Astrochemistry (2)

Planets and Astrobiology (2023)
G. Vladilo

Interstellar dust

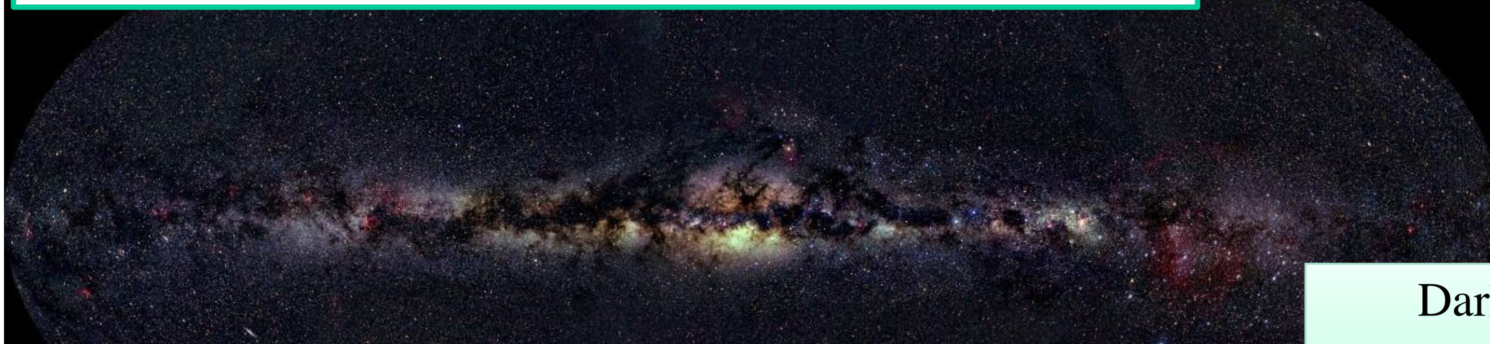
The solid phase component of the ISM

Importance of interstellar dust in astronomy

- Effects on astronomical observations
  – Reddening and extinction of astronomical sources
  – Depletion of chemical abundances in the interstellar gas
- Physical effects in the interstellar medium
  – Transformation of UV photons into IR photons
  – Cooling of the ISM by means of thermal emission
- Effects on planetary formation
  – Essential ingredient of planetary formation in protoplanetary
- Importance in astrochemistry
  – Catalyst for the formation of interstellar molecules

Observational evidence of interstellar dust (1)

- Dark regions, dark clouds
  - Absence of stars in large field images
  - Dust grains absorb the optical/UV light of background stars



The Horsehead Nebula

Dark cloud B68

ESO-VLT Alves et al. (2001)

In some cases, dark clouds are associated with pre-stellar cores

Observational evidence of interstellar dust (2)
Reflection nebulae

- Dust grains in reflection nebulae scatter the stellar photons

- A detailed study of reflection nebulae provides information on some physical properties of the grains
  - Albedo

    Ratio between scattering and extinction cross-sections of dust grains
  - Phase function

    Angular distribution of scattered light

Observational evidence of interstellar dust (3)

Galactic infrared emission

- Thermal emission from interstellar dust
  - Dust is heated by interstellar radiation
  - The infrared emission cools the gas
- Galactic infrared emission maps the distribution of interstellar dust

  1983, IRAS satellite
  - All sky map in the bands at12, 25, 60 e 100 μm
  - The emission is concentrated in the Galactic plane
  - IR clouds ("cirrus") found outside the Galacic plane

Composite mid-and far-infrared intensity observed in the 12, 60, and 100 μm wavelength bands. Mosaic of IRAS Sky Survey Atlas images. Emission from interplanetary dust in the solar system, the "zodiacal emission," was modeled and subtracted.

