THE INTERSTELLAR MEDIUM: VIII
Interstellar Dust

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Outline

- Background.
- Molecule formation.
- Interstellar dust: Basics.
- Interstellar extinction.
- The polarization of starlight.
- The scattering of starlight.

BACKGROUND

- Critical density reduced at high opacities, due to stimulated emission, by $\beta \sim 1/(1+0.5\tau_0)$: $n_{crit} \sim 50$ cm^{-3} for CO (1→0) if $\tau \sim 50$.

- Two lines, optically-thick (^{12}CO) & optically-thin (^{13}CO), can be used to infer the H_2 column density, within a factor of ~ few.

- CO-to-H_2 conversion factor: ^{12}CO luminosity used to infer the total molecular gas mass! Depends on galaxy type, metallicity, etc.

- Conversion from total CO luminosity to molecular gas mass:

$$M_{MOL} = \alpha_{CO} L_{CO} \qquad \alpha_{CO} \sim 4.3\ M_{\odot}\ (\mathrm{K\ km/s\ pc^2})^{-1}$$

- Conversion from integrated CO line intensity to $N(H_2)$:

$$N(H_2) = X_{CO} I_{CO} \qquad X_{CO} \sim 2 \times 10^{20}\ \mathrm{cm^{-2}\ (K\ km/s)^{-1}}$$

(e.g. Bolatto et al. 2013)

- Large amounts of molecular gas in the central 1.5 kpc, "hole" at 1.5 – 3.5 kpc, "ring" at 4 – 8 kpc, steep decline beyond 8 kpc.

MOLECULE FORMATION

- Gas phase formation mechanisms:

  (1) $H + H \rightarrow H_2 + \gamma$: Very low rate coefficient (10^{-23} cm^3 s^{-1}).

  (2) $H + e^- \rightarrow H^- + h\nu$: Rate coefficient ~ $1.9 \times 10^{-16} \times T^{0.67}$ cm^3 s^{-1}

  $H + H^- \rightarrow H_2 + e^- + KE$: Rate coefficient ~ 1.3×10^{-9} cm^3 s^{-1}

  (Dalgarno & McCray 1973)

- But... H^- photo-detachment: $H^- + h\nu \rightarrow H + e^-$ (2.4×10^{-7} cm^3 s^{-1} !).

  ⇨ Low gas phase formation of H_2 in the diffuse ISM today!!!

- Dominant process: Grain surface catalysis! H atoms bind to grain surfaces and then diffuse across until they get tightly bound. If another H atom arrives at the same location: H_2 formation + 4.5 eV.

  (McCray & McNally 1960; Gould & Salpeter 1963)

- Large, cold grains (< 100 K), to prevent H-atom evaporation.

- Typical timescale for H_2 formation on grains ~ 10^9 n^{-1} years.

  ⇨ Rapid conversion of HI to H_2 in high-density environments.

INTERSTELLAR DUST

- Solid, macroscopic particles: Poorly understood physics.
- Grain composition and physical properties unknown
  ⇨ Highly empirical studies, attempting to explain observations.
- Roughly 1% of the ISM is in the dust phase.
- 30 – 50% of starlight is absorbed by dust and re-radiated at FIR wavelengths: Dust contributes ~ 30 – 50% of a galaxy's luminosity!
- Dust grains: Primary sites of molecule formation in the ISM.
- Photo-electrically ejected electrons from dust grains: Most important heating source in the ISM.

OBSERVING INTERSTELLAR DUST

- Dust Absorption / Extinction:
  (1) Wavelength-dependent absorption of starlight.
  (2) Wavelength-dependent polarization of starlight.
  (3) Diffuse interstellar bands (DIBs), Silicate bands, etc.
  (4) Reflection nebulae: Scattered starlight.

- Dust Emission:
  (1) Thermal continuum emission, in the mid-IR and far-IR bands.
  (2) Thermal emission from tiny grains in the near-IR and mid-IR.
  (3) IR emission bands from thermally-heated grains.
  (4) Microwave continuum emission, from rotating grains.

