

ON THE ABSORPTION AND EMISSION PROPERTIES OF INTERSTELLAR DUST GRAINS

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Outline

- ★ Dust: what, where, why?
- ★ Extinction: Absorption and Scattering
- ★ Polarization
- ★ Dust Emission
- ★ Dust emission in Galaxies

PREFACE: INTERSTELLAR DUST

Interstellar dust reveals its presence in astrophysical environments and its (both positive and negative) role in astrophysics mainly through its interaction with electromagnetic radiation:

- obscuring distant stars by the absorption and scattering of starlight by dust (the combined effects of absorption and scattering are called extinction);
- reddening starlight because the extinction is stronger for blue light than for red;
- generating "reflection nebulae" by the scattering of starlight by dust in interstellar clouds near one or more bright stars;

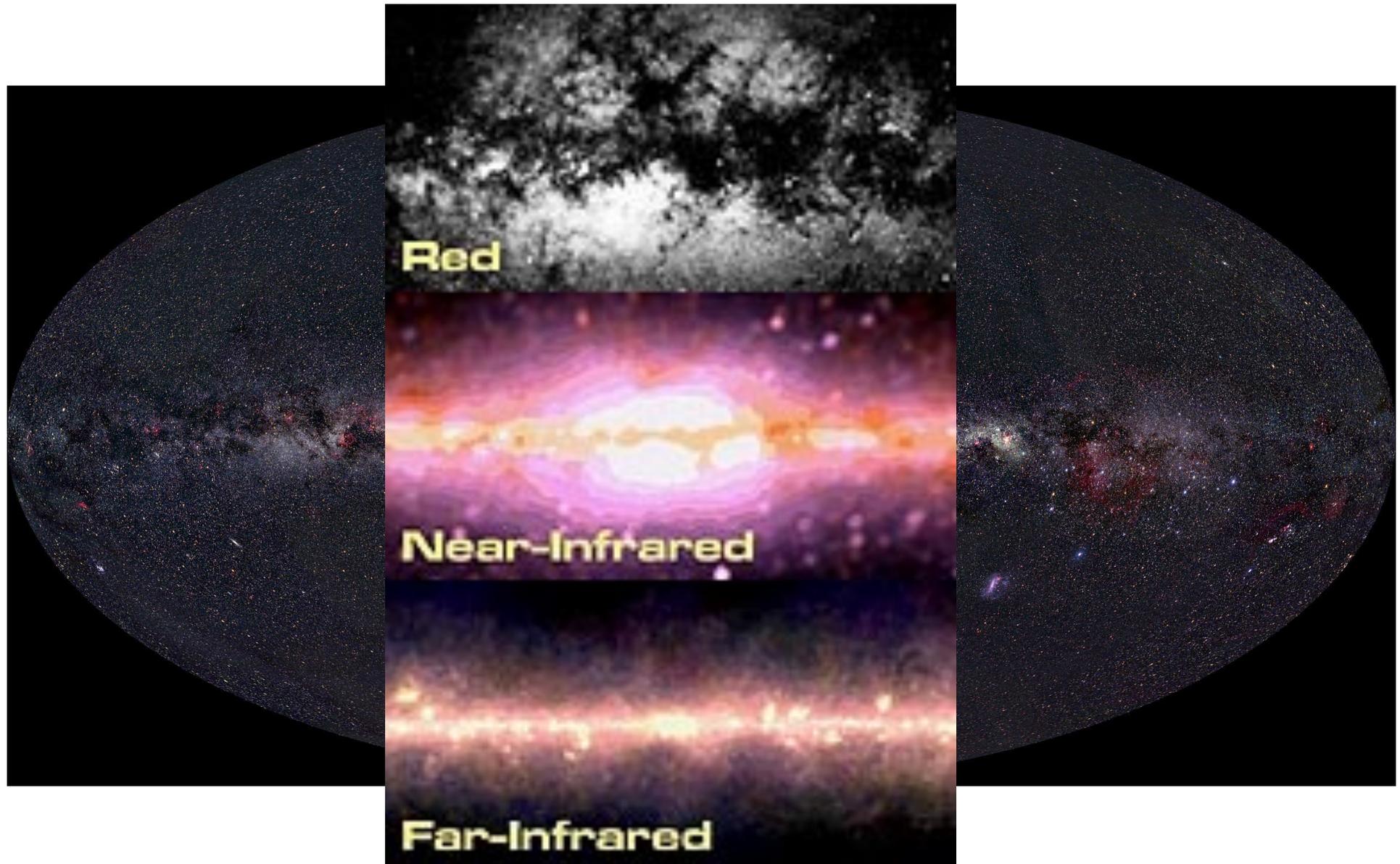
PREFACE: INTERSTELLAR DUST

- generating X-ray halos by small-angle dust scattering of X-ray sources;
- polarizing starlight as a result of preferential extinction of one linear polarization over another by aligned nonspherical dust;
- heating the interstellar gas by ejecting photoelectrons created by the absorption of energetic photons;
- radiating away absorbed short-wavelength radiation at longer wavelengths from near infrared (NIR) to millimeter (mm) in the form of thermal emission.

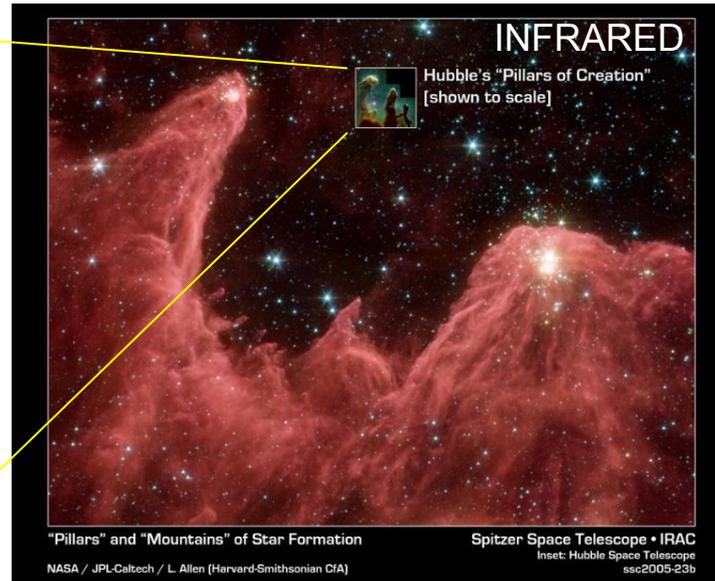
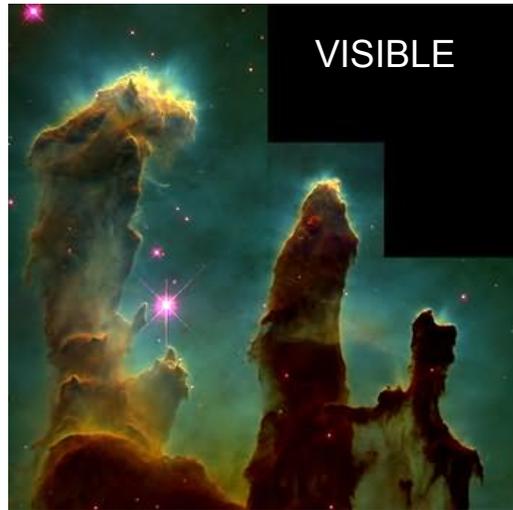
Dust: where in the Universe?

- Dust is a ubiquitous feature of the cosmos:
- Solid particles pervade interstellar space in the Milky Way and other galaxies
- It occurs in a wide variety of astrophysical environments, from comets to giant molecular clouds, from circumstellar shells to galactic nuclei.

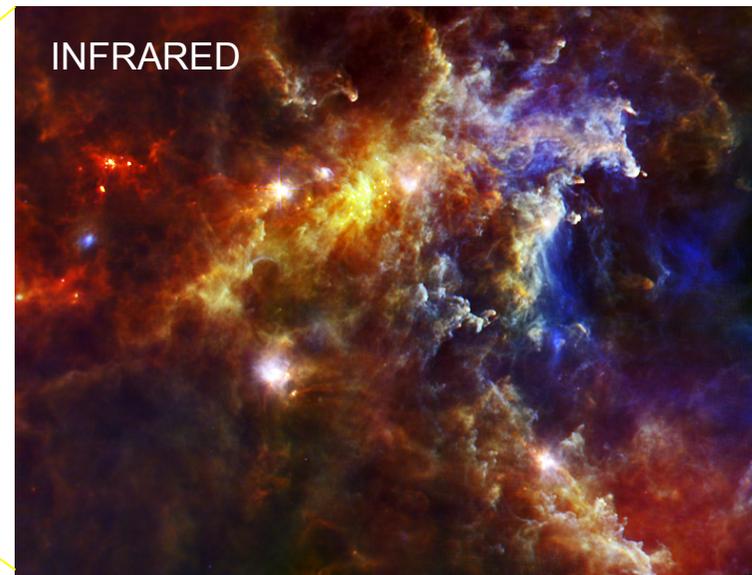
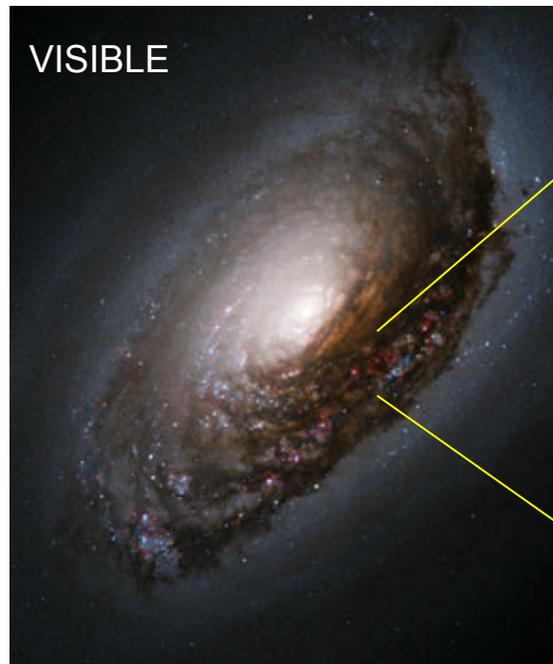
Dust: where in the Universe?



Dust: where in the Universe?

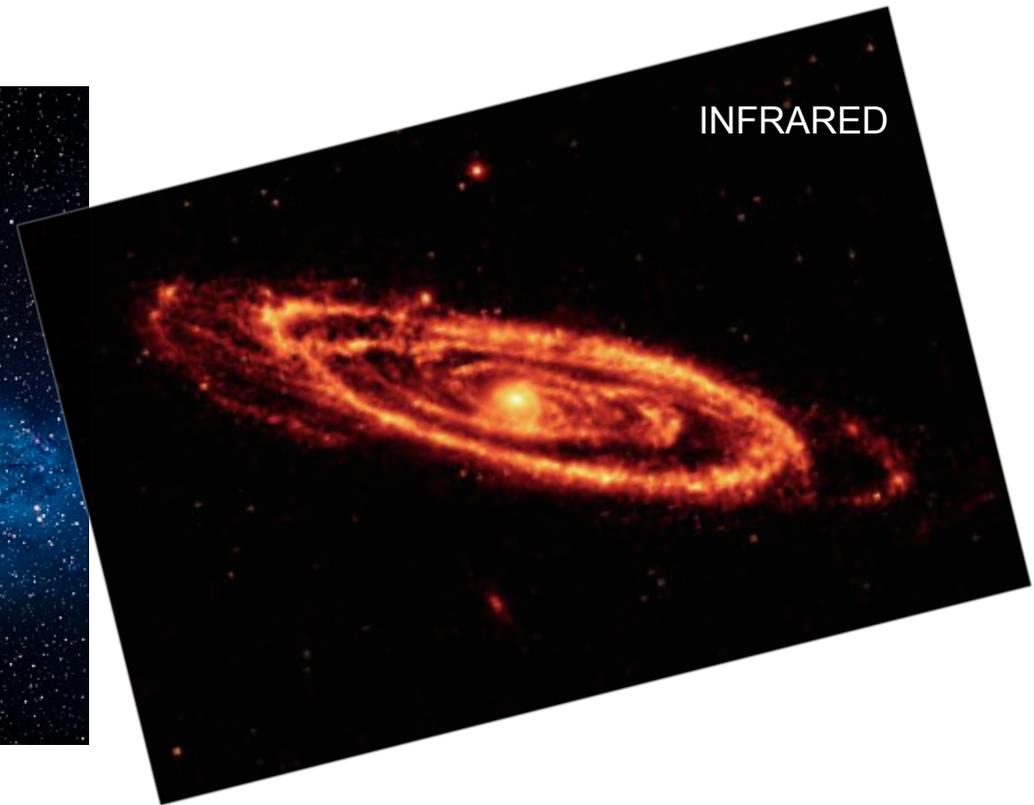


Dust associated
to the birth of stars
in our Galaxy



Dust in the
spiral
arms of
external
galaxies

Dust: where in the Universe?



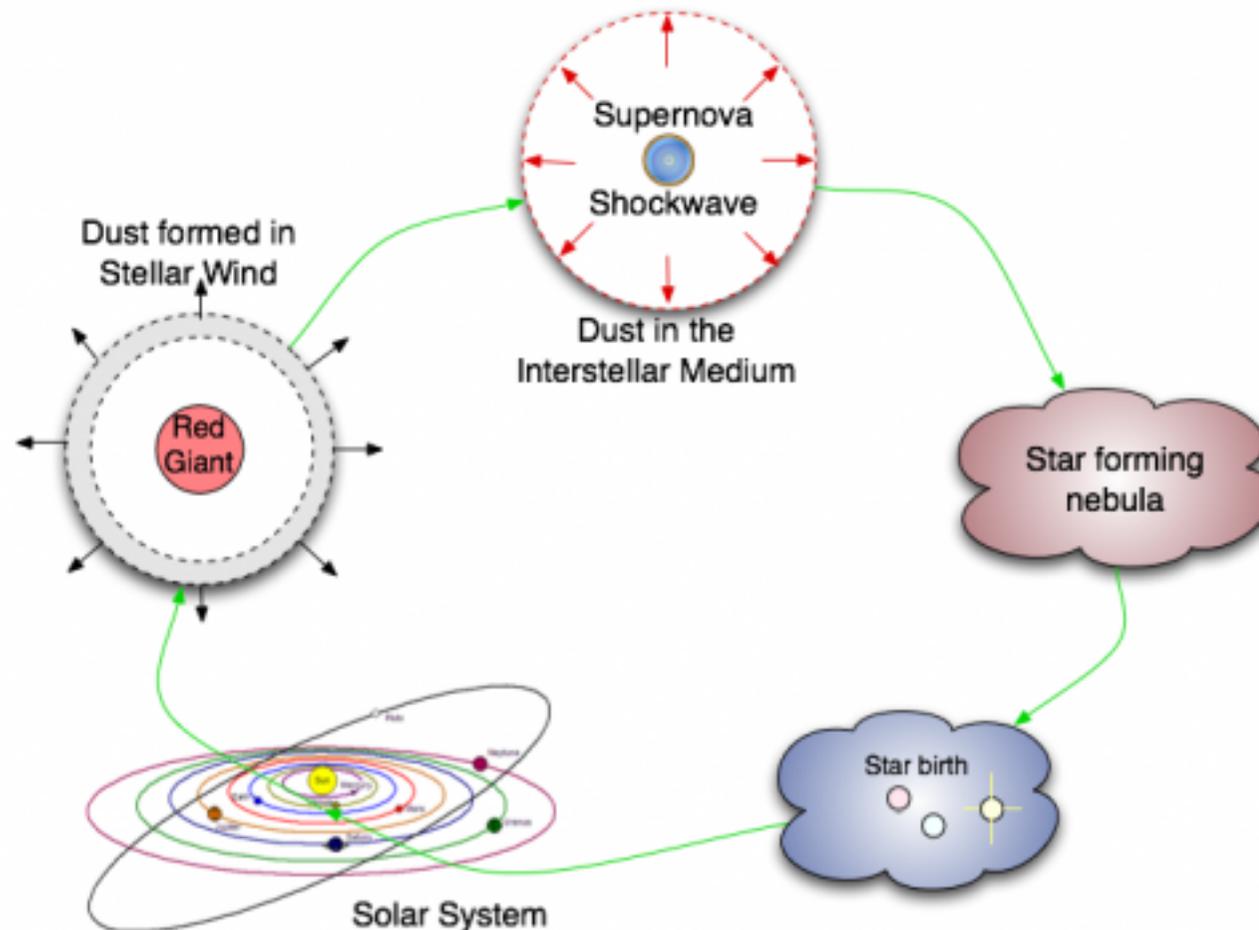
Why dust appears as a "dark", absorbing material in visible light, while it "shines" in the infra-red?

What is interstellar DUST?

- The Interstellar Medium (ISM) is continually interacting with stars :
 - ★ new stars condense from interstellar clouds,
 - ★ they bathe the ISM with radiation
 - ★ many stars return a substantial fraction of their mass to the ISM, which is continuously enriched with heavier elements
- These heavier atoms are locked up in sub-micron sized ($< 1 \mu\text{m}$) solid particles → DUST GRAINS

The cosmic DUST cycle

Dust is formed in stars, then it is blown-off in a slow wind or a massive star explosion. The dust is then “recycled” in the clouds of gas between stars and some of it is consumed when the next generation of stars begins to form.



What is interstellar DUST?

- Cosmic dust was once solely an annoyance to astronomers, as it obscures objects they wish to observe.

- The study of dust is a many-faceted research topic that brings together different scientific fields: physics (solid-state, electromagnetic theory, surface physics, statistical physics, thermal physics), fractal mathematics, chemistry (chemical reactions on grain surfaces), meteoritics, as well as every branch of astronomy and astrophysics.

What is interstellar DUST?

- These disparate research areas can be linked by the following theme: the cosmic dust particles evolve cyclically; chemically, physically and dynamically.
- The evolution of dust traces out paths in which the Universe recycles material, in processes analogous to the daily recycling steps with which many people are familiar: production, storage, processing, collection, consumption, and discarding.
- Observations and measurements of cosmic dust in different regions provide an important insight into the universe's recycling processes.

The Role of Interstellar DUST

- Interstellar dust is an important constituent of the Galaxy:
- It obscures all but the relatively nearby regions in visual and ultraviolet wavelengths, and reradiates the absorbed energy in the far-infrared part of the spectrum, thereby providing a major part (~ 30%) of the total luminosity of the Galaxy.
- The far-IR radiation from dust removes the gravitational energy of collapsing clouds, allowing star formation to occur.

The Role of Interstellar DUST

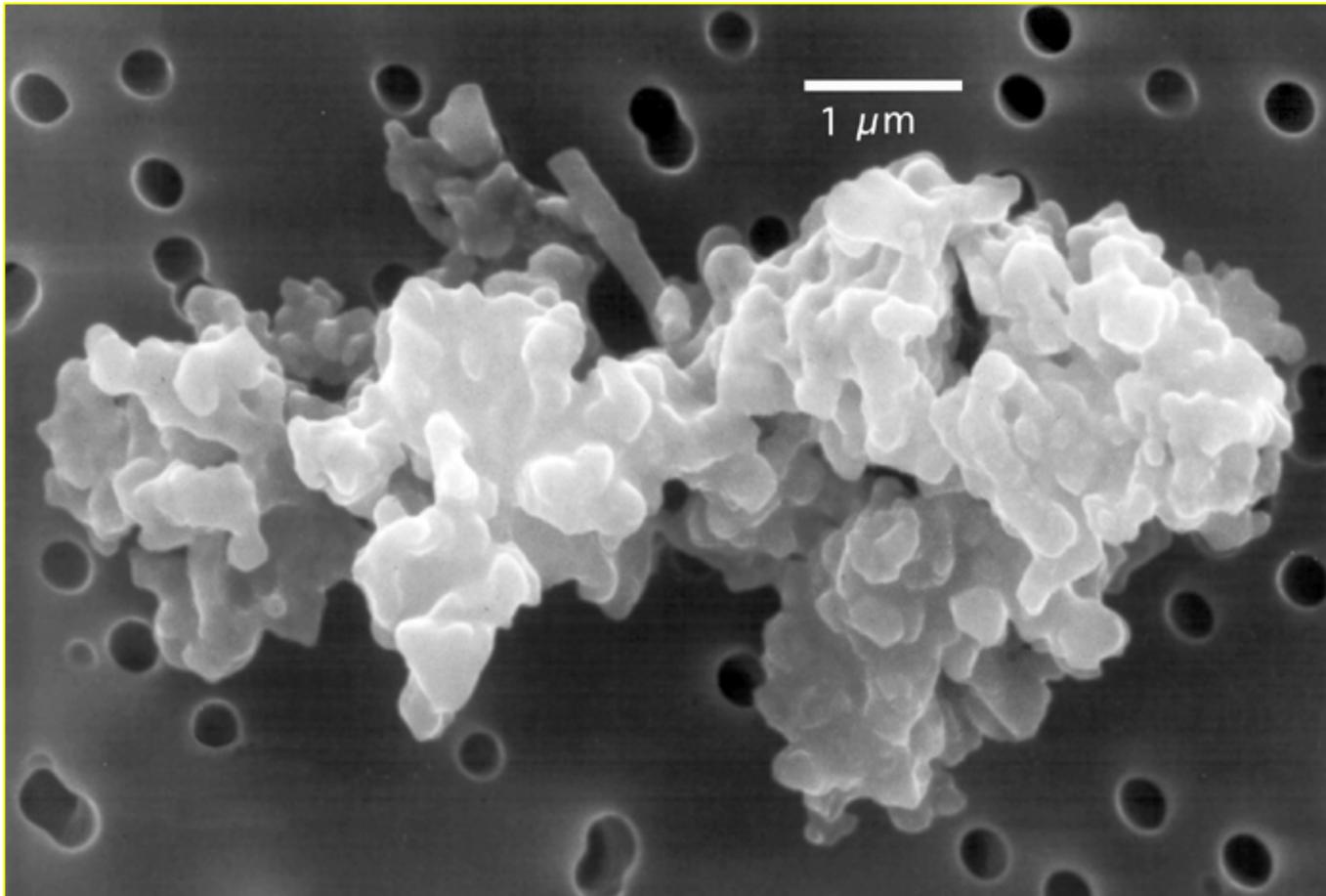
- Dust is crucial for interstellar chemistry by reducing the ultraviolet (UV) radiation which causes molecular dissociations and
- providing the site of the formation of the most abundant interstellar molecule, H_2 .
- Dust controls the temperature of the interstellar medium (ISM) by accounting for most of the elements which provide cooling, but also providing heating through electrons ejected photoelectrically from grains.

