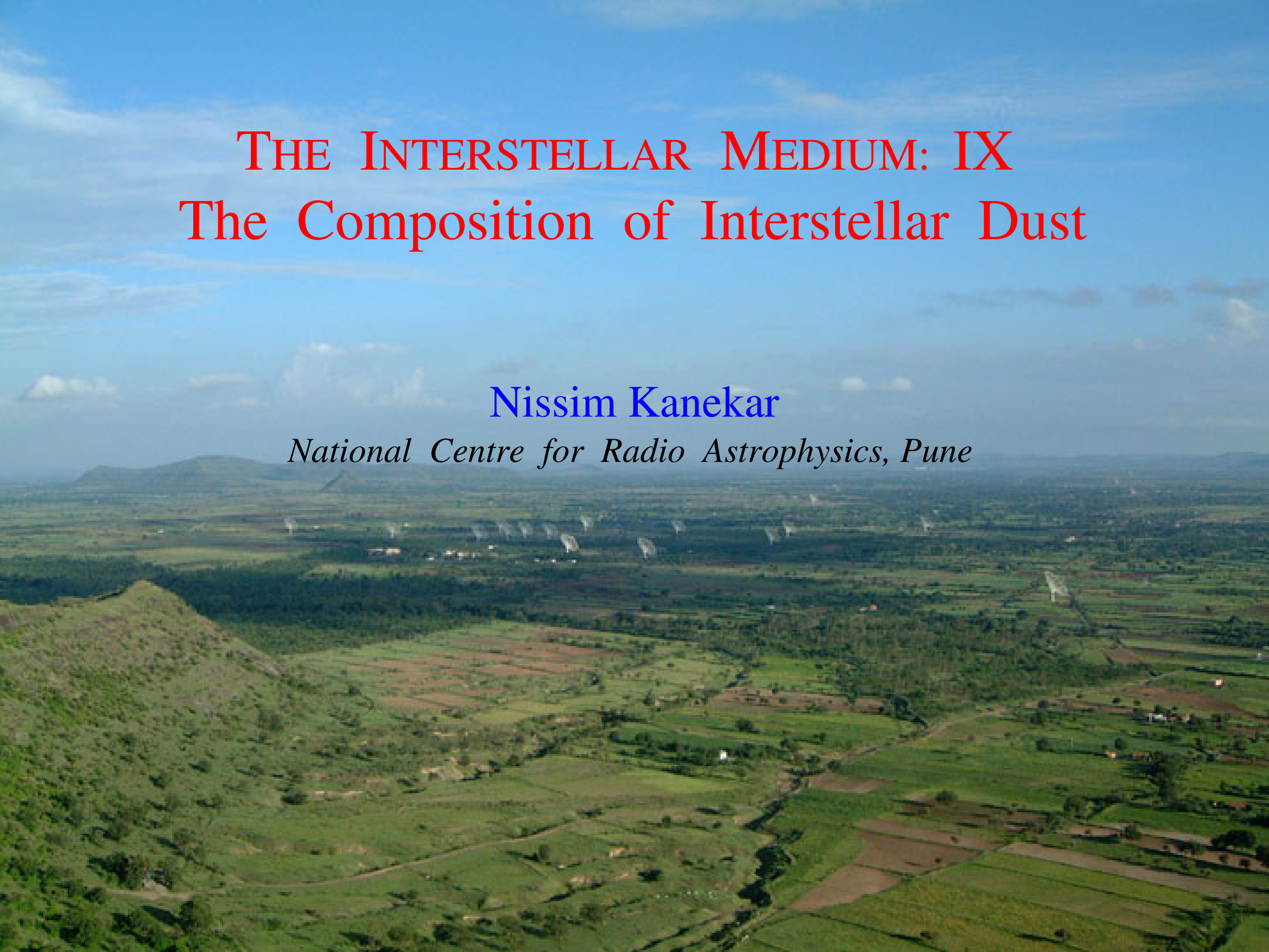

The Interstellar Medium: IX
The Composition of Interstellar Dust

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OUTLINE

- Background.
- Depletion: What do dust grains consist of ?
- Spectral features.
- The size distribution of dust grains.
- Models of dust composition and size.

BACKGROUND

- H_2 produced by grain surface catalysis in the ISM!
  H-atoms bind together on a grain surface & H_2 molecule ejected.

- Dust grains: Primary sites of molecular formation today!
  $< 1\%$ of baryonic mass, but $30 - 50\%$ of Galaxy's luminosity!
  Main source of heating of the ISM.

- Dust physics poorly understood; grain composition unknown.

- Extinction curve: Near-linear rise from IR to UV wavelengths.
  Parametrized by R_V: $R_V \sim 3.1$ (diffuse gas), $R_V \sim 5.1$ (dense gas).

- Mie scattering: $\lambda \approx 2\pi a$: Extinction efficiency, $Q_{ext} \propto \lambda^{-1}$.

- Grain sizes range from at least 0.015 μm to ~ 0.1 μm.

- High polarization in the optical, low in UV: Non-spherical grains
  aligned by B-fields ⇨ Radiative torques & spherical small grains ?

DEPLETION

- Elements "deplete" out of the gas phase, condensing onto grains.
- Depletion relative to solar abundance for sightline towards ζOph.

(Draine 2011; Asplund et al. 2009)

- Solar abundances:

$He/H = 0.0955$

$C/H = 3.0 \times 10^{-4}$

$O/H = 5.4 \times 10^{-4}$

$Ne/H = 9.3 \times 10^{-5}$

$N/H = 7.4 \times 10^{-5}$

$Mg/H = 4.4 \times 10^{-5}$

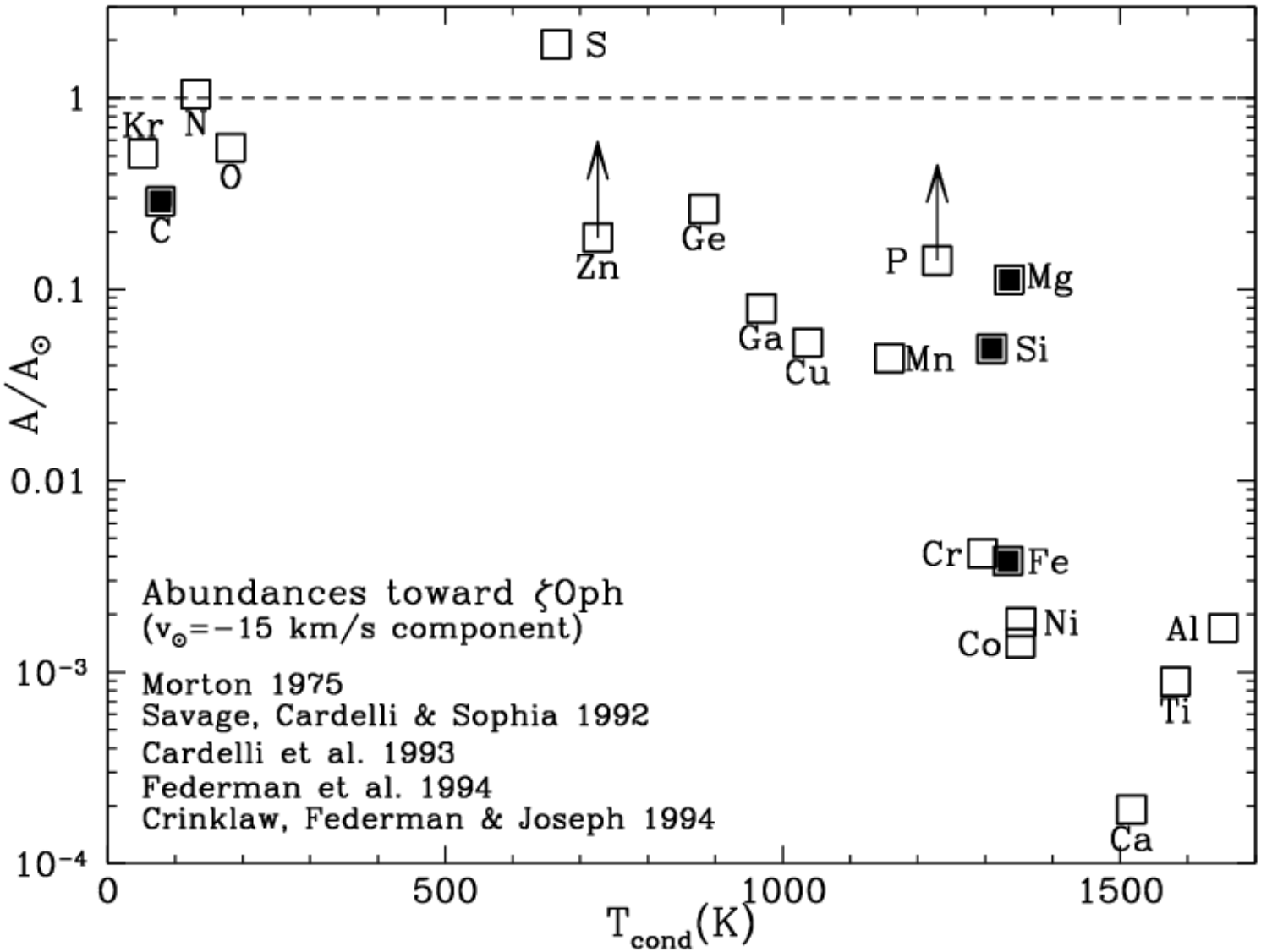
$Si/H = 3.6 \times 10^{-5}$

$Fe/H = 3.5 \times 10^{-5}$

$S/H = 1.5 \times 10^{-5}$

$Al/H = 3.0 \times 10^{-6}$

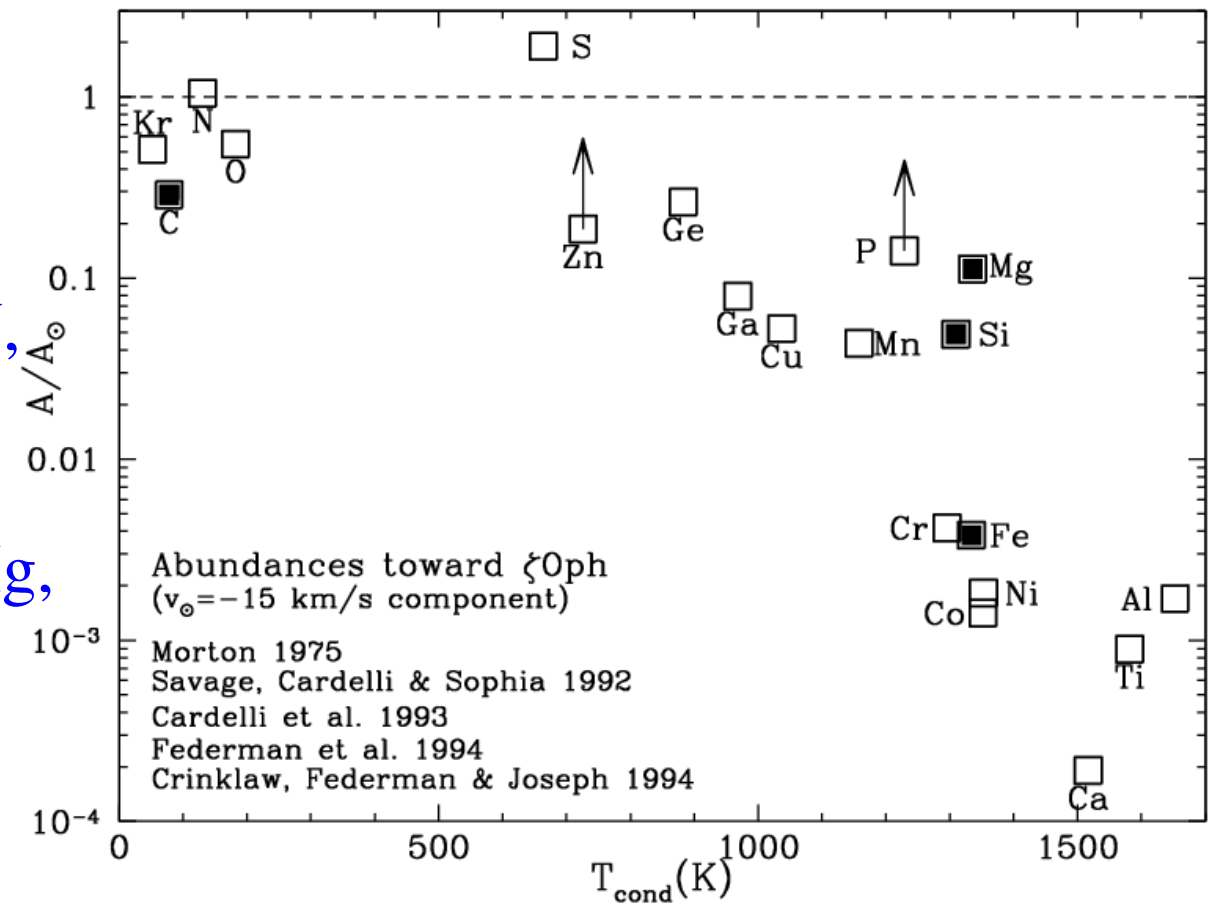
$Ar/H = 2.8 \times 10^{-6}$



Depletion: Dust Composition and Mass

(Draine 2011)

- H contributes little mass.
- He, Ar, Ne: Non-reactive.
- High abundances: {C, O, N, Mg, Si, Fe, S, Al}.
- Depleted species: {C, O, Mg, Si, Fe, Al}.
- 65% C, > 90% Fe, Si, Mg!



