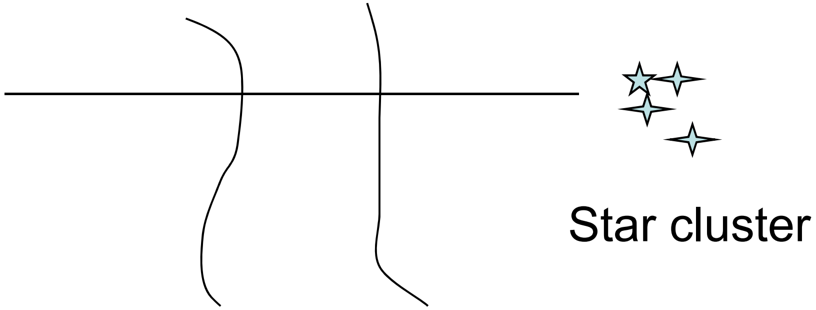
Interstellar Extinction

<Extinction> = **<Absorption>** + **<Scattering>**



Cloud we are not aware of

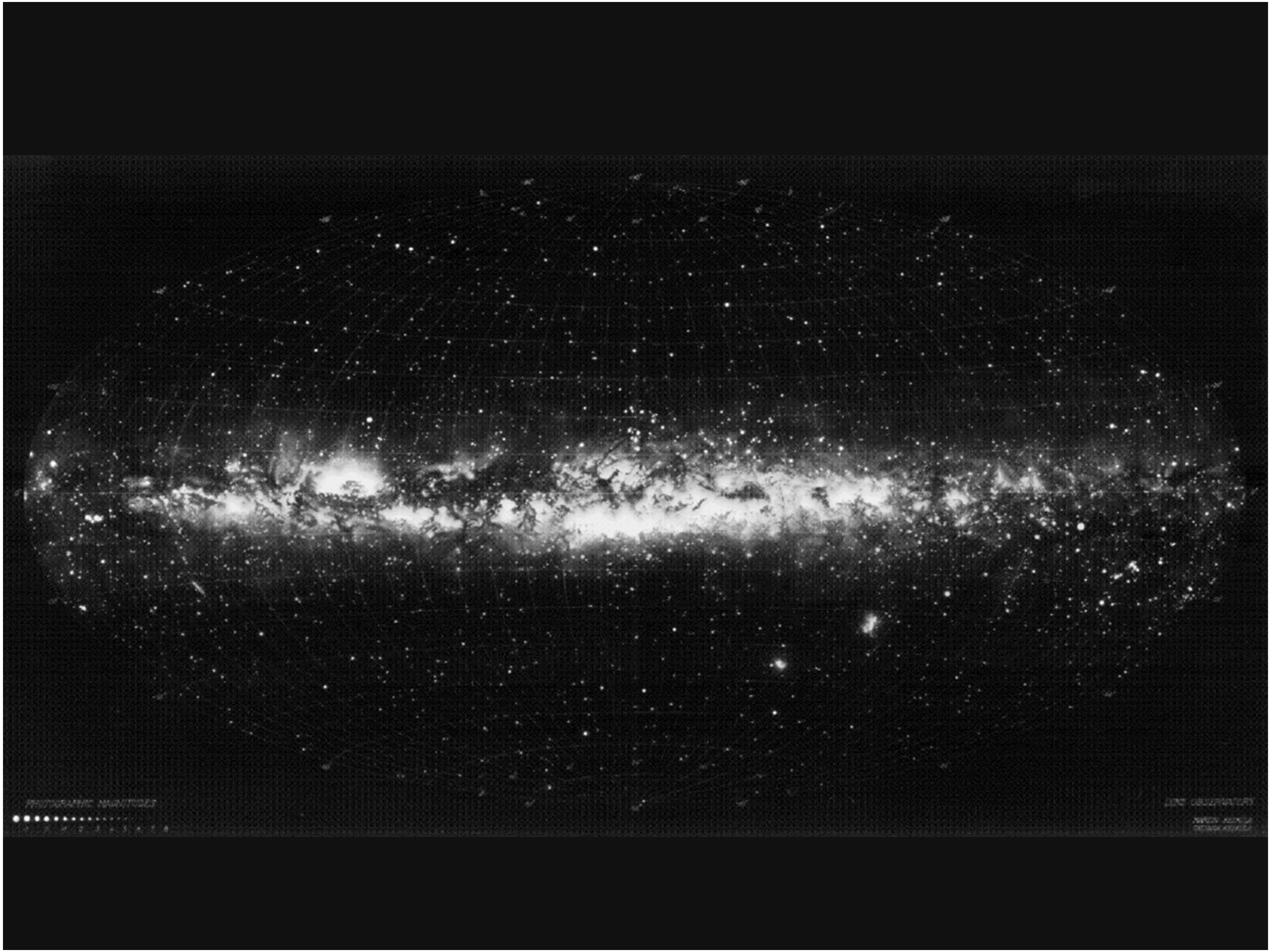
Evidence of extinction

(a) dark clouds in photographs

(b) Statistically star clusters brightness ←→ size

e.g., dimmer ←→ smaller, but Trumpler in 1930s found clusters appear fainter

(c) star count



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ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

By Robert J. Trumpler

1930, PASP, 42, 214

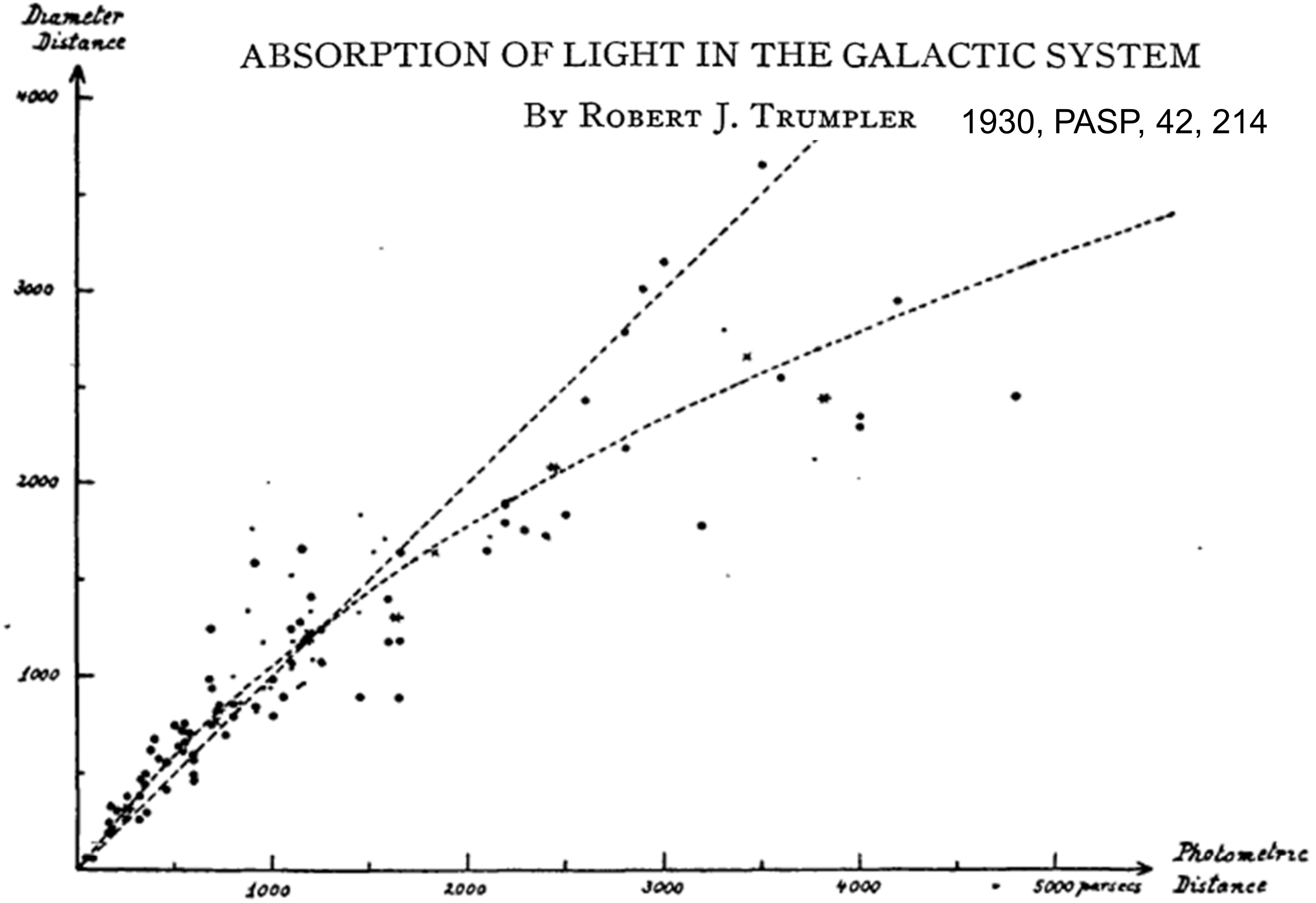
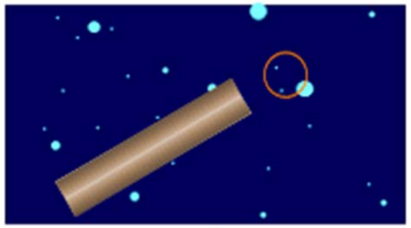
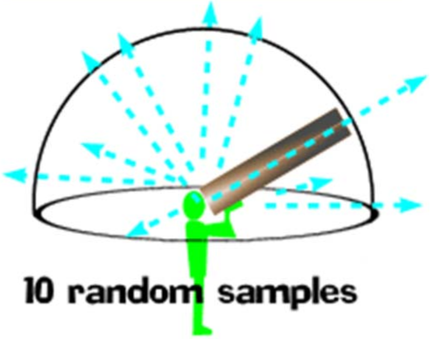


