PC4691 – Frontiers of Astrophysics – Interstellar Dust

Lectures 9&10
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Grains in Cosmic History

- AGB stars are typically very old $\left(10^{10} yr\right)$.
- Where did grains come from in the early universe?
- The obvious source is supernovae
- No agreement that SN are even a net source at current epoch
- Evolutionary models show that they must have been in the early universe

Observations of Dust in Supernovae

- Observations of SN1987A at 10 microns
  - Dust forms after only 460 days
  - $0.23 M_{\odot}$ formed between 460 & 730 days
- Bolometric observations of young remnants with SCUBA
  - Remnants centuries old: cold dust 400, 800 μm.
  - So far, good results for Kepler (~500 years old), Cas. A (~a few thousand years old)
  - Derived dust mass of $2-5 M_{\odot}$ in Kepler.

Dust Processing

- Accretion, Sputtering, Heating, Collisions
- Single particle collisions give accretion or sputtering
- Most colliding particles will be H, He and e.
- Important parameter: surface energy ($7.4 eV$ for C_{gr} - graphite [an organized carbon molecule])
- Particles with $E < E_{surf}$ won't sputter
- Cold clouds $\left(< 5000 K\right)$ have no thermal sputtering
- Non-thermal sputtering mostly in shockwaves.

Heating and Cooling

- Cooling by thermal radiation (in IR, mm, sub-mm)
- Heating by starlight, X-rays and cosmic rays, chemistry
- If heating dominated by radiation, energy density $U(\lambda)$, then in the steady state the heating rate equals the cooling rate.
- $c\int_0^{\infty} Q(\lambda) U(\lambda) d\lambda = 4\pi \int_0^{\infty} Q(\lambda) B\left(\lambda, T^{dust}\right) d\lambda$
- $Q(\lambda)$ is the efficiency.
- Dust temperature, T_{dust}, from solution of integral equation
- Heating term for cosmic rays has the same form
- Additional (different) terms for gas particles, etc.

Accretion Rate

- For one projectile species, j, at one speed, v_j

- $\left(\frac{dM}{dt}\right)_{j,v_j} = n_j m_j v_j \sigma(M) S_{v_j} f(v_j) dv_j$
- S is the "sticking probability".
- One species at all speeds and angles
- $\left(\frac{dM}{dt}\right)_j = n_j m_j \oint \int_0^\infty v_j \sigma(M, v_j) S_{v_j} f(v_j) dv_j d\Omega$
- Spherical grain $\sigma(M, v_j) = \pi b^2(v_j)$, and Maxwellian speeds

  $f(v_j) = \left(\frac{m_j}{2\pi kT}\right)^{3/2} e^{-\frac{m_j v_j^2}{2kT}} v_j^2 \sin\theta$
- $\frac{dM}{dt} = \sum_{j=1}^{J} 4\pi^2 n_j m_j \left(\frac{m_j}{2\pi kT}\right)^{3/2} \int_0^\infty v_j^3 e^{-\frac{m_j v_j^2}{2kT}} b^2(v_j) S(v_j) dv_j$

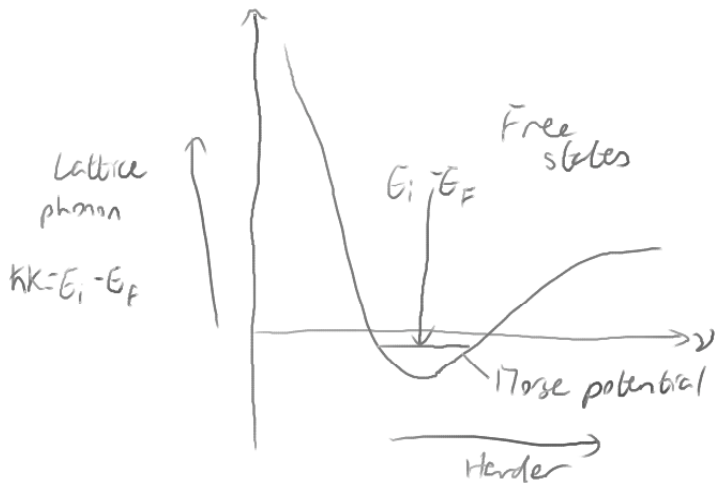
Low energy regime

- Important parameter: surface energy γ $\left(\gamma_{C_{gr}} \sim 7.4eV\right)$
  - About the energy needed to eject an atom from the surface
- Projectiles with $E < \gamma$ won't sputter
- All cold clouds $(< 5000k)$ have no thermal sputtering
- Shock and cosmic ray sputtering
- Thermal and thermochemical absorption
  - These two points are the main erosion processes in cold material
- Accretion only regime

Theory

- Fully QM theory by Leitch-Devlin M.A. & Williams D.A., Royal Astronomical Society, Monthly Notices, vol. 213, March 15, 1985, p. 295–306.