- High condensation temperatures: Ability to form solid species.
- Difference between solar abundance and gas phase abundance: Contribution made by the element to the dust mass towards ζOph.

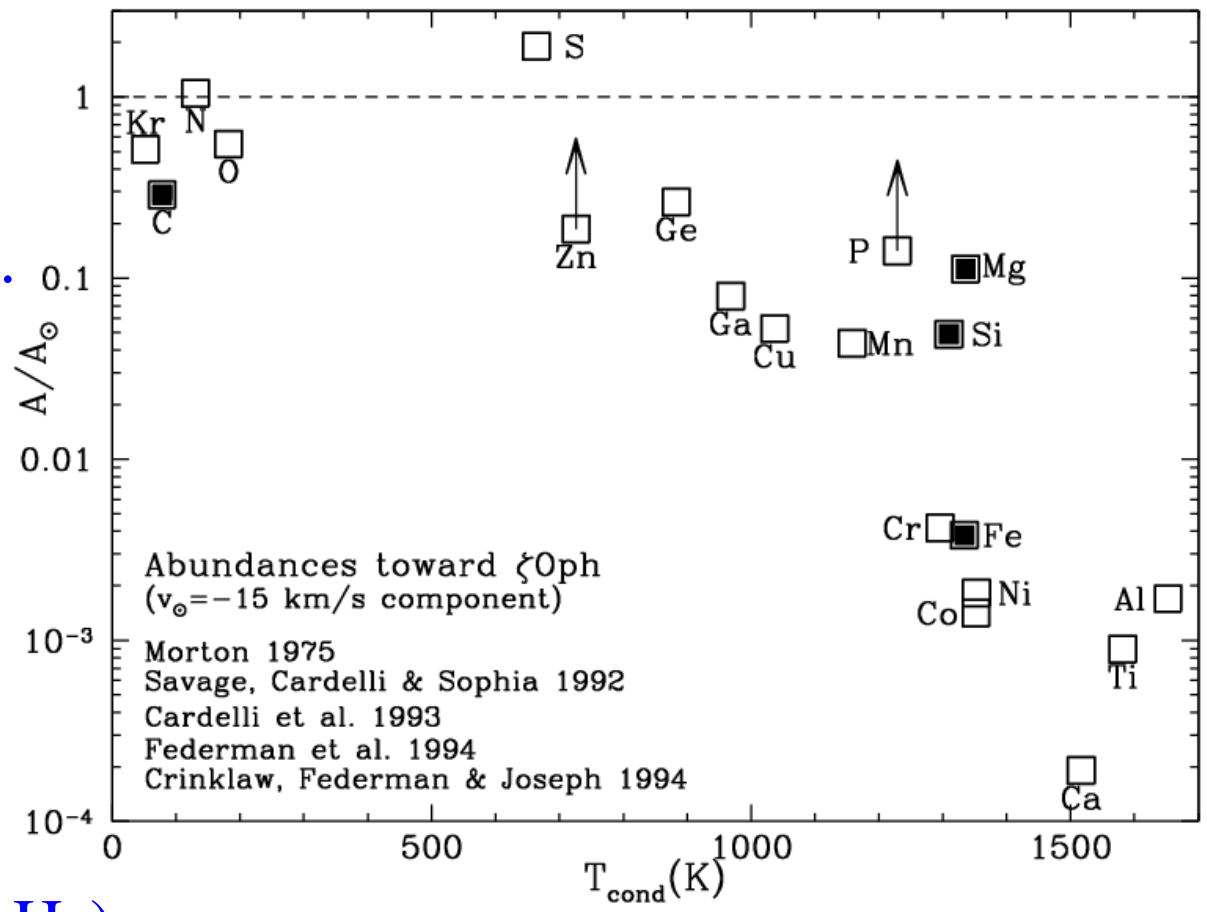
  ⇨ Dust/H mass ratio ~ 1%.

  28% in C, 72% in {Mg, Si, Fe, Al}, mostly in silicates.

Depletion: Dust Composition

(Draine 2011)

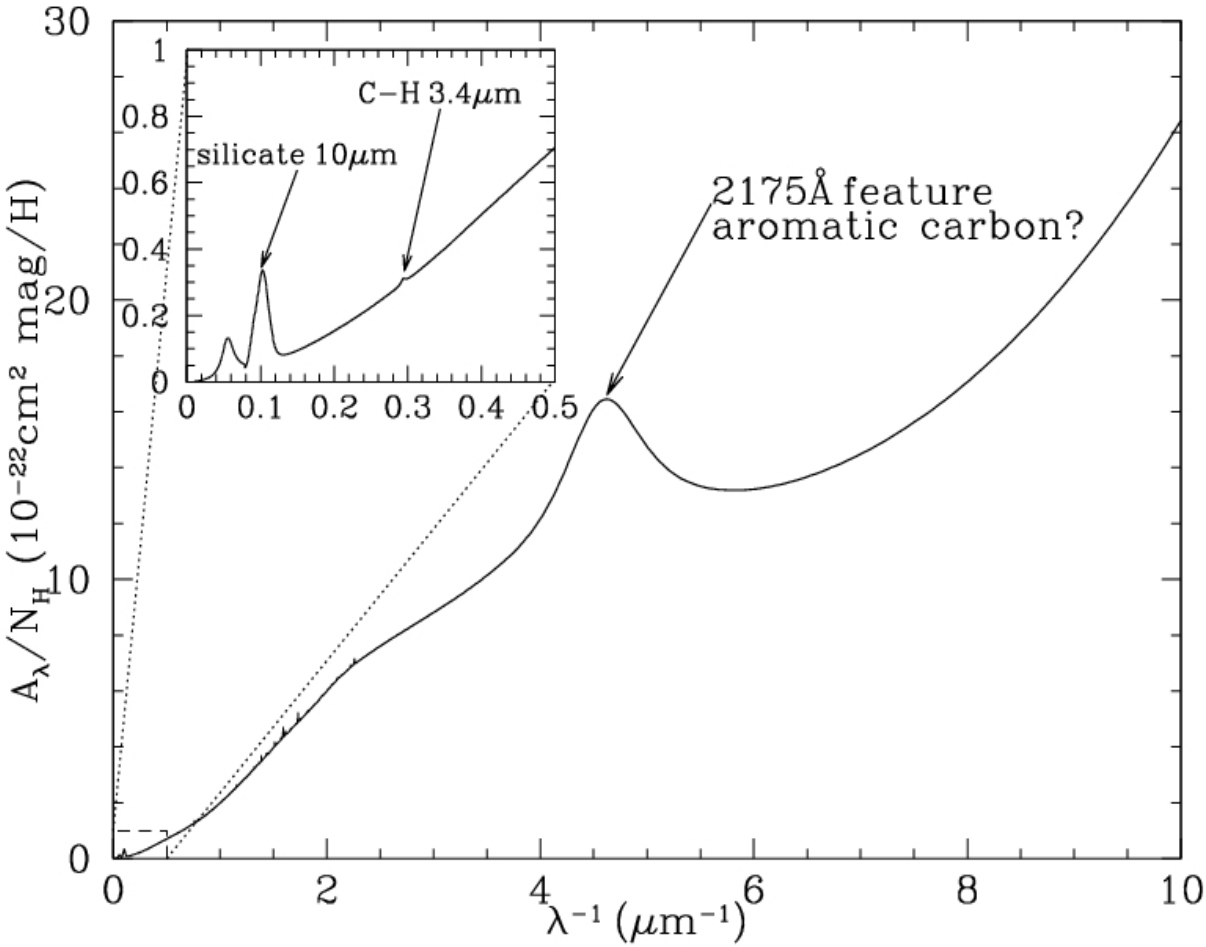
- {C, O, Mg, Si, Fe}
- Carbon solids: graphite, diamond, amorphous carbon.
- Silicates: $Mg_xFe_{1-x}SiO_3$, $Mg_{2x}Fe_{2-2x}SiO_4$.
- Oxides of Si, Mg, Fe: SiO_3, MgO, FeO_4.
- Hydrocarbons (especially PAHs).
- Carbides (especially silicon carbide).
- Metallic Fe.
- Match observed extinction / emission curves with the above species!