Fig. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Star Count

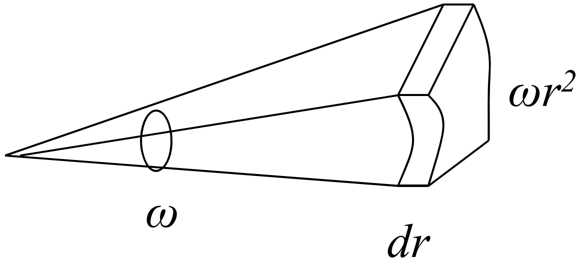




Prediction of a uniform galaxy

Assumptions:

(i) stars uniformly distributed: D stars pc^{-3}
(ii) our galaxy infinite in extent
(iii) no extinction
(In reality, none of the above is true!)



Total number of stars out to *r*

$$N(r) = \omega\, D \int_0^{\infty} r'^2\, dr' = \frac{1}{3}\omega\, D\, r^3$$

If all stars have absolute magnitude M (i.e., same intrinsic brightness --- another untrue assumption), since

$$m - M = 5 \log r_{\rm pc} - 5$$

$$\longrightarrow \quad r_{\rm pc} = 10^{0.2(m-M)+1}$$

$$N(r) = 10^{0.6m - \mathbf{C}} \qquad \text{where } \mathbf{C} = \mathbf{C}(D, \omega, M)$$

$$\longrightarrow \quad \boxed{N(m) \propto 10^{0.6m}}$$

$10^{0.6}$ ~ 4, so # of stars increases 4 times as we go 1 mag fainter

This is logically unlikely, because if we integrate over *m*, the sky would have been blazingly bright (**Olbers' paradox**)

Olbers' Paradox --- Why is the night sky dark?

The paradox can be argued away in the case of the Galaxy by its finite size, but the same paradox exists also for the Universe → expansion of the Universe

The star count result was recognized by Kapteyn → Kapteyn Universe: star density falls as the distance increases

Extinction effect: If w/o absorption we observe m mag, then with $a(r)$ mag absorption at r, we would observe $m + a(r)$

Without extinction: $\log r = 0.2(m - M) + 1$

So the apparent distance r' ($> r$)

$$\begin{aligned}\log r' &= 0.2[m + a(r) - M] + 1 \\ &= 0.2(m - M) + 1 + 0.2\,a(r) \\ &= \log r + 0.2a(r)\end{aligned}$$

$$\longrightarrow \quad r' = 10^{0.2\,a(r)}\,r$$

So dimming of 1.5 mag
→ overestimate of distance by 2 x
→ underestimate space stellar density by 8 x

Both the star density falling off and extinction should be taken into account → Galactic structure

Galactic poles: minimal extinction

Galactic disk: extinction significant ~ **1 mag kpc^{-1}**

In general, $\boxed{m_\lambda - M_\lambda = 5 \log r_{\rm pc} - 5 + A_\lambda}$

Because $A_\lambda = -2.5 \log \dfrac{F_\lambda}{F_{\lambda,0}}$ $F_{\lambda,0}$: flux that would have been observed w/o extinction

and $F_\lambda = F_{\lambda,0}\, e^{-\tau_\lambda}$

$$\longrightarrow \boxed{A_\lambda = -2.5 \log(e^{-\tau_\lambda}) \equiv 1.086\tau_\lambda \equiv 1.086 N_d\, \sigma_\lambda\, Q_{ext}}$$

N_d: # of dust grains cm^{-2}
σ_λ : geometric cross section ($=\pi a^2$)

Q_{ext}: [dimensionless] '**extinction efficiency factor**'
= [optical cross section] / [geometric cross section]
Q_{ext}: $Q_e(\lambda)$

Note: $A_\lambda \leftarrow\rightarrow \lambda$

Why dust? (what causes 1 mag kpc^{-1})

Possibilities:

(1) Scattering by free electrons --- Thomson scattering

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right) \approx 6.6 \times 10^{-25}\ (\mathrm{cm}^2)\ \mathrm{for}\ \nu < 10^{20}\ \mathrm{Hz}$$

Since
$$\begin{aligned} A_v &= 1.086\bar{n}\,\sigma\,\ell \\ 1 &= 1.086\bar{n}6.6 \times 10^{-25} \cdot \underbrace{3 \times 10^{21}\ \mathrm{cm}}_{\mathrm{1kpc}} \\ &\rightarrow \bar{n} \approx 500\ cm^{-3} \end{aligned}$$

(2) Scattering by bound charges --- Rayleigh scattering?

$$\begin{aligned} \sigma_R &\sim \sigma_T\left(\frac{\nu}{\nu_0}\right)^4\ \mathrm{cm}^2\ (\nu \ll \nu_0) \\ &\sim \sigma_T\frac{\nu^4}{(\nu^2 - \nu_0^2)^2}\ \mathrm{cm}^2\ (\nu < \nu_0) \end{aligned}$$

Both $\sigma_R < \sigma_T$

$\bar{n} \sim$10-100 x

$\sim 10^4$

(2) Absorption by solid particles?

