Astrochemistry (2)

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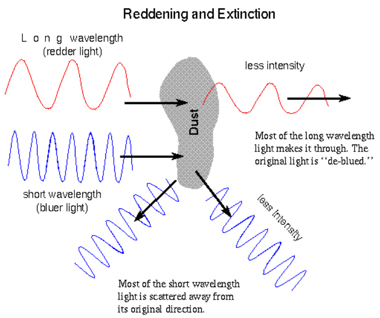
Observational evidence of interstellar dust

Interstellar reddening and extinction

- Interstellar dust grains absorb and scatter stellar photons
  - Both effects are wavelength dependent and result in a dimming (extinction) and reddening of the background star
  - The scattering is particularly efficient at short wavelengths (e.g., in the UV)

    As a result, the radiation that reaches the observer contains a larger fraction of long wavelength photons (e.g. in the red)



Measurement of the reddening

- The reddening of stellar colours casts light on the properties of the foreground interstellar dust
- The reddening is measured from photometric data
  - First one estimates the "color index": difference between magnitudes measured in two different spectral bands

    For instance, the color index (B-V) based on photometric measurements in the bands B (445 nm) e V (550 nm)
  - The spectral distribution of stars with the same spectral type, but increasing amount of foreground dust, will show increasig reddening
  - Stars in lines of sight without dust can be used to estimate the reference color of the unreddened star
  - The color excess (reddening) is then defined as

    $E(\mathrm{B-V}) = (\mathrm{B-V}) - (\mathrm{B-V})_0$

Interstellar extinction

- Dimming of the photons of a background source resulting from the combined effect of absorption and scattering by intervening dust
- If the emission of the medium can be neglected (as in the case of point-like background sources) the transport equation that relates the observed intensity to the intensity emitted by the star is:

$$I_\lambda = I_{\lambda 0}\, e^{-\tau(\lambda)}$$

Where $\tau_\lambda = N_d\, Q_{ext}\, \sigma$ is the optical depth

σ_d geometrical cross section of the dust grains

N_d column density of dust grains

Q_{ext} Extinction efficiency factor (ratio between the optical and geometrical cross-section)

- The extinction at wavelength λ is defined as

$$A_\lambda\ (\mathrm{mag}) = -2.5 \log_{10} (I_\lambda / I_{\lambda 0}) = 1.086\, \tau_\lambda$$

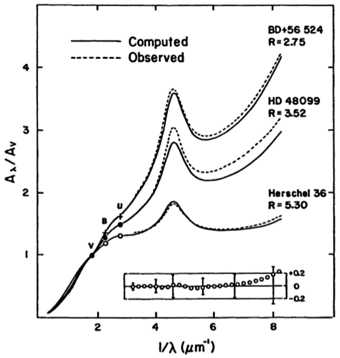
Interstellar extinction curves

- Extinction as a function of wavelength
  - Fundamental diagnostic tools to cast light on the nature of dust grains
  - The extinction curves are obtained using low-resolution stellar spectra

    By comparison with:

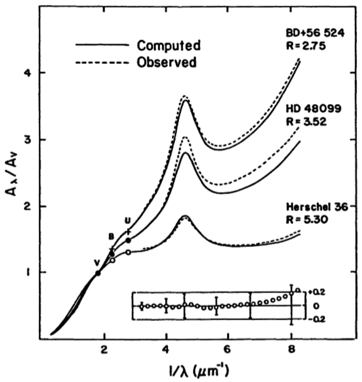
    - the spectrum of an unreddened star of the same spectral type

    - or a synthetic spectrum of the star
  - The extinction curves are normalized to the value of extinction in the visible band, A_V
  - Traditionally the normalized extinction is plotted versus 1/λ



Interstellar extinction curves

- Main properties
  - At long wavelengths the extinction increase as λ^{-1}
  - An "extinction bump" is present at λ ~ 2175 Å
- The extinction curves vary in different types of clouds
  - The curves can be more or less steep in the UV
  - The extinction bump can be more or less pronounced



Ratio between extinction and reddening

- Definition

  $R_V \equiv A(V) / E(B\text{-}V)$
- Typical value in the Milky Way ISM

  $R_V \approx 3.1$

  Can vary between ~2.1 e ~5.5
- The shape of the extinction curves varies with R_V
  - The curves become flatter with increasing R_V

Draine (2003)

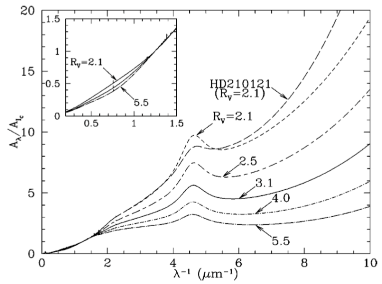


Figure 1 Extinction curves from prescription of Fitzpatrick (1999), with diffuse interstellar bands (DIBs) added as described in Section 3.3. The DIBs are barely visible on this plot.