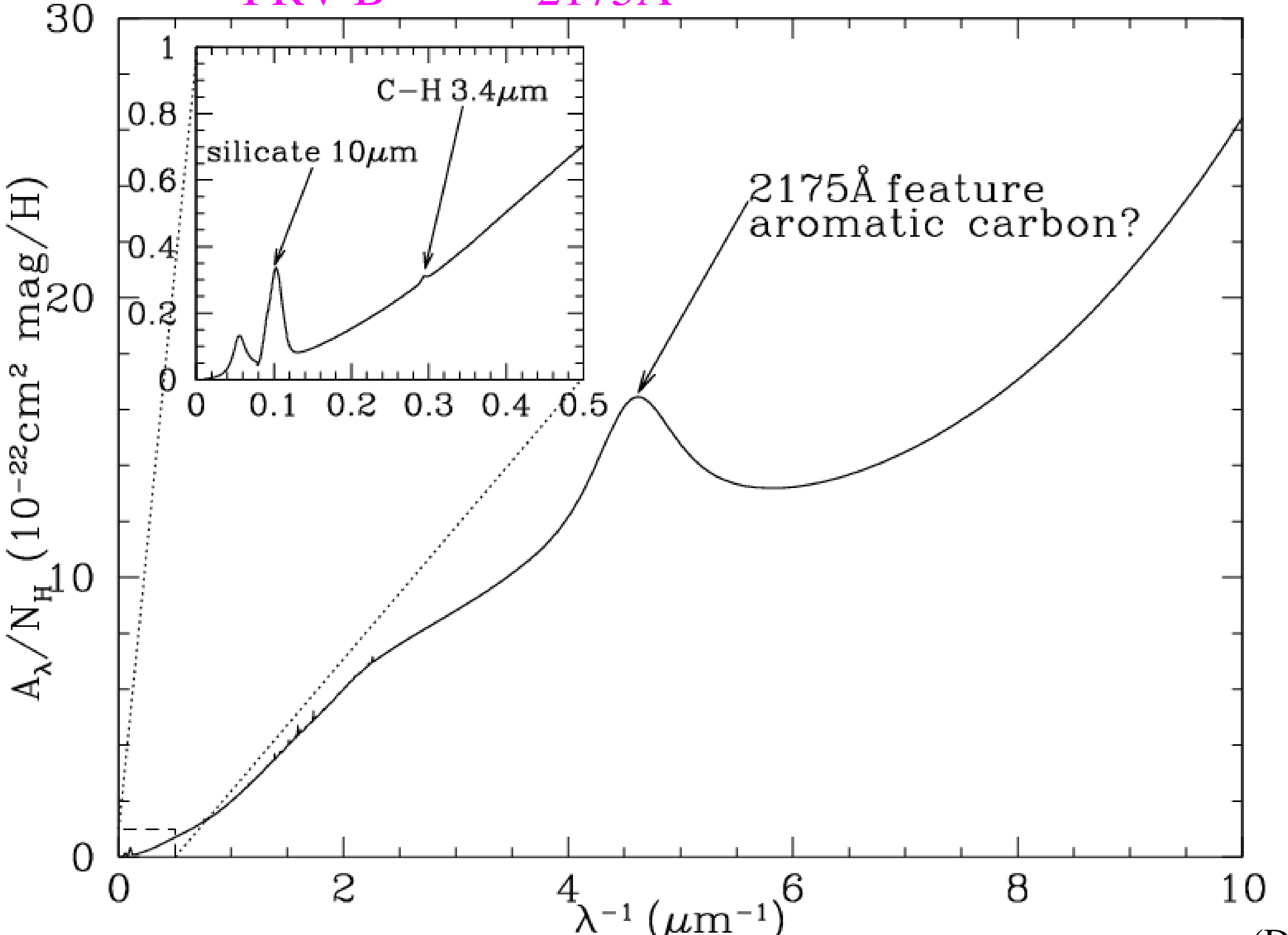
- "Depletion": Paucity of *refractory* elements in the gas phase.

- Pre-solar grains preserved in meteorites: e.g. *Stardust* mission.

INTERSTELLAR EXTINCTION

- Extinction, $A_\lambda = 2.5\ \mathrm{Log}_{10}[I_{\lambda,0} / I_\lambda] = 2.5\ \mathrm{Log}_{10}[e^{\tau_\lambda}] \approx 1.086\ \tau_\lambda$.