For particle radius ~ wavelength, Q_e ~1

$$\begin{aligned} A_v &= 1.086\,\bar{n}\,\sigma\,\ell \\ 1 &\approx \bar{n}\,\pi(5\times10^{-5})^2\cdot3\times10^{21} \\ &\rightarrow \bar{n}\approx4\times10^{-14}\ cm^{-3} \end{aligned}$$

Size of grains

Volume mass density

If ρ(material) ~ 2 g cm^{-3}

$$\frac{4}{3}\pi a^3\bar{n}\rho\sim4\times10^{-26}(\mathrm{g\ cm^{-3}}) \longrightarrow$$ 1% of Oort's limit

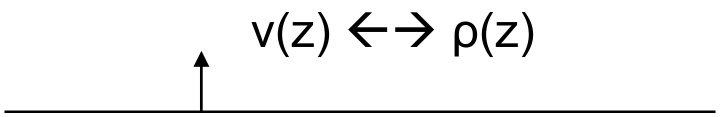
Note: wavelength dependence

Extinction Q ~ λ^{-1}

Thomson ~ λ^0

Rayleigh ~ λ^{-4}

Oort's Limit



ρ(z): (total) mass density; v(z): velocity dispersion of stars

$$\Delta\phi = \underbrace{-\frac{dg_z(z)}{dz}}_{\text{observed}} = \underbrace{4\pi G\rho(z)}_{\text{yielded}}$$ Poisson eq.

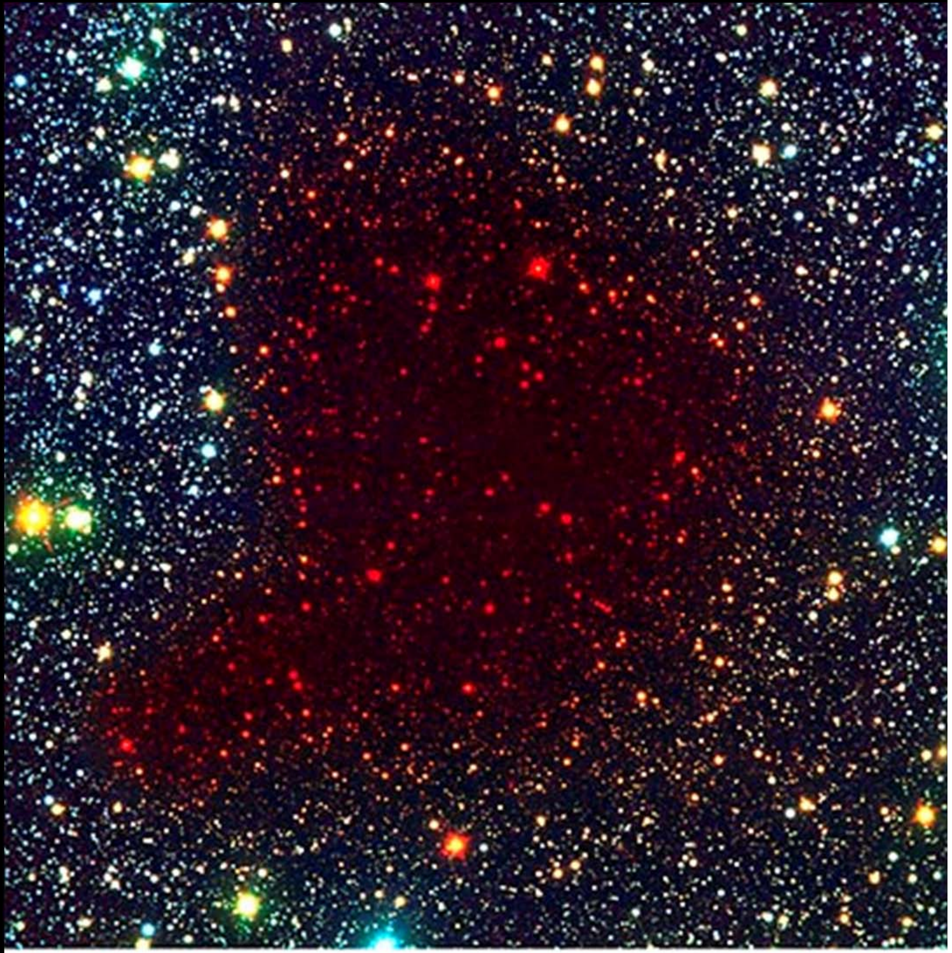
$$\boxed{\rho_{\mathrm{ISM}} \lesssim 6 \times 10^{-24}\ (\mathrm{g\ cm^{-3}})}$$

~ about 2-3 H atoms cm^{-3} assuming He/H ~ 10% by number

So, a volume mass density of 4 x 10^{-26} g cm^{-3} is ok, and if dust is responsible for the extinction, this implies a **gas-to-dust ratio of ~100**

Pre-Collapse Black Cloud B68 (visual view)
(VLT ANTU + FORS 1)

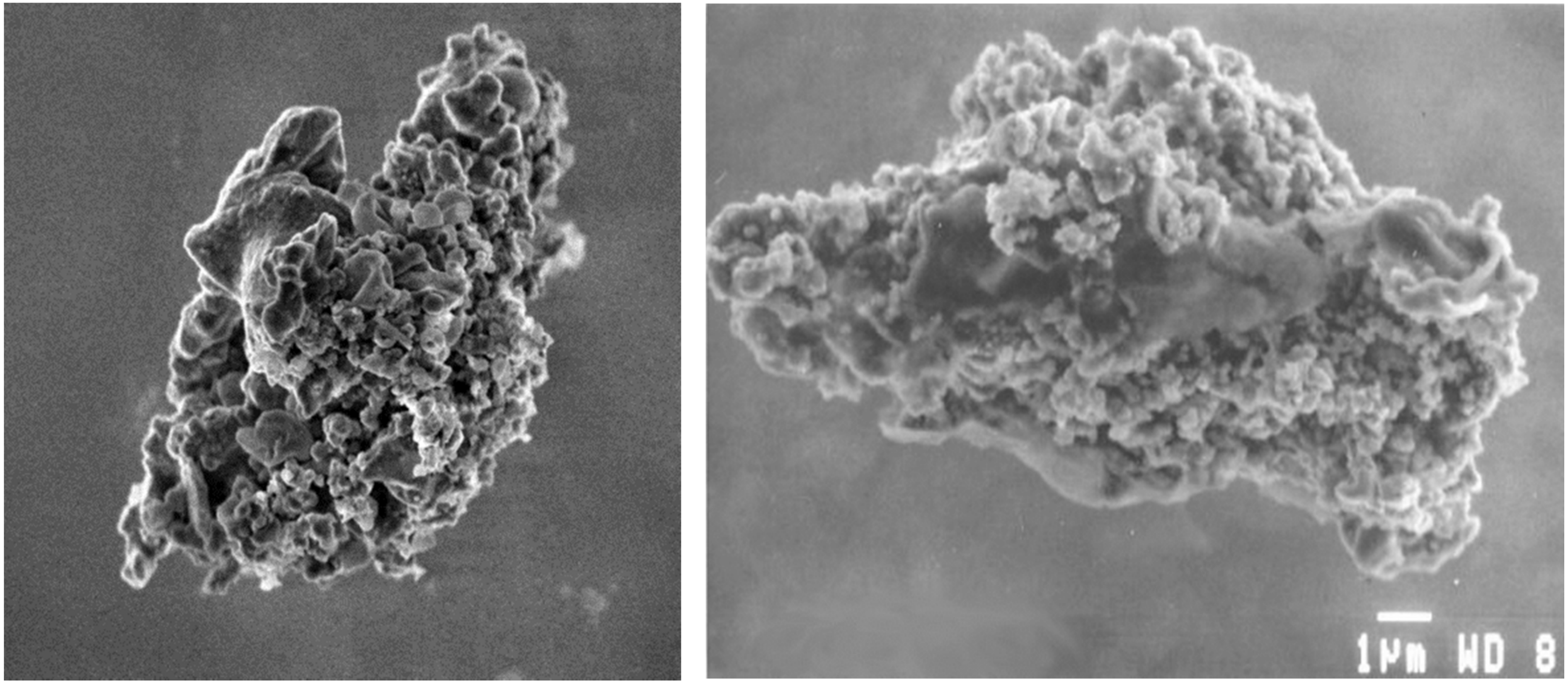
ESO PR Photo 02a/01 (10 January 2001)



Seeing Through the Pre-Collapse Black Cloud B68
(VLT ANTU + FORS 1 - NTT + SOFI)

ESO PR Photo 02b/01 (10 January 2001)

http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html



The grains appear to be loose conglomerations of smaller specks of material, which stuck together after bumping into each other.