What is interstellar DUST?

- Cosmic dust is made of dust grains and aggregates of dust grains. These particles are irregularly-shaped with porosity ranging from fluffy to compact.
- The composition, size, and other properties depends on where the dust is found, and conversely, a compositional analysis of a dust particle can reveal much about the dust particle's origin.
- For example, grains in dense clouds have acquired a mantle of ice and on average are larger than dust particles in the diffuse interstellar medium. Interplanetary dust particles (IDPs) are generally larger still.

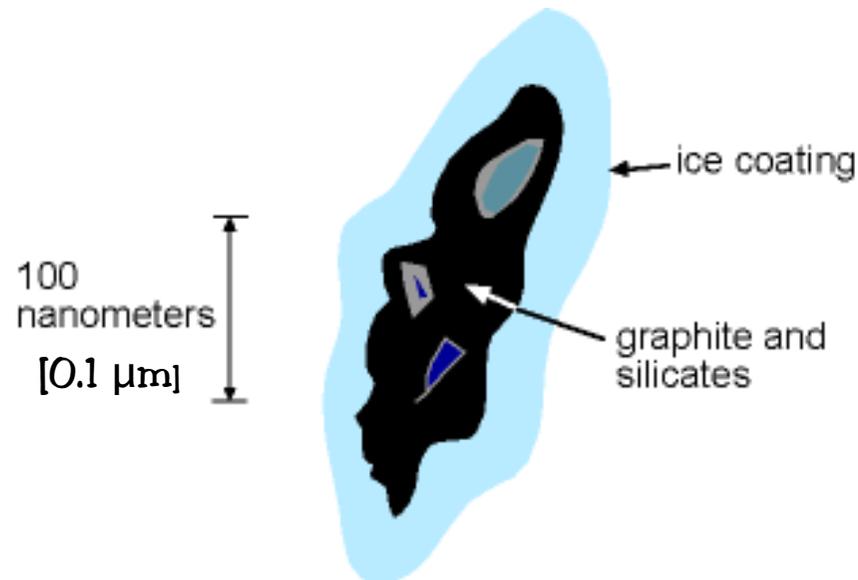
What is interstellar DUST?

- dust particles are usually aggregates of large numbers of sub-micrometer grains, clustered in a random open order.



What is interstellar DUST?

- The dust is made of thin, highly flattened flakes of graphite (carbon) and/or silicates (rock-like minerals) often coated with water ice.
- Each dust flake is roughly the size of the wavelength of blue light or smaller: $\sim 0.1 \mu\text{m}$.



A typical dust grain (note the tiny scale!).

Sites of DUST formation

- Most dust is injected into the ISM from stars on the asymptotic giant branch, either C rich or O rich,
- supernovae, in spite of a low rate of mass injection, might be important because of their large heavy-element composition.
- Dust is also found within hot supernova remnants, but it might have been produced by a pre-supernova red supergiant. How much dust is actually formed in supernovae is not known.

What is interstellar DUST ?

- Dust is made of solid grains, whose sizes range from 5×10^{-4} - $0.5 \mu\text{m}$ and composes 1% by mass of the Interstellar Medium (ISM).
- Dust absorbs optical and ultra-violet (UV) light, scatters optical - x-rays and emits in the infra-red (IR).
- Dust spatial density: $(n_g =) 1 \text{ grain} / 10^{12} \text{ H atoms}$ for grains of radius $0.1 \mu\text{m}$ ($n_g = a^{-3.5} \rightarrow$ more smaller)

Mathis, Rumpl, Nordsieck (MRN, 1977) grain size distribution

What is interstellar DUST ?

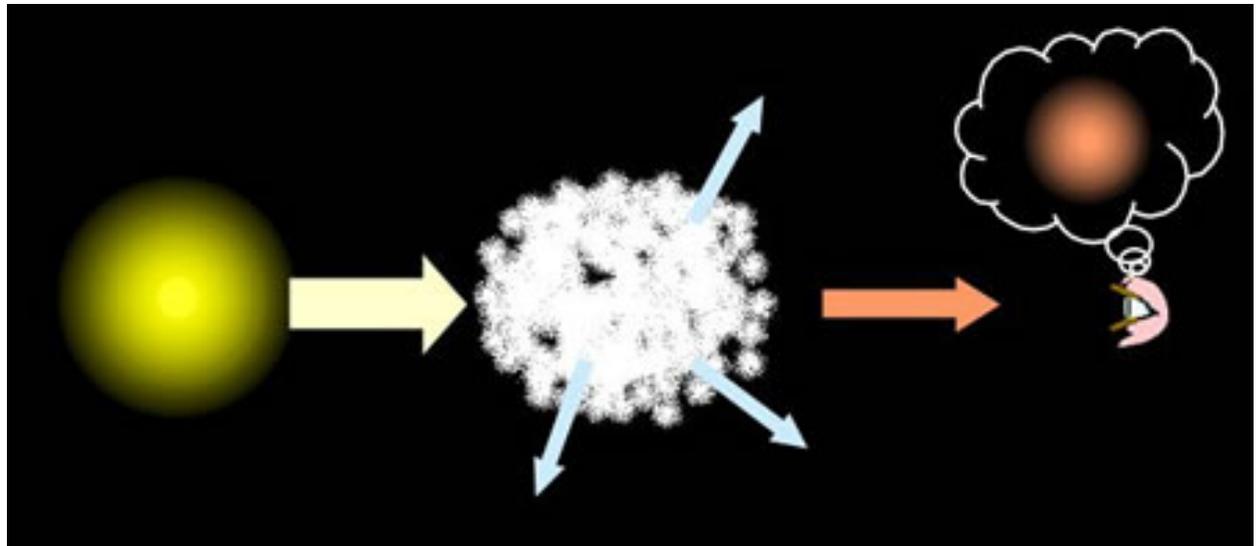
▪ IR emission provides 30% of the flux of a typical galaxy (e.g. Milky Way). Two-thirds of this is in the far infra-red (far-IR, $\lambda \geq 50\mu\text{m}$) from cold, larger grains ($T \sim 20\text{ K}$, $\geq 0.01\ \mu\text{m}$) near early-type stars. The remaining third is from smaller grains ($\leq 0.005\ \mu\text{m}$) cooling from photo-absorption.

▪ Large dust grains provide the most efficient source of cooling in the ISM and provide UV-free surfaces for chemical reactions to occur, including formation of the H_2 molecule.

The effects of DUST

Despite their small contribution to the total mass of the ISM (~1%), dust grains have a significant impact on our view of the Universe, since they:

- scatter
 - absorb
 - re-radiate
- starlight



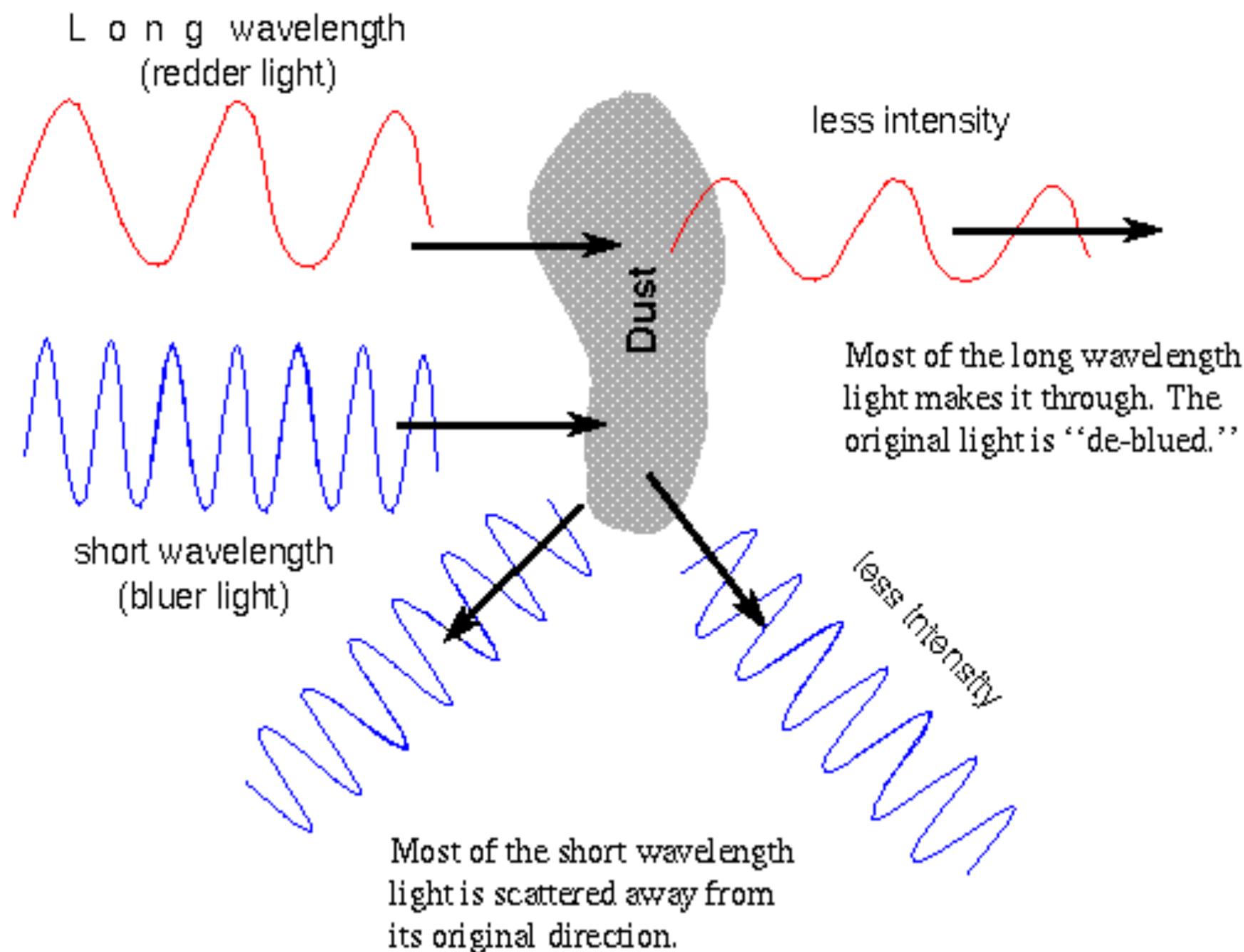
Dust Extinction

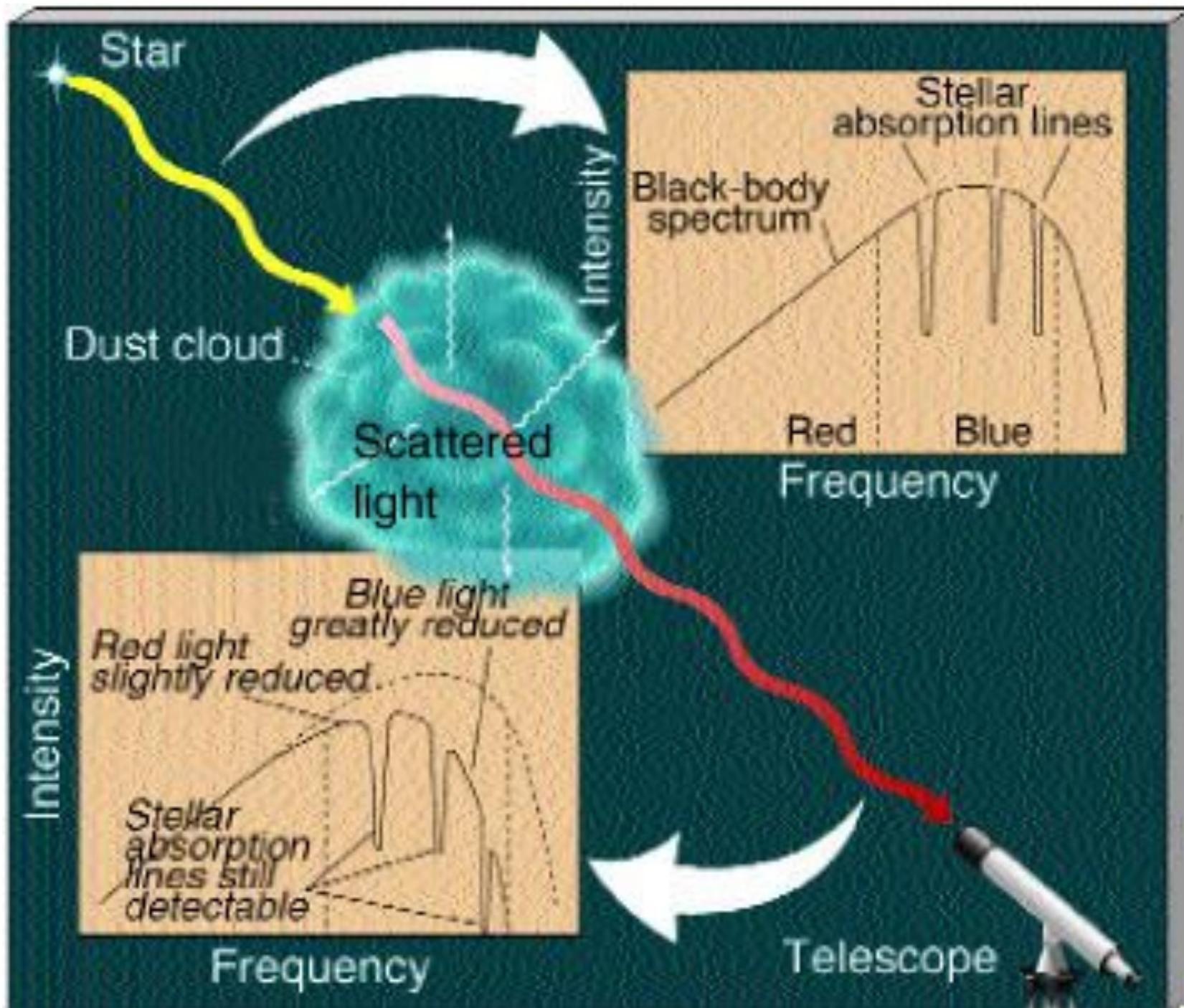
EXTINCTION occurs whenever electromagnetic radiation propagates through a medium containing small particles.

The transmitted beam is reduced in intensity by two physical processes: **ABSORPTION** and **SCATTERING**.

The energy of the absorbed photon is converted into internal energy of the particle (heated), whilst the scattered photon is deflected from the line of sight

Reddening and Extinction

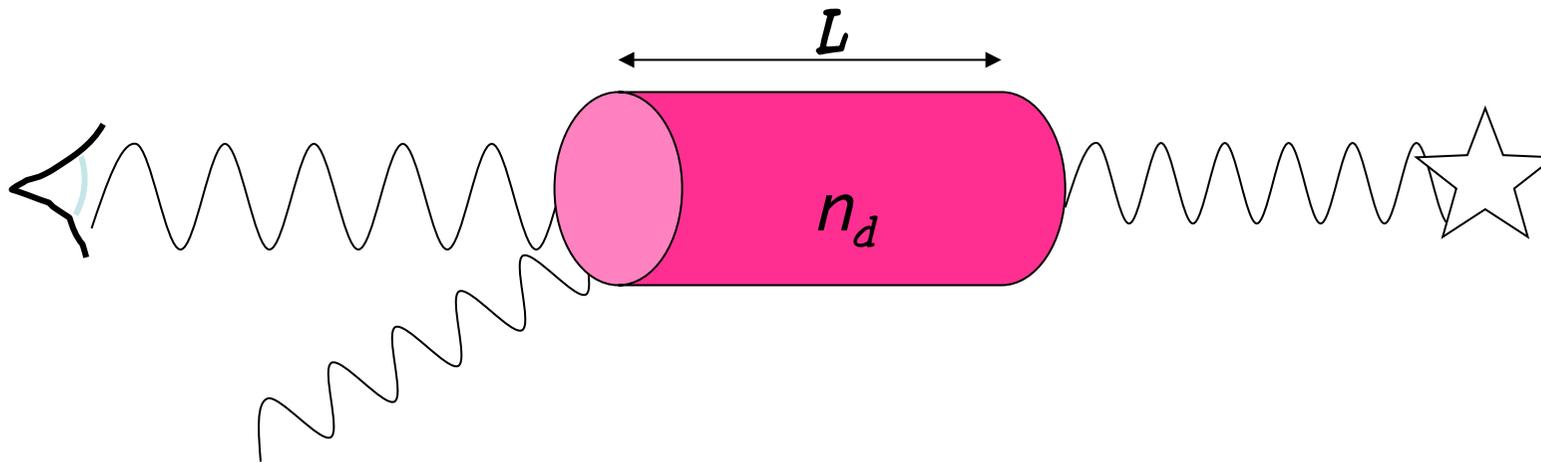




Extinction

Consider the grains as small spheres of radius = a

distributed with number density n_d per unit volume in a cylindric column of length L and unit cross-sectional area along the line of sight from a distant star



The reduction in starlight intensity resulting from the extinction in an element dL and cross-section C_{ext} :

$$dI / I = -n_d C_{ext} dL$$

Extinction

EXTINCTION CROSS SECTION C_{ext} :

It is an *area*

Total energy absorbed per second

Energy incident per square meter per second

This area describes the amount of the incident beam that is effectively absorbed.

It depends on the geometric cross section (πa^2) along with the optical properties of the material.

Extinction

Integrating over the entire path-length:

$$I = I_0 e^{-\tau}$$

where I_0 is the initial value of I (at $L=0$) and

$$\tau = \int n_d dL C_{ext} = N_d C_{ext}$$

is the **OPTICAL DEPTH** of extinction caused by the dust.

N_d is the column density of the dust (i.e. total number of grains in the unit column)

Extinction and Scattering

Expressing the intensity reduction in magnitudes, the total extinction at some wavelength λ is:

$$\begin{aligned} A_\lambda &= -2.5 \log(I/I_0) \\ &= 1.086 N_d C_{ext} \end{aligned}$$

A_λ is usually expressed in terms of the extinction efficiency factor Q_{ext} given by the ratio of the extinction cross section to geometric cross section:

$$Q_{ext} = C_{ext} / \pi a^2$$

Extinction

Hence

$$A_{\lambda} = 1.086 N_d \pi a^2 Q_{ext}$$

If, instead of grains of constant radius a we have a size distribution such that $n(a) da$ is the number of grains per unit volume in the line of sight with radii in the range a to $a+da$:

$$A_{\lambda} = 1.086 \pi L \int a^2 Q_{ext}(a) n(a) da$$

Absorption and Scattering

The problem of evaluating the expected spectral dependence of extinction A_λ for a given grain model (with an assumed composition and size distribution) is essentially that of evaluating Q_{ext} .

The extinction efficiency is the sum of corresponding efficiency factors for absorption and scattering

$$Q_{ext} = Q_{abs} + Q_{sca}$$

Absorption and Scattering

These efficiency factors depend on two quantities:

1. a dimensionless size parameter

$$X = 2 \pi a / \lambda$$

2. a composition parameter (the complex refractive index of the grain material)

$$m = n - ik$$

Extinction and Scattering

Q_{abs} and Q_{sca} may, in principle, be calculated for any assumed grain model and the resulting values of the total extinction compared with observational data

PROBLEM: solving the Maxwell's equations with appropriate boundary at the grain surface

Solution first formulated by Mie (1908) → Mie theory

For pure dielectric materials ($k=0$) the refractive index is empirically given by the Cauchy formula

$$m = n \approx c_1 + c_2 \lambda^{-2}$$

Absorption and Scattering

It is helpful to regard these plots in terms of the variation of extinction with λ^{-1} for constant grain radius (or with grain radius for constant λ)

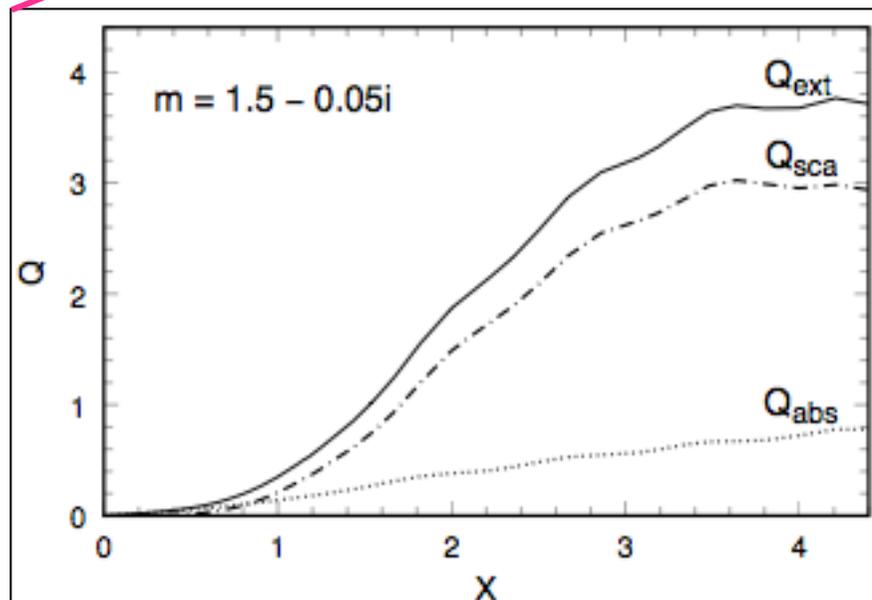


Figure 3.2. An enlargement of figure 3.1 showing the initial rise in extinction efficiency with X near the origin.