Slope of the extinction curves

- The slope is determined by the grain size distribution
  - The extinction curve becomes flatter when the fraction of small grains (sizes ≤ 100 Å) is small
- Possible effects that may impact the grain size distribution

  - The size of the grains may increase in dense clouds due to coagulation of small solids (e.g. ice condensation)

  - The smallest grains may be destroyed in some lines of sight

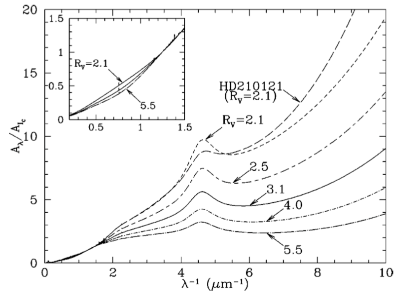


Figure 1 Extinction curves from prescription of Fitzpatrick (1999), with diffuse interstellar bands (DIBs) added as described in Section 3.3. The DIBs are barely visible on this plot.

The extinction bump at 2175 Å

- Main observational properties
  - The position of the central wavelength is constant
  - The width shows a modest variation between different lines of sight
    Fitzpatrick & Massa (1986)
  - The intensity indicates that the bump is produced by an element with high cosmic abundance
    Draine (1989)

- Origin of the bump
  - Long debate in the literature
  - Some form of carbonaceous material
    - Originally attributed to graphite
    - Currently attributed to aromatic molecules

Observational evidence of interstellar dust

Interstellar polarization

- The thermal radiation of stars is not usually appreciably polarized
- Scattering of stellar photons by elongated dust grains aligned in the galactic magnetic field can impose polarization on starlight over long distances
- Starlight is polarized in regions of high extinction, with one polarization state selectively removed by scattering
- The elongated grains can be conducting or dielectric particles
- The polarization of starlight was first observed by William Hiltner and John S. Hall in 1949
- Jesse Greenstein and Leverett Davis, Jr. developed theories allowing the use of polarization data to trace interstellar magnetic fields

Properties of interstellar dust grains

The modelization of extinction curves is one of the main instruments to cast light on the properties of dust grains

Main parameters of the models
Grain size distribution
Refraction index of grains

Observational contraints
Scattering and absorption properties of the grains
Chemical composition of the grains

The solution is not univoque

Grain size distribution

- From the modelization of extinction curves
  - Different grain populations are required to explain the different properties of the extinction curves

    - Large grains (~ 0.12 μm)
      Extinction in the visible spectral band
    - Small carbonaceous grains (< 0.01 μm)
      Bump at 2175 Å
    - Small silicate grains (< 0.01 μm)
      Extinction in the far UV

Internal structure of grains

- The core-mantle model
  - Li & Greenberg (1997)
  - Idealized model of dust grains
    - Refractory core (silicates and organic refractory material)
    - Icy mantle
      - Resulting from processing of simple ice molecules, such as H_2O, CO, CH_3OH (methanol), H_2CO (formaldehyde), and others
  - According to this model, the mantle would be present in cold, dense regions and absent in low-density regions

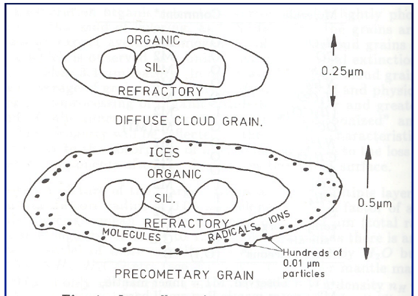
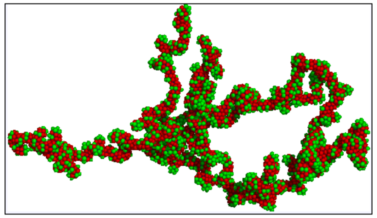


Fig. 1. Interstellar grains as core-mantle structures.

Geometrical properties

- General features
  - Porosity
  - Possible fractal form
  - Generally amorphous
- The properties change in different interstellar regions
  - In some cases crystalline material, rather than amorphous, is detected



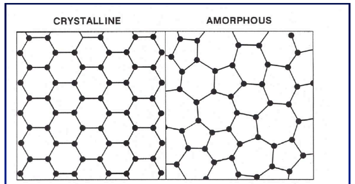


Figure 1. Atomic arrangement in a crystalline and an amorphous solid. The dots indicate the equilibrium positions about which the atoms vibrate, and the lines indicate the chemical bonds.