Selective Extinction

--- the wavelength dependence of extinction

Choose 2 stars of the same spectral types and luminosity classes. Observe their magnitude difference Δm at λ_1 and λ_2

Δm is caused by (1) different distances, and (2) extinction by intervening dust grains

OB stars are good choices because they can be seen at large distances and their spectra are relatively simple

Observed at 2 λs: $\Delta m_{\lambda 1} - \Delta m_{\lambda 2}$
distance dependence canceled out

$$\Delta m_{\lambda 1} - \Delta m_{\lambda 2} = \Delta(A_{\lambda 1} - A_{\lambda 2})$$

If $A_{\lambda2} = 0$, e.g., a nearby star with negligible extinction

$$E_{\lambda1-\lambda2} = (m_{\lambda1} - m_{\lambda2}) - (m_{\lambda1} - m_{\lambda2})_0$$

E.g., λ1=4350 Å (B band) , λ2=5550 Å (V band)

$\mathbf{E_{B\text{-}V}}$ **[color excess] = [measured color] – [observed color]**

Always shorter minus longer, e.g., E(B-V), E(I-K), E(U-B)

$$E_{B\text{-}V} = (B\text{-}V) - (B\text{-}V)_0 = A_B - A_V$$

IS reddening

Observed SED

Intrinsic SED

Total Extinction Quantified by A_V (at 5550 Å)

Ratio of total-to-selective extinction

$$\boxed{R = \frac{A_{\mathrm{V}}}{E_{\mathrm{B-V}}}}$$

A generally accepted value **<R> ~ 3.1 +/– 0.1**,
i.e., A_V= 3.1 E(B-V)

$$N_H/E(B\text{-}V) = 5.8 \times 10^{21} \text{ H atoms cm}^{-2} \text{ mag}^{-1}$$

A_V can be estimated by observing stars

The estimate is not reliable toward any particular direction or object, because of clouds are patchy.

In dark molecular clouds, R can be large ~5-7
large R value ~ large average size of dust grains

Whitford (1958) AJ, 63, 201 → Distant stars appear redder than nearby stars of the same spectral type.

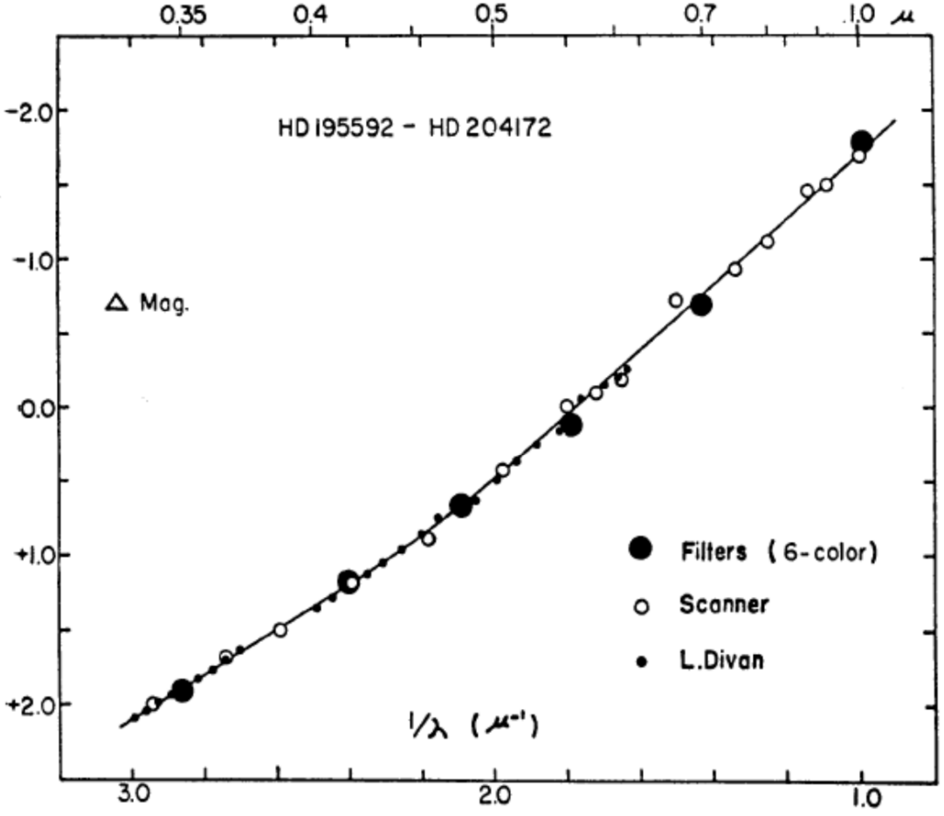
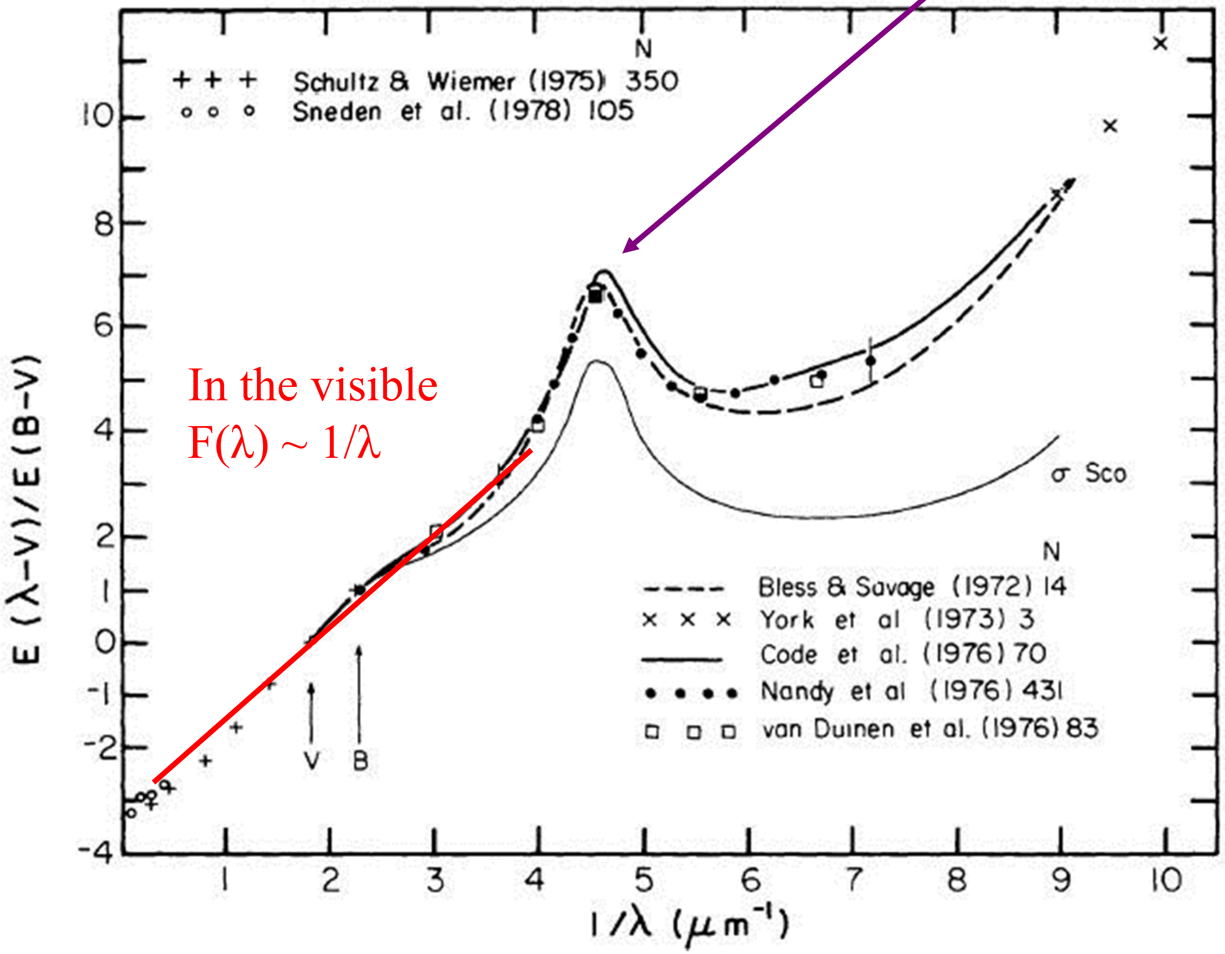