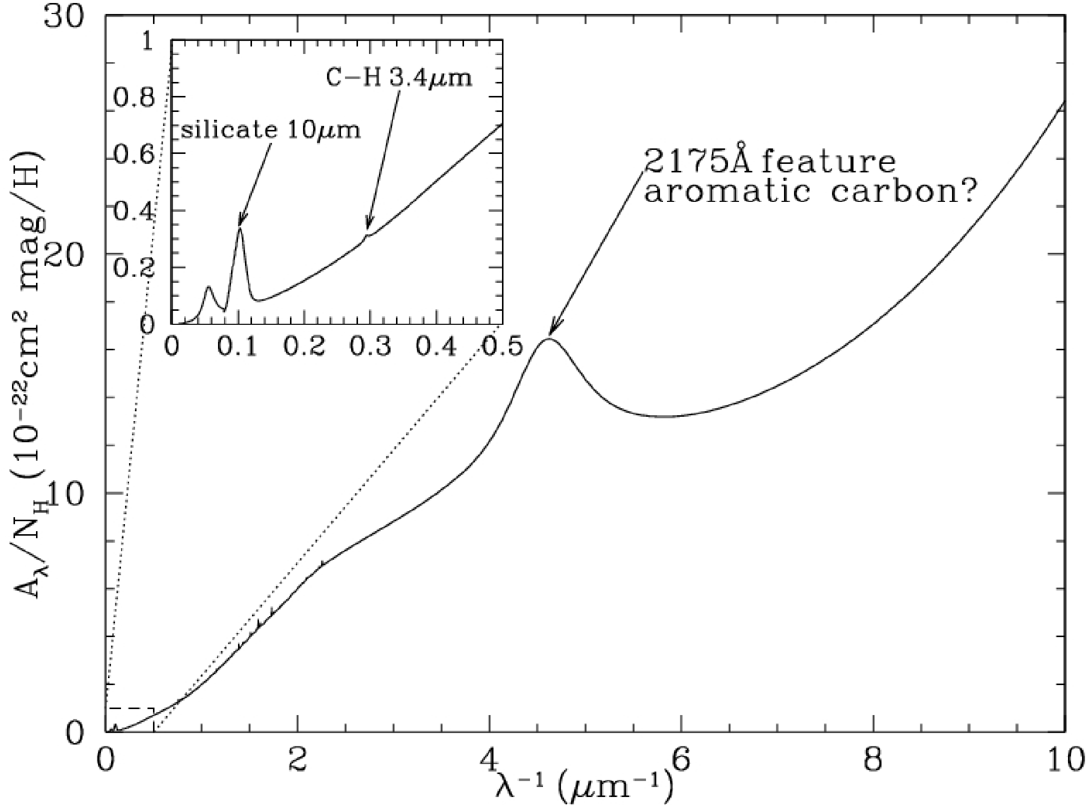
I RV B 2175Å



(Draine 2011)

INTERSTELLAR EXTINCTION

IRVB 2175Å



(Draine 2011)