Observational evidence of interstellar dust (4)

Infrared absorptions

- Observations of background sources with strong IR emission along lines of sight interstecting dust-rich regions
  – Vibrational bands of solid compounds are detected in absorption
- Ice and organic compounds
  – H_2O, CO, CO_2, CH_3OH …
- Silicates
  – 9.7 μm e 18 μm

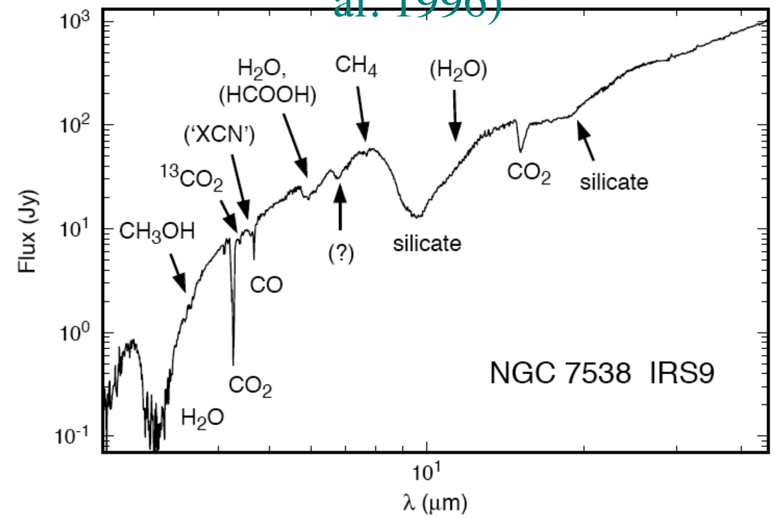
    Stretching vibration modes of Si–O bonds and bending vibration modes O–Si–O modes, respectively

Examples of silicates

Pyroxenes: $Mg_xFe_{(1-x)}SiO_3$

Olivines: $Mg_{2y}Fe_{2(1-y)}SiO_4$

ISO SWS spectrum in the mid-IR (2.4 to 45 μm) towards the young stellar cluster NGC7538 IRS9 embedded in a molecular cloud (Whittet et al. 1996)



Vibration modes of interstellar solids: ice and dust

A high spectral resolution is required to discriminate between different types of silicates

Pyroxenes: $Mg_xFe_{(1-x)}SiO_3$

Olivines: $Mg_{2y}Fe_{2(1-y)}SiO_4$

Molecule	Mode	λ (μm)
H_2O	O–H stretch	3.05
	H–O–H bend	6.0
	libration	13.3
NH_3	N–H stretch	2.96
	umbrella	9.35
CH_4	C–H stretch	3.32
	C–H deformation	7.69
CO	C–O stretch	4.67
CO_2	C–O stretch	4.27
	O–C–O bend	15.3
CH_3OH	O–H stretch	3.08
	C–H stretch	3.35
	C–H stretch	3.53
	O–H bend, C–H deformation	6.89
	C–O stretch	9.75
$MgSiO_3$	Si–O stretch	9.7
	O–Si–O bend	19.0
Mg_2SiO_4	Si–O stretch	10.0
	O–Si–O bend	19.5
$FeSiO_3$	Si–O stretch	9.5
	O–Si–O bend	20.0
Fe_2SiO_4	Si–O stretch	9.8
	O–Si–O bend	20.0
SiC	Si–C stretch	11.2

Observational evidence of interstellar dust (5)