Dust Composition: The 2175 Å Bump

IRVB 2175Å (Draine 2011)

- Very strong feature: Must arise from compounds of {H, C, O, N, Mg, Si, S, Fe}.
- Fixed central wavelength, variable width.
  (Fitzpatrick & Massa 1986)
- Little or no polarization: Small, spherical, non-aligned ?



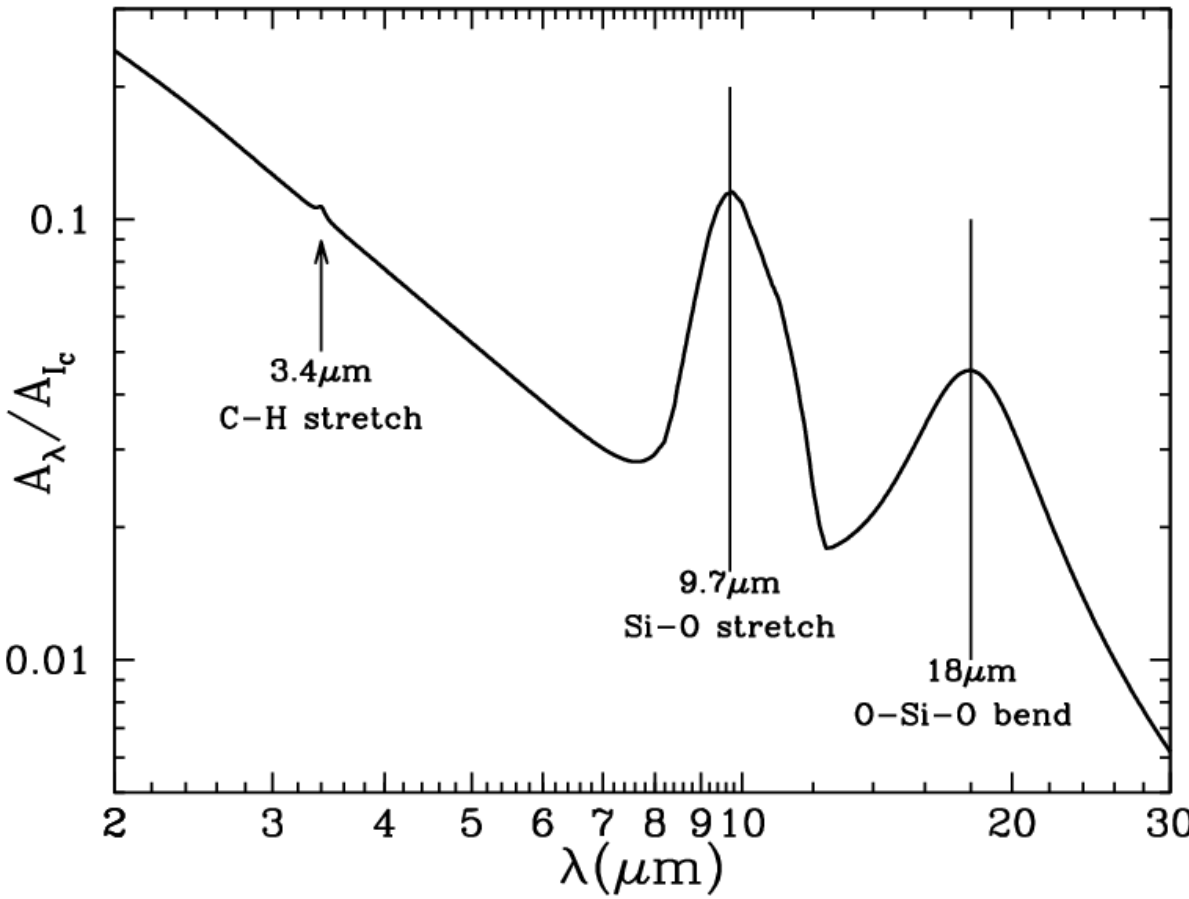
- Absorption in electronic transitions in sp_2-bonded graphite grains or PAH molecules. PAH molecules current favourite. (Stecher & Donn 1965)
- Strong in the Galaxy, weaker in the LMC, absent in the SMC ! Indicates that carbonaceous grains are lacking in the SMC.

Dust Composition: Silicate Features

(Draine 2011; Henning 2010)

- Broad feature at 9.7 μm and weaker feature at 18 μm.
- Good IDs: Si–O stretch and O–Si–O bending modes in amorphous silicates.
- Broad lines: Few (<~ 5%) crystalline silicates in the interstellar medium.

