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/\textit{reddening} (scattering and absorption)
  - Reflection (e.g., reflection nebula)
  - Broad absorption features (e.g., 2200 Å, 9.7\,\mu m, 18\,\mu m)
  - 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 \textendash 11\,\mu m 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)

\[ \text{Let } X = \frac{F_{\lambda 0}}{F_{\lambda}} = \frac{\text{observed flux of unreddened object}}{\text{observed flux of reddened object}} \]

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

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:

\[ R_{\lambda} = \frac{A_{\lambda}}{E(B - V)} = \frac{E(\lambda - V)}{E(B - V)} + R_V \quad \text{where } R_V = \frac{A_V}{E(B - V)} \]
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 \[
F_{V0} = \frac{D_1^2}{D_0^2} F_{V1}
\]

\[
A_V = 2.5 \log \left( \frac{F_{V0}}{F_V} \right) \quad \left( \frac{\text{intrinsic (unreddened) flux}}{\text{observed flux}} \right)
\]

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: \( F_0 = F_\lambda 10^{0.4A_\lambda} = F_\lambda 10^{0.4R_\lambda E(B-V)} \)
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

- $X = \text{ratio of continuum fits: NGC 4151/NGC3227}$
- $E(B-V) = 0.18,$ $E(\lambda-V)/E(B-V)$ 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: \( N(H) = 5.2 \times 10^{21} E(B-V) \text{ (cm}^{-2}\text{)} \)

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: $\sim 0.0027$

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

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

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

- 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 μGauss),
What is the dust like? Theoretical Extinction Curves: The decrease in flux due to dust extinction is:

\[ F = F_0 \exp(-\tau_D) \quad \text{where} \quad \tau_D = n_D \pi a^2 s Q_E \quad \text{(assuming spheres)} \]

\( n_D = \text{dust particles per cm}^{-3}, \, a = \text{grain radius}, \, s = \text{path length} \)

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

\[ Q_E = Q_S + Q_A \quad (Q_S = \text{scattering efficiency}, \, Q_A = \text{absorption efficiency}) \]

\( Q_S, Q_A \) are functions of:

1) \( a, \lambda \rightarrow \text{parameterized by} \quad x = 2\pi a/\lambda \)

2) \( m = \text{complex index of refraction for material} \)

(\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)

- 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)

$a = \text{cylinder radius, length } = 2a$
A distribution of grain sizes can match the observations (Mathis, Rumpl, & Nordsieck (1977, ApJ, 217, 425) :
\[ n_D \propto a^{-3.5} \quad (n_D = dust\ density) \]
\[ a = 0.005\mu m\ to\ 0.25\mu m \]
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 \( B = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT_D) - 1} \) (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”: \( T_D \approx 20 \text{ K} \) ➔ peaks at \( \approx 150 \mu\text{m} \), (far-IR)
- Star formation regions: \( T_D \approx 100 \text{ K} \) ➔ peaks at \( \approx 30 \mu\text{m} \) (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 μm).
- 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