Dust

• Observational signatures
• Dust absorption
  – Reddening curves
  – The dust/gas ratio
  – Scattering and absorption theory
• Dust emission
• Lifestyles of dust grains
What are the observational signatures of dust?

- **Absorption/Scattering:**
  - Extinction/reddening (scattering and absorption)
  - Reflection (e.g., reflection nebula)
  - Broad absorption features (e.g., 2200 Å, 9.7µm, 18µm)
  - Diffuse Interstellar Bands (DIBs) in optical: weak, relatively broad absorption
  - Polarization (elongated and aligned dust grains)

- **Emission in the IR:**
  - Thermal continuum (modified blackbody)
  - Very Small Grain (VSG) continuum
  - Polycyclic Aromatic Hydrocarbon (PAH) features in 3 -11µm region
Absorption: Extinction and Magnitudes

Magnitudes: \[ m_1 - m_2 = -2.5 \log \left( \frac{F_1}{F_2} \right) \]

Extinction: \[ A_\lambda = m_\lambda - m_0 = -2.5 \log \left( \frac{F_\lambda}{F_0} \right) \]
where \( F_\lambda \) = observed flux
\( F_0 = \) flux if no dust

Why do we use magnitudes to measure extinction?

\[
A_\lambda = -2.5 \log \left( \frac{F_\lambda}{F_0} \right) = (2.5)(0.434) \ln \left( \frac{F_0}{F_\lambda} \right)
\]

\[
A_\lambda = 1.086 \tau_\lambda
\]

So \( A_\lambda \) is proportional to \( \tau_\lambda \) and the dust column
Extinction and Reddening

Separate into two terms: \( A_\lambda = R_\lambda E(B - V) \)

\[
R_\lambda = \frac{A_\lambda}{E(B - V)} \quad \text{(reddening curve)}
\]

\[
E(B - V) \equiv A_B - A_V \quad \text{(measures amount of reddening)}
\]

\[
A_B = -2.5 \log \left( \frac{F_B}{F_{B0}} \right) \quad A_V = -2.5 \log \left( \frac{F_V}{F_{V0}} \right)
\]

\( E(B - V) \) is known as the color excess or “the reddening”

B magnitude is at \( \sim 4400\text{Å} \)

V magnitude is at \( \sim 5500\text{Å} \)
How do we determine a reddening curve?

- find an identical object with no reddening
- get the fluxes at each wavelength (i.e., spectra)

Let \( X = \frac{F_{\lambda_0}}{F_\lambda} = \frac{\text{observed flux of unreddened object}}{\text{observed flux of reddened object}} \)

\[
E(B - V) = 2.5 \left( \log X_B - \log X_V \right)
\]

To get reddening at any wavelength, relative to \( E(B - V) \):

\[
\frac{E(\lambda - V)}{E(B - V)} = \frac{A_\lambda - A_V}{A_B - A_V} = \frac{\log X_\lambda - \log X_V}{\log X_B - \log X_V}
\]

So to get the extinction curve observationally:

\[
R_\lambda = \frac{A_\lambda}{E(B - V)} = \frac{E(\lambda - V)}{E(B - V)} + R_V \quad \text{where} \quad R_V = \frac{A_V}{E(B - V)}
\]
How do we determine $A_V$?

- Need to know the reddened star’s intrinsic (unreddened) flux ($F_{V0}$)
- Assume the reddened (0) and unreddened (1) stars have identical luminosities (e.g., same exact spectral type)

$$L_V = 4\pi D_1^2 F_{V1} = 4\pi D_0^2 F_{V0} \quad (D = \text{distance})$$

So $F_{V0} = \frac{D_1^2}{D_0^2} F_{V1}$

$$A_V = 2.5 \log \left( \frac{F_{V0}}{F_V} \right)$$

From determinations of $A_V$ for local stars in Galaxy:

$$R_V = \frac{A_V}{E(B-V)} = 3.1$$
Standard Galactic Extinction Curve
(Savage & Mathis, 1979, ARAA, 17, 731)

- Sharp rise to UV: due to small dust grains
- 2200 Å bump: due to carbon (graphite? PAHs?)

To correct for extinction: $F_0 = F_\lambda 10^{0.4A_\lambda} = F_\lambda 10^{0.4R_\lambda E(B-V)}$

$R_\lambda = \frac{A_\lambda}{E(B-V)}$

$R_v=3.1$
All Galactic reddening curves are not the same!

