PC4691 – Frontiers of Astrophysics – Interstellar Dust

Lectures 9&10
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Dust: An Overview

- Observations: extinction, reddening, (infra-red) features, polarization.
- Models: size distribution, composition, efficiencies
- Source of dust: Asymptotic Giant Branch (AGB) stars, Wolf-Reyat (?) (WR) stars, novae, SN, cool dwarfs
- Processing: accretion/spluttering, irradiation, collisions
- Dust and Chemistry: surface processes, reactions
- Formation and Destruction processes
- Dust in Protoplanetary Systems

Classical (optical, early 20th century) observations: Extinction

- Makes stars appear fainter (more distant) than they are
- Damaged some early 20th century surveys (e.g. Kapteyn's)
- Extinction is the sum of absorption and scattering
  $Q_{ext} = Q_{abs} + Q_{scat}$
  Absorption involves the destruction of the photon, so there is an increase in the energy of the grain, while scattering just redirects the photon.
- Usually measured in magnitudes: continuum effect – extinction across the whole of the optical spectrum, and into the UV and IR.
- Patchy: largest extinctions near Galactic plane
- Association with young (Popular 1: O and proto-) stellar objects

Classical observations: Reddening

- Extinction varies with wavelength: blue light is more extincted than red.
- Often expressed as $R = \frac{A_v}{E(B-V)}$
  Bottom is the excess of blue compared to violet light.
- R is typically 3.1 in the Milky Way.
- Some dependence on direction, e.g. towards the bulge.
- Lower R implies smaller grain populations.
- Plot $\frac{E(\lambda - V)}{E(B-V)}$ (the excess at a particular wavelength) to get the "Reddening Law".
- Don't extend classical formulae to IR colours or dark clouds.

Contributions to Reddening Law

- Different species have characteristic extinction behaviour
- Observed reddening law allows us to identify species responsible. Note that electrons have been included as a control.
  Mie scattering is a more complicated case – there is contribution from many different poles, rather than just the usual dipole.

Species	**Law**	**Cross Section σ**	**Scattering Type**
Electrons	λ^0	σ_T	Thomson Scattering
Molecules	λ^{-4}	$\sim \pi a^2$	Rayleigh Scattering
Grains: $a << \lambda$	λ^{-4}	$<< \pi a^2$	Rayleigh Scattering
Grains: $a >> \lambda$	λ^0	πa^2	Geometrical optics
Grains: $a \sim \lambda$	λ^{-1}	$Q_{ext} \pi a^2$	Mie scattering

- Most heavy elements must be in grains, rather than in the gas phase, to get observed extinctions – unless the grains have an extremely fractal structure, so that you get a large area for comparatively little mass.

Classical Observations: Polarization

- Spherical grains will not display polarization; hence as we observe a lot of polarization, they must be aspherical.
- Aspherical charged grains align with B field; they align so that the B field goes through the least amount of matter (i.e. vertical field, long axis of molecule will be horizontal)
- Grains rotate: short axis parallel to B.
- Strong polarization if line of sight is perpendicular to B.
- Weak, random polarization if the line of sign is parallel to B.
- Spin-up time $\tau_{spin} \sim \dfrac{\pi a \rho}{m_H n_H v_g}$

  v_g is the grain thermal velocity; ρ is the mineral density.
- Typical τ_{spin} is $10^7 years$.
- Polarization $P = \dfrac{[Q_{ext}]_H - [Q_{ext}]_E}{[Q_{ext}]_H + [Q_{ext}]_E}$

Modern Observations (looking in non-optical regions of the spectrum)

- Radio, mm and sub-mm (only in the last few decades, in places such as the Rayleign telescope in Hawaii): Rayleigh Law continuum
- Cold dust observations in supernovae (SCUBA, JCMT) – odd because most of a supernova will be very hot, but the ejecta can be very cold.
- Infra-Red: many molecular line-like features, which are important as they tell you what is in / on the grain.
- Features correspond to bond vibrations: no rotation in lattices
- Give information about mineral content of grains
- Problem: features are broader than molecular equivalents: lattice.

Grain Models

- Often assume spherical grains, radius a
- A size spectrum is assumed: often a power-law

  e.g. $dn(a) = K n_H a^\beta da$

  K is a normalization constant; n_H is the number density of hydrogen nuclei.
- A well-used value for β is -3.5, from MRN (a classic dust-modelling paper)
- The size spectrum can be used to compute other quantities.

Total Mass in Grains

- Mass density of grains $m=\frac{4}{3}\pi\rho a^{3}n(a)$
- Chain rule: $\frac{dm}{da}=\frac{dm}{dn}\frac{dn}{da}$
- Substitute $\frac{dm}{da}=\frac{4}{3}\pi\rho a^{3}\frac{dn}{da}$
- Use size spectrum: $\frac{dm}{da}=\frac{4}{3}\pi\rho K n_{H}a^{3+\beta}$
- Integrate: $m=\frac{4\pi\rho K n_{H}}{3}\int_{a_{\min}}^{a_{\max}}a^{3+\beta}da$

  A typical $a_{\max}$ would be around 1-10 microns. A typical $a_{\min}$ would be around a nanometer.
- $m=\frac{4\pi\rho K n_{H}}{3(4+\beta)}\left[a_{\max}{}^{4+\beta}-a_{\min}{}^{4+\beta}\right]$