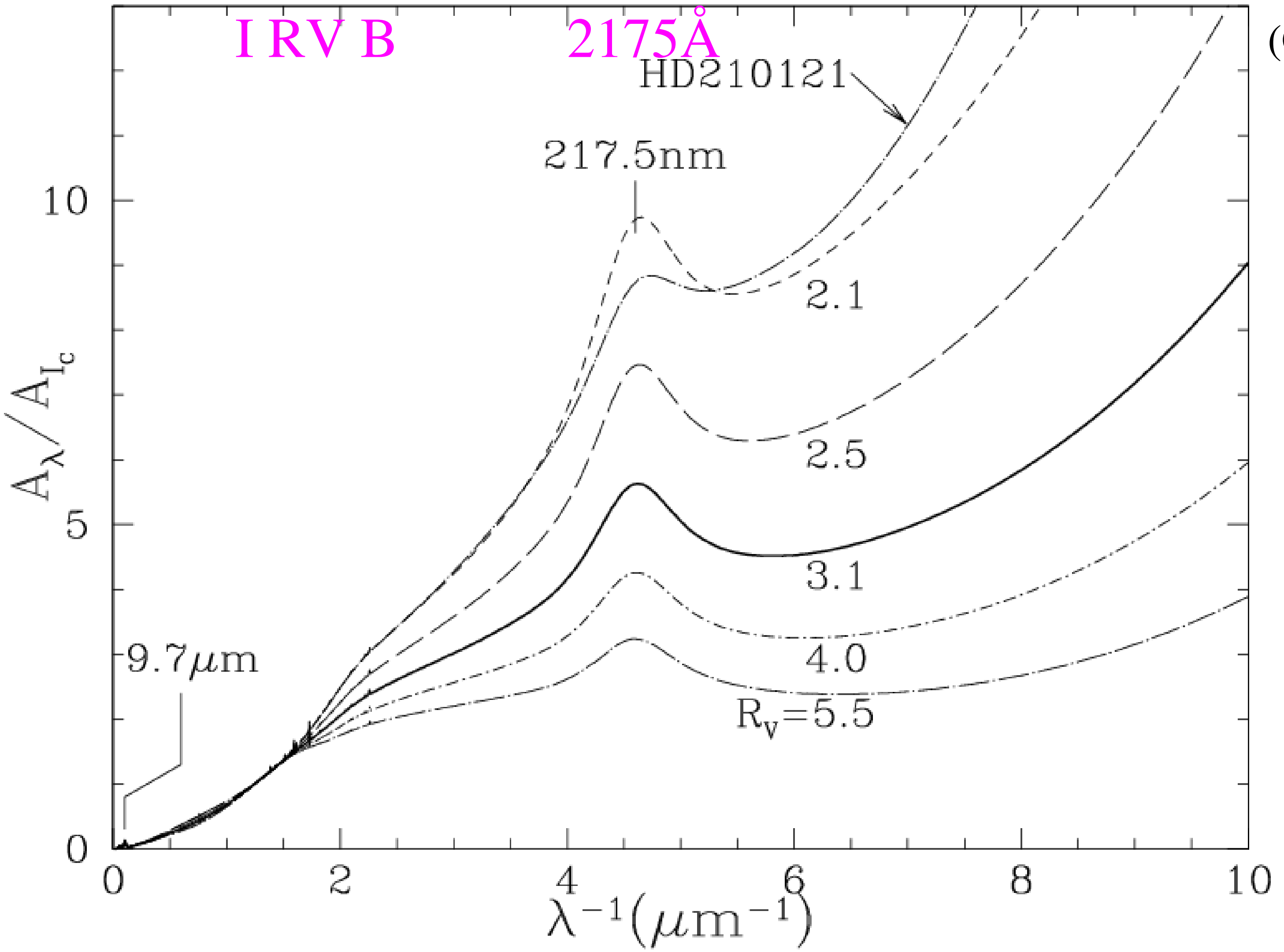
- Extinction curve: main features:
  - (1) Broad rise from IR to UV wavelengths.
  - (2) 2175 Å "bump": Electronic transitions in graphite or PAHs.
  - (3) 9.7, 18 μm: Stretch, bend Si–O & O–Si–O modes in silicates.
  - (4) 3.4 μm: C−H stretch mode in hydrocarbons; seen for $A_V > 10$.
  - (5) ~ 400 lines: Diffuse interstellar bands. Unidentified !!!

Variations in Extinction

(Draine 2011)

- $R_V = A_V / (A_B - A_V) = A_V / E(B-V)$: $R_V \sim 2-5$ (diffuse – dense).
- Significant variation. Can parametrize extinction curve by R_V !

(Cardelli et al. 1989)



(Draine 2011)

- N_H – Reddening correlation: $N_H / E(B-V) \approx 5.8 \times 10^{21}$ cm^2 mag^{-1}.

INTERSTELLAR EXTINCTION

- Homogenous spherical grains: solved by Mie (1908).