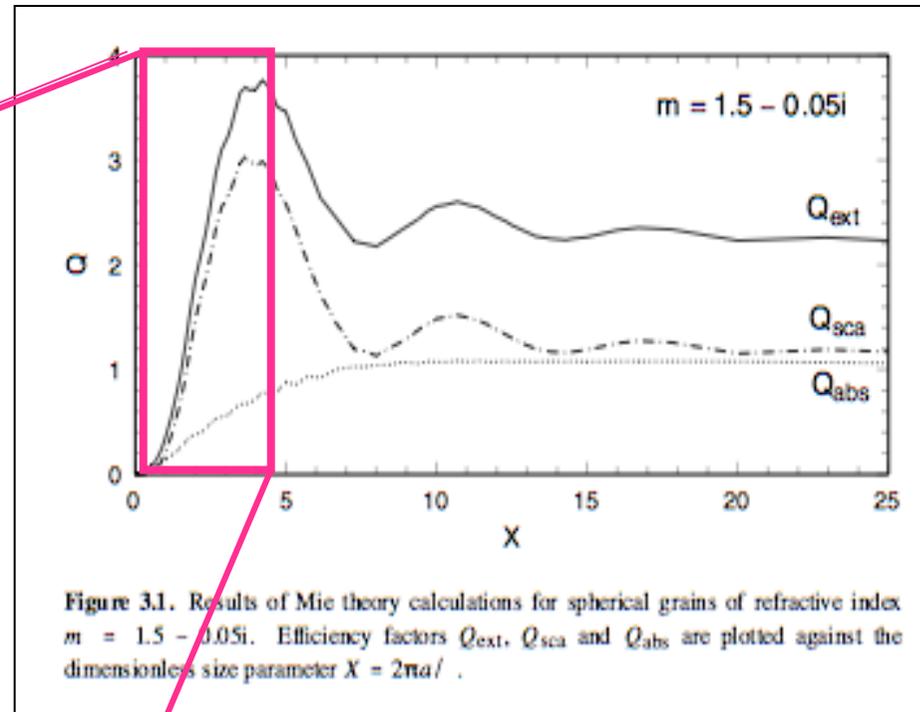


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext} , Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

Q_{ext} increases monotonically with X for $0 < X < 4$

In this domain extinction is dominated by scattering. Q_{ext} becomes constant for large X

Absorption and Scattering

When $X \ll 1$:

(i.e. particles are small compared with the wavelength)

$$Q_{sca} \approx \frac{8}{3} (2\pi a/\lambda)^4 \left| \frac{m^2-1}{m^2+2} \right|^2$$

$$Q_{abs} \approx 8\pi a/\lambda \operatorname{Im} \left\{ \frac{m^2-1}{m^2+2} \right\}$$

The quantity $(m^2-1)/(m^2+2)$ is only weakly dependent on λ for materials that are not strongly absorbing in this case we have (Rayleigh scattering):

$$Q_{sca} \propto \lambda^{-4} \quad \text{and} \quad Q_{abs} \propto \lambda^{-1}$$

Absorption and Scattering

Scattering from grains provides another diagnostic for their nature and composition.

However, the relative locations of the illuminating sources, scattering grains, and the observer are very important in determining the actual intensity of scattered radiation.

In practice, the geometry is so uncertain that one attempts to determine only two quantities characterizing the scattering process:

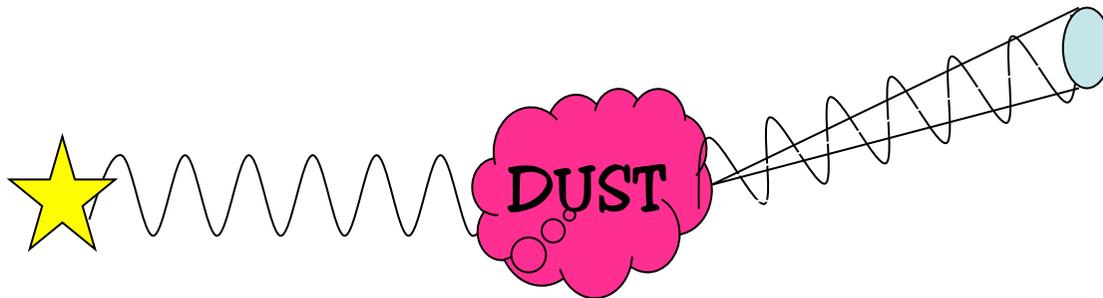
- the albedo, or fraction of the extinction that is scattering;
- g , the mean value of the cosine of the angle of scattering.

(For isotropic scattering, $g = 0$; for completely forward-throwing scattering, $g = 1$)

Scattering

Scattering Function $S(\theta)$ = angular distribution of light upon scattering by a dust grain

it is defined such that, for light of incident intensity I_0 , the intensity of light scattered into unit solid angle about a direction at an angle θ to the direction of propagation of the incident beam is $I_0 S(\theta)$



Unit solid angle

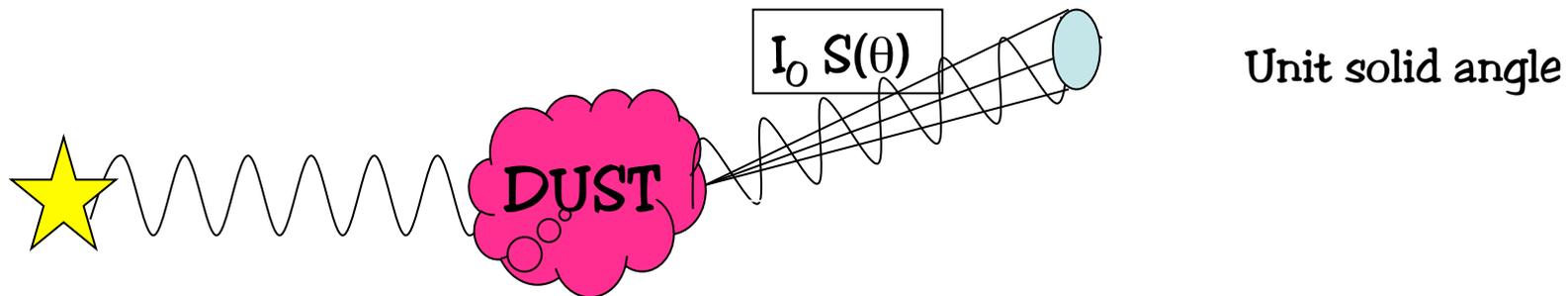
Extinction and Scattering

Scattering Cross-Section: $C_{sca} = 2 \pi \int_0^\pi S(\theta) \sin\theta d\theta$

Asymmetry parameter: $g(\theta) = \langle \cos\theta \rangle =$

$$= 2 \pi \int_0^\pi S(\theta) \sin\theta \cos\theta d\theta / \int_0^\pi S(\theta) \sin\theta d\theta =$$

$$= 2 \pi / C_{sca} \int_0^\pi S(\theta) \sin\theta \cos\theta d\theta$$



For dielectric spheres $g(\theta)=0$ in the small particle limit (spherically symmetric scattering) and $0 < g(\theta) < 1$ for larger particles (forward-directed scattering)

Continuous Extinction

- Each line of sight has its own “extinction law”, or variation of extinction with wavelength, usually expressed by $A(\lambda) / A(V)$.
- it has been common practice to use instead the ratios of two colors, $E(\lambda - V) / E(B - V)$, where $E(\lambda - V) = A(\lambda) - A(V)$.
- the optical total-to-selective extinction ratio, $R_V = A(V) / E(B - V)$, is also used as a parameter.

How can we determine extinction curves observationally?

- The most widely used technique involves the “pairing” of stars of identical spectral type and luminosity class, but unequal reddening and determining their colour difference.

- The apparent magnitude of each star can be written as:

$$m_1(\lambda) = M_1(\lambda) + 5 \log d_1 + A_1(\lambda)$$

$$m_2(\lambda) = M_2(\lambda) + 5 \log d_2 + A_2(\lambda)$$

where M , d and A are absolute mag, distance and total extinction.

If $M_1(\lambda) = M_2(\lambda)$ and $A(\lambda) = A_1(\lambda) \gg A_2(\lambda)$ then:

$$\Delta m(\lambda) = m_1(\lambda) - m_2(\lambda) = 5 \log (d_1/d_2) + A(\lambda)$$

How can we determine extinction curves observationally?

$$\begin{aligned}
 E_{norm} &= (\Delta m(\lambda) - \Delta m(\lambda_2)) / (\Delta m(\lambda_1) - \Delta m(\lambda_2)) \\
 &= (A(\lambda) - A(\lambda_2)) / (A(\lambda_1) - A(\lambda_2)) \\
 &= E(\lambda - \lambda_2) / E(\lambda_1 - \lambda_2)
 \end{aligned}$$

Extinction curves are commonly normalised with respect to the *B* and *V* passbands in the Johnson system :

$$E(\lambda - V) / E(B - V)$$

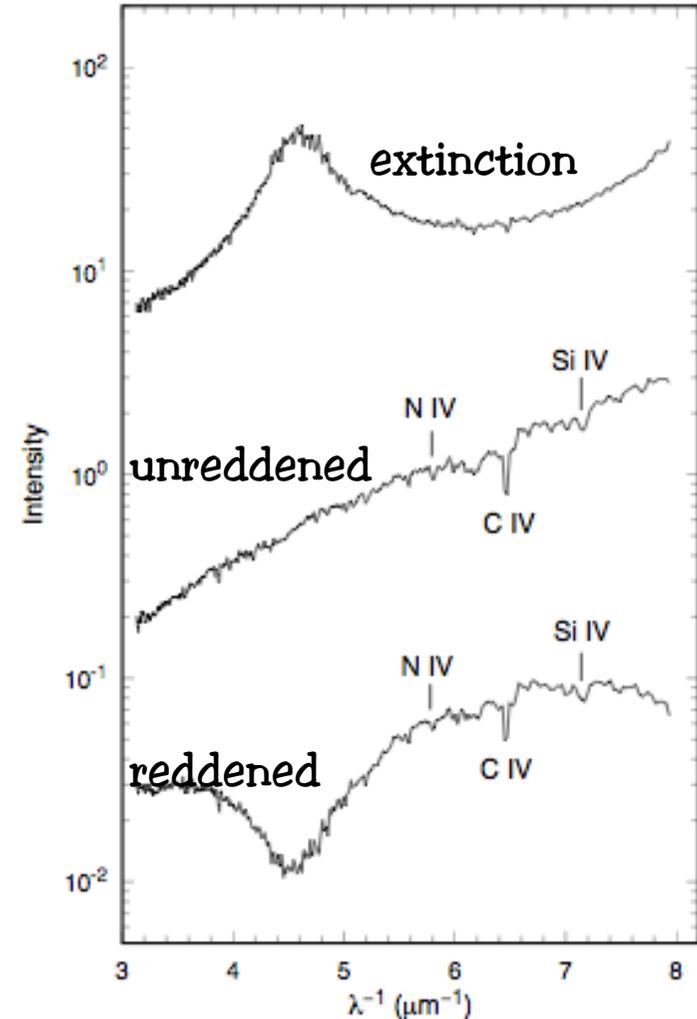


Figure 3.3. An illustration of the pair method for determining interstellar extinction curves. The lower curve is the ultraviolet spectrum of a reddened star (HD 34078, spectral type O9.5 V, $E_{B-V} = 0.54$) and the middle curve is the corresponding spectrum of an almost unreddened star of the same spectral type (HD 38666, $E_{B-V} = 0.03$). A few representative spectral lines are labelled. The vertical axis plots intensity in arbitrary units – note that the scale is logarithmic and hence equivalent to magnitude. The upper curve is the resulting extinction curve, obtained by taking the intensity ratio (equivalent to magnitude difference) of the two spectra. Based on data from the *IUE Atlas of Low-Dispersion Spectra* (Heck et al 1984).

THE AVERAGE EXTINCTION CURVE

The extinction curve takes the same general form in many lines of sight

The average extinction curve for many stars provides a valuable benchmark for comparison with curves deduced for individual stars and regions and a basis for modelling

We can define the *RELATIVE EXTINCTION*:

$$E_{\lambda-V} / E_{B-V} = (A_{\lambda} - A_V) / E_{B-V} = R_V \{ A_{\lambda} / A_V - 1 \}$$

where $R_V = A_V / E_{B-V}$ is the ratio of total-to-selective extinction

THE AVERAGE EXTINCTION CURVE

$$R_V = A_V / E_{B-V} = A_V / (A_B - A_V)$$

- For small grains (Rayleigh scattering): $Q_{ext} \propto \lambda^{-\beta}$ ($\beta \leq 4$)
(absorption dominated extinction : $\beta \sim 1$)

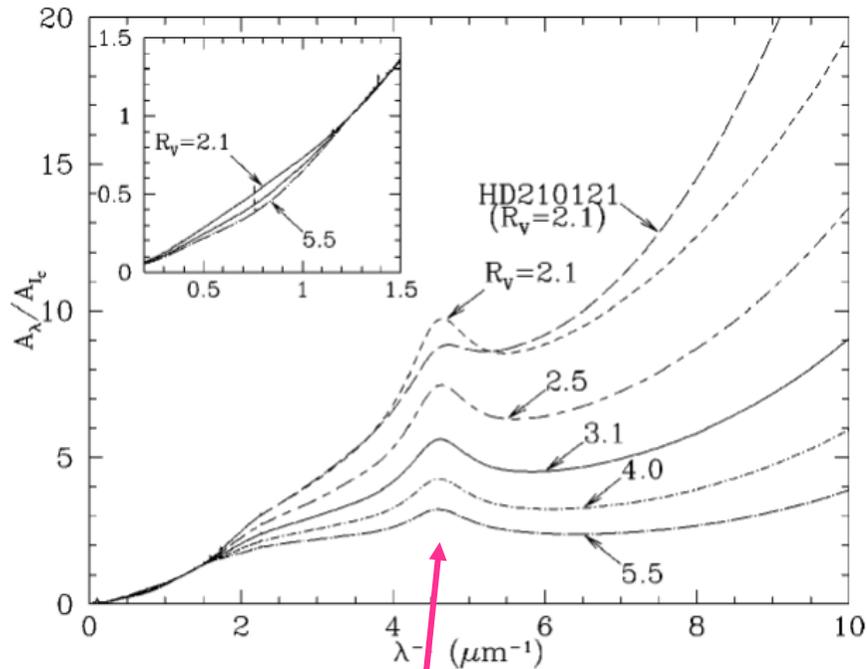
$$R_V \approx 1.2$$

- For large grains: $R_V \rightarrow \infty$

➤ in the galactic diffuse ISM and in the Large Magellanic Cloud: $R_V \approx 3.1$ varying along linesight from 2.1 to 5.8

➤ In the Small Magellanic Cloud $R_V \approx 3.2$

THE AVERAGE EXTINCTION CURVE



A bump at 2175 Å is present in almost all the extinction curves: it is ubiquitous, strong and with uniform profile

The 2175 Å absorber must be cosmically abundant and sufficiently robust to survive in a variety of interstellar environments
 → GRAPHITE with $a \sim 0.01 \mu\text{m}$

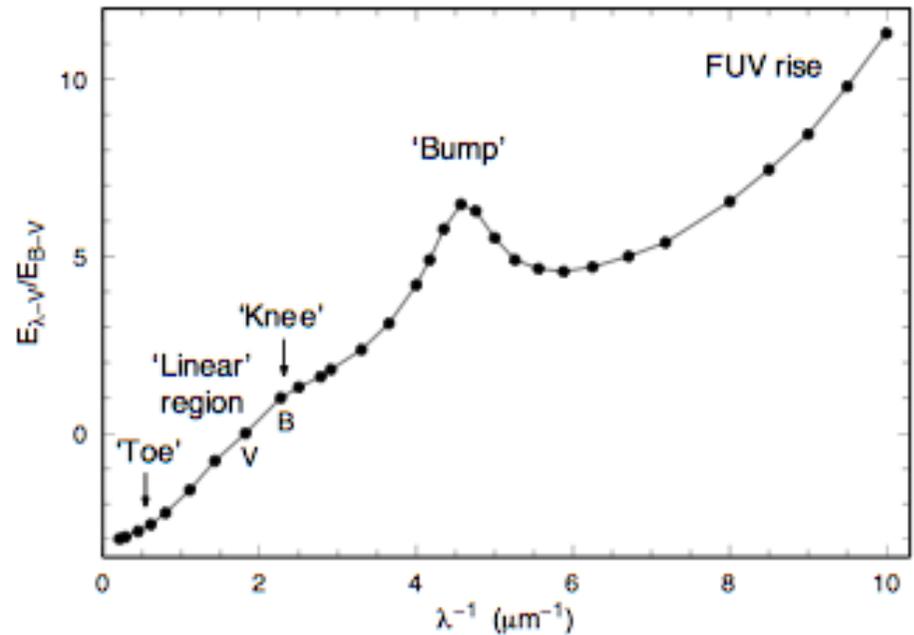


Figure 3.4. The average interstellar extinction curve ($E_{\lambda-V}/E_{B-V}$ versus λ^{-1}) in the spectral range 0.2–10 μm^{-1} . Data are from table 3.1. Various features of the curve

MODELLING THE EXTINCTION CURVE

To construct a model for interstellar extinction, one must assume a composition and a size distribution for the dust:

- refractive index $m(\lambda)$
- size distribution function $n(a) \propto a^{-\beta}$ ($a_{min} < a < a_{max}$)
small grains needed for the FUV rise, large grains for visual-infrared extinction
- two distinct populations:
graphite and silicate

Mathis et al. 1977; Draine & Lee 1984

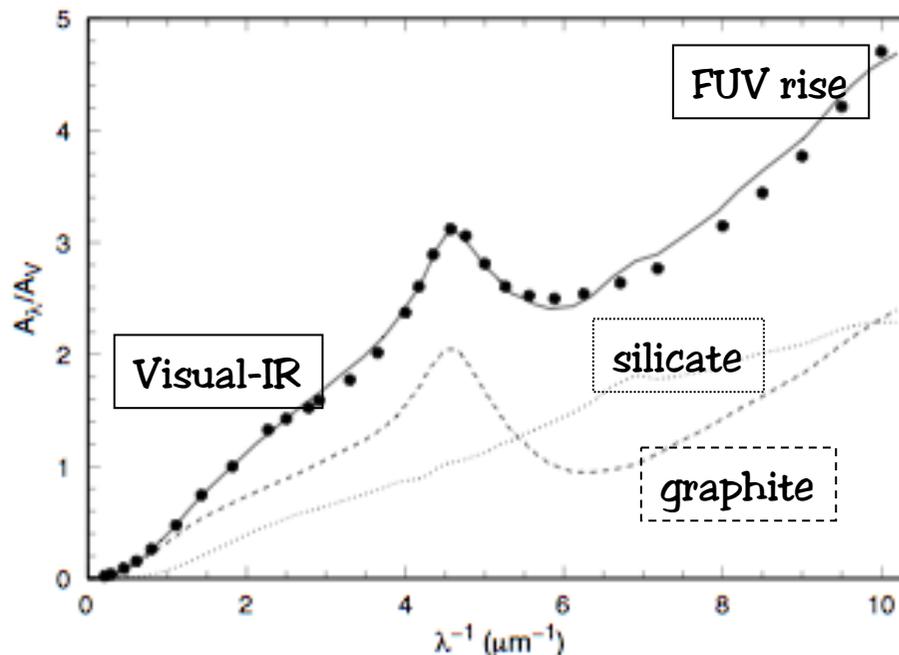


Figure 3.18. A fit to the extinction curve based on the 'MRN' two-component model (in the version of Draine and Lee 1984). The total extinction predicted by the model (continuous curve) is the sum of the contributions from graphite grains (broken curve) and silicate grains (dotted curve). The mean observational curve (table 3.1) is plotted as full circles.

POLARIZATION

✦ An electromagnetic wave is a transverse wave that has both an electric and a magnetic component.

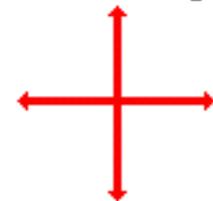
✦ The electric and magnetic vibrations of an electromagnetic wave occur in numerous planes.

✦ A light wave that is vibrating in more than one plane is referred to as unpolarized light. Light emitted by the sun, by a lamp, or by a candle flame is unpolarized light. Such light waves are created by electric charges that vibrate in a variety of directions, thus creating an electromagnetic wave that vibrates in a variety of directions.