  Calculate $S(E)$ - sticking probability



  Projectile energy released to gain free states.

  Lattice phonon $\hbar k = E_i - E_f$
- 4 lattices C_g, SiO_2, C_{gr} and H_2O layer, MgO

- $S\uparrow$ for soft lattice, chemisorbed projectile
- Peak S typically at around $20 \to 50k$
- $S\uparrow$ as $T_{gr}\uparrow$ (higher T_{gr} gives richer photon spectrum)
- Typical curve shape.

Sputtering

- Sputtering tends to replace grain atoms with projectiles
- Typical yields rarely $>100\%$, but H, He can diffuse out
- Sputtering in SFR outflows: non-thermal
- Sputtering in SNR shocks: mostly thermal
- In ISM, grains are slowly eroded
- SNR gas is metal enriched: may be net embedding
- Tendency to embed is enhanced by organic mantle.

Higher Energy Collisions

- When significant number of projectiles have $E > \gamma$, the projectiles can penetrate the grain. There are three regimes:

- Heavy ions cause localized spikes near surface – give up their energy quickly.
- Tielens (1997) obtains a "universal sputtering law"

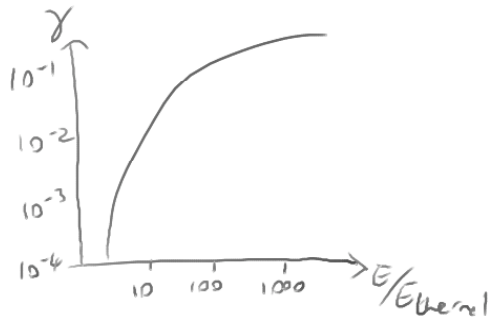
  $$\gamma(E) = \frac{4.2\times10^{14}}{\gamma}\alpha\sigma_N(E) \text{ atoms } (ion)^{-1}$$

  where $\sigma_N(E)$ is the nuclear stopping cross-section in $erg\,cm^{-2}$

  $\alpha\sigma_N(E)$ determines the deposited energy.

  $$\alpha = 0.3\left(\frac{M_{target}}{M_{projectile}}\right)^{2/3}$$

- Ignores electron stopping – convection near γ
- Ignores grain sizes – transmission loss
- Much work only uses $\theta = 0$.



Grain-Grain Collisions

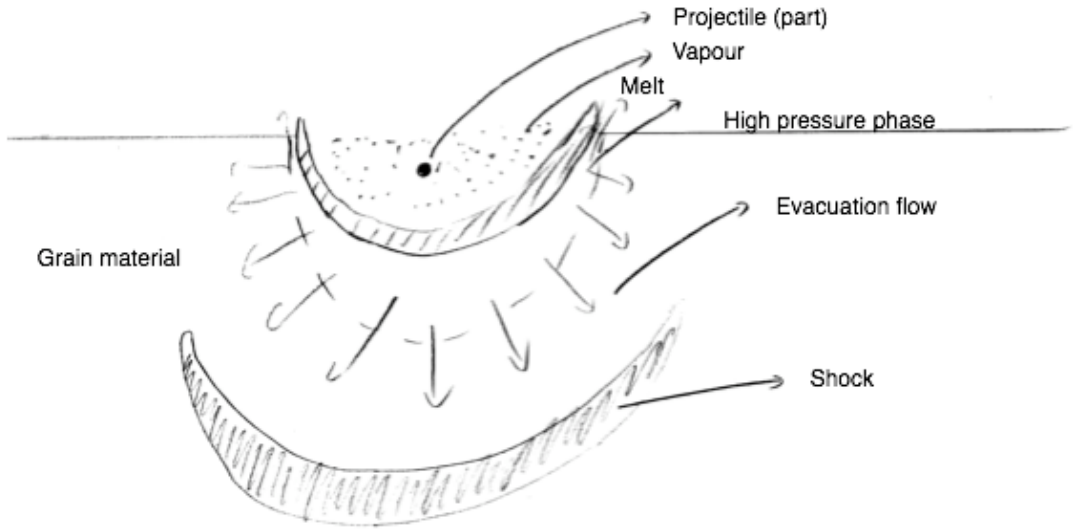
- Almost certainly accumulative if $v_{rel} < c_o$
  v_{rel} is the relative velocity in the collisions, c_o is the sound speed in the mineral.
- Thermal speed of grain
  $$v_{th} \sim 1.6\left(\frac{T_{100}}{N_H}\right)^{1/2} kms^{-1}$$
  T_{100} is the temperature in units of 100k. N_H is the total number of protons or neutrons in the grain.
- Typical molecular cloud grains (the coldest part of the ISM) have $v_{th} << 1kms^{-1}$.
- Shattering velocities $(> c_o)$ for common dust materials:

Material	c_o	**Catastrophic Destruction**
C_{graph}	$1.2kms^{-1}$	$75kms^{-1}$
H_2O_{ice}	$1.8kms^{-1}$	$115kms^{-1}$
Typical silicate grain		Between these
SiC	$8.8kms^{-1}$	$560kms^{-1}$
$C_{diamond}$	$16.1kms^{-1}$	$1000kms^{-1}$

- Conclusion: there is no shattering in molecular clouds.
- Upper size limit set by cloud lifetime ~ growth time for largest grains: sets $a_{\max} \sim 100\mu m$.
- Only collapse and star formation $(T\uparrow, n\uparrow)$ can allow growth towards planetessimal size.

Fragmenting Collisions

- $v_{rel} > c_o$



If this leads to a cracking of the crystal structure, then the whole grain may fragment.

1. Shock waves propagate into both projectile and target – generates high pressures
2. Shock reaches free surfaces of target:- rarefraction waves travel back into the shocked region, which will relieve the high pressure.
   - Phase changes may follow
   - Target may shatter.

- Tielens et. al. (1994) obtain a semi-empirical formula for the mass compressed to a given normalized pressure. $\phi_1 = \frac{p_1}{\rho_0 c_0^{\,2}}$, corresponding to Mach number M

$$\frac{M}{m_{proj}} = \frac{1+2R(v_s)}{2(1+R)^{16/9}} \frac{1}{\sigma_2^{\,1/9}\sigma_1^{\,8/9}} \left(\frac{M_0^{\,2}}{M_1^{\,2}}\right)^{8/9}$$

M_0 - impact Mach number.

M_1 - final Mach number.

σ_1, σ_2 - parameters of order unity

[“AGGM Tielens” – Figure 2: schematic P, V diagram of a realistic material. With increasing strength of the shock wave …]

- Shock compression can induce many phase transitions
- Isentropic expansion behind shock generates more.
- Any isentrope arriving at $P > P_{crit}$ produces only vapour.
- Partial vapourization needs ~ 2 x binding energy. Complete vapourization requires ~ 3 x binding energy.
  For a typical silicate, $E_{bind} \sim 1.7 \times 10^{11} erg\ g^{-1}$.

Fragmenting collisions – continued

- For many materials, the relation between shock velocity and the velocity of the shocked material is unclear. $v_{shock} \sim c_o + sv_1$
- The jump condition, $\frac{v_1}{v_s} = \frac{P_1}{\rho_0 v_s^{\ 2}}$ then gives a relation between ϕ_1 and M_1:

  $M_1 = \frac{2\phi_1}{1+\left(1+4S\phi_1\right)^{1/2}}$ vs. $M_1 = \frac{v_1}{c_o}$
- The parameter R is $R = \left(\frac{s\rho_0}{s_{proj}\rho_{0,proj}}\right)$.
- The shock is somewhere between an energy conserving vs. a momentum conserving blast-wave.

  $r \propto t^{\eta}$:- η between $2/5$ and $1/4$.

  This is not the same as R as before – it is the expansion radius.
- Energy coupled to target

  $E = \frac{1}{2} m_{proj} v_{rel}^{\ 2} \frac{1+2R}{(1+R)^2}$

  Most efficient deposition of energy for density target material.
- Peak pressure on collision axis ~ constant over ~ projectile size, and then decays rapidly with distance – negligible after ~ $3a_{proj}$.
- Shattering effects dominated by high energy impacts of small grains.