(Li & Draine 2001; Kemper et al. 2005)



- 9.7 μm line: Outflows from O-rich stars, not from C-rich stars.
- Polarization detected in both features: Silicates can be aligned!
- Suggested composition: $MgFeSiO_4$, with most of the Mg, Fe, Si.
- $A_V/\Delta\tau_{9.7\mu m} \approx 18.5$ near the Sun; $A_V/\Delta\tau_{9.7\mu m} \approx 9$ towards the GC !

Dust Composition: 3.4 μm Feature

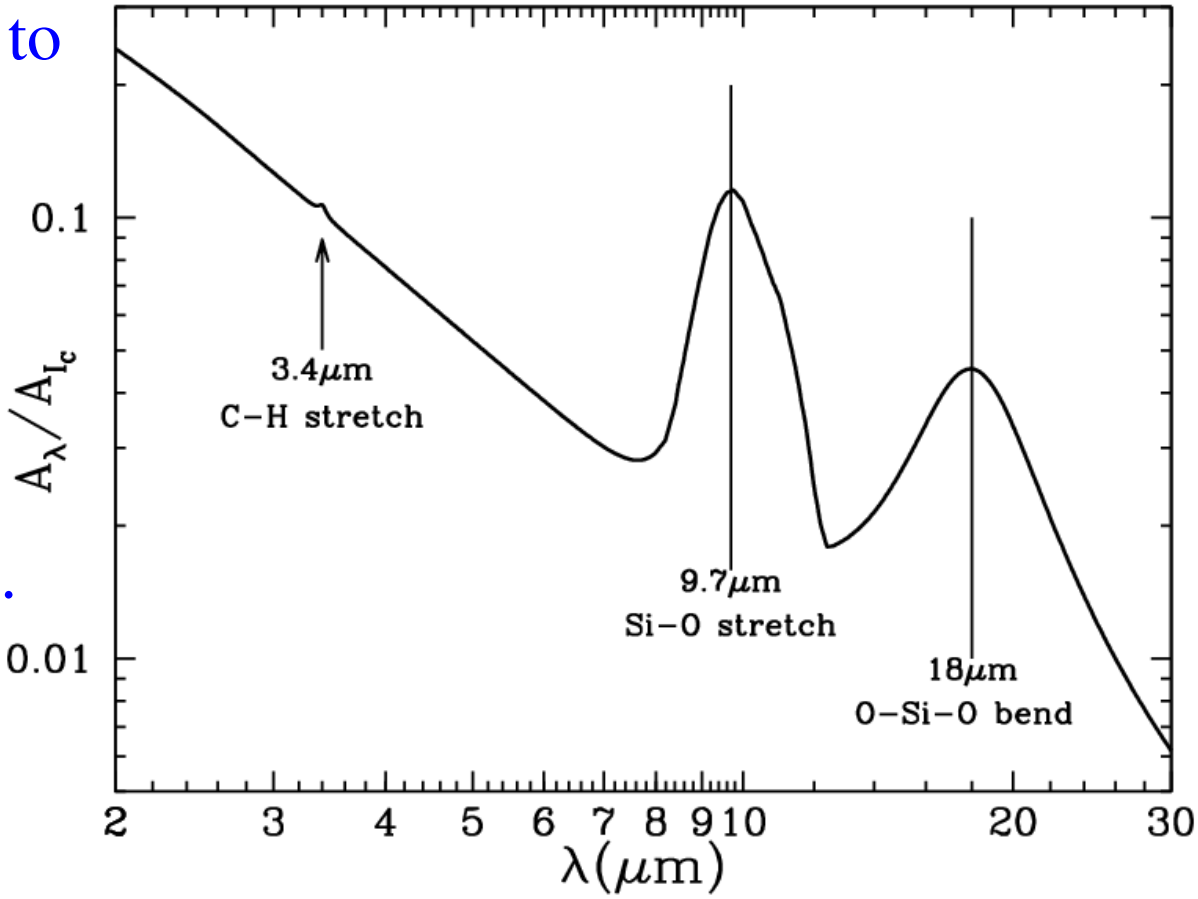
(Draine 2011)

- Broad feature, probably due to a C–H stretching mode in hydrocarbons.
- Type and amount of hydrocarbons unknown!
- 85% aromatic, 15% aliphatic.

(Pendleton & Allamandola 2002)

But... < 15% aromatic.

(Dartois et al. 2004)



- Strength of 3.4 μm feature depends on environment: Stronger in diffuse clouds, weaker in dense clouds. Suggests that C–H bonds are destroyed in dark clouds, possibly by cosmic rays.

(Shenoy et al. 2003; Mennella et al. 2003)

Dust Composition: H_2O Ice

(Kemper et al. 2004)

- Broad 3.1 μm feature, due to O–H stretching mode in H_2O ice.

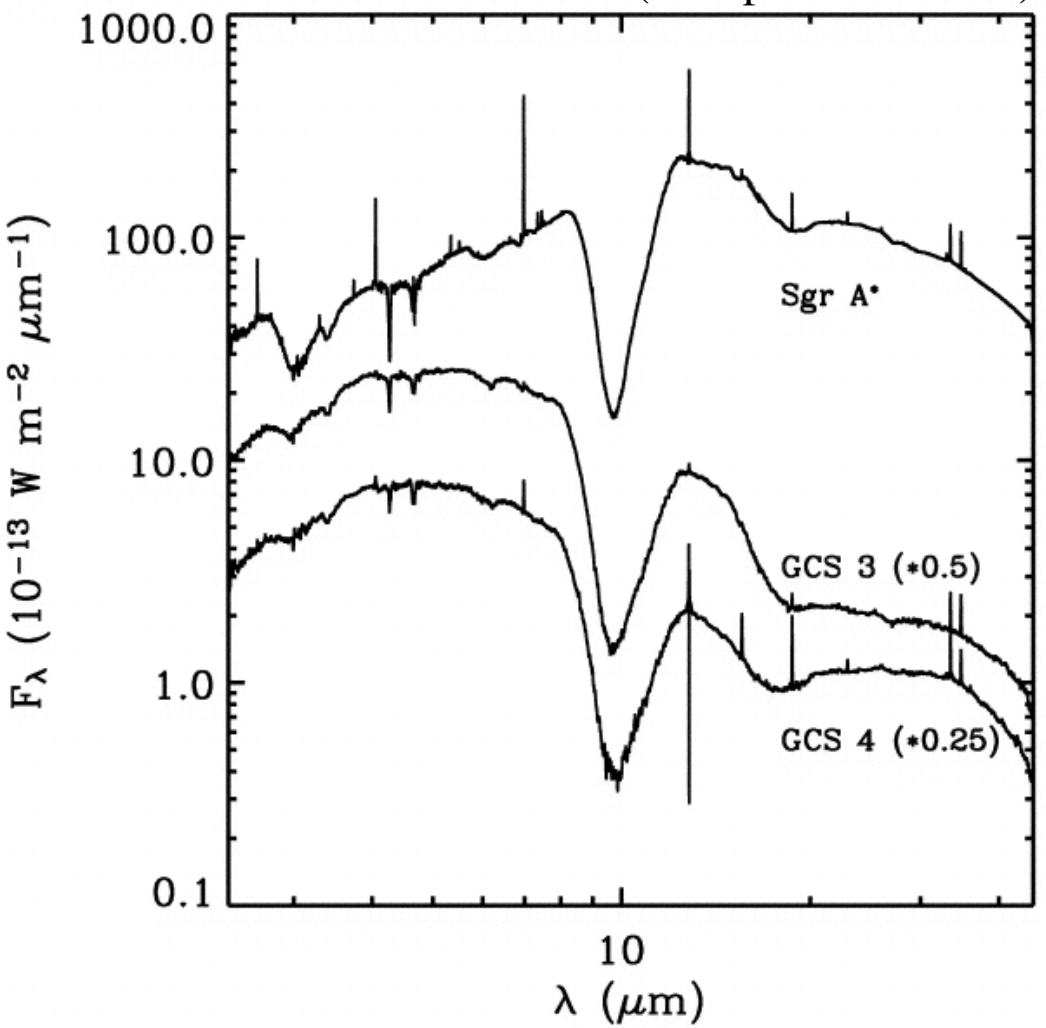
- Diffuse ISM appears ice-free: $< 0.5\%$ of the grain mass.