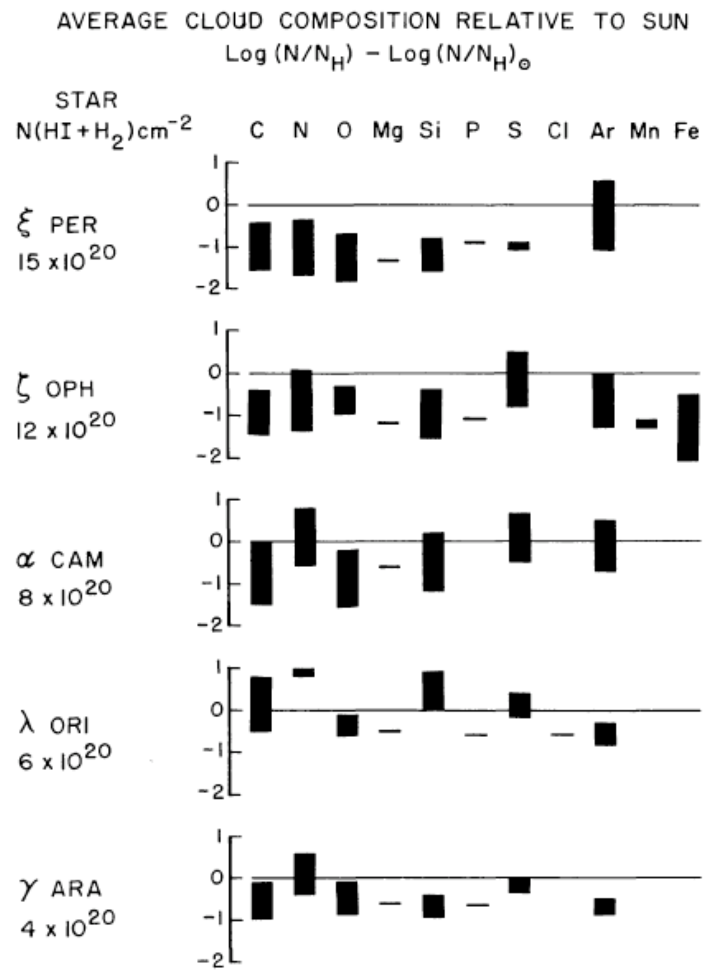
Elemental depletions

Gas-phase interstellar abundances are measured with high-resolution UV spectroscopy

The interstellar (resonance) transitions of the main ionization stages of the most abundant astrophysical elements are found in the UV range

The measurements of interstellar abundances indicate that:

- –For most elements the interstellar abundances X/H, measured in the gas phase, are lower than the corresponding solar abundances
- –This deficiency is known as "interstellar depletion"



Interstellar depletions

– Interpretation

a fraction of the atoms is incorporated in dust grains and, as a result, is not counted in the gas-phase column density measurements

– Galactic interstellar depletions are calculated assuming that the total abundance of the interstellar medium (gas plus dust) is solar

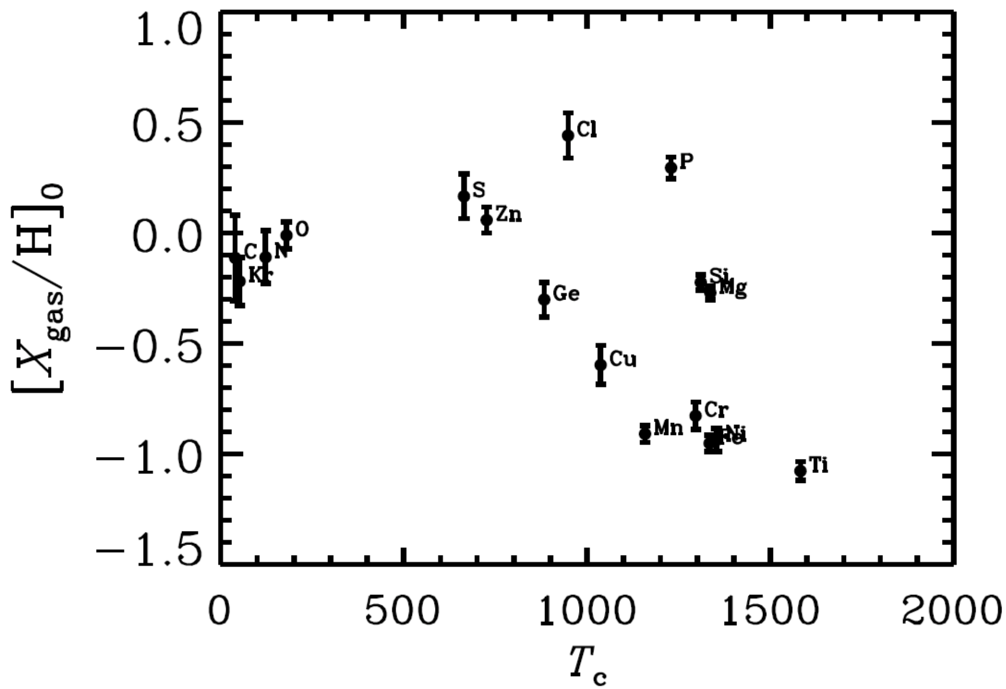
$$\delta_X = \log_{10} (N_X/N_H) - \log_{10} (X/H)_{sun}$$

This expression is similar to the definition of [X/H], but the physical meaning is completely different