A light wave is known to vibrate in a multitude of directions ...



... In general, a light wave can be thought of as vibrating in a vertical and in a horizontal plane.



POLARIZATION

Polarization generally just means “orientation.”

It is possible to transform unpolarized light into polarized light.

Polarized light waves are light waves in which the vibrations occur in a single plane. The process of transforming unpolarized light into polarized light is known as polarization.

★Polarization by Transmission

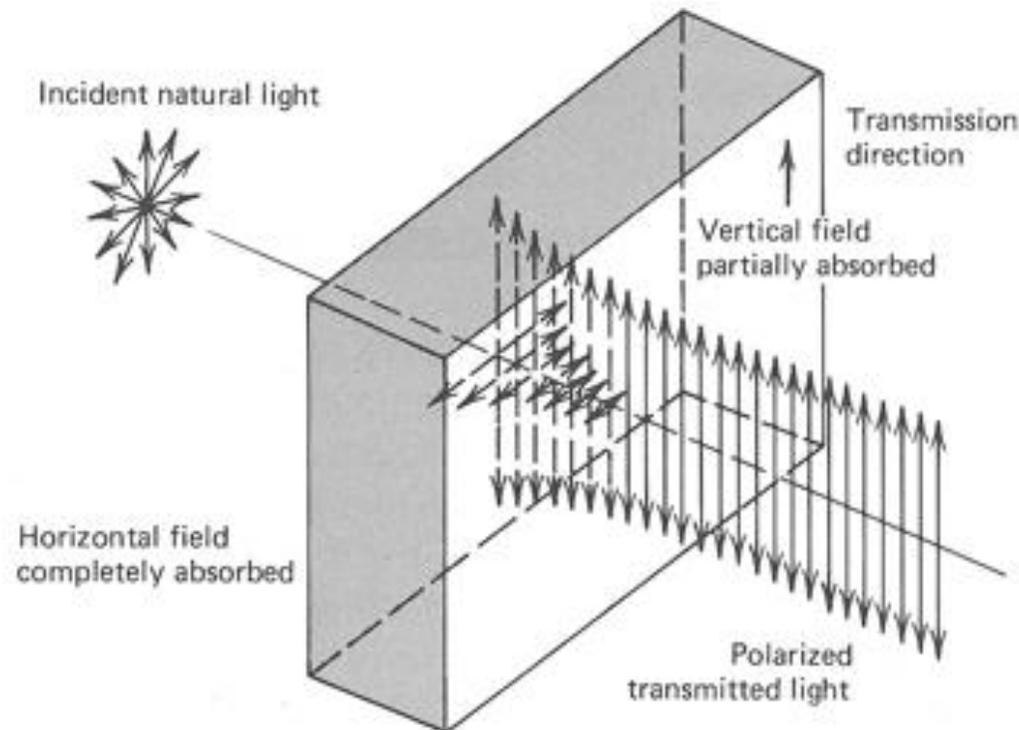
★Polarization by Reflection

★Polarization by Refraction

★Polarization by Scattering

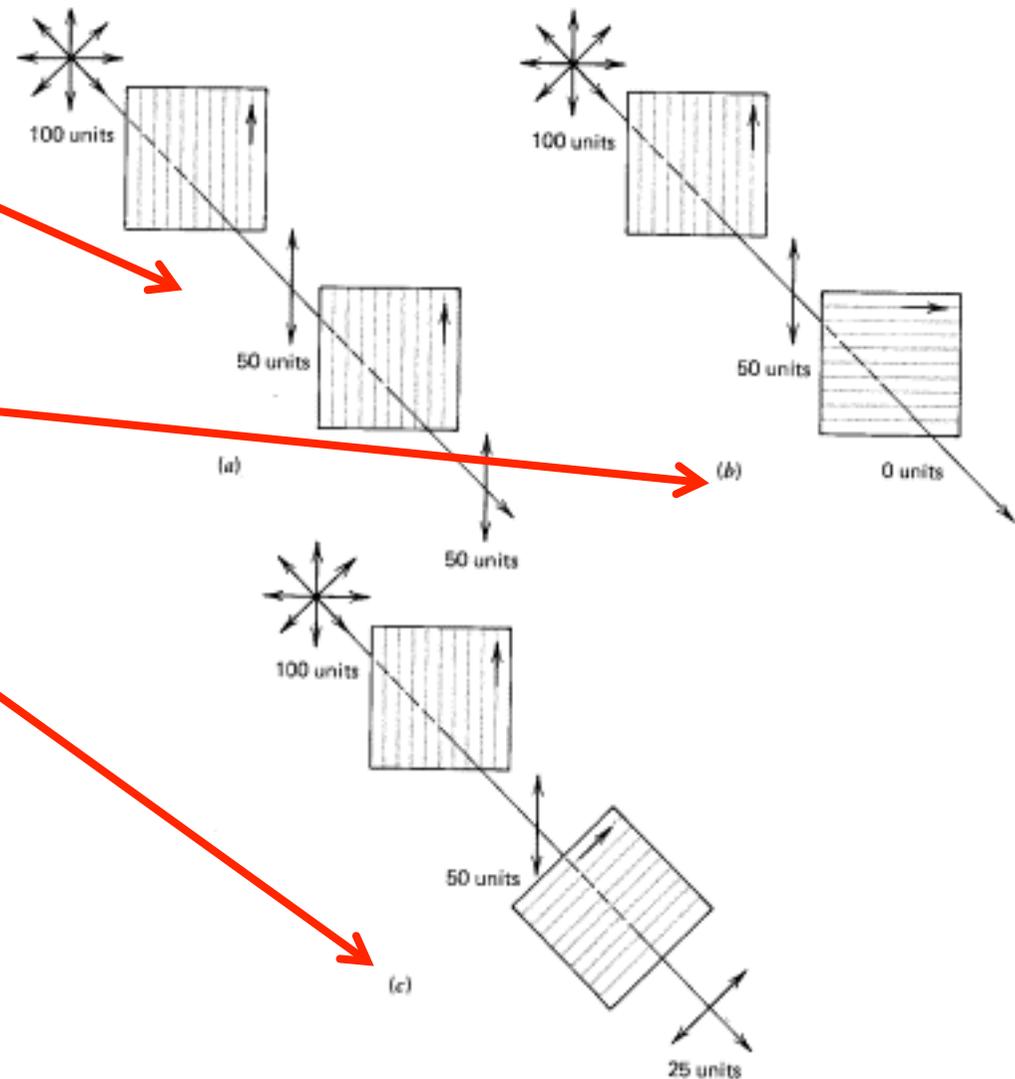
POLARIZATION by TRANSMISSION

Polarizing filters, such as those in Polaroid sunglasses, are designed to allow only one plane of light through (although they are not 100% effective, they can be pretty close to that value).



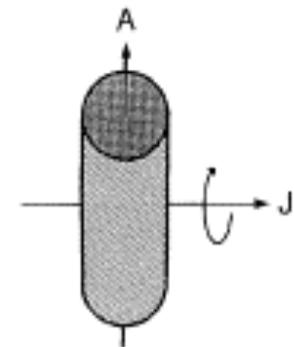
POLARIZATION by TRANSMISSION

The second filter allows only that component that lies in the "transmission direction" though. In (a), *all of the amplitude is in the transmission direction, so it all gets through.* In (b), *none of the amplitude is in the transmission direction, so none gets through.* In (c), *the transmission direction is rotated 45° to the direction of the amplitude, so some of the light gets through.*



POLARIZATION AND GRAIN ALIGNMENT

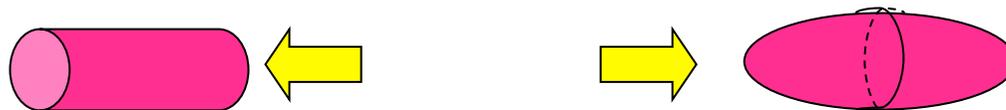
- Light from distant stars in the Galaxy is polarized by interstellar dust grains (acting like little Polaroid filters!)
- The polarization reaches a maximum at visible wavelengths, suggesting that the grains responsible must be about $1 \mu\text{m}$ in size
- It is thought that elongated silicate grains, pinning end-over-end and aligned by the galactic magnetic field are responsible.



POLARIZATION AND GRAIN ALIGNMENT

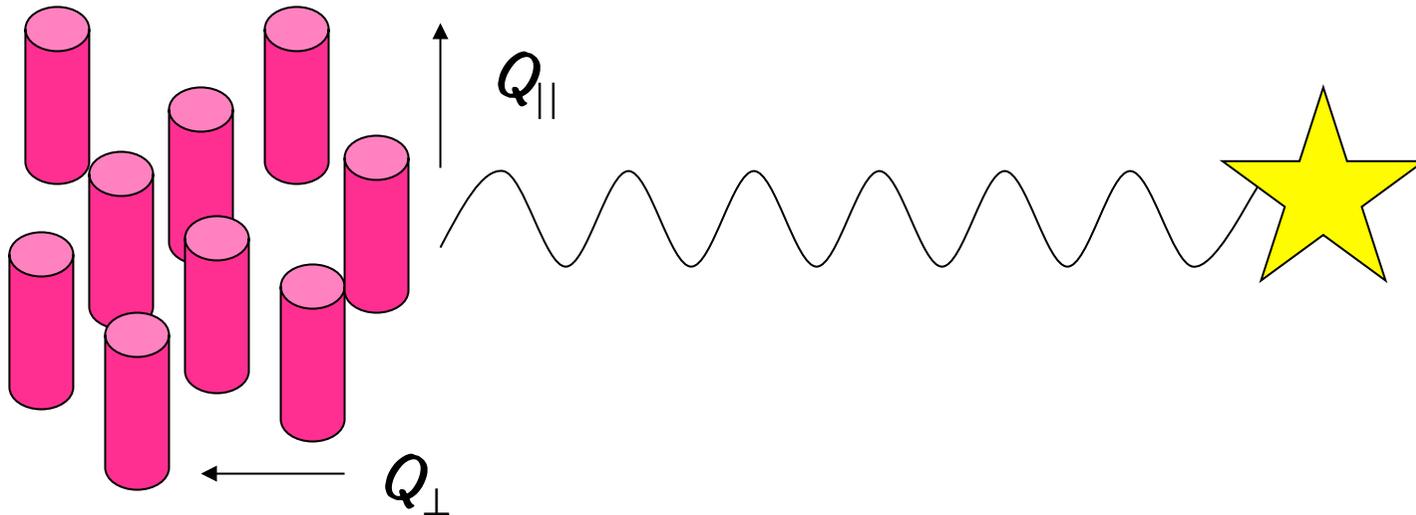
- A beam of unpolarized light transmitted through a dusty medium will become partially plane polarized if:
 - i. Individual dust particles are optically anisotropic
 - ii. There is net alignment of the axes of anisotropy
- The source of anisotropy is the asymmetry in the shape of the particle

We assume, for simplicity, axially symmetric forms such as cylinders or spheroids (extinction cross-section from Mie theory)



POLARIZATION AND GRAIN ALIGNMENT

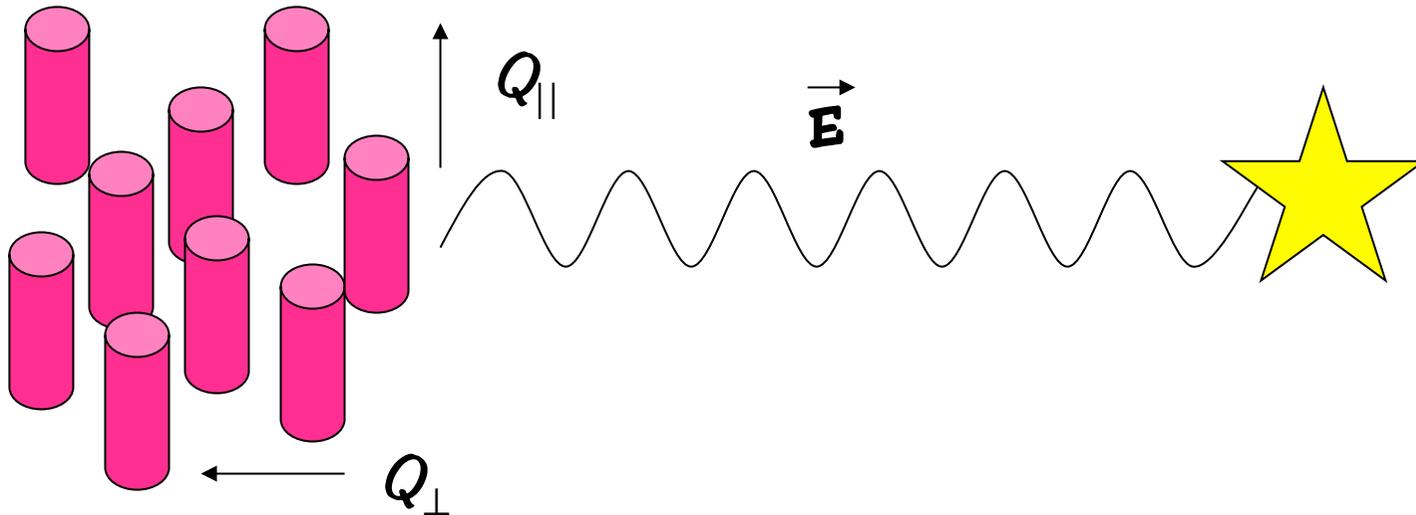
- Consider an ensemble of elongated grains such as long cylinders, orientated with long axis perpendicular to the direction of propagation of incident radiation



- We may define Q_{\parallel} and Q_{\perp} as the values of the extinction efficiency Q_{ext} when the E-vector is parallel and perpendicular to the long axes of the grain

POLARIZATION AND GRAIN ALIGNMENT

- The anisotropy in physical shape introduces a corresponding anisotropy in extinction



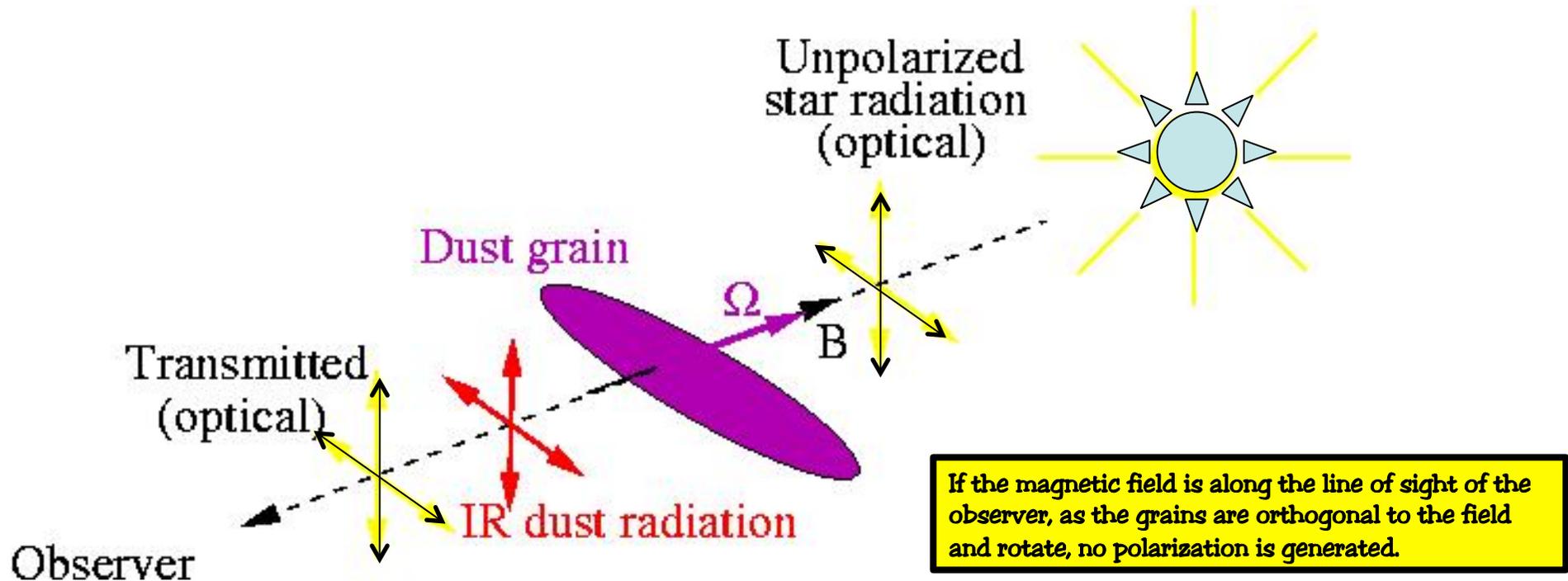
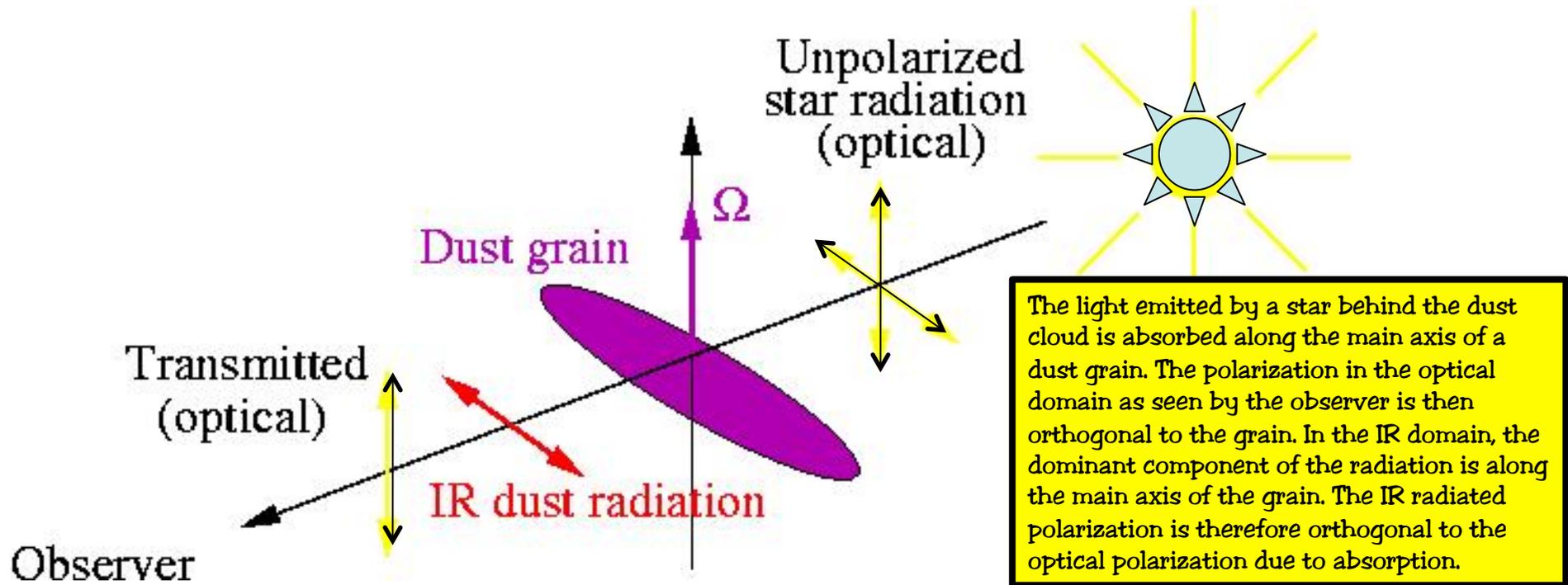
- Because the \vec{E} -vector "sees" an apparently larger grain in the parallel direction: $Q_{\parallel} \geq Q_{\perp}$

POLARIZATION AND GRAIN ALIGNMENT

As more dipoles are created along the largest axis of the grain, the extinction is higher in this direction: the observed polarization in the optical domain is then in the direction of the smallest dimension of the grains.

On the other hand, Kirchhoff's law guarantees that the emissivity will follow absorption.

The dust radiation, in the IR domain should therefore also be polarized, but in the direction of the main axis of the grain this time. Optical and IR polarization are therefore expected to be orthogonal.



POLARIZATION AND GRAIN ALIGNMENT

- ✦ To observe a significant degree of polarization the grains must be well aligned.
- ✦ There is such a rich variety of physical conditions in the ISM, that different mechanisms are likely to take place.
- ✦ The polarization of dust radiation therefore provides valuable information on various astrophysical issues: dust intrinsic dielectric properties, magnetic field geometry and coherence... which in turn are related to star formation, turbulence...