Figure 1. Monochromatic magnitude differences between a reddened and a normal star, as observed by three methods.

The ‘normalized’ extinction (extinction law)

$$F(\lambda) = \frac{A_\lambda - A_V}{A_B - A_V} = \frac{E_{\lambda-V}}{E_{B-V}}$$

The UV ‘bump’
1/λ~4.6 μm →
λ~2200Å

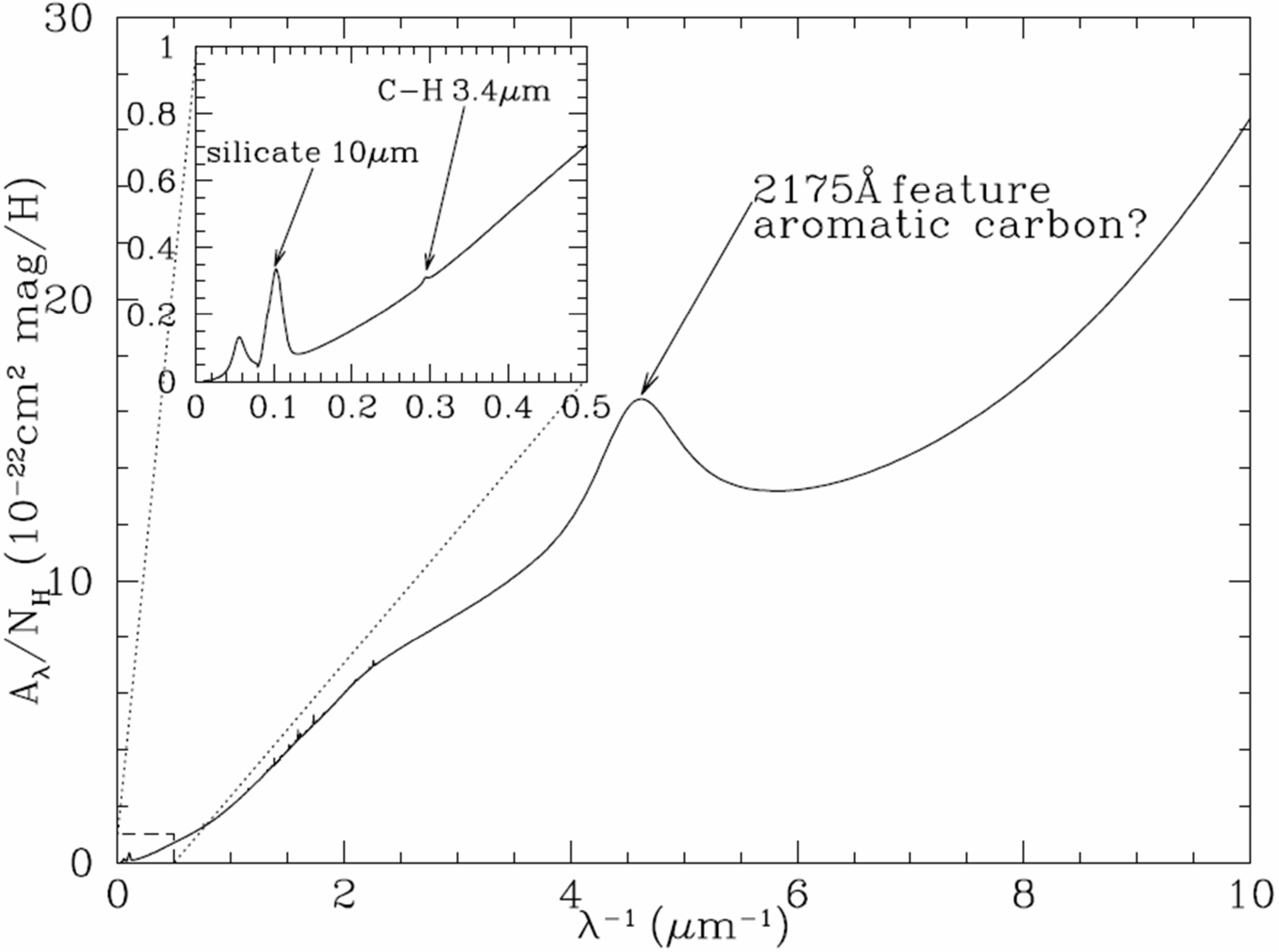


In the visible
F(λ) ~ 1/λ

$F(V) = 0$

$F(B) = +1$

Find
$A_B/A_V=?$



30
20
10
0
0
2
4
6
8
10
A_λ/N_H (10^{-22}cm^2 mag/H)
λ^{-1} (μm^{-1})
2175Å feature
aromatic carbon?
silicate 10μm
C–H 3.4μm
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5