- Interstellar depletions vary
  – for different elements
  – in different types of interstellar regions

Element-to-element variations of interstellar depletions

- Refractory elements
  - Strong depletions
    e.g., Ti, Ni, Fe, Cr, Mn, ..
- Volatile elements
  - Weak depletions
    e.g., S, Zn



- Correlation between depletion and condensation temperature
  - Empirical evidence that supports the interpretation of depletions in terms of incorporation of a fraction of elements in dust form

Condensation temperature

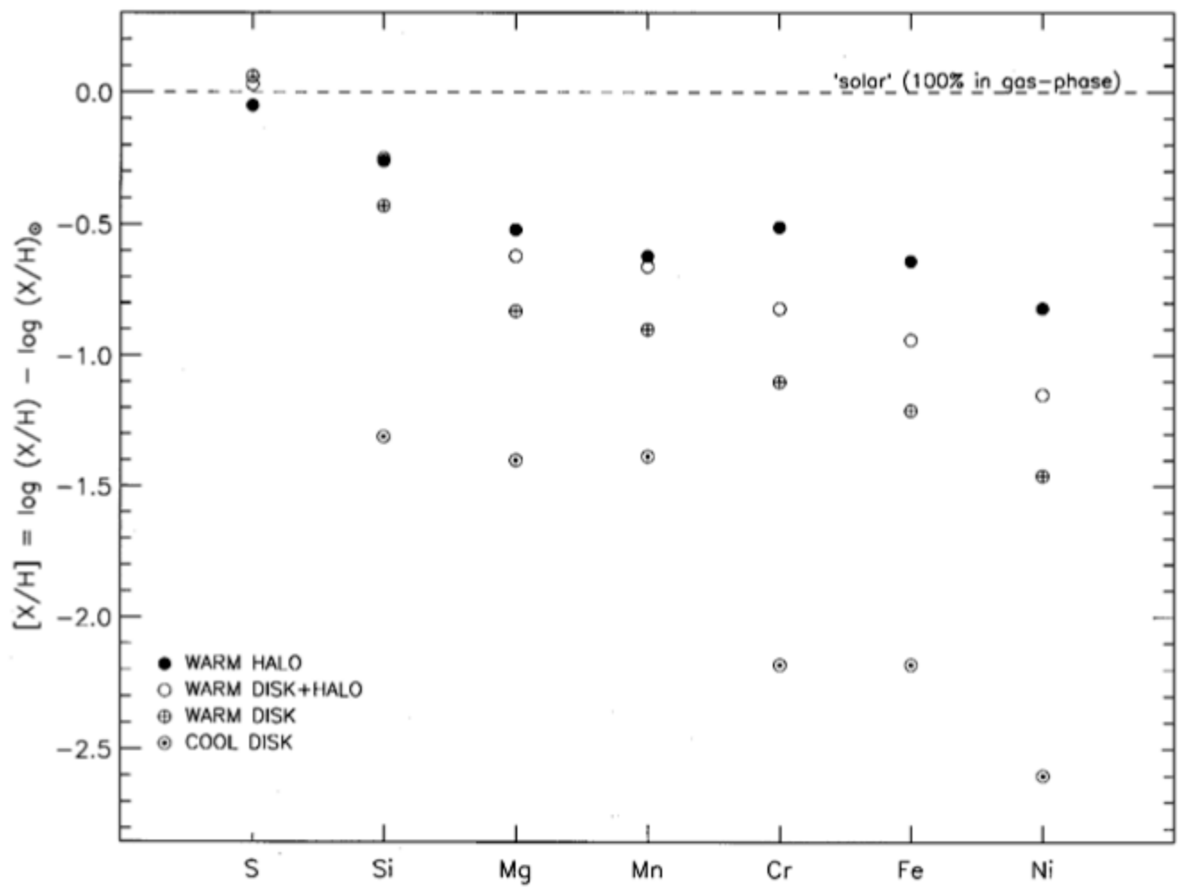
Temperature at which the 50% of an element condenses to a solid compound in a cooling gas of solar chemical composition

See Lodders K, 2003, ApJ, 591, 1220

Variations of depletions in different types of interstellar regions

- Cold and dense clouds
  - Strong depletions
- Warm and hot gas
  - Weak depletions