- reddening curves are similar at $\lambda > 7000$ Å, diverge in UV
- the UV extinction can be parameterized by $R_V^{-1}$

(see also: Mathis, 1990, ARAA, 28, 27)
Relative Extinction vs. $R_v^{-1}$ (CCM)

- Extinction at a particular wavelength only depends on one parameter (increases linearly with $R_v^{-1}$)
  → only one set of reddening curves for the Galaxy
Fitzpatrick (1999) gives a prescription for reddening correction. (available as IDL procedure FM_UNRED; good from 912 Å to 3.5 µm)

- Which curve do I use? Depends on the information you have:
  1) Derive from the star (or one nearby), best
  2) Measure or assume \( R_V \) from environment. OK
  3) Assume \( R_V = 3.1 \) (average curve). not so great
Extragalactic Reddening Curves

Ex) STIS Spectra of Seyfert 1 Galaxy NGC 3227

- X = ratio of continuum fits: NGC 4151/NGC 3227
- E(B-V) = 0.18, \( \frac{E(\lambda-V)}{E(B-V)} \) from X
- Don't know intrinsic flux: get R\(_V\) from adding constant to match other extinction curves in IR (Galaxy, LMC, SMC): R\(_V\) = 3.2
Extragalactic Reddening Curves

- Sharp rise to UV in SMC and NGC 3227
  → Larger number of small dust grains
- 2200 Å feature decreases from Galaxy to LMC to SMC
  → Decreases with metallicity
Gas Column vs. Dust Reddening

There is a fairly uniform gas/dust ratio in the local ISM.

Standard relation: \[ N(\text{H}) = 5.2 \times 10^{21} \ E(B-V) \ (\text{cm}^{-2}) \]

So what is the dust/gas ratio (locally)?

- Depletions: about 1/3 of the CNO is depleted
- Cosmic abundances: the mass fraction of CNO is 0.011
- The heavier elements are mostly depleted; their mass fraction is 0.0027
- So the mass fraction of CNO in dust is: $\sim 0.0037$
- The mass fraction of heavier elements is: $\sim 0.0027$

$$\frac{\rho_{\text{dust}}}{\rho_{\text{gas}}} \approx 0.006$$

If $n_H \approx 1 \, \text{cm}^{-3}$, $\rho_{\text{gas}} \approx 1.6 \times 10^{-24} \, \text{g cm}^{-3}$

Then $\rho_{\text{dust}} \approx 1 \times 10^{-26} \, \text{g cm}^{-3}$

- Dust mass is only $\sim 1\%$ of the gas mass, but the dust is much more effective in reprocessing starlight than the gas!
Dust Absorption in the Mid-IR


- 9.7 and 18 µm absorption due to silicates (9.7 µm: Si-O bending and stretching, 18 µm: O-Si-O bending modes) – may appear in emission in hot dust.
- 3 µm absorption due to O-H bond in H₂O ice
  - evidence for ice mantles around dust grains in molecular clouds
Diffuse Interstellar Bands


- High resolution spectrum of one band: weak (low contrast)
- Correlates with ISM column density and dust extinction, but origin still unknown.
Polarization

- Many stars show linear polarizations of up to a few percent.
- The polarization is due to dust, so:
  1) The dust grains are elongated, to preferentially absorb the E or B vector.
  2) They are preferentially aligned, so that the polarization caused by individual grains do not cancel out
     - they are aligned by the Galactic B field, which induces a magnetic moment in each grain
     - Polarization as a function of Galactic latitude and longitude have been used to map the Galactic B field \((1 - 10 \, \mu\text{Gauss})\),
What is the dust like? Theoretical Extinction Curves:
The decrease in flux due to dust extinction is:
\[ F = F_0 \exp(-\tau_D) \]
where \( \tau_D = n_D \pi a^2 s Q_E \) (assuming spheres)
\( n_D = \) dust particles per \( \text{cm}^{-3} \), \( a = \) grain radius, \( s = \) path length

\[ Q_E = \text{extinction efficiency} = \frac{\text{optical cross section}}{\text{geometric cross section}} \]

\[ Q_E = Q_S + Q_A \] (\( Q_S = \) scattering efficiency, \( Q_A = \) absorption efficiency)

\( Q_S, Q_A \) are functions of:
1) \( a, \lambda \rightarrow \) parameterized by \( x = 2\pi a/\lambda \)
2) \( m = \) complex index of refraction for material
   \( \text{(real: scattering, imaginary: absorption)} \)
and can be determined from the Mie theory of scattering (solution
of Maxwell's equations for spherical particles)
Theoretical Efficiency Factors (Spheres)