POLARIZATION AND GRAIN ALIGNMENT

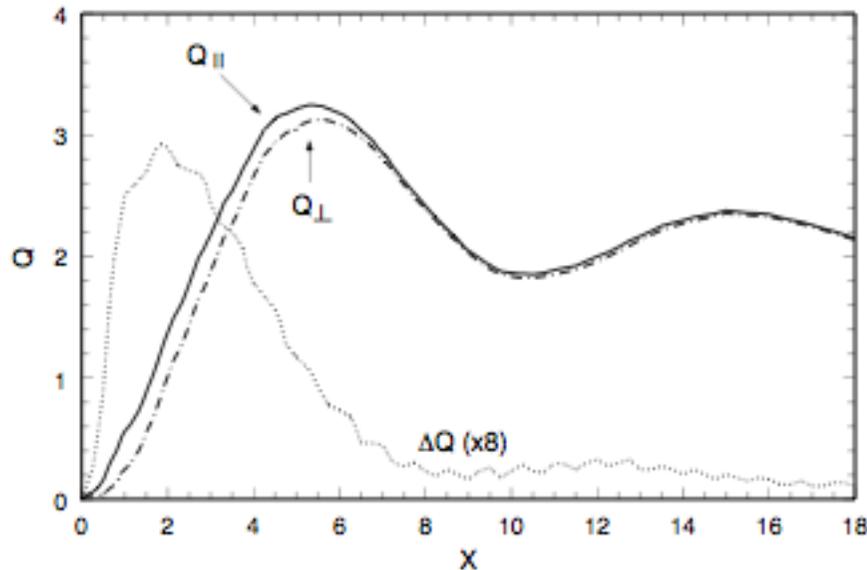


Figure 4.1. Extinction efficiency factors $Q_{||}$ (continuous curve) and Q_{\perp} (broken curve) plotted against $X = 2\pi r a / \lambda$ for cylinders of radius a and refractive index $1.33 - 0.05i$. The cylinders are assumed to be very long ("infinite") in comparison to their radii. Note that $Q_{||} \geq Q_{\perp}$ for all values of X . The dotted curve is the difference, $\Delta Q = Q_{||} - Q_{\perp}$, scaled up by a factor of eight. The equivalent calculation of Q_{ext} for spheres (section 3.1.1) would show a dependence on X qualitatively similar to the mean of $Q_{||}$ and Q_{\perp} .

Extinction:

$$A_{||} = 1.086 N_d \sigma Q_{||}$$

$$A_{\perp} = 1.086 N_d \sigma Q_{\perp}$$

N_d = particle column density

σ = cross-sectional area of each particle $\sim \pi a^2$

Total extinction: $A = 1.086 N_d \sigma \{Q_{||} + Q_{\perp}\} / 2$

Amplitude of linear polarization: $p = A_{||} - A_{\perp} = 1.086 N_d \sigma (Q_{||} - Q_{\perp})$

Ratio of polarization to extinction: $p/A = 2\{(Q_{||} - Q_{\perp}) / (Q_{||} + Q_{\perp})\}$

POLARIZATION AND GRAIN ALIGNMENT

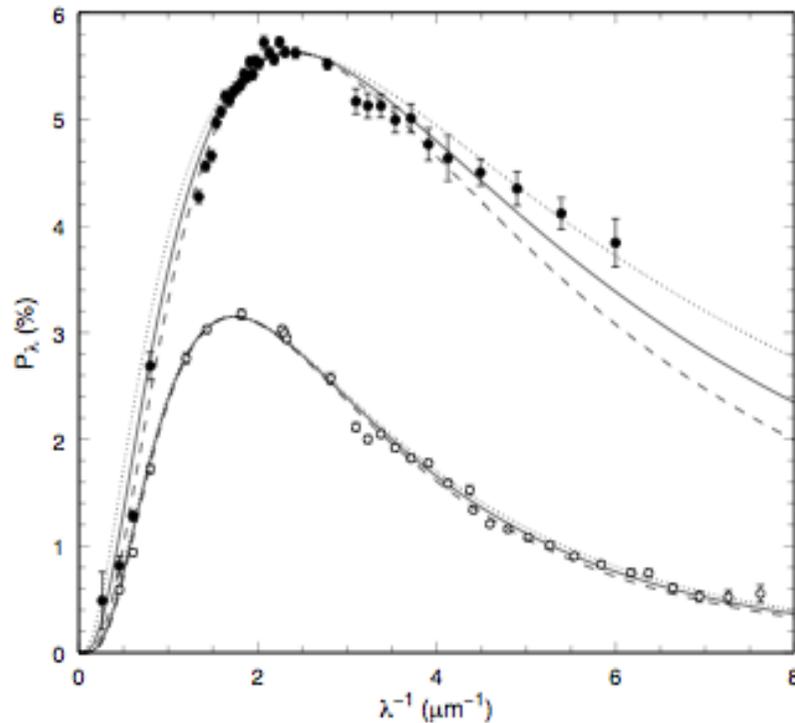


Figure 4.7. Interstellar linear polarization curves for two stars with different values of the wavelength of maximum polarization. Top: HD 204827 (full circles, $\lambda_{max} = 0.42 \mu\text{m}$); bottom: HD 99872 (open circles, $\lambda_{max} = 0.58 \mu\text{m}$). Observational data are from Martin *et al* (1999) and references therein. Also shown are empirical fits based on the Serkowski law: VIR-optimized fit (broken curve); VUV-optimized fit (dotted curve); compromise fit (full curve).

Degree of polarization:

$$P = 100 \left\{ \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \right\}$$

I_{max} , I_{min} = max and min intensities measured

Polarization Law (Serkowski 1975):

$$P(\lambda) / P(\lambda_{max}) = \exp[-K \ln^2 (\lambda / \lambda_{max})]$$

with $P(\lambda_{max}) = \%$ of polarization at the peak

POLARIZATION AND GRAIN ALIGNMENT

The quantity K was originally taken to be constant (=1.15),

but an improved fit gave

$$K = c_1 \lambda_{max} + c_2 \quad \text{with} \quad 0.3 \mu\text{m} < \lambda_{max} < 5 \mu\text{m}$$

Empirically:

$$K = -0.10 + 1.86 \lambda_{max}$$

!!! This law is entirely empirical !!!

POLARIZATION AND GRAIN ALIGNMENT

Salient features of the polarization law are:

1. The averaged value of λ_{max} is $0.55 \mu\text{m}$.
2. The polarization typically rises with wavelength through the UV to a maximum in the optical and then falls slowly through the NIR.
3. The value of λ_{max} is almost proportional to R_V .
4. The polarization law $p(\lambda)$ varies as $p(\lambda) \propto \lambda^{-1.8}$ for both diffuse dust and outer-cloud dust in the range $0.9 \mu\text{m} < \lambda < 5 \mu\text{m}$

POLARIZATION AND GRAIN ALIGNMENT

5. The maximum value of $p(\lambda_{max}) / A(\lambda_{max})$ is about 0.03 mag^{-1} , far less than from perfectly aligned spinning cylinders.

- Perhaps there are two or more separate types of grains, only some of which are aligned.

- Alternatively, all grains might be well aligned but have shapes that are less efficient than a spinning cylinder for producing polarization.

- A third possibility is that there is always a randomly oriented component to the field.

POLARIZATION AND GRAIN ALIGNMENT

An explanation for the form of the polarization law assumes that grains can be aligned only if they contain one or more ``superparamagnetic'' particles (magnetite or other magnetic materials), which dissipate rotational energy as heat.

Large grains are preferentially aligned because they are relatively likely to contain magnetic inclusions.

Polarization is not specific to any particular grain model; if the large grains are aligned, and a model predicts the extinction correctly, it will do well for the polarization also.

DUST Emission:

What happens to the absorbed star-light?

- The balance of the energy absorbed by a dust grain over the entire electromagnetic spectrum must re-emerge at some λ 's
- A dust particle gains energy mainly by absorption of ultraviolet photons from the ambient interstellar radiation field

What happens to the absorbed star-light?

- A steady state is established such that the dust grain emits a power equal to that absorbed, at some temperature T_d , depending on its size and composition
- For classical dielectric spheres of radii $a \sim 0.1 \mu\text{m}$
 $T_d = 10\text{-}30 \text{ K} \rightarrow \text{Far-Infrared (far-IR, } \lambda \geq 50 \mu\text{m)}$

The situation is a bit more complicated, but...

Emission by Dust Grains

- Kirchoff's Law tells us that bodies that are good absorbers must also be equally good radiators.
- Equilibrium temperatures of grains are in the range of 30-50 K or more, which means that they radiate predominantly in the far-IR (50-100 μm).
- NOTE that grains are NOT blackbodies, but radiate as modified blackbodies with a strong wavelength-dependent emissivity.

Emission by Dust Grains

- Dust grains are NOT perfect blackbodies:

in general grains are inefficient radiators at long wavelengths, with an emission efficiency

$$Q_{em} \propto \lambda^{-1} - \lambda^{-2}.$$

This means that grains will have an equilibrium temperature that is **HOTTER** than the temperature of a perfect blackbody immersed in the same radiation field.

Dust Emission

Dust grains radiate like little black bodies at temperatures 10-100 K,
i.e. a continuous spectrum with most of the energy at large wavelengths.

The equilibrium temperature (and hence thermal emission) of the grains of each species in each sample element is found by solving the thermal equilibrium equation ($W_{em} = W_{abs}$):

$$\int Q_{abs}(\nu) u_{\nu} d\nu - 4\pi \int Q_{em}(\nu) B_{\nu}(T_{gr}) d\nu = 0$$

Dust Emission

Consider a spherical dust grain with radius a located a distance d away from a star with luminosity L_ν (*):

The balance between the energy absorbed by the grain and the thermal energy emitted by the grain is given by:

$$\pi a^2 \int_0^\infty L_\nu Q_{abs}(\nu) d\nu = 4\pi a^2 \int_0^\infty Q_{em}(\nu) \pi B_\nu(T_{gr}) d\nu$$

With $B_\nu(T_{gr}) = \text{Planck function} = \frac{2h\nu^3}{c^2} \times \frac{1}{(e^{h\nu/kT} - 1)}$

Dust Emission

The star emits primarily at UV, visible and near-IR wavelengths, where $Q_{\text{abs}} \sim \nu^1 - \nu^2 \Rightarrow$ *most grain absorption is preferentially in the UV/visible/near-IR*

Most of the emission is in the mid- to far-IR, because of the dust temperature (Typically few 10s to few 100s of Kelvin)

$Q_{\text{abs}}(\nu) =$ *absorption efficiency* $\sim \langle Q_{\text{UV}} \rangle$

$Q_{\text{em}}(\nu) =$ *emission efficiency* $\sim \langle Q_{\text{IR}} \rangle$

To within an order of magnitude the equation of thermal balance becomes:

$$L / (4 \pi d^2) \langle Q_{\text{UV}} \rangle - 4 \langle Q_{\text{IR}} \rangle \sigma T^4 = 0$$

$L =$ *total luminosity of the star located distance d away*

$\sigma =$ *Stefan-Boltzmann constant*

Dust Emission

Solving for the dust temperature gives:

$$T_{gr} \approx (\langle Q_{UV} \rangle / \langle Q_{IR} \rangle)^{1/4} [L / (16\pi\sigma d^2)]^{1/4}$$

Note that the expected temperature of the grain gets cooler the further it gets from the star.

$\langle Q_{IR} \rangle$ is generally a function of T_{gr} and the grain size a . Simple expressions can be derived by assuming that the grain emissivity scales like $Q \propto \nu^\beta$, where $0 < \beta < 2$

Dust Emission

For $Q \propto \nu^1$:

$$\langle Q_{IR} \rangle \approx 2 \times 10^{-3} a_{\mu m} T_{gr}$$

For $Q \propto \nu^2$:

$$\langle Q_{IR} \rangle \approx 4 \times 10^{-6} a_{\mu m} T_{gr}^2$$

The total IR flux from the grain, $\langle Q_{IR} \rangle \propto \pi B_{\nu}(T_{gr})$, therefore scales like T_{gr}^5 or T_{gr}^6 , depending on the emissivity law. This is much steeper than the T_{gr}^4 scaling expected for a perfect blackbody

Dust Emission

TO KEEP IN MIND:

The dust temperature will depend critically on the form of the assumed emissivity law.

For example, as the power law index of Q steepens (e.g. Q_ν changes from ν^1 to ν^2), the grains become inefficient radiators at long wavelengths, shifting the peak of the emergent spectrum towards shorter wavelengths.

*The result is a spectrum that looks **HOTTER** than a typical blackbody (e.g. as per Wien's law).*

Dust Emission

The wavelength at which the spectrum peaks (analogy with the Wien law) is related to T_{gr}

$$\lambda_{peak} \approx 3000 \{5/(p + 5)\} T_{gr}^{-1}$$

For interstellar grains $1 < p < 2$
thus

$$\lambda_{peak} \approx 2300 T_{gr}^{-1} (\mu\text{m})$$

Dust Emission

Emission from dust is thermal, described by the “grey body” spectrum:

$$B_\nu(T) = (2h\nu^3/c^2) (e^{(h\nu/kT)} - 1)^{-1} [1 - e^{-\tau(\nu)}]$$

Where $\tau(\nu)$ is the optical depth at a given ν

If $\tau(\nu) \ll 1$ (optically THIN regime) $e^{-\tau(\nu)} \rightarrow 1 - \tau(\nu)$:

$$B_\nu(T) = \tau(\nu) (2h\nu^3/c^2) (e^{(h\nu/kT)} - 1)^{-1}$$

If $\tau(\nu) \gg 1$ (optically THICK regime) $e^{-\tau(\nu)} \rightarrow 0$:

$$B_\nu(T) = (2h\nu^3/c^2) (e^{(h\nu/kT)} - 1)^{-1}$$

Dust Mass Estimate

Consider an idealized cloud containing N spherical dust grains of uniform size, composition and temperature

Assume that the grains are classical spheres of radius $a \sim 0.1 \mu\text{m}$ and that each grain is in thermal equilibrium with the ISRF

If the cloud is optically thin in the Far-IR, a flux density

$$F_\lambda = N (\pi a^2 / d^2) Q_{em}(\lambda) B_\lambda(T_d)$$

is received, where d is the distance to the cloud and $(\pi a^2 / d^2)$ is the solid angle subtended by an individual grain



Dust Mass Estimate

The flux observed from a heated cloud may be used to deduce the mass of the cloud and to place constraints on dust properties.

The total volume of the dust in the cloud is given by

$$V = Nv$$

Where $v = (4/3) \pi a^3$ is the volume of an individual grain

Dust Mass Estimate

$$\text{Flux } F_\lambda = N (\pi a^2 / d^2) Q_{em}(\lambda) B_\lambda(T_d)$$

$$\rightarrow \text{Volume } V = F_\lambda d^2 / (\pi a^2 Q_{em}(\lambda) B_\lambda(T_d)) v$$

If the grains are composed of material of density ρ
we can write the above equation in terms of the total dust
mass

$$M_d = V \rho = 4 \rho F_\lambda d^2 / (3 B_\lambda(T_d)) \{ a / Q_{em}(\lambda) \}$$

With $v = 4/3 \pi a^3$

Adopting a suitably weighted average of $a / Q_{em}(\lambda)$ the
above equation *can be used to estimate the total mass of
dust in a cloud from the observed flux density without
detailed knowledge of the grain-size distribution*

Dust Mass Estimate

$$M_d = V \rho = 4 \rho F_\lambda d^2 / (3 B_\lambda(T_d)) \{ a / Q_{em}(\lambda) \}$$

The usual practice is to compute a flux ratio at two wavelengths (e.g. 60 and 100 μm), as the flux ratio is independent of the distance to the source,

then estimate T_{gr} given an assumed emissivity power law

[The usual dust emissivity law is: $Q_\nu \approx (2\pi a \nu / c)^\beta$ with $1 < \beta < 2$]

Given T_{gr} one can then derive the dust mass given an estimate of the distance to the source.

Dust Emission

- Dust heating is by starlight photons at various energies
- for large grains with radii $> 0.02 \mu\text{m}$:
steady thermal process
- for smaller grains the heating can be erratic and highly
quantized excitation and emission (35% of starlight re-
emission)
- Unidentified Infrared bands (10% optical/UV photons): the
best candidates are Polycyclic Aromatic Hydrocarbons

Candidates Grain Materials

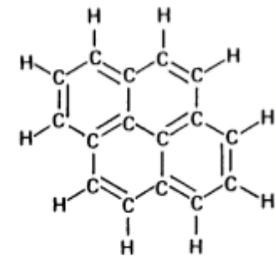
- *Silicates*: at least 95% amorphous (Li & Draine 2002), expected to be predominantly Mg and Fe compounds from cosmic abundances. Where crystalline silicate are found, they are Mg rich.
- *Carbonaceous materials*: including diamond, graphite, amorphous/glass carbon, PAH, aliphatic hydrocarbons.
- *SiC*: found in meteorites and an 11.3 μm feature in carbon stars (< 5% of dust).
- *Carbonates*: found in dusty discs, but estimated to contribute < 1% of dust mass.

Galaxies Emission in the IR

the Mid-InfraRed (mid-IR): 3 - 40 μm

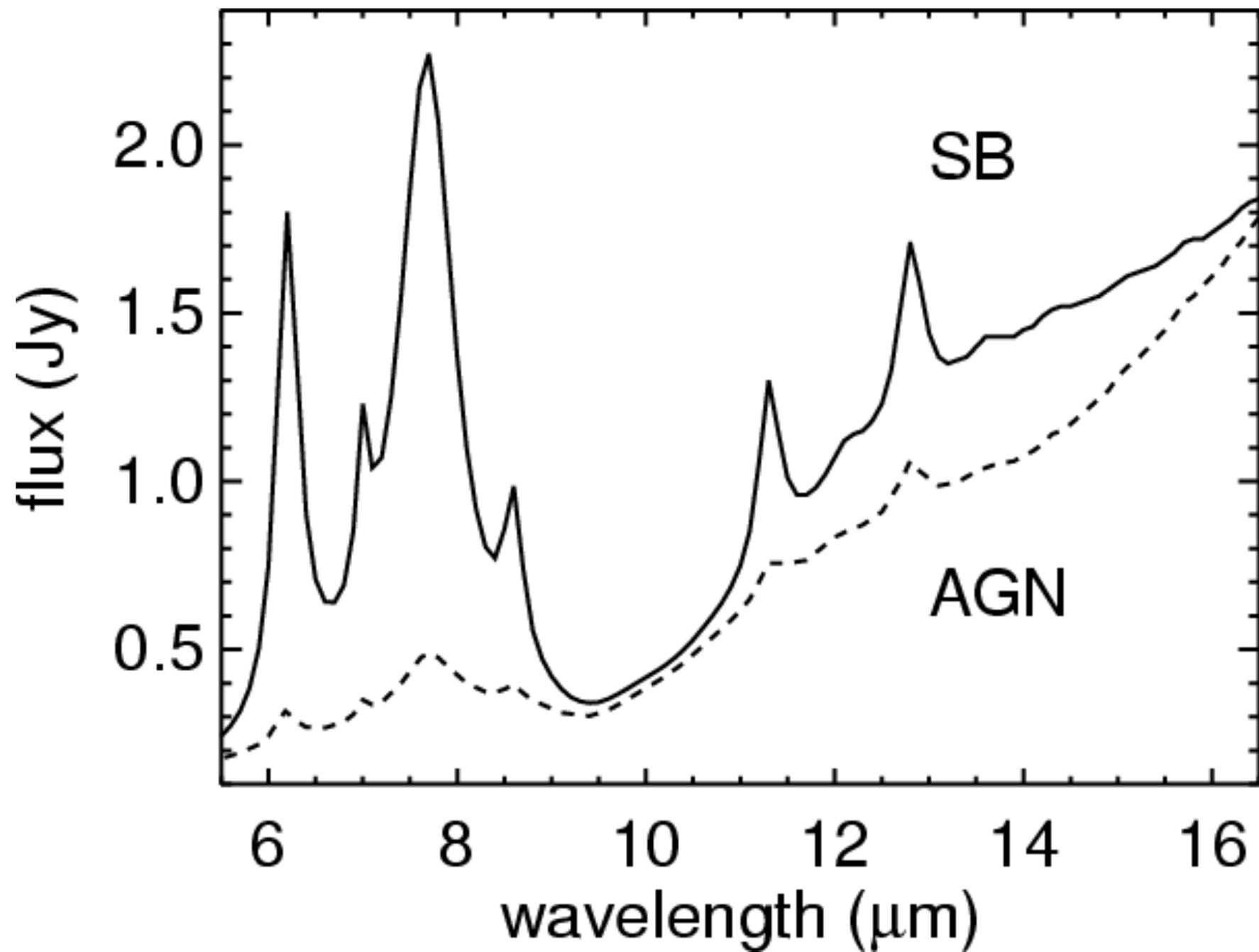
Unidentified Infrared Bands (UIBs)

at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm produced by polycyclic aromatic hydrocarbons (PAH) heated by stellar photons (vibration)



Warm Dust (Very Small Grains: 5×10^{-4} - 5×10^{-3} μm)

at $T > 150$ K: originates a rapidly increasing continuum



The Unidentified Infrared Bands (UIBs)

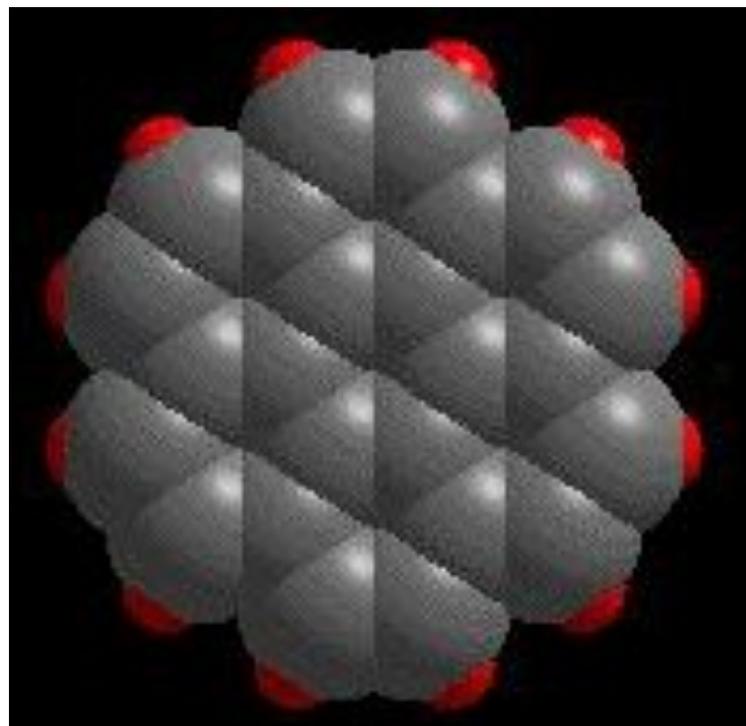
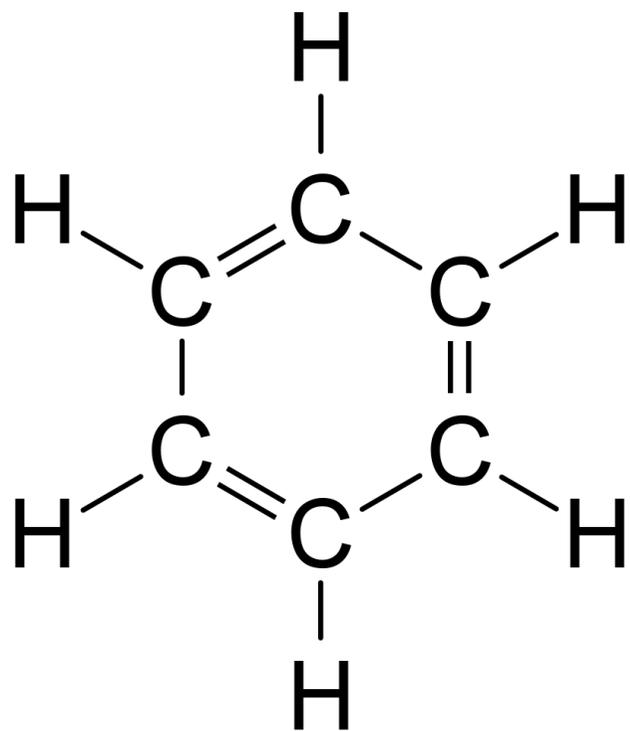
- The strongest bands are at 3.3, 6.2, 7.7, 8.6 and 11.3 μm . These wavelengths correspond to the C-H or C-C bond vibrations in aromatic (benzene-ring) structures: planar molecules called polycyclic aromatic hydrocarbons (PAH) excited by single UV photons.
- Polycyclic aromatic hydrocarbons can be found on Earth, in dirty barbecues and automobile exhaust pipes, among other places. They are thought to be necessary for primitive life to evolve.
- Diffuse UIB emission is responsible for 10-20% of the total radiation from dust.

