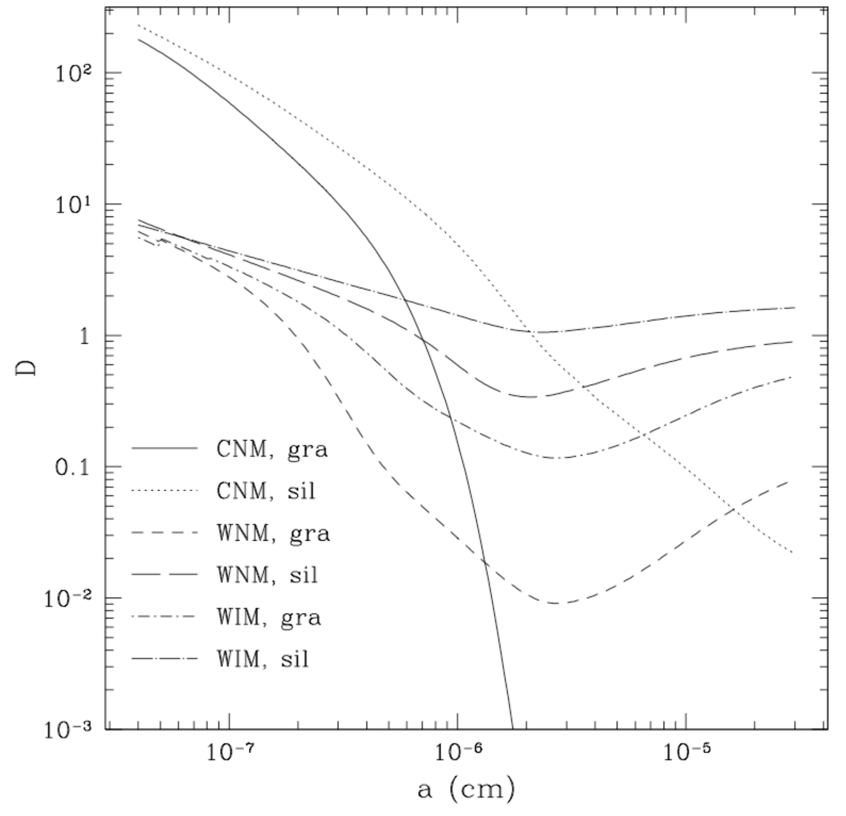
After Destruction

- Re-accretion onto small dust grains?

$$R_{\mathrm{arr}} = \int_0^\infty dv \left(\frac{2}{\pi}\right)^{1/2}\left(\frac{m}{kT}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT}\right)\pi b_{\mathrm{max}}^2(v) v n$$

$$b_{\mathrm{max}}(v) = a\left[1 + \left(\frac{4Z_i^2 e^2}{mv^2 a}\right)^{1/2}\right]^{1/2}$$

$$\tau_a^{-1} \equiv -\frac{1}{n}\frac{dn}{dt} = A^{-1/2} s \left(\frac{8\pi kT}{m_p}\right)^{1/2} \int da\, a^2 \frac{dn_{\mathrm{gr}}}{da} D(a)$$



Coagulation?

- Perhaps dust grains accrete a small mantle of volatile material (like ice) that has a larger “sticking” coefficient than graphite/silicates.
- UV processing of icy surfaces can lead to organic compounds that act like a glue to help grains coagulate.
- These grains have low specific densities and thus are more resistant to Betatron acceleration.
- This effect not enough by itself to explain observed dust depletion.

Conclusion

- Sputtering and grain vaporization are the two mechanisms that move metals from dust phase to gas phase.
- Grain shattering destroys large grains, but actually helps keep metals in the dust phase.
- The timescale of dust destruction is short compared to the dust creation timescale, this suggests an efficient dust accretion/coagulation mechanism.