(e.g. Whittet et al. 1997)

- Visible in dark clouds: $\Delta\tau_{3.1\mu m} \approx 0.093\ (A_V - 3.3\ \text{mag})$.

  ⇨ Dust shielding needed against the interstellar radiation field.

(Whittet et al. 1988)



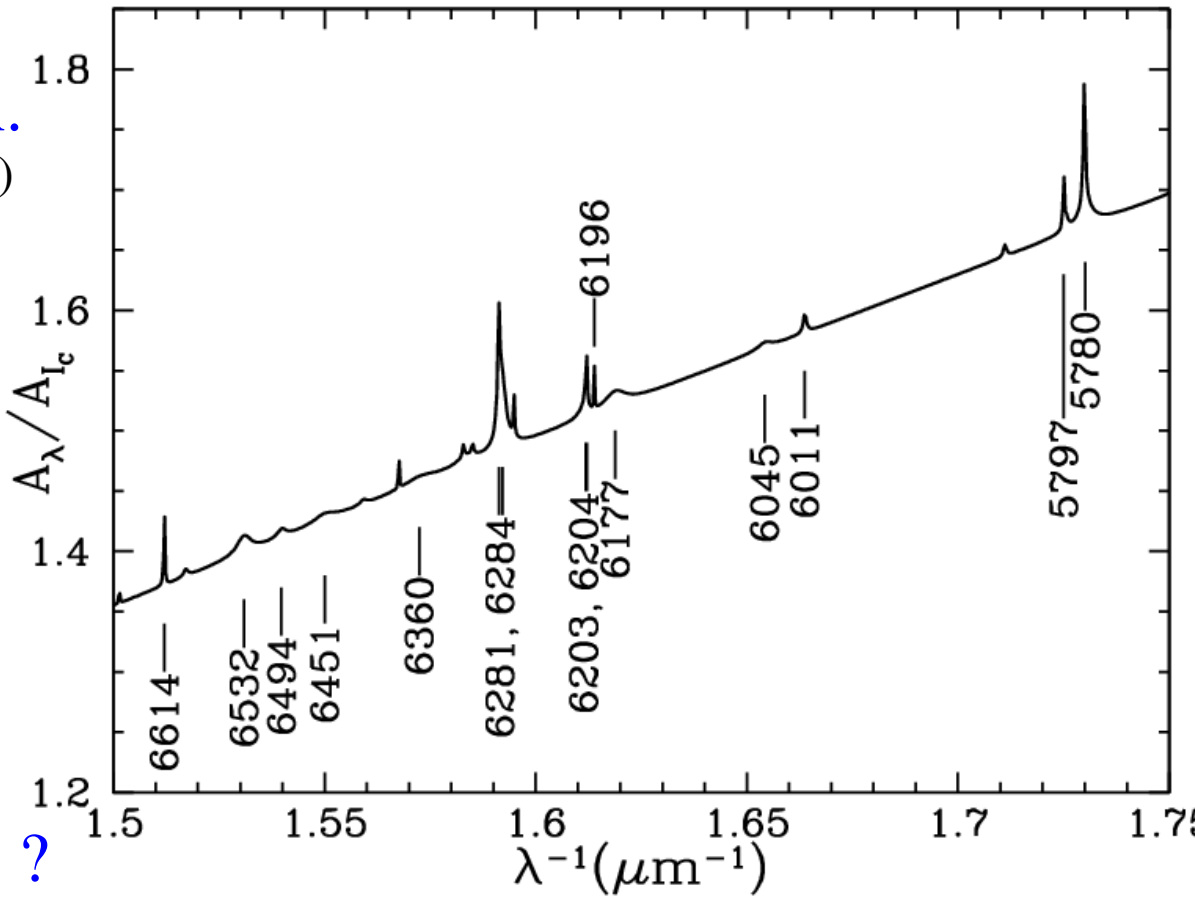
- Strong 3.1 μm feature correlates with the presence of features at 4.67 μm (CO), 3.53 μm (CH_3OH) and 15.2 μm (CO_2).

- H_2O appears to be the dominant ice species in the ISM.

The Diffuse Interstellar Bands

(Draine 2011)

- First detected in 1922!!!
  ~ 400 lines at 3900 – 8100 Å.
  (Heger 1922; Hobbs et al. 2009)
- Not one identification!!!
- Width ≈ 1 Å: Too broad for atoms and small molecules.
- Individual large molecules ?
  Fine structure: Yes!
  Correlations in line strengths ?



- But... Strengths of DIB features uncorrelated with each other.
  Correlation recently found between 6196.0 Å and 6613.6 Å lines.
  (McCray et al. 2010)
- Lack of correlated strengths: Multiple carriers of DIB features ?