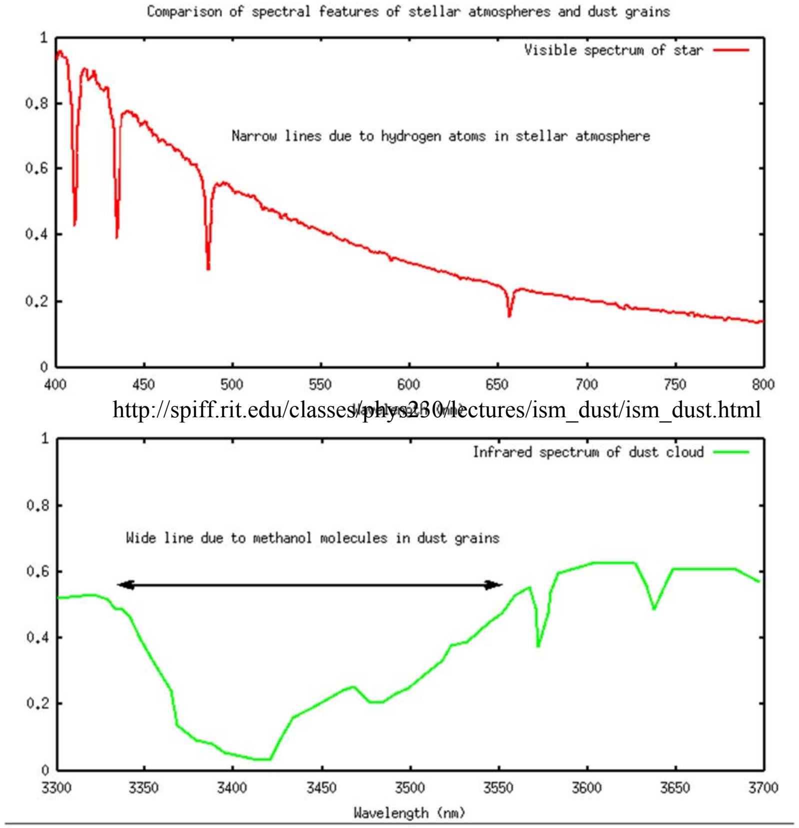
In FIR, extinction law F(λ) ~ -3

At other wavelengths,

$$\frac{A_\lambda}{A_V} = 1 + \frac{E_{B-V}}{A_V} F(\lambda)$$

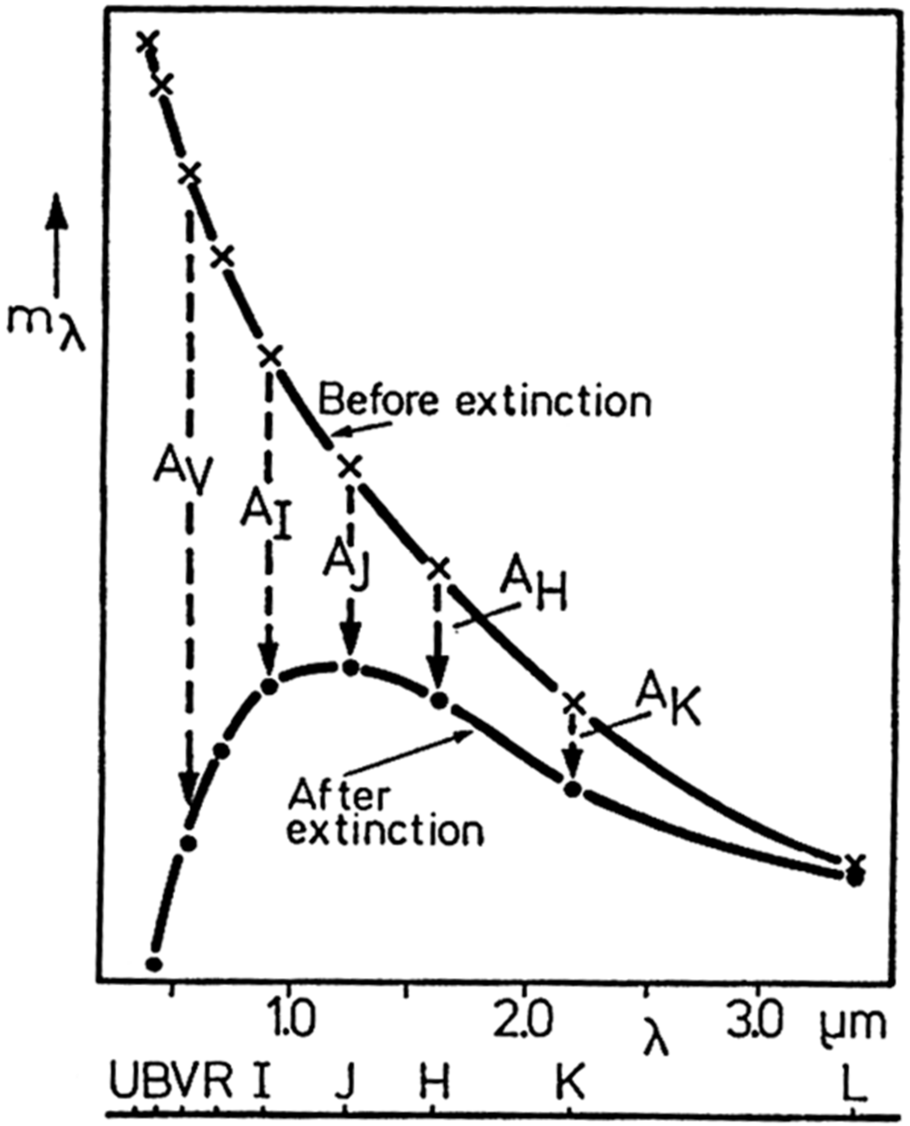
Or equivalently

$$A_\lambda = 1 - \frac{E_{V-\lambda}}{E_{B-V}} \frac{1}{R}$$



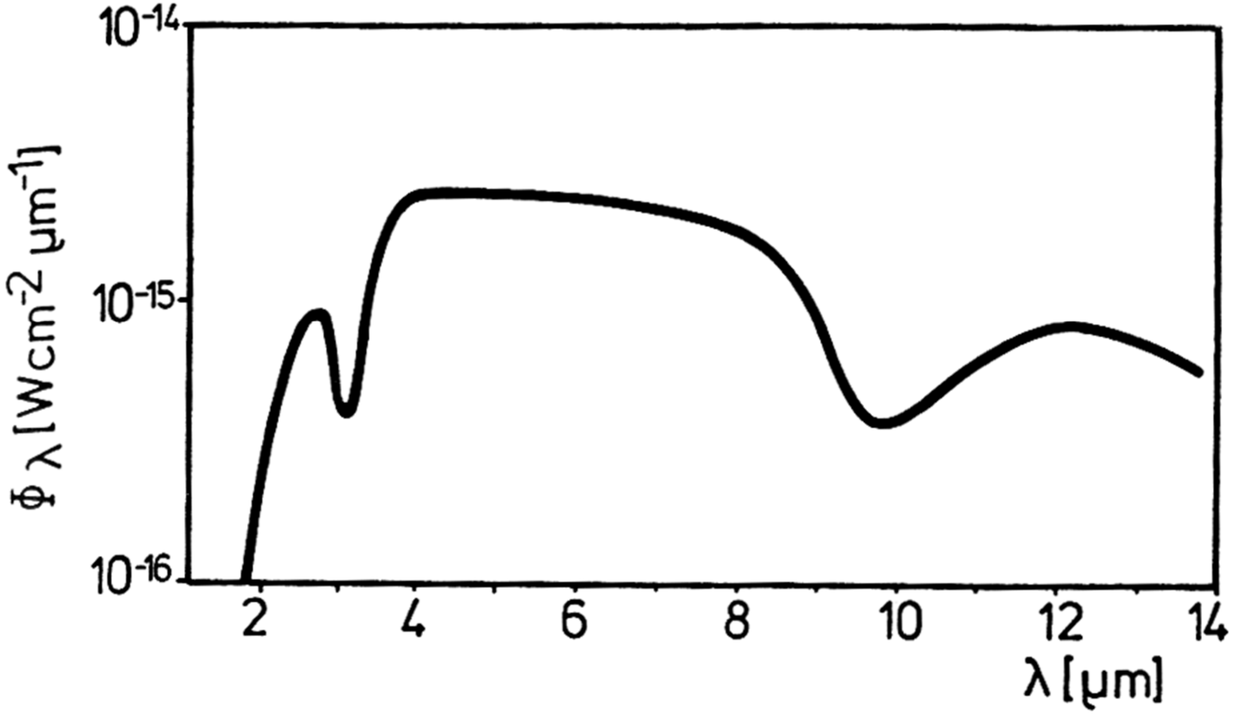
http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html