- Further evidence that depletions are due to the incorporation of atoms in dust form
  - Dust grains survive (or grow by accretion) in cold and dense clouds
  - Dust grains tend to be destroyed in hot, low density regions

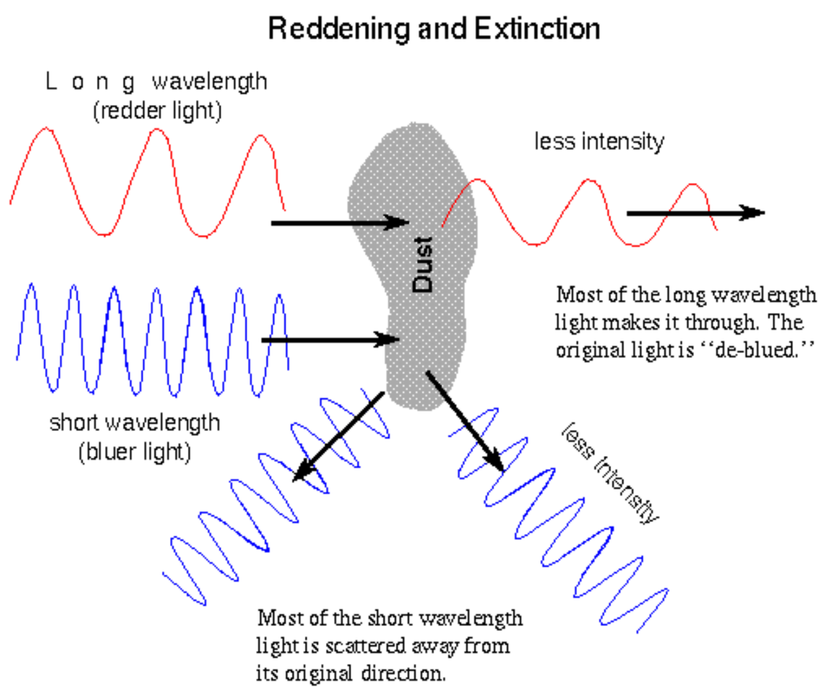


Observational evidence of interstellar dust

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

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

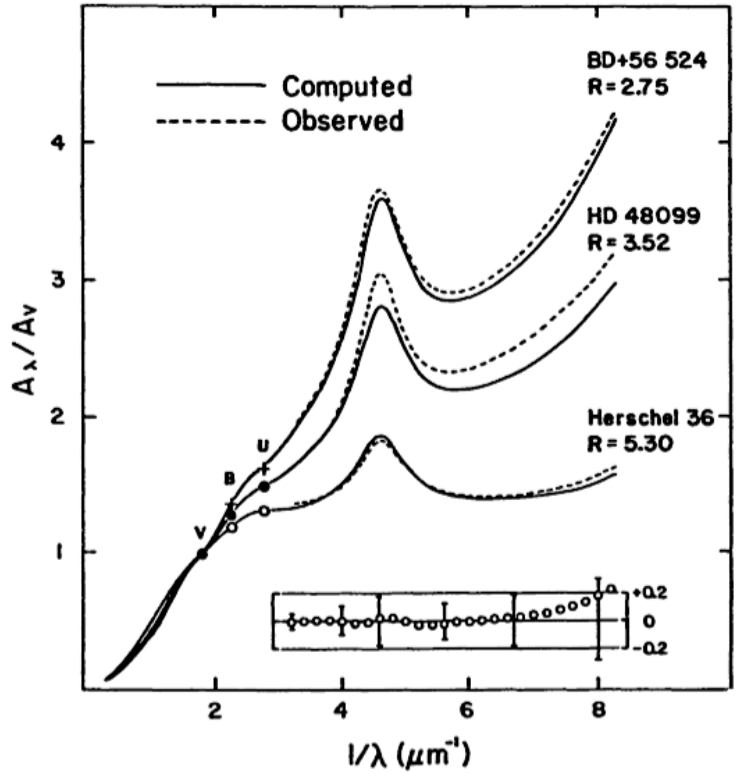
Interstellar extinction curves

- 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

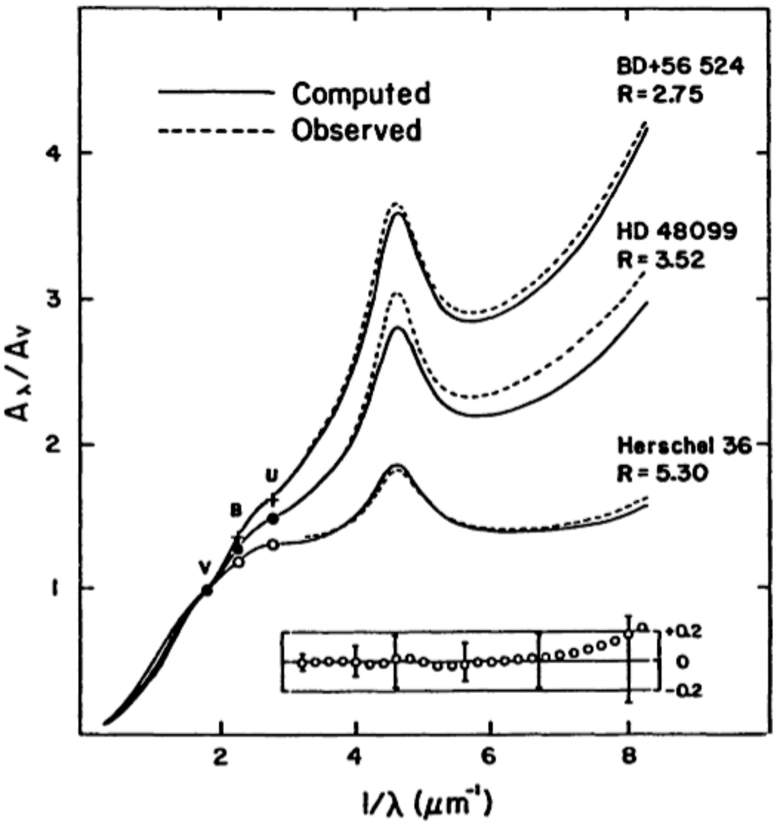
    - or a synthetic spectrum of the star