POLYCYCLIC AROMATIC HYDROCARBONS

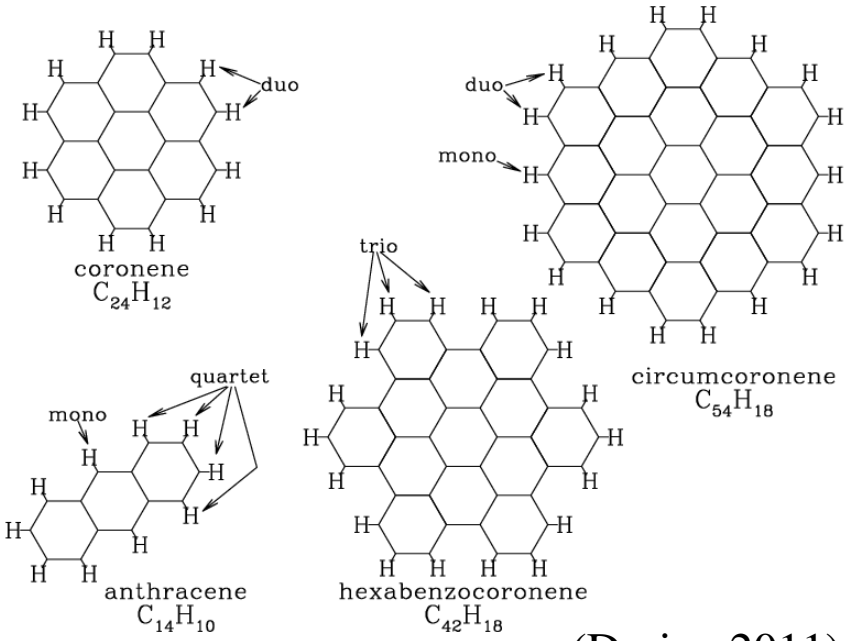
- Planar structures: Hexagonal C-rings with H-atoms on the boundary.

- Vibrational modes, excited on heating small PAHs to ~ 250 K. Lines at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm .

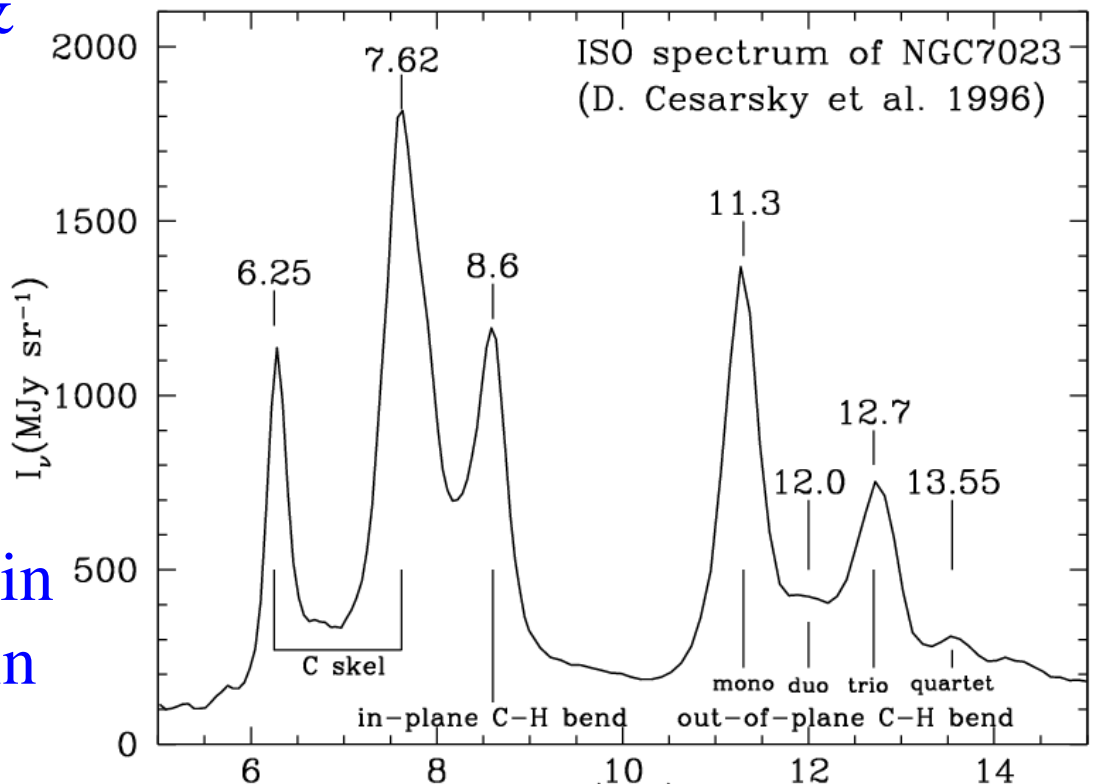
- C–H stretch and bend modes & vibrational modes of skeleton.

- Integrated PAH emission ~ 20% of total IR emission!
  ⇨ Absorbs ~ 20% of starlight!

- 15% of the total C abundance in PAHs! At least 5% of the grain mass in PAHs.



(Draine 2011)



MODELS FOR DUST COMPOSITION

- Match extinction curve with different ingredients + size distribution.

- MRN model: Graphite + SiC + $(Fe, Mg)SiO_3$ + $(Fe, Mg)_2SiO_4$ + Fe + Fe_3O_4 : Decent match! Size distribution $dn/da \propto a^{-3.5}$.
  Spherical graphite ($0.005 - 1\ \mu m$), others ($0.025 - 0.5\ \mu m$).
  More mass in large grains, more area in small grains!
  (Mathis, Rumpl & Nordsieck 1977)