The Unidentified Infrared Bands (UIBs)

- The infrared emission is due to relaxation from highly vibrationally and electronically excited states. The excitation is caused by UV photon absorption (excitation mechanism similar to single photon excitation process).
- The abundance of PAHs relative to hydrogen is $\sim 2 \times 10^{-7}$.
- About 1% of all the available carbon is in the form of PAHs.

The Unidentified Infrared Bands (UIBs)

Polycyclic Aromatic Hydrocarbons (PAH) are a class of very stable organic molecules made up of only carbon and hydrogen. These molecules are flat, with each carbon having three neighboring atoms much like graphite.



The Unidentified Infrared Bands (UIBs)

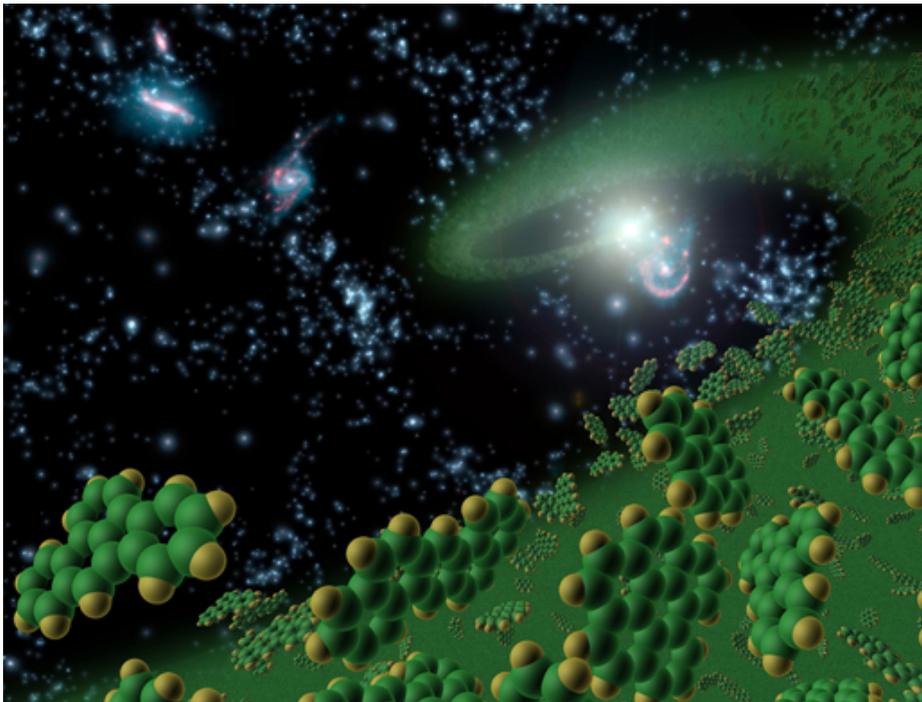
These large molecules, comprised of carbon and hydrogen, are among the building blocks of life.

These complex molecules are very common on Earth and form carbon-based materials are not burned completely. They can be found in sooty exhaust from cars and airplanes, and in charcoal broiled hamburgers and burnt toast.



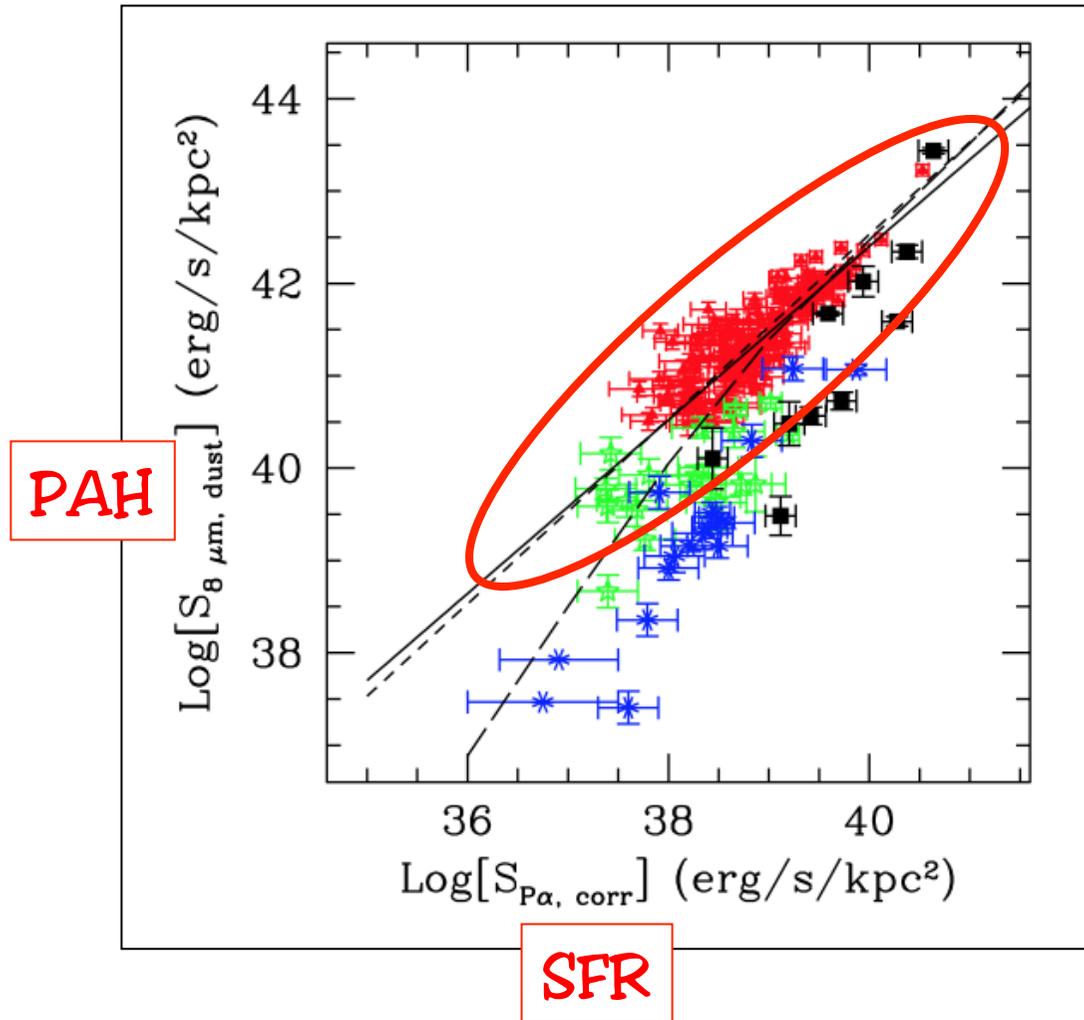
The Unidentified Infrared Bands (UIBs)

The presence of UIBs in a variety of objects suggests a ubiquitous presence of PAHs in the InterStellar Medium.



Polycyclic aromatic hydrocarbons are pervasive in galaxies like our own Milky Way, and play a significant role in star and planet formation.

PAHs as Star-Formation Rate Indicators



There is generally a linear correlation between the PAH luminosity and the Star-Formation Rate (SFR).

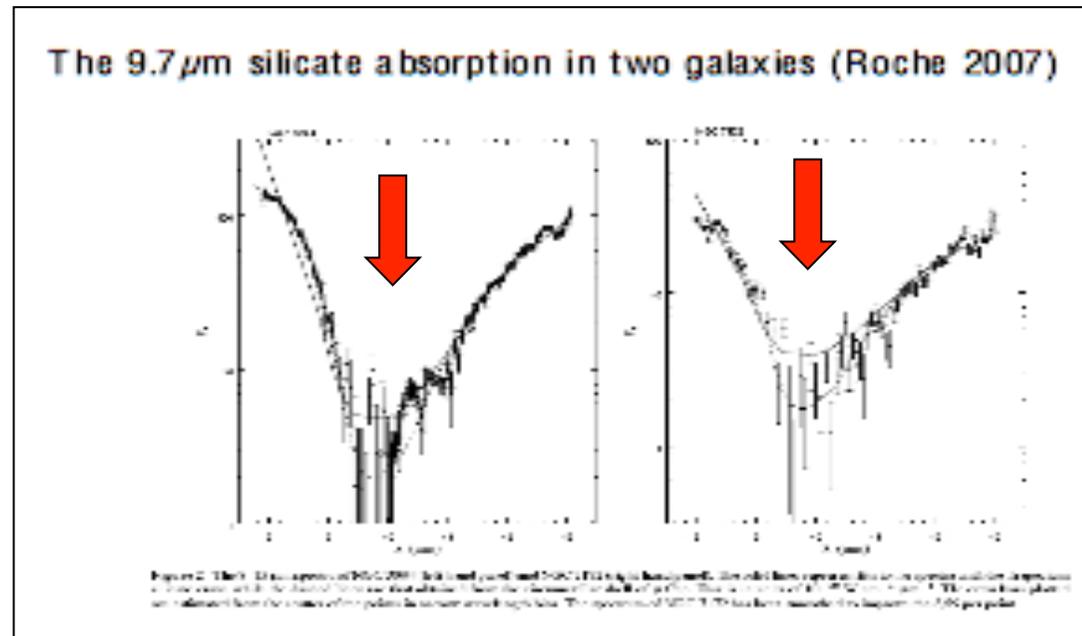
This indicates that the PAH emission can be considered a reliable SFR indicator.

Continuum Emission

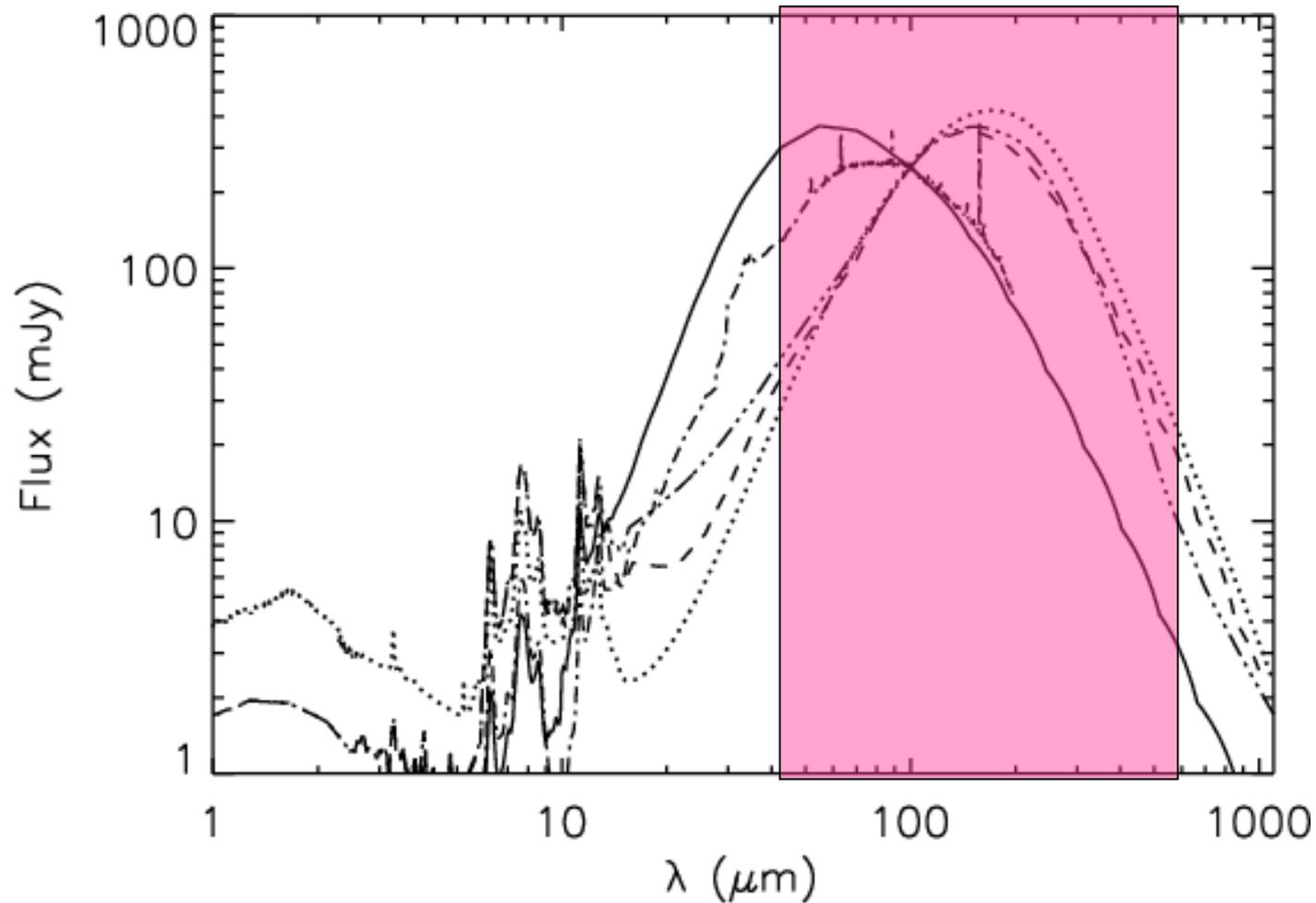
- *Continuum Emission in the NIR/MIR range*, arising from warm grains ($T_d \sim 100$ K) in the size range $5 \times 10^{-4} - 5 \times 10^{-3}$ μm . Such grains are large enough to have an almost continuous density of energy states \rightarrow they radiate a continuum rather than emission bands.
- *Continuum Emission in the FIR range*: grains with sizes of ≥ 0.01 μm are cold ($T_d \sim 20$ K) and reradiate most of the energy that they absorb in the far-IR (about 30% of the total luminosity of a galaxy is radiated in the far-IR)

Absorption Features

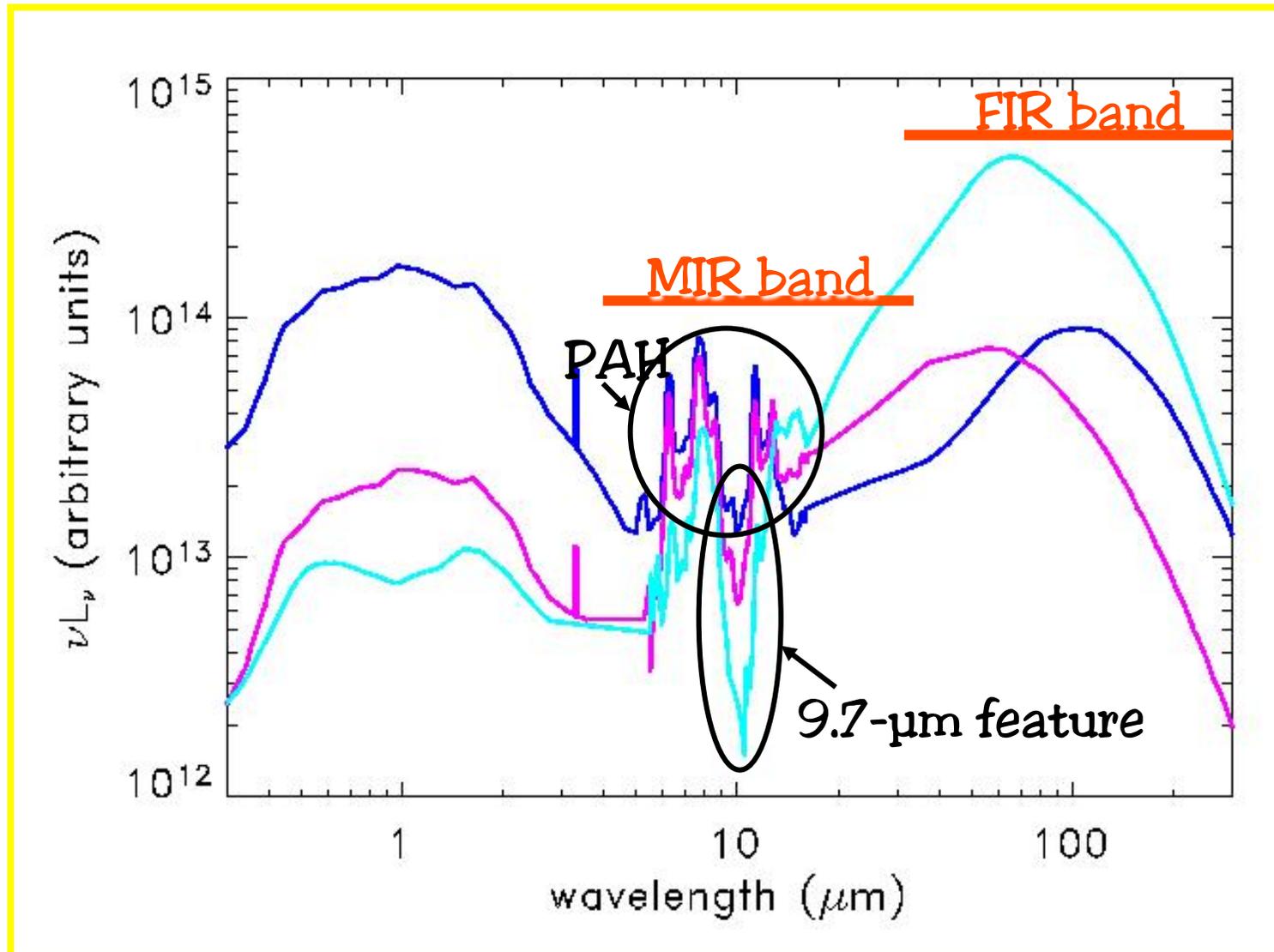
- Spectral absorption features can provide a great deal of information about the nature and composition of dust grains:
- *9.7 and 18 μm absorption:* these features, seen in interstellar dust when A_V is suitably large, are attributed to the Si-O stretching and O-Si-O bending modes in silicates



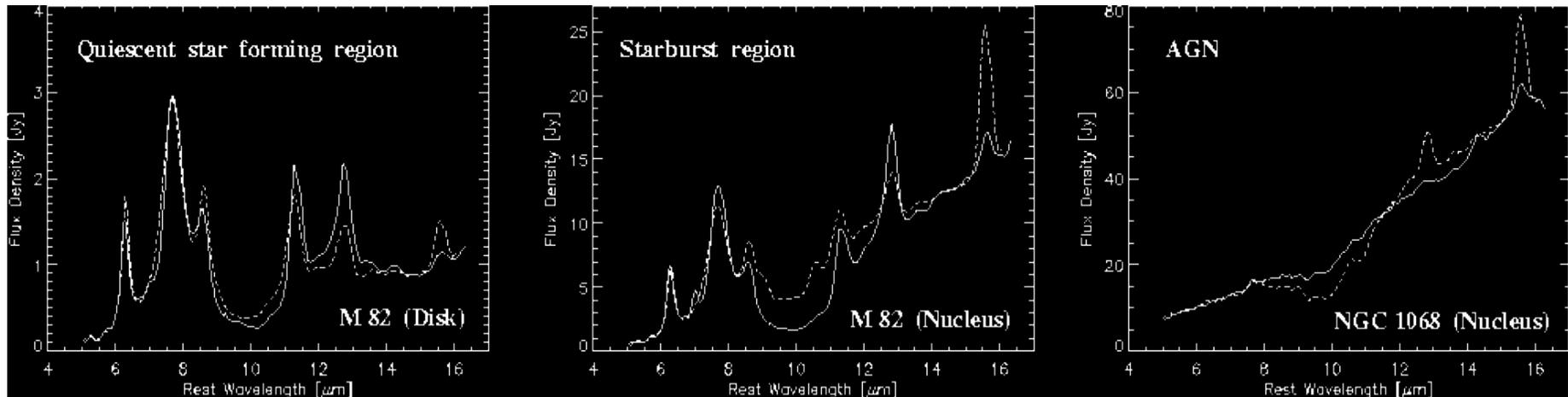
Galaxies Emission in the Far-InfraRed (far-IR): 40 - 200 μm