  - The extinction curves are normalized to the value of extinction in the visible band, A_V
  - Traditionally the normalized extinction is plotted versus $1/\lambda$



Interstellar extinction curves

- Main properties
  - At long wavelengths the extinction increase as λ^{-1}
  - An "extinction bump" is present at $\lambda \sim 2175$ 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



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

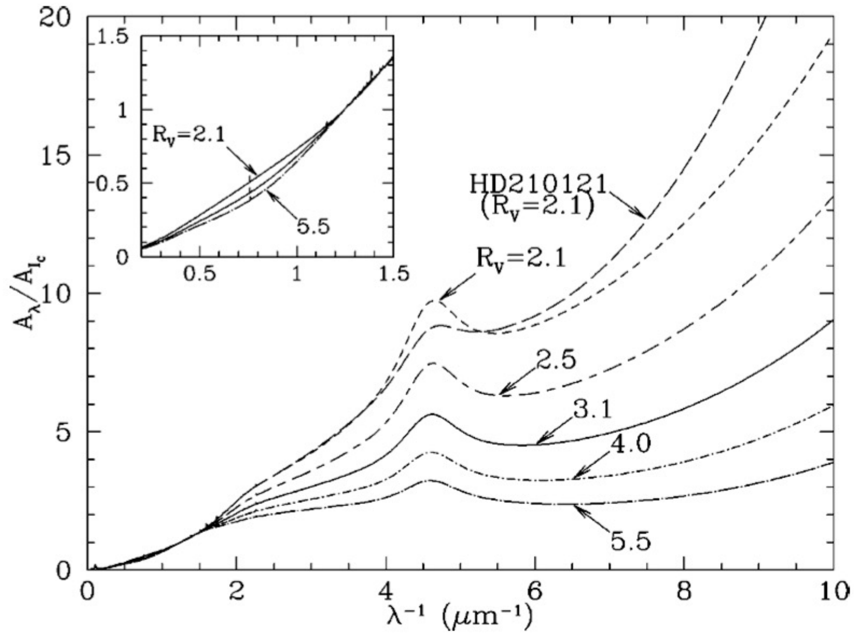


Figure 1 Extinction curves from prescription of Fitzpatrick (1999), with diffuse interstellar bands (DIBs) added as described in Section 3.3. The DIBs are barely visible on this plot.