Chemical composition of dust grains

- Observational constrains
  - Extinction curves
  - Absorption lines in the near IR
  - Elemental depletions
- Uncertain results because the observational constraints do not provide unique solutions
  - For instance, the uncertainties in the reference (solar) values adopted to calculate the depletions imply a large uncertainty in the amount of carbon or oxygen that may be present in the solid phase

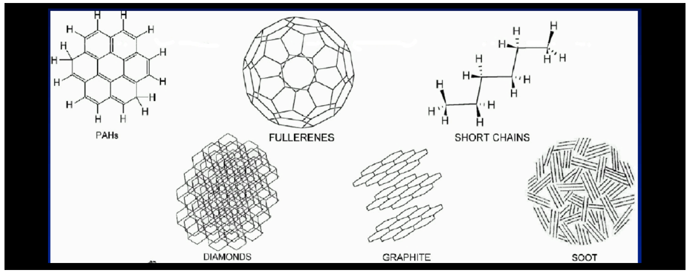
Chemical composition of dust grains

Table 1.1. *Jenkins (2004) Grain Composition: One Illustrative Possibility*

Material	C [a]	O [a]	Mg [a]	Si [a]	Al [a]	Ca [a]	Fe [a]	Ni [a]	ρ [b]	V [c]
Grain Cores										
C,PAH,HAC,...	71	-	-	-	-	-	-	-	2.2	6.5
$MgFeSiO_4$ olivine	-	52	13	13	-	-	13	-	3.8	9.8
$CaMgSiO_4$ monticellite	-	8	2	2	-	2	-	-	3.2	1.6
Fe_2O_3 hematite	-	18	-	-	-	-	12	-	5.3	3.0
Al_2O_3 corundum	-	4.5	-	-	3	-	-	-	4.02	0.6
Ni_2O_3 dinickel trioxide	-	2.4	-	-	-	-	-	1.6	4.84	0.5
Illustrative Core Total	71	85	15	15	3	2	25	1.6	3.5	22.1
Observed Core Total [d]	71^{+61}_{-71}	53^{+49}_{-53}	15	14	3.0	2.2	25	1.6		
Grain Mantles										
C,PAH,HAC,...	35	-	-	-	-	-	-	-	2.2	3.2
$Mg_{0.9}Fe_{0.1}SiO_3$ pyroxene	-	57	17	19	-	-	2	-	3.3	9.9
Illustrative Mantle Total	35	57	17	19	-	-	2	-	3.5	13.1

Carbonaceous compounds in the ISM

- Graphite
  - Originally it was believed to be an important constituent of the dust
- PAHs
  - Polyciclic Aromatic Hydrocarbons: a collection of benzene rings
    similar to sheets of graphite with hydrogen atoms at the border
  - PAHs have characteristic emission lines at 3.3, 6.2, 7.7 μm
- Fullerenes
- Nanodiamonds



Interstellar iron

- Iron depletion is very high, suggesting that most of interstellar iron is in solid form
- In principle, iron could be incorporated in silicates and/or oxides, such as FeO or Fe_3O_4
- In practice, the amount of interstellar silicates or oxides is insufficient to accommodate all the iron atoms missing from the gas phase
- These arguments suggest that Fe could be in metal form, for instance in form of alloy (e.g., FeNi)
- The condensation temperature of Fe alloys are relatively high, suggesting that iron dust would be a refractory component
- Models of dust grain composition should incorporate a population of iron metal solids

Dust versus other interstellar components

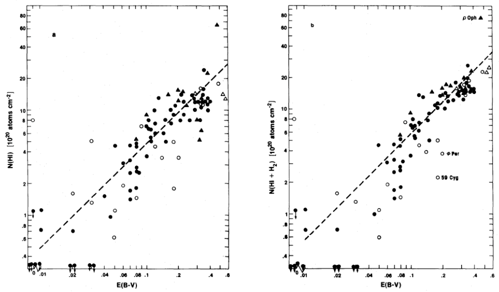
Dust versus gas

Dust-to-gas ratio

Dust versus molecules

Experimental trends

Gas and dust trace each other: Reddening and extinction versus HI column density



- Total hydrogen column density versus color excess
  $\langle N(HI+H_2)/E(B-V)\rangle = 5.8 \times 10^{21}$ atoms cm^{-2} mag^{-1}
  Bohlin et al. (1978)
  - Sometimes called "gas-to-dust ratio"
- Extinction per hydrogen atom
  - For R_V=3.1 ⇒ $\langle A_V/N_H\rangle \sim 5.3 \times 10^{-22}$ mag cm^2 atomo^{-1}