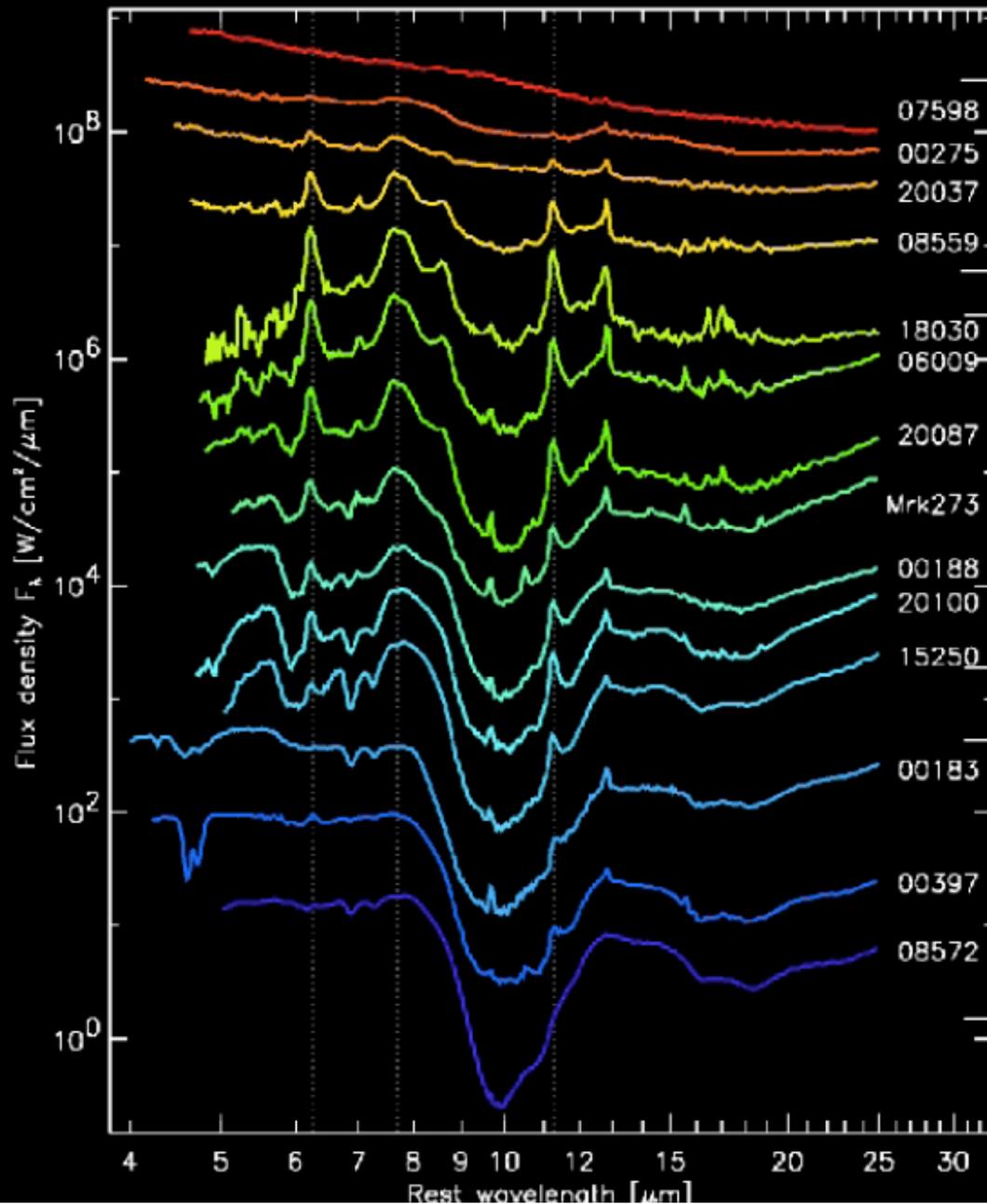
How does the spectral energy distribution (SED) of a galaxy appear in the IR?



★ Mid-IR Spectroscopy: powerful tool to distinguish star-formation (PAHs) from AGN activity (continuum)
(i.e. Laurent et al., 2000)



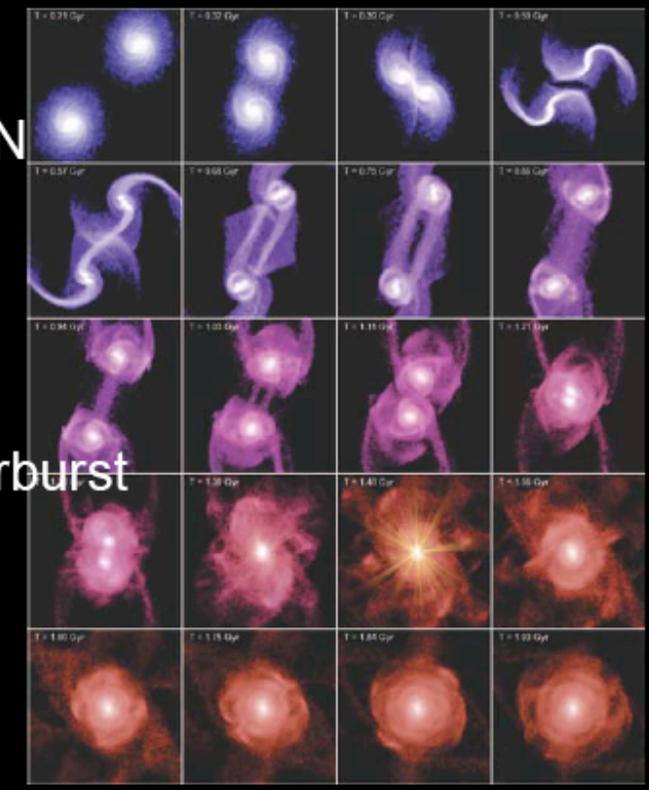
Mid-IR Spectroscopy: AGN versus Starburst



AGN

Starburst

Embedded (AGN?)

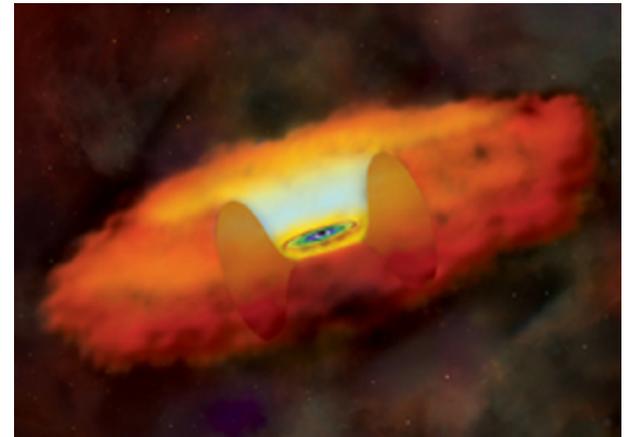


Hopkins et al. 2006

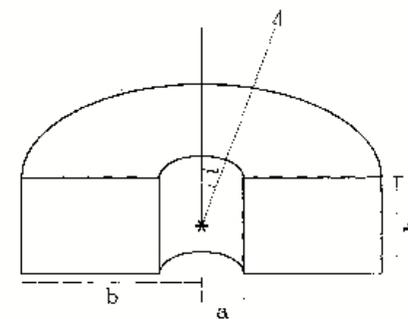
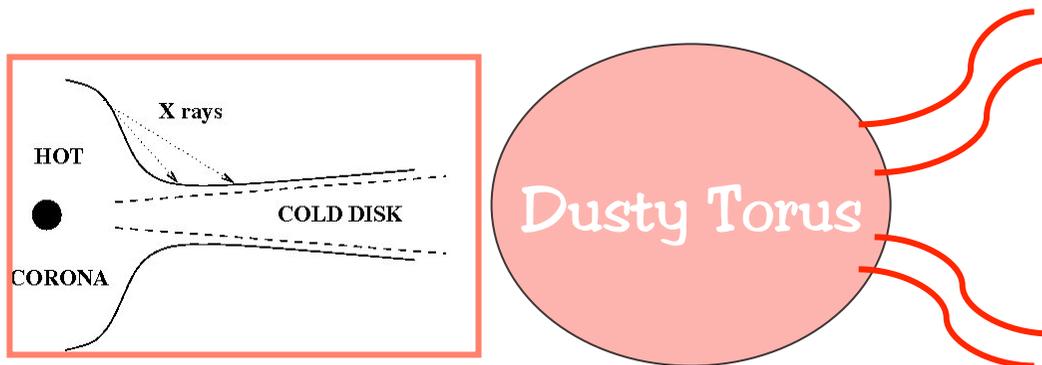
Armus et al. (2006, IRS GTO
ULIRG program)
Veilleux et al. (2006, 2009
QUEST)

AGN in the IR

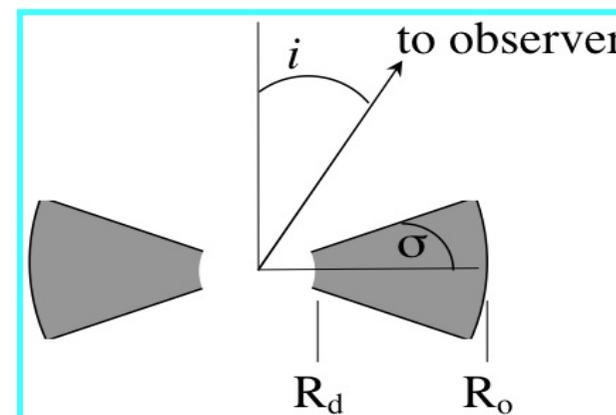
- ★ The obscured AGN IR Spectral Energy Distribution (SED) is dominated by thermal emission from dust (*Neugebauer 1979*), heated by the primary optical/UV continuum dominating the unobscured AGN SEDs.
- ★ The broadness of the IR SED, which could not be reproduced by means of single-temperature blackbody, was explained in terms of multiple temperature component dust.
- ★ According to the AGN Unified Model, the dust is distributed as a (clumpy?) annular ring (torus) around the central BH.
- ★ The different orientations of the dusty torus with respect to the line of sight are responsible for the differences observed in the X-rays/optical spectra/SEDs/etc of type 1 and type 2 AGN.



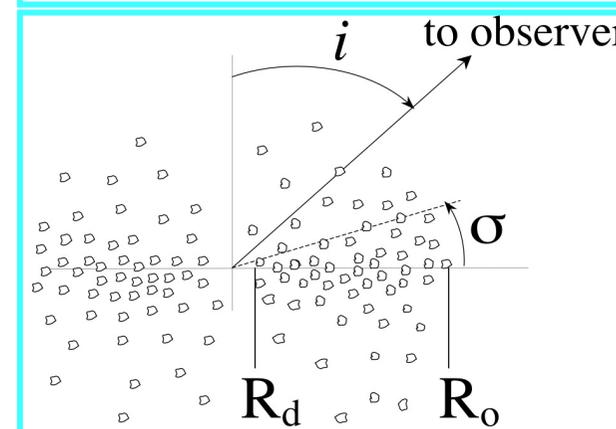
Models for the IR emission of AGN



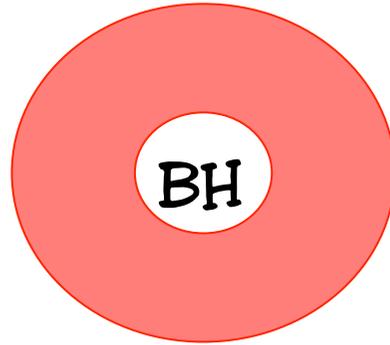
Smooth dust distribution: dust grains around a central source (AGN) in a smooth distribution (e.g., Pier & Krolik 1992, Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995, Fritz et al. 2006)



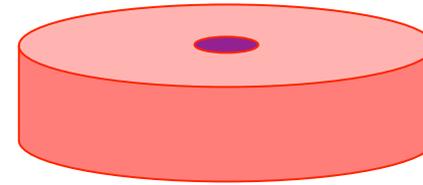
'Clumpy' models: dust grains in clouds (not uniform distribution) A Type 2 AGN can be seen also at large inclination angles over the equatorial plane (e.g., Nenkova et al. 2002, 2008a,b; Hoenig et al. 2008; Schartmann et al. 2008)



AGN SEDs in the IR

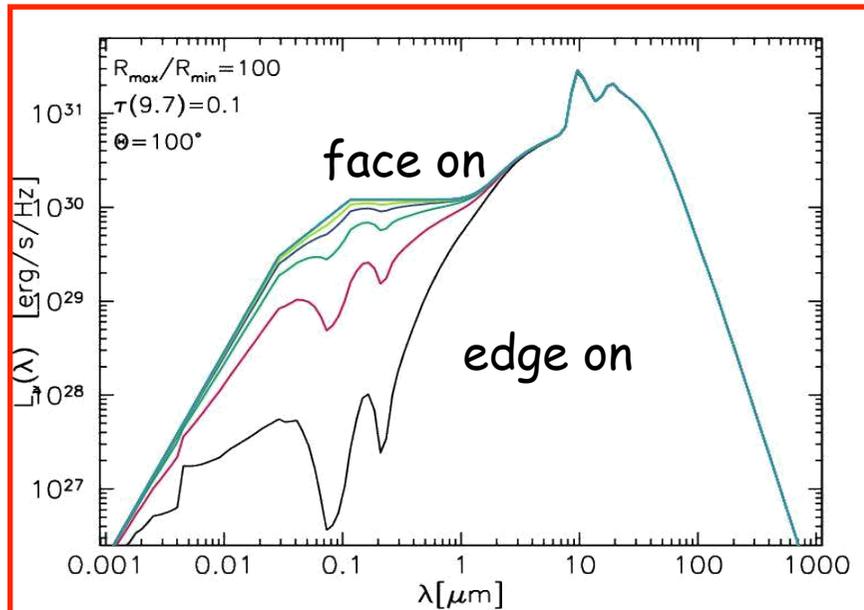


FACE ON TORUS

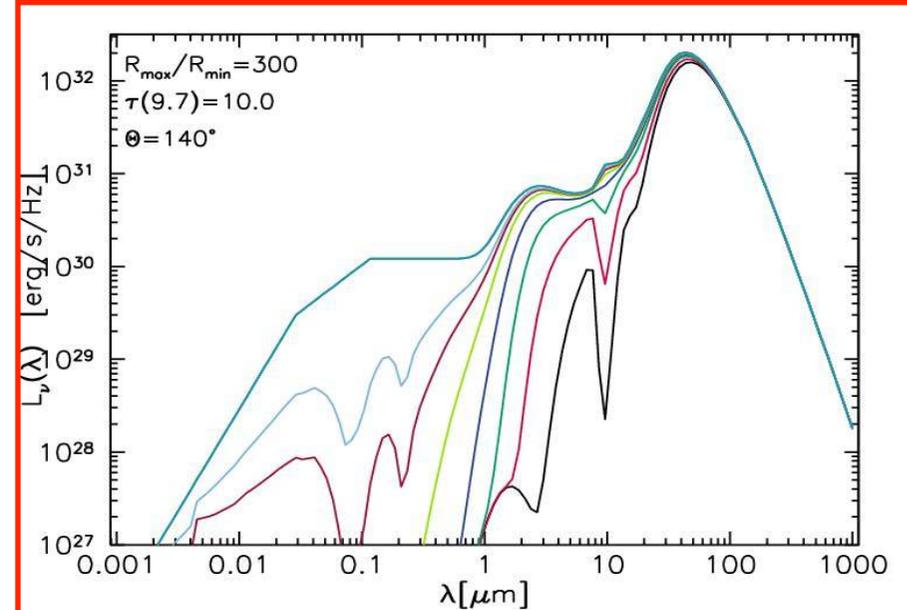


EDGE ON TORUS

Low $\tau_{eq}(9.7\mu\text{m}) \Rightarrow$ Silicate feature in emission



High $\tau_{eq}(9.7\mu\text{m}) \Rightarrow$ Silicate feature in absorption



Solving the Radiative Transfer Equation

The equilibrium temperature (and hence thermal emission) of the grains of each species in each sample element is found by solving the thermal equilibrium equation

$$\int_{\lambda_{\min}}^{\lambda_{\max}} Q_{\text{abs}}(\lambda) J^{\text{ik}}(\lambda) d\lambda - \int_{\lambda_{\min}}^{\lambda_{\max}} Q_{\text{em}}(\lambda) B(\lambda, T_{\text{ik}}) d\lambda = 0,$$

$Q_{\text{abs}}, Q_{\text{em}}$ = grain absorption/emission efficiency

$B(\lambda, T_{\text{ik}})$ = blackbody emission

T_{ik} = temperature of a given grain within the ik^{th} sample element

J_{ik} = incoming specific intensity on the volume element

For the first iteration:

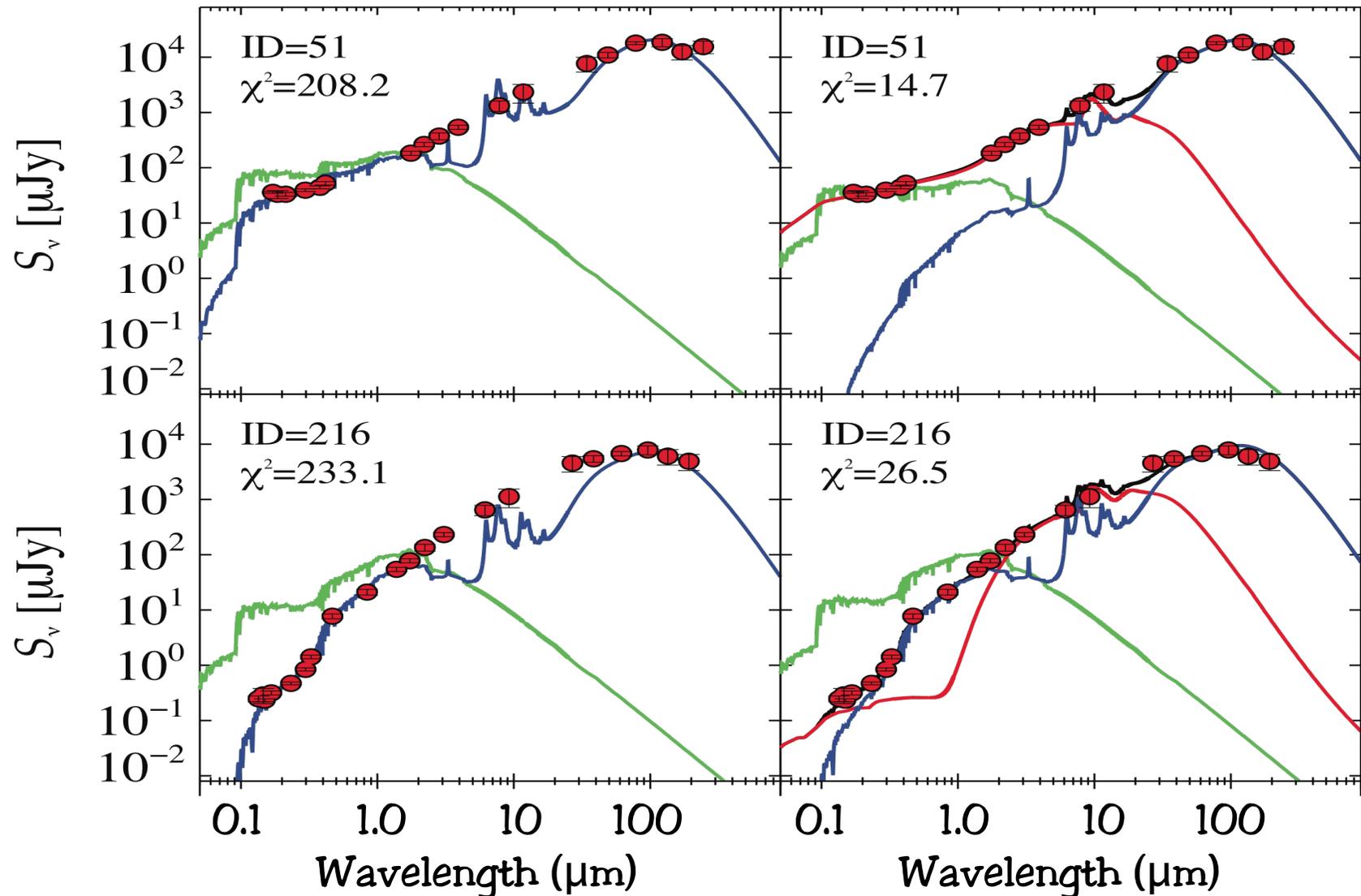
$$J^{\text{ik}}(\lambda) = I_{\text{AGN}}(\text{ik}, \lambda) = \frac{1}{4\pi} \frac{L(\lambda)}{4\pi r_{\text{ik}}^2} \exp[-\tau_{\text{ik}}(\lambda)].$$