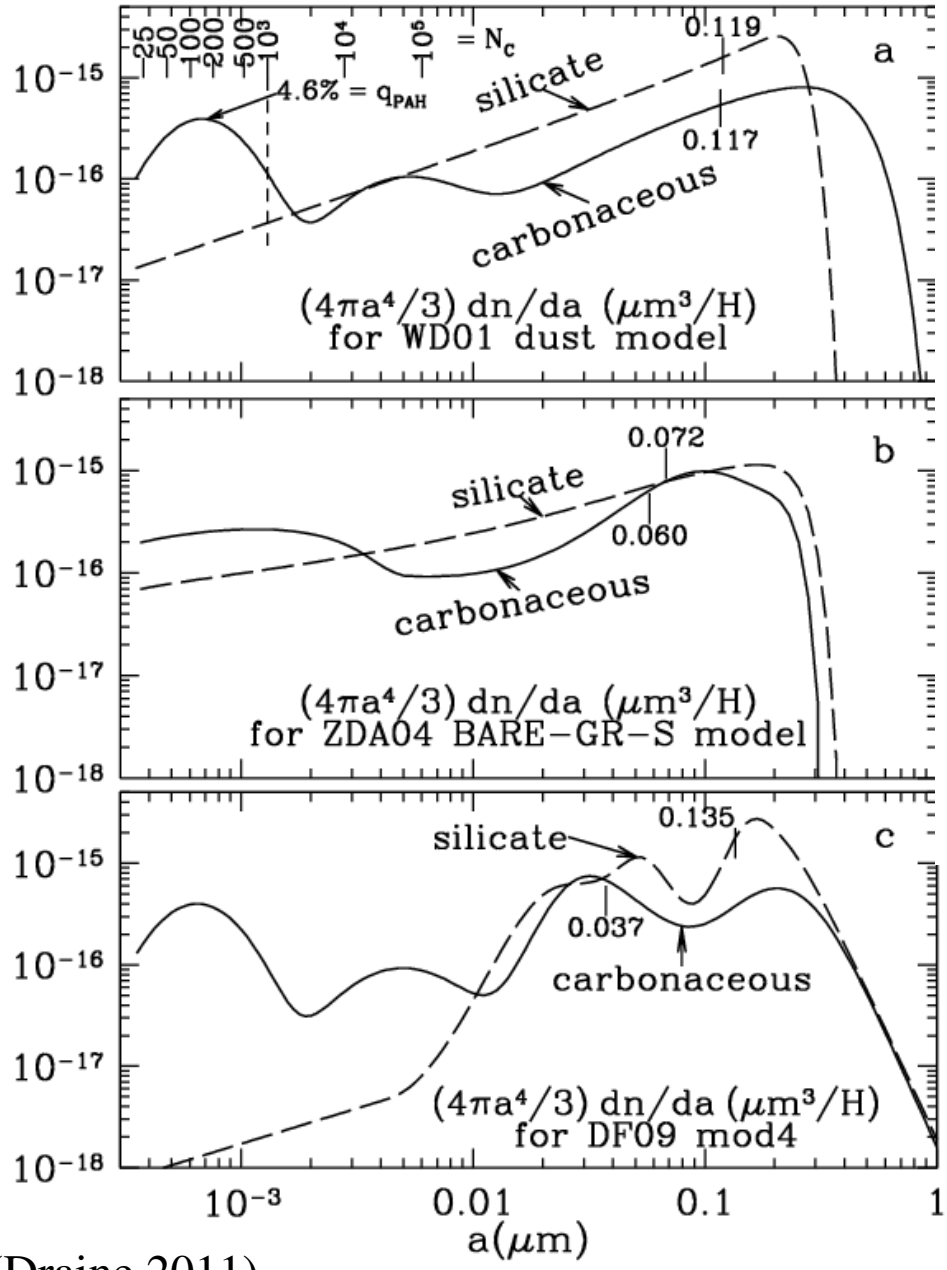
- Fit only to near-IR to UV data; excludes mid-IR PAH features.

- Modern models: Similar, but include PAHs. Fit extinction and polarization curves from IR to UV, as well as depletion data.
  (e.g. Desert et al. 1990; Weingartner & Draine 2001; Zubko et al. 2004; Draine & Li 2007)

- Reasonable match to extinction curves, but problems with depletion: "Carbon crisis" and ~ 50% over-consumption of Si.
  (e.g. Weingartner & Draine 2001; Draine & Fraisse 2009)

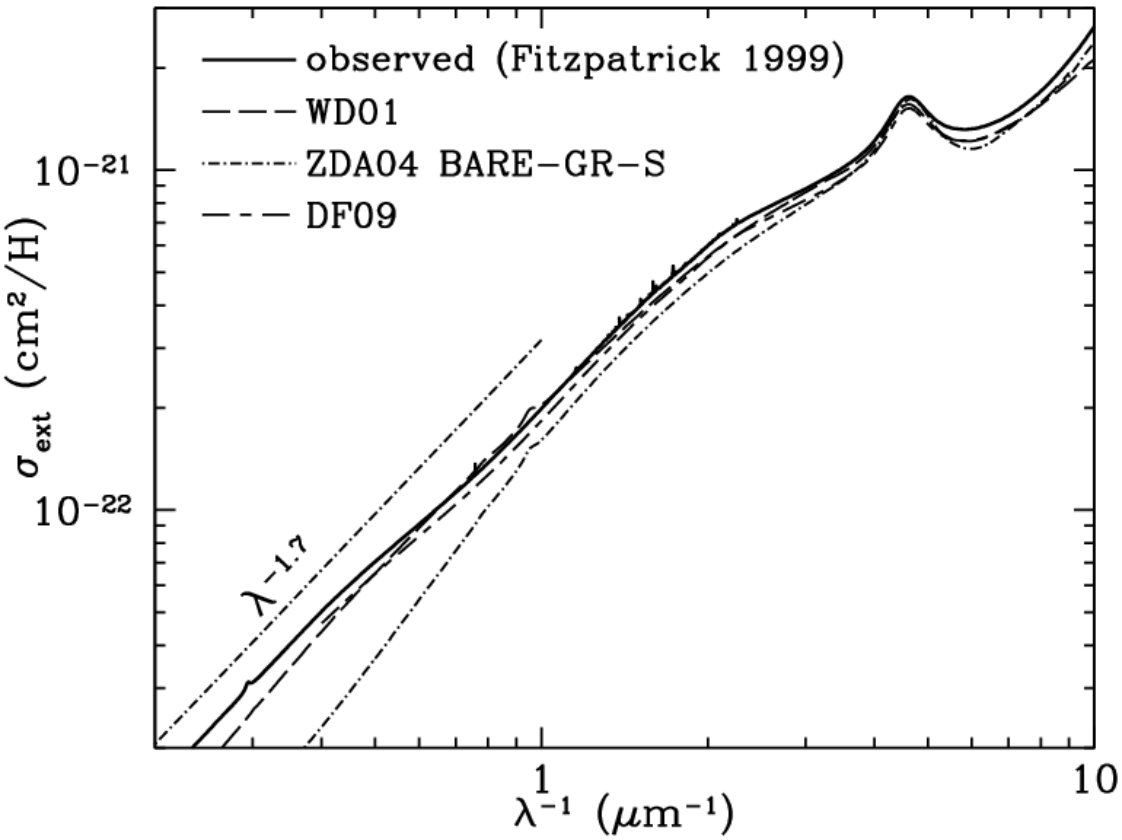
Models for Dust Composition

Size distribution



(Draine 2011)

Extinction curve



- Very different size distributions.
- Si over-consumption unclear.
  Differences between CNM, ζOph.
- Non-spherical grains do better!

(Weingartner & Draine 2001; Zubko et al. 2004; Draine & Fraisse 2009)