- no absorption for pure reflections and ice spheres
- sharp increase near $\lambda \sim 2\pi a$ (classic diffraction case)

(Spitzer, page 152)
Theoretical Efficiency Factors for Cylinders (m=1.33)

\( a = \) cylinder radius, length = 2a
- Extinction declines more sharply with decreasing \( \lambda \)
- Difference between E and H vectors give polarization
  (wiggles average out for a distribution of particles)

(Spitzer, page 173)
A distribution of grain sizes can match the observations (Mathis, Rumpl, & Nordsieck (1977, ApJ, 217, 425) :

\[ n_D \propto a^{-3.5} \quad (n_D = \text{dust density}) \]

\[ a = 0.005 \mu m \text{ to } 0.25 \mu m \]
Problems (or Challenges)

• Large number of extinction curves to understand!
• Many combinations of
  1) a C-based grain (e.g., graphite, PAHs, amorphous) and
  2) a silicate grain (e.g., pyroxenes, olivenes, amorphous)
  can provide a general match to curves and absorption features
• Need to match specific models against high-accuracy extinction curves and spectral features
• But note: m affected by damage to grain by UV photons or cosmic rays, or by ion contamination
Thermal Continuum Emission

- In the diffuse ISM, the dust temperature ($T_D$) is due to ambient starlight (otherwise it would be 3K).
- At a distance $r$ from a star with luminosity $L$, the flux balance for a dust sphere with radius $a$ is:

$$\int \frac{L\lambda}{4\pi r^2} \pi a^2 Q_A(a, \lambda) \, d\lambda = \int 4\pi a^2 Q_{Em}(a, \lambda) \pi B(\lambda, T_D) \, d\lambda$$

where $B = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc / \lambda k T_D) - 1}$ (Planck fct.)

- Given $Q_A$ and $Q_{Em}$ (absorption in the UV, emission in the IR), the above can be solved for $T_D$
- Typically $Q_{Em} \sim \lambda^{-1}$ (dust grains radiate inefficiently at long $\lambda$) → shifted slightly toward shorter $\lambda$ (“hotter” than a BB would be).
- For the IR “cirrus”: $T_D \approx 20$ K → peaks at $\sim 150 \mu m$, (far-IR)
- Star formation regions: $T_D \approx 100$ K → peaks at $\sim 30 \mu m$ (mid-IR)
Very Small Grain (VSG) Continuum

- VSGs (< 100 Å in size) are *not* in thermal equilibrium with the radiation field.
- A VSG is heated by a single photon and releases energy quickly (temperature of a single grain is highly time-dependent).
- Results in emission at shorter $\lambda$, in near- to mid-IR (1 - 30 $\mu$m).
- About 1/3 of the diffuse ISM dust emission can be attributed to VSGs (Draine, 2003, ARAA, 41, 241).
PAH Emission Features

ISO spectrum of starburst region in M82

- Polycyclic Aromatic Hydrocarbons (PAHs): linked benzene ($C_6H_6$) rings: naphthalene ($C_{10}H_8$) … ovalene ($C_{32}H_{14}$) …
- Seen in emission in photodissociation regions (PDRs) - responsible for 2200 Å absorption feature?
Lifestyles of Galactic Dust Grains

• Created in dense, cooling gas flows
  - primarily red giant winds and ejection of planetary nebulae; also novae, supernovae, and supermassive stars (η Car).
  - molecules with refractive elements condense to solid phase first
  - clusters of molecules clump together to form dust grains
  - high temperatures (300 – 1500 K) and densities ($n_{H} \approx 10^{9}$ cm$^{-3}$) provide the pressure for molecules to stick together

• Grains cycle through molecular clouds ~10 times before being incorporated in a new star (Mathis, 1990, ARAA, 28, 37)
  - grains grow massive by coagulation of smaller grains and condensation of molecules onto grains
  - ice mantles form (or ice fills the voids in fluffy dust grains?)

• Grains can be destroyed or reduced in size by:
  - cosmic-ray sputtering (atoms knocked out by + ions)
  - shocks from SNRs, UV photoejection of electrons
  - sublimation: graphites and silicates sublimate at ~ 1500 K, ice mantles sublimate at 20 - 100K
What are the dust particles like?
- shapes, masses, and exact compositions still uncertain