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

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

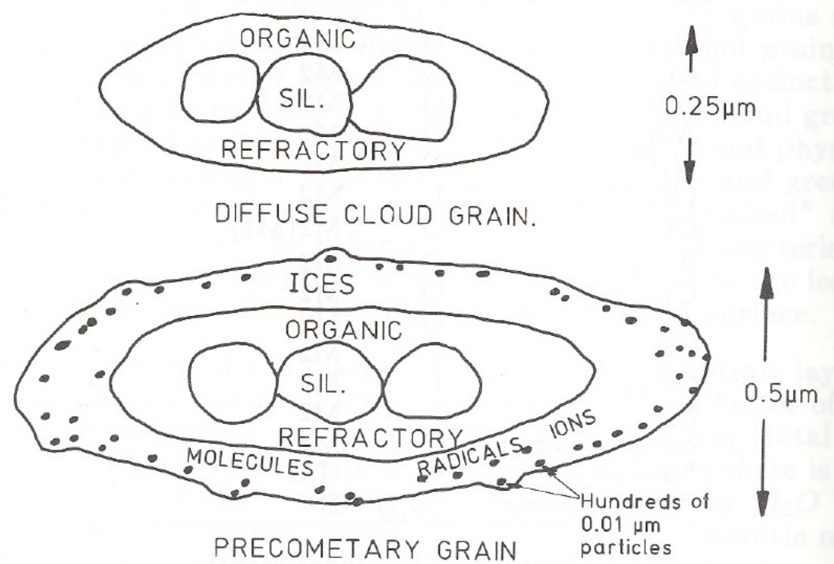
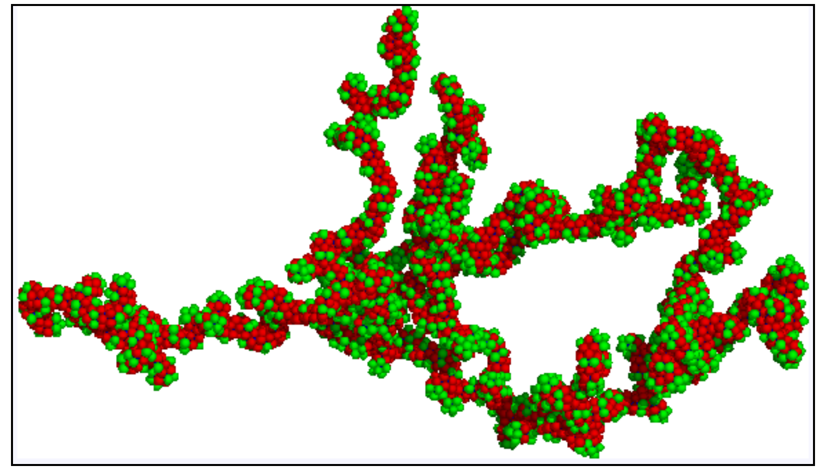


Fig. 1. Interstellar grains as core-mantle structures.

Geometrical properties of dust grains

- 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

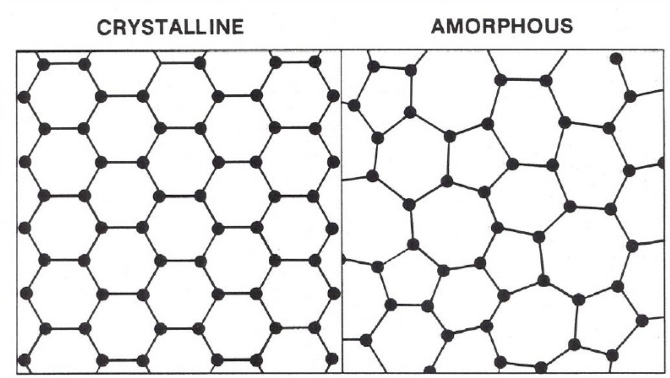


Figure 1. Atomic arrangement in a crystalline and an amorphous solid The dots indicate the equilibrium positions about which the atoms vibrate, and the lines indicate the chemical bonds.

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