Filter	A_λ/A_V
U	1.531
B	1.324
V	1.000
R	0.748
I	0.482
J	0.282
H	0.175
K	0.112
L	0.058
M	0.023
N	0.052



Stellar atmosphere → absorption lines

ISM dust → extinction profile with no strongly marked lines or bands, except a few weak bands at 3.1 µm (H_2O ice) and 9.7 µm (silicates)



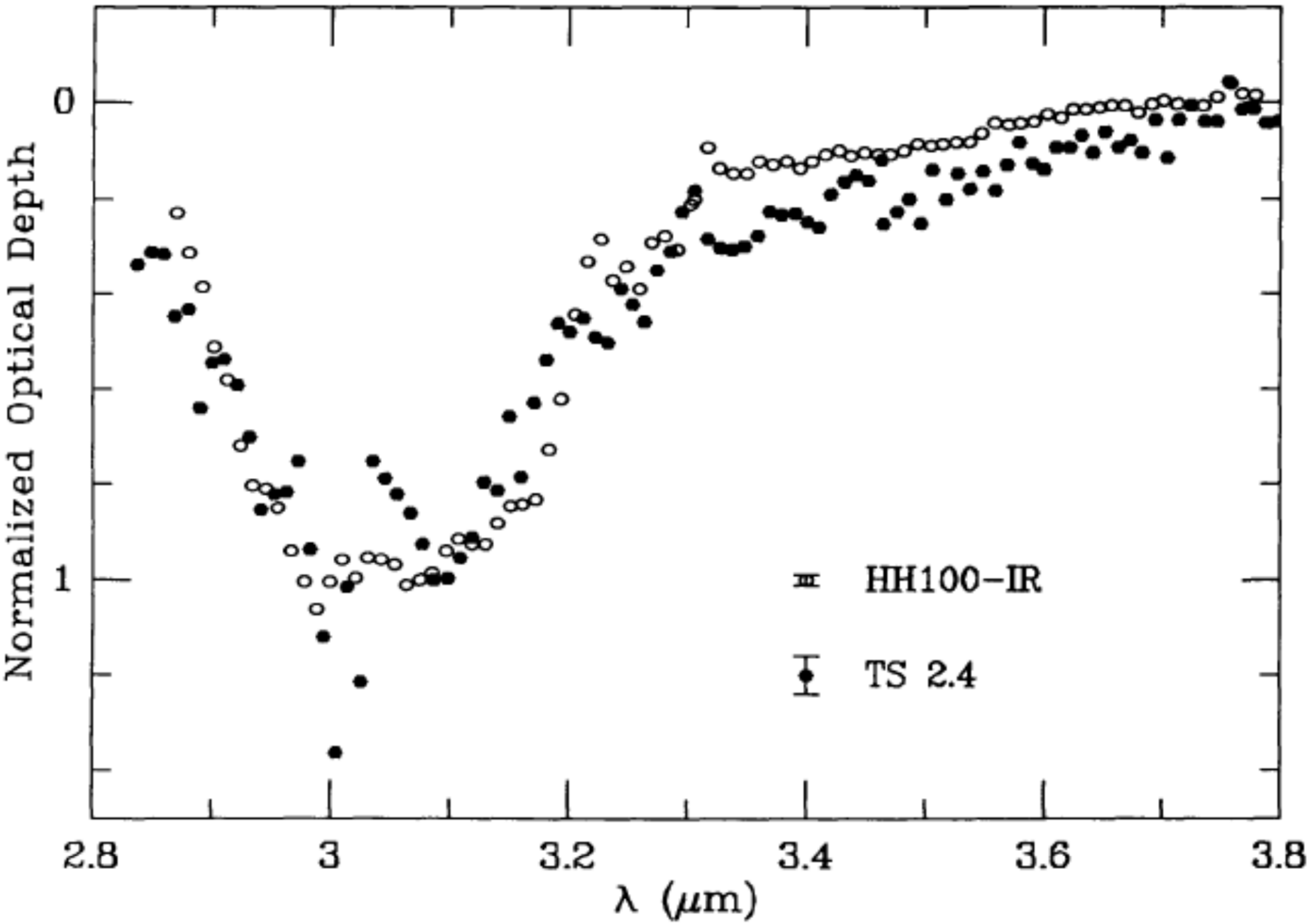
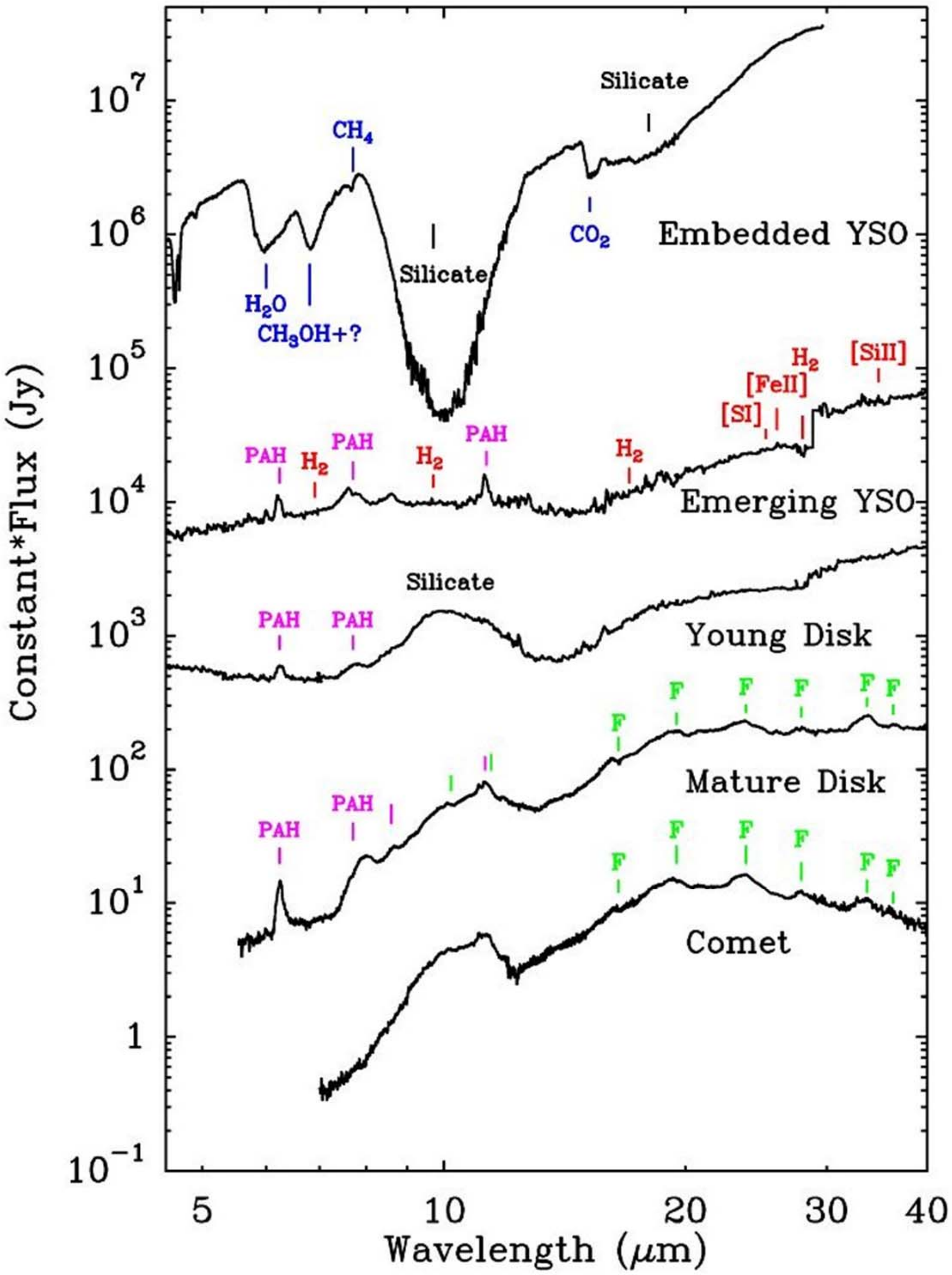


FIG. 2.—Optical depth (τ_λ) profiles of TS 2.4 and HH 100−IR, each rescaled to roughly align at 3.1 μm. The 3 σ error is marked for each profile, which is computed by the difference from a running-averaged curve at the long-wavelength end.