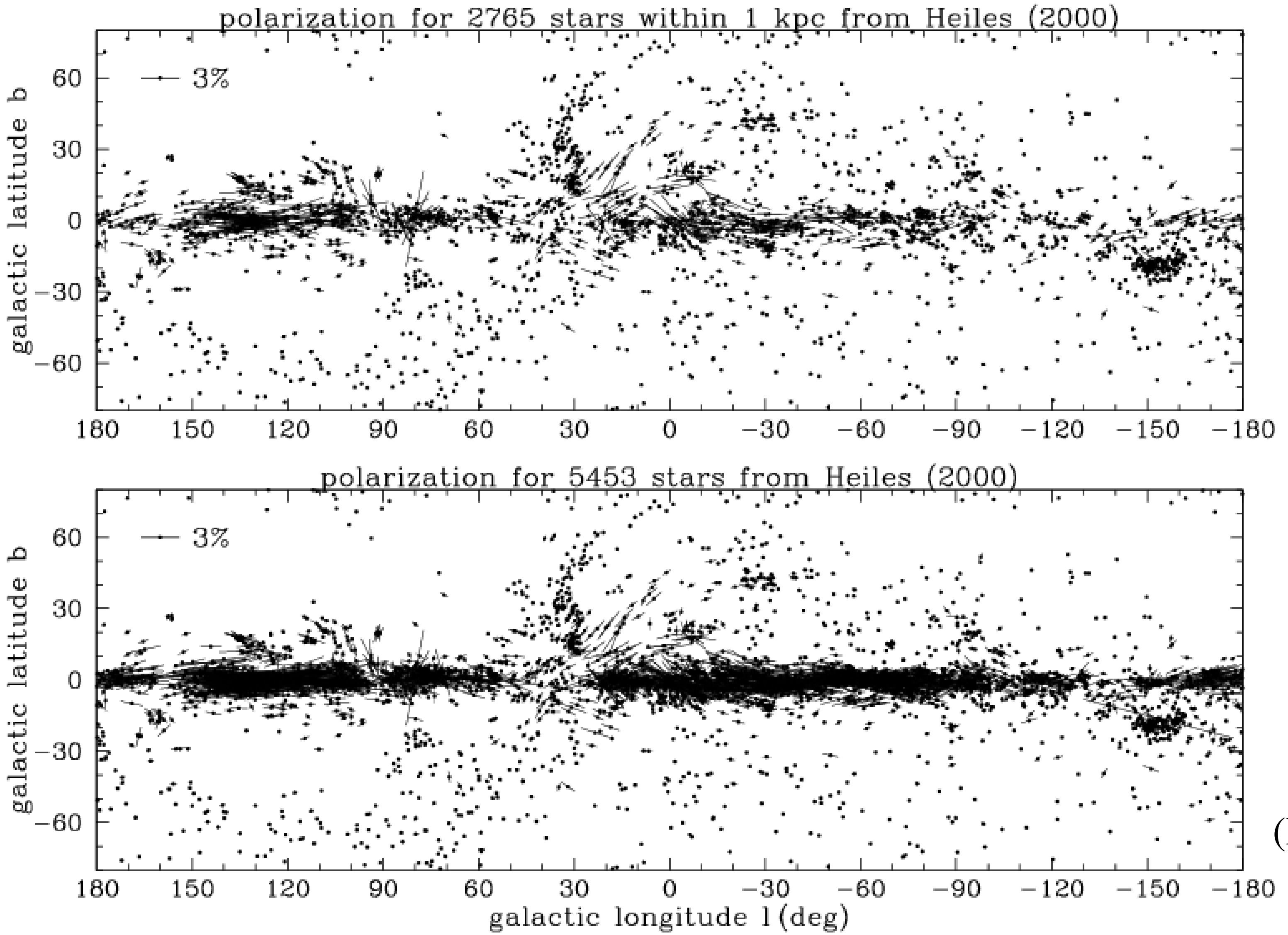
- Three regimes, depending on $x = 2\pi\, a/\lambda$; a is the grain size.
  - (1) $\lambda \gg a$: Extinction efficiency $Q_{ext} \propto \lambda^{-4}$ (Rayleigh scattering)
  - (2) $\lambda \approx 2\pi a$: $Q_{ext} \propto \lambda^{-1}$ ($x \geq 1$; Mie scattering)
  - (3) $\lambda \ll a$: $Q_{ext} \propto$ *Constant* (Geometric scattering)

- Rise for $1\ \mu m^{-1} < \lambda^{-1} < 10\ \mu m^{-1}$ ⇨ $a \leq 0.1\ \mu m$ [else regime (3)].
  ⇨ Dust grains definitely not much larger than ~ 0.1 μm !

- Strong rise down to $\lambda \sim 0.1\ \mu m$ ⇨ Large abundance of grains of size <~ 0.015 μm.

- Large range of grain sizes, at least ~ 0.015 – 0.1 μm.