Mean Grain Radius

- $\langle a\rangle=\frac{\int_{a_{\min}}^{a_{\max}}a\frac{dn}{da}da}{\int_{a_{\min}}^{a_{\max}}\frac{dn}{da}da}$
- Use size spectrum: $\langle a\rangle=\frac{\int_{a_{\min}}^{a_{\max}}a^{1+\beta}da}{\int_{a_{\min}}^{a_{\max}}a^{\beta}da}$
- Integrate: $\langle a\rangle=\frac{1+\beta\left[a_{\max}{}^{2+\beta}-a_{\min}{}^{2+\beta}\right]}{2+\beta\left[a_{\max}{}^{1+\beta}-a_{\min}{}^{1+\beta}\right]}$
- A typical mean radius is 0.05 microns.

Efficiencies, Q

- Generally obtained from Mie Theory: complicated.
- If $x=2\pi\frac{a}{\lambda}$, Rayleigh limit forms are:
- $Q_{scat}=\frac{8x^{4}}{3}\Re\left\{\left(\frac{n^{2}-1}{n^{2}+1}\right)^{2}\right\}$

  NB: $\Re$ means take the real component
- $Q_{abs}=-4x\,\mathrm{Im}\left\{\frac{n^{2}-1}{n^{2}+2}\right\}$

  NB: Im means take the Imaginary component.
- n is the complex refractive index, $n=n'-in''$. The minus sign is a convention to make the math easier.
- Note: dielectric constant is often used instead of the refractive index: $\varepsilon=\varepsilon'+i\varepsilon''$

$$\varepsilon' = (n')^2 - (n'')^2$$
$$\varepsilon'' = 2n'n''$$

Points to Note:

- As $x \to \infty$, Q_{abs} and $Q_{scat} \to 1$
  BUT: $Q_{ext} \to 2$: diffraction pattern.
- Optical efficiency for radiation pressure has $Q_P = Q_{ext} - Q_{scat}\langle\cos\theta\rangle$
- For a particular scattering pattern, $S(\theta)$,
  $$\langle\cos\theta\rangle = \frac{\int_0^\pi S(\theta)\cos\theta\sin\theta d\theta}{\int_0^\pi S(\theta)\sin\theta d\theta}$$
- Effect on wave: $A = A_0 e^{i(\omega t - kxn')} e^{-kn''x}$
- Note: real part of n gives refraction; imaginary part gives absorption.

Absorption (Scattering) Coefficient

- Absorbing area per unit volume: $\kappa(\lambda) = \pi a^2 Q(a,\lambda) n(a)$
- Chain rule: $\dfrac{d\kappa}{da} = \dfrac{d\kappa}{dn}\dfrac{dn}{da}$
- Substitute: $\dfrac{d\kappa}{da} = \pi a^2 Q(a,\lambda)\dfrac{dn}{da}$
- Use size spectrum: $\dfrac{d\kappa}{da} = \pi K n_H Q(a,\lambda) a^{2+\beta}$
- Integrate: $\kappa(\lambda) = \pi K n_H \int_{a_{\min}}^{a_{\max}} Q(a,\lambda) a^{2+\beta} daw$
- Evaluation requires full knowledge of size-dependence of Q.

Greenberg's Composite Model

- Attempts to match extinction law AND polarization
- Three dust components:
  i. PAHs for rise in far UV extinction
  ii. Small carbonaceous grains for 'UV bump'
  iii. Larger (carbonaceous-)coated silicates (cores) for polarization and optical extinction. These can also have an ice mantel, which can also turn into (ii).
- Fragments of coating of (iii) form component (ii).
- Number density of (iii):
  $$n(a) = N n_H e^{-5\left(\frac{a-a_c}{a_m}\right)^q}$$
  for core radius a_c and turn-over radius a_m.

Greenberg or "gobstopper' model

1. Starts off with a silicate core from CSE.
   Cooling in diffuse clouds → 2
2. Mantle formed by accretion of simple molecules.
   Cooling in molecular clouds → 3

3. Outer mantle of ices forms.
   Protostellar collapse → destruction? Growth to form comets, planitessimals?
   Ejection to hot or warm ISM → 4
4. Tough mantle of refractory organic material.
   UV processing of mantle → 2 (on top of previous layers).

- Track through ISM is important for layer sequence.
- Needs Mie theory for multiple coatings.

Sources of Grains

Estimated stellar / explosive contributions:

- O-rich AGB stars: $3.7 \times 10^{-3} M_{\odot} pc^{-2} Gyr^{-1}$; silicates
- C-rich AGB stars: $2.8 \times 10^{-3} M_{\odot} pc^{-2} Gyr^{-1}$: C, SiC
- Wolf-Rayet stars: $2 \times 10^{-4} M_{\odot} pc^{-2} Gyr^{-1}$; mostly C
  (each star forms a lot, but they're rare objects)
- Novae: $3 \times 10^{-6} M_{\odot} pc^{-2} Gyr^{-1}$; C
- Type II SN: $7.0 \times 10^{-3} M_{\odot} pc^{-2} Gyr^{-1}$ of silicates and $1.5 \times 10^{-3} M_{\odot} pc^{-2} Gyr^{-1}$ of C.
  (NB: they probably destroy a comparable amount of grains as well)