$\tau_{\text{ik}}(\lambda)$ = optical depth between the central source and the ik^{th} element r_{ik} = distance

At the second iteration, the new incoming radiant flux is:

$$J^{\text{ik}}(\lambda) = I_{\text{AGN}}^{\text{ik}}(\lambda) + \frac{1}{4\pi} \sum_{i=1}^{N-1} \times \frac{1}{4\pi r_{\text{ik},i}^2} \left\{ \sum_{\text{id}}^{N_{\text{dust}}} [4\pi r_{\text{id}}^2 Q_{\text{id}}^{\text{em}}(\lambda) B(\lambda, T_{e,\text{id}}) + 4\pi r_{\text{id}}^2 Q_{\text{id}}^{\text{scat}}(\lambda) J_{\text{tot}}^e(\lambda)] e^{-\tau_{\text{ik},i}(\lambda)} \right\}$$

AGN SEDs in the IR

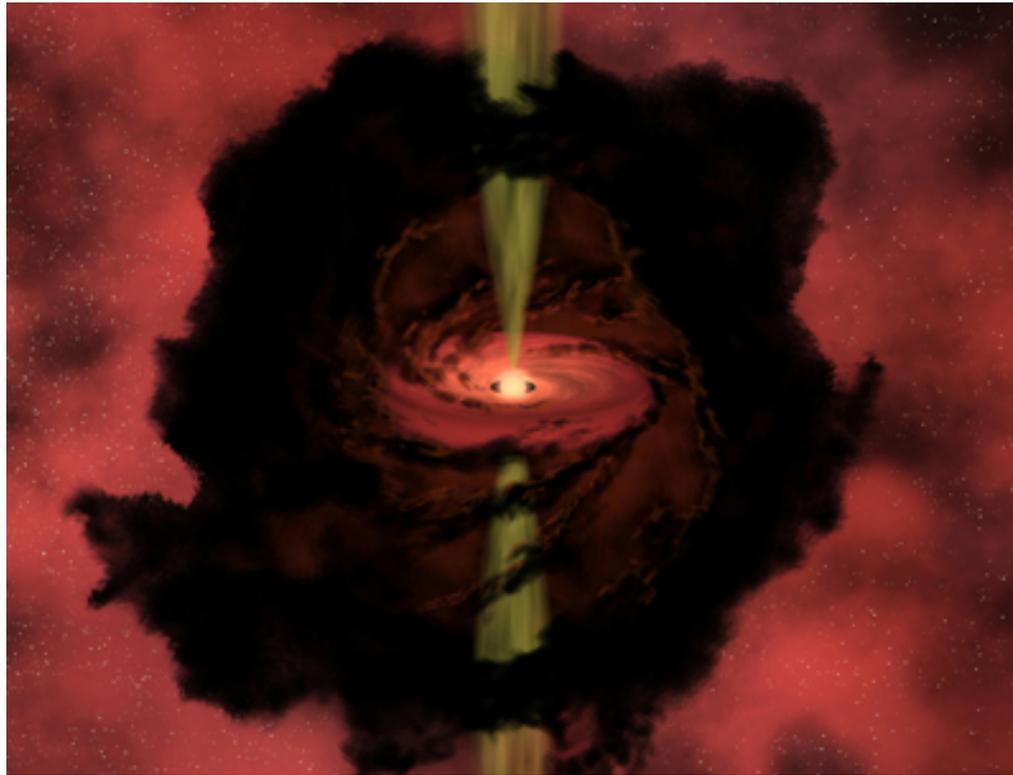


Space Dust Pictures



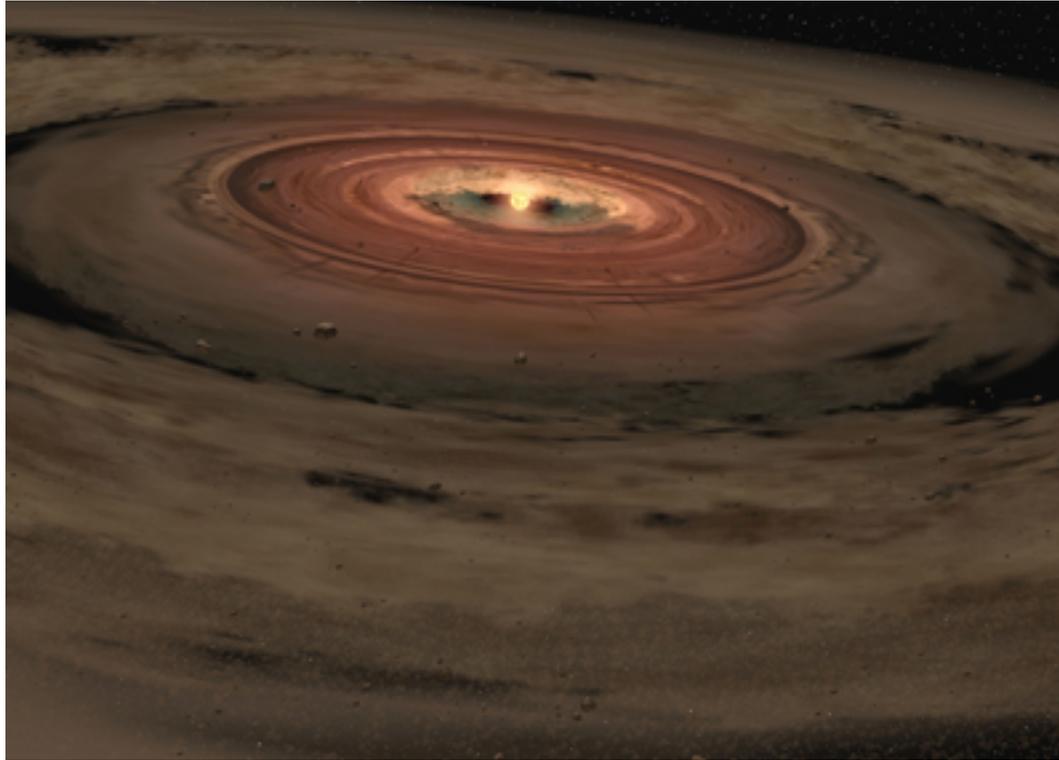
This infrared image of baby stars in a nebula of the Perseus constellation was taken by NASA's Spitzer Space Telescope. The stars appear as reddish-pink dots to the right, and the pinkish color indicates that they're still shrouded by the cosmic dust that collapsed to form them.

Space Dust Pictures



In this artist's conception, we peer through the dark dust to witness the birth of a star. Astronomers believe that stars form in massive pockets of dust and gas. As gravity begins to act on the matter in these clouds, they collapse into denser and denser and hotter and hotter forms, eventually becoming the fusion engines we know as stars.

Space Dust Pictures



The dust around this brown dwarf star is a proto-planetary disk, from which planets may form. Astronomers believe planets like our Earth come together in a process known as accretion, where hot masses of gas and dust swirl around a star until, by the force of gravity, the gases and the dust begin to collect into distinct clumps of matter, which eventually become planets.

Space Dust Pictures



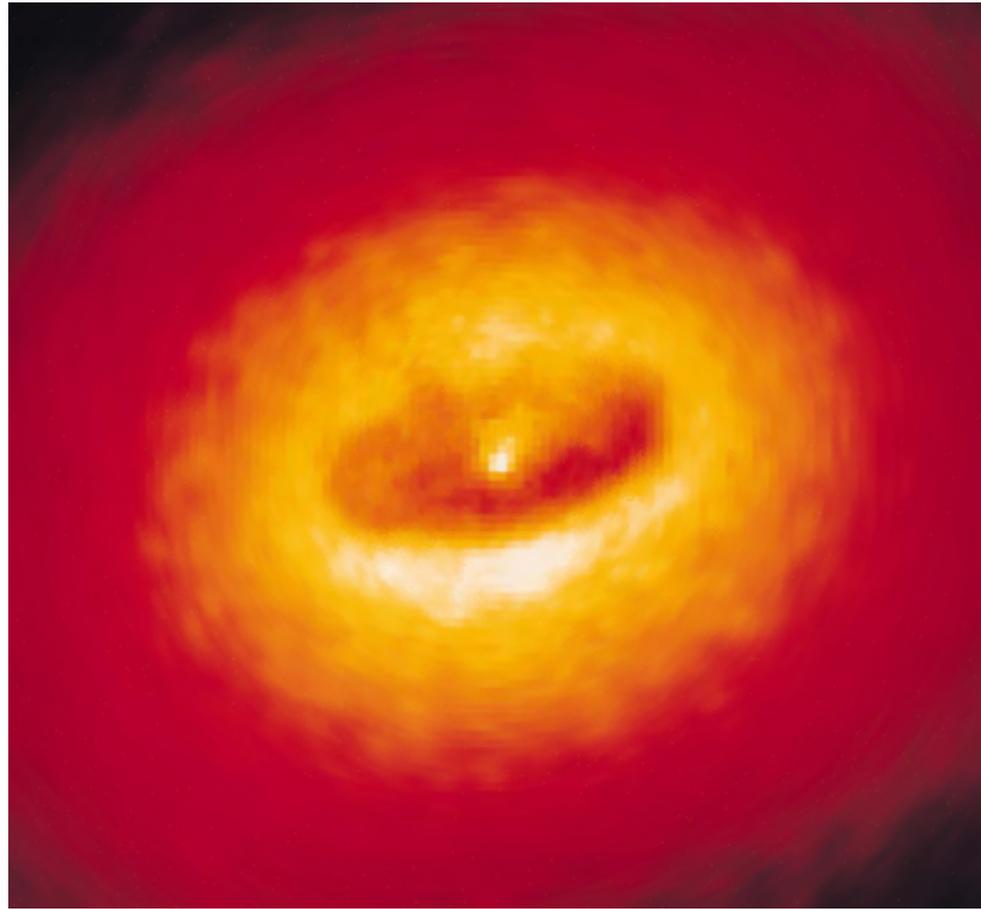
The Seven Sisters star cluster, also known as Pleiades, is one of our most recognizable friends in the night sky. These stars are normally visible with the naked eye, but infrared images like the one above allow us to get a look at the nebular dust that obscures the direct light of these beautiful stars.

Space Dust Pictures



One of the biggest galaxies in the cluster known as Virgo, the Sombrero Galaxy is a remarkable collection of stars. It has a bright nucleus, and around its central bulge of stars there is a large disk of dust.

Space Dust Pictures



A giant disk of cold gas and dust fuels a suspected black hole. Black holes are so dense that they pull everything within range into their gravitational field -- even light itself. Fine particle matter is no exception.

Evolution of Dust

★ Relevant timescales show that the present form of interstellar dust must be more a reflection of the processing it has received within the ISM than of the conditions at its origin.

★ A typical parcel of gas and dust is cycled back and forth through molecular clouds several times during its lifetime, changing its grain properties significantly each time.

Evolution of Dust

★ The lifetime of a grain against incorporation into stars can be estimated by:

dividing the surface density of the ISM by the rate of star formation.

Evolution of Dust

The local H I surface density is $\sim 10^7 M_{\odot} \text{ kpc}^{-2}$ and for H_2 is $3 \times 10^6 M_{\odot} \text{ kpc}^{-2}$

- A mean rate of star formation of $3.4 \times 10^{-3} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ would account for the present surface density of low-mass ($M < M_{\odot}$) stars over 10^{10} yr
- High-mass stars contribute about $1.1 M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$.



the mean lifetime of a parcel of gas/dust in the ISM is more than 3 Gyr.

Evolution of Dust

- On the other hand, about 30% of the local ISM is in molecular clouds, each with a lifetime of $\sim 10^8$ yr (the time for the gas to proceed from one spiral arm to the next) or less.
- These numbers imply that a given parcel of gas has been into and out of a molecular cloud at least every 3×10^8 yr, or more than 10 times during its mean lifetime.
- Each time, the differences in extinction laws between diffuse dust and inner-cloud dust require that the grains be heavily modified.

What information do we get from the integrated IR light?

Assembly of matter into stars and galaxies → release of radiant energy
Cosmic expansion and absorption of short- λ radiation by dust and reemission at long λ → shift into infrared background radiation.

The total intensity alone does not allow us to address the nature and evolution of the Extragalactic Background Light (EBL) sources, the relative contributions of AGN and star-forming galaxies at various wavelengths, and the history of star and element formation

→ we must consider the spectral energy distribution of the background.

What information do we get from the integrated IR light?

The spectral intensity $I(\nu)$ of the EBL at the observed frequency ν is given by the integral over its sources (*Peebles 1993*):

$$I_\nu(\nu_0) = \left(\frac{c}{4\pi} \right) \int_0^\infty \mathcal{L}_\nu(\nu, z) \left| \frac{dt}{dz} \right| dz,$$

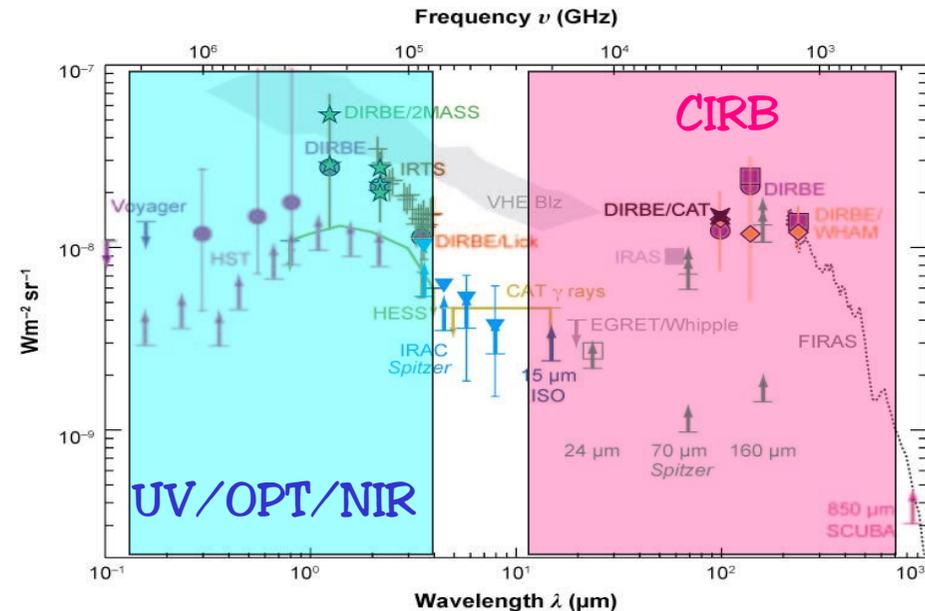
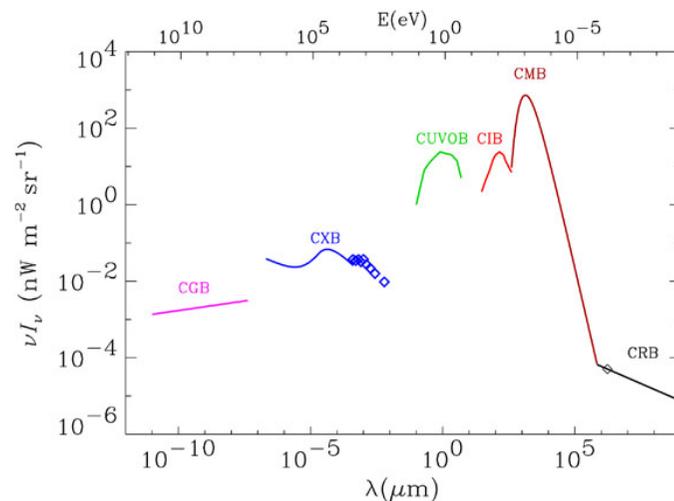
where $\mathcal{L}_\nu(\nu, z)$ is the spectral luminosity density of all luminous objects in a comoving volume element at redshift z , $\nu = \nu_0(1+z)$ is the frequency in the rest frame of the luminous objects

$$H_0 \left| \frac{dt}{dz} \right| = (1+z)^{-1} \left[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda \right]^{-1/2},$$

Observed Emission from diffuse IS dust

The integrated background intensity provides constraints on the history of energy releases in the Universe.

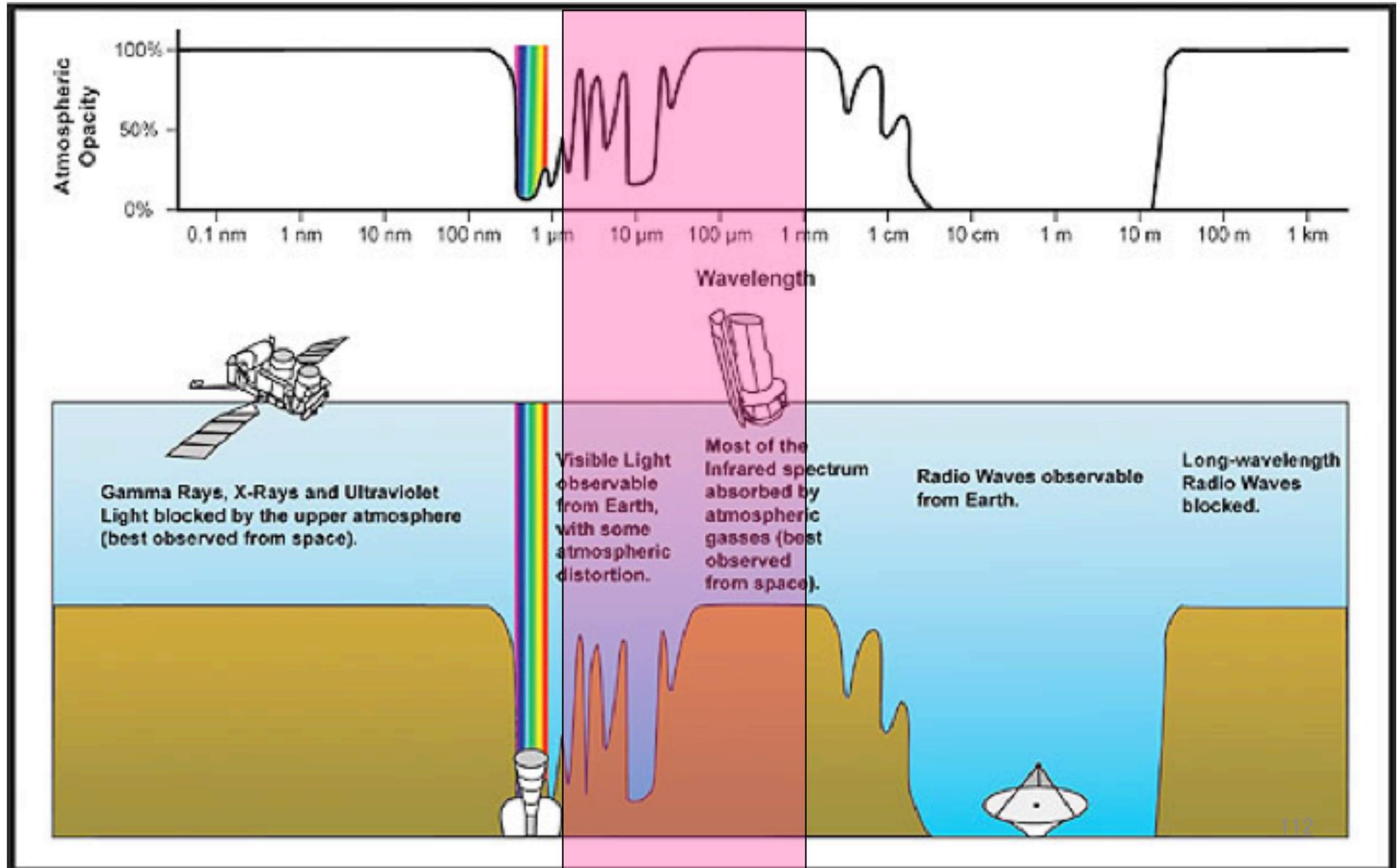
The IR glow from IS dust has been first measured by COBE (see Hauser & Dwek 2001 for a detailed review)



Soifer BT, et al. 2008. Annu. Rev. Astron. Astrophys. 46:201–40

The Cosmic IR Background (CIRB) contains as much energy as the optical/UV/NIR one and can be explained only if **Galaxies & AGNs have evolved fast in the MIR/FIR bands**

Observing in the IR: How ?





IRAS (1983)

- 57 cm
- 12-100 μm



ISO (1995-98)

- 60 cm
- 2.4-240 μm



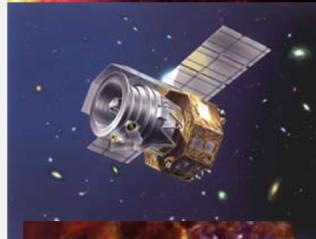
Spitzer (2003-09)

- 85 cm
- 3.6-160 μm



AKARI (2006-07)

- 67 cm
- 1.7-180 μm



Herschel (2009 -12)

- 3m-class, $T_{\text{tel}} \sim 80\text{K}$
- 55-672 μm



SPICA

- 3m-class, actively cooled ($T_{\text{tel}} < 6\text{K}$)
- 5-210 μm
- Nominal 3 year lifetime, goal 5 years
- Sensitivity limited by sky-background

FUTURE

...seeing what nobody has seen before..