The dust-to-gas ratio by mass

- Different types of estimates yield a consistent value $M_{dust}/M_H \sim 0.01$
  - Value commonly adopted, also in models of planetary formation
- Estimate of M_{dust}/M_H from interstellar depletions
  - Counting the fraction of refractory elements incorporated in the dust

    Can be estimated from measurements of interstellar depletions of the most abundant elements

    One obtains $M_{dust}/M_H \sim 0.008$

Dust is associated with molecules

- Correlation between molecular fraction $f(H_2)$ and color excess

  Example in the figure: Rachford et al. (2002)

$$f \equiv \frac{2n(H_2)}{n(H)+2n(H_2)} \approx \frac{2N(H_2)}{N(H)+2N(H_2)}$$

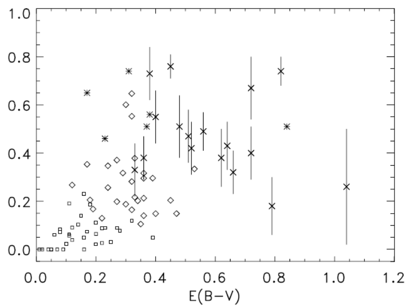


FIG. 7.—Molecular fraction vs. color excess. *Crosses: FUSE; asterisks: FUSE* points with no independent measurement of N(H I); *diamonds: Copernicus* points with $N(H_2) > 10^{20}$ cm^{-2}; *squares: Copernicus* points with $N(H_2) < 10^{20}$ cm^{-2}.

Observational evidence for small grains or large molecules in the ISM

It is hard to establish a clearcut distinction between small grains and large molecules

Diffuse Interstellar Bands (DIBs)

Unidentified Infrared Bands (UIBs)

Diffuse Interstellar Bands (DIBs)

- About 200 broad and shallow absorptions
  - detected in the visible spectrum, between 4000 Å and 10000 Å
  - can be grouped into families

    for a given family the intensity of the bands scale together in different lines of sight
- DIBs carriers are hard to identify
  - Originally associated with impurities or ice on dust grains
  - Currently believed to be absorption bands of large molecules in the gas phase
  - Many possible identifications have been proposed, difficult to be confirmed

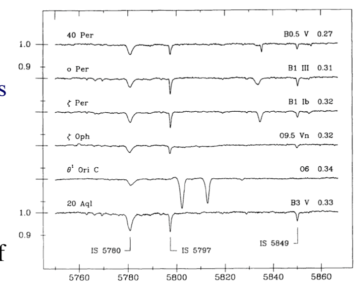


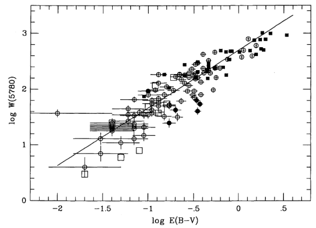
FIG. 3.—CFHT spectra of six stars having $E(B-V)$ values near 0.3. The DIBs λ5780 and especially λ5797 may have quite different equivalent widths at essentially the same degree of reddening.

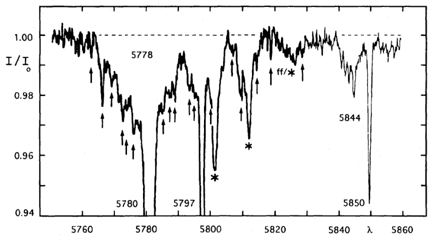
Diffuse Interstellar Bands (DIBs)

- Empirical correlations confirm the interstellar nature of DIBs
  - For instance, the intensity of the 5780 Å band scales with the color excess E(B-V)

    Herbig (1993)
- High resolution spectroscopic data supports the molecular nature
  - The structure of some bands is similar to that typical of roto-vibrational molecular spectra

    Jenniskens et al. (1996)





Infrared emission bands

- Emissions from diffuse medium and circumstellar regions

  Photodissociation interfaces between HII regions and neutral medium
  - Intense emission bands at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm

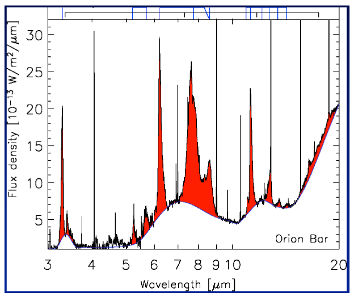
  Originally called UIBs (Unidentified Infrared Bands)

  Later attributed to small grains/large molecules containing hydrogenated aromatic rings

  Examples:

    3.3 μm: stretching vibration mode of C−H attached to an aromatic ring

    6.2 μm e 7.7 μm: stretching mode of C−C in a solid or in an aromatic molecule



Peeters et al. (2004)