Polarization of Starlight

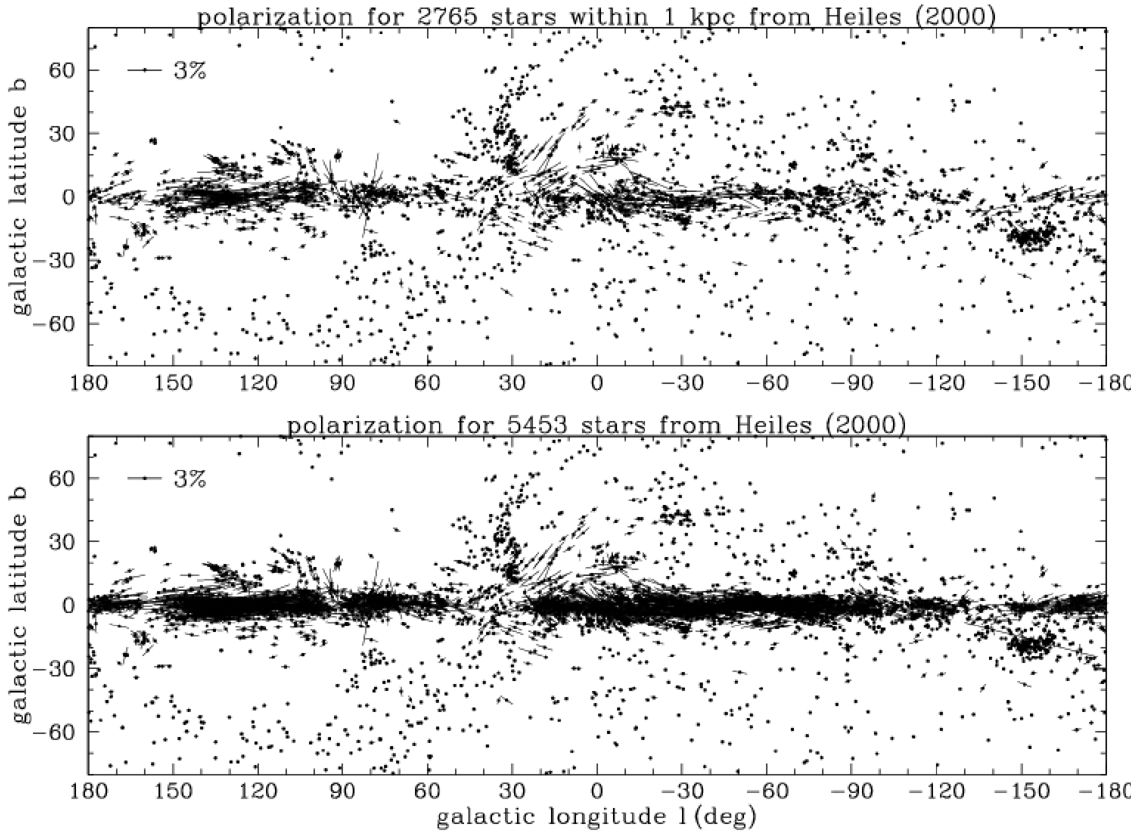


(Draine 2011)

- High degree of polarization for high reddening: Dust!
  Low polarization in the ultraviolet; high polarization in the optical.
- Spatially coherent: Alignment determined by the magnetic field.

POLARIZATION OF STARLIGHT

(Draine 2011)



- No polarization without dust.
- Serkowski law: 0.35 – 1 μm:
  $p(\lambda) = p_{max} \exp[-K. \lg^2(\lambda / \lambda_{max})]$
  $K = 1.15. \quad \langle \lambda_{max} \rangle = 5500$ Å.
  $0 < p_{max} < 0.03 \; A_V$.
- Non-spherical, 0.1 μm grains.
- Rotating grains in a magnetic field: Paramagnetic dissipation!
  Shorter axis aligned with the field direction. (Davis & Greenstein 1967)
- Q_{ext} depends on cross-section! Waves with electric vectors along the longer grain axis will see a larger cross-section: Polarization!
- Smaller grains giving UV absorption do *not* cause polarization!
  Spherical grains ? Or harder to align ? : Supra-thermal rotation!

Reflection Nebulae: Scattering Starlight

- Bluish gas clouds near less-massive stars. Blue due to reflected starlight.
- Compare original and scattered intensity: probe nature of scattering process. Also possible for dark clouds & diffuse light.
- Measure the relative importance of scattering and absorption: Albedo: $\omega = Q_{scat} / Q_{ext}$. Total scattered flux depends on the albedo.
- Measure the scattering angle <Cosθ>: Asymmetry in the scattering.
- Must model the surface brightness of the star and the scattered light: Monte Carlo simulations, including the cloud geometry.

(e.g. Gordon et al. 2010)

- Albedo ~ 0.5 in the optical ⇨ Scattering ≈ Absorption!
- Scattering angle <Cosθ> ~ 0.5 ⇨ Mie scattering; $a \sim \lambda/2\pi \approx 0.1\ \mu m$!