Chen & Graham 1993, ApJ, 409, 319



http://www.astron.nl/miri-ngst/old/public/science/phase-a/phase-a-images/mario_fig.jpg

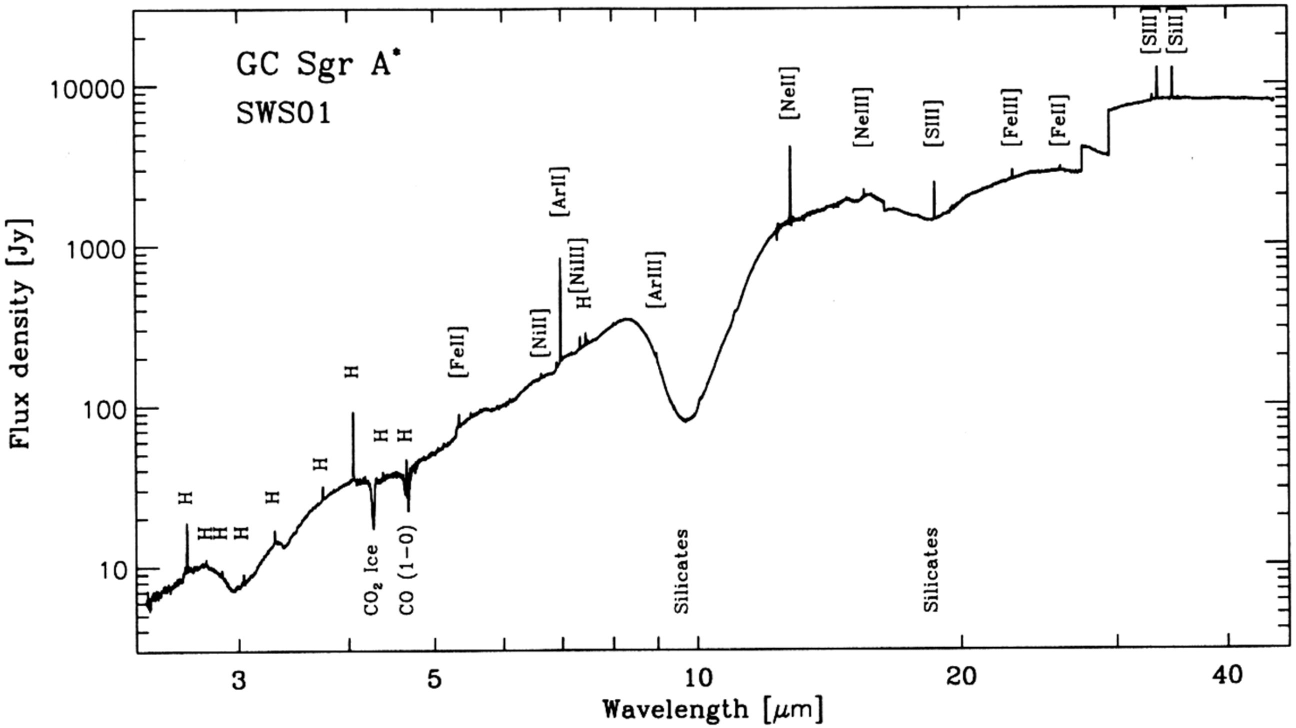


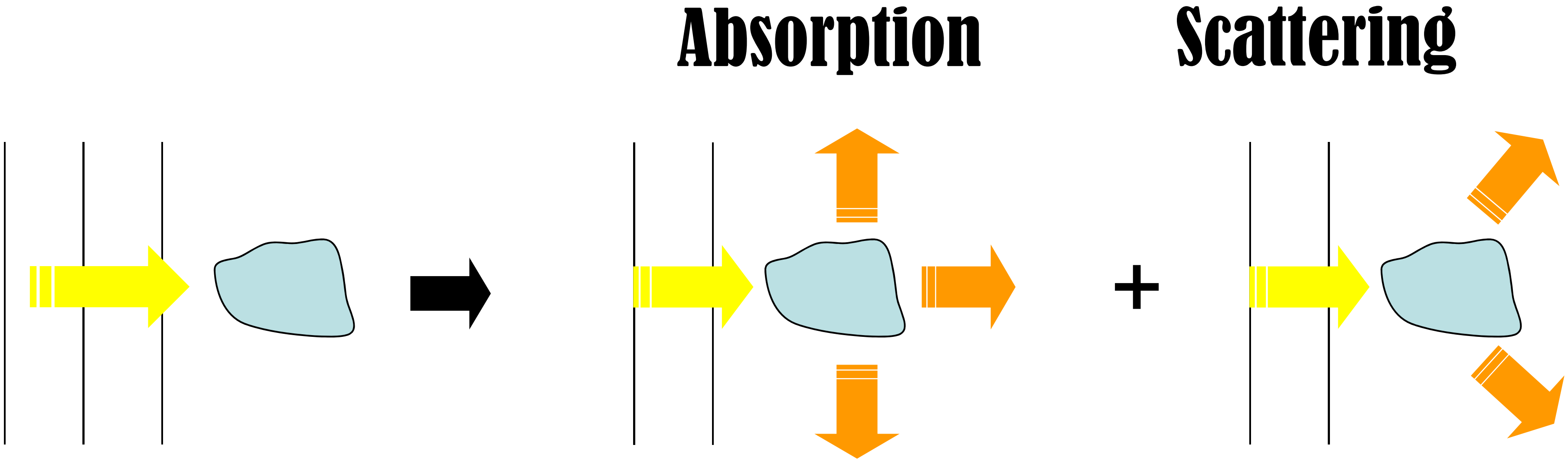
Figure 4.3. The infrared spectrum of the Galactic centre, taken over a wavelength range 2.4–45 μm by the Short Wavelength Spectrometer on the Infrared Space Observatory (ISO). In addition to various emission lines from the hotter regions along this line of sight, there are strong absorptions due to material in the dust grains near 3 μm (H_2O ice), 9.7 μm and 18 μm (silicates). Some weaker features are formed, including those at 3.4 μm (hydrocarbons) and 4.3 μm (solid carbon dioxide). (Courtesy D Lutz *et al* 1996.)

$$E_{B-V} = A_B - A_V = 1.086(\tau_B - \tau_V) = 1.086\pi a^2 n_d \ell (Q_B - Q_V)$$

So it all amounts to discussion of Qs (efficiency)

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

Scattering by spherical particles (the simplest case)
→ Mie scattering



Cross-Linked Hetero Aromatic Polymers in Interstellar Dust

by N.C. Wickramasinghea, D.T. Wickramasingheb and F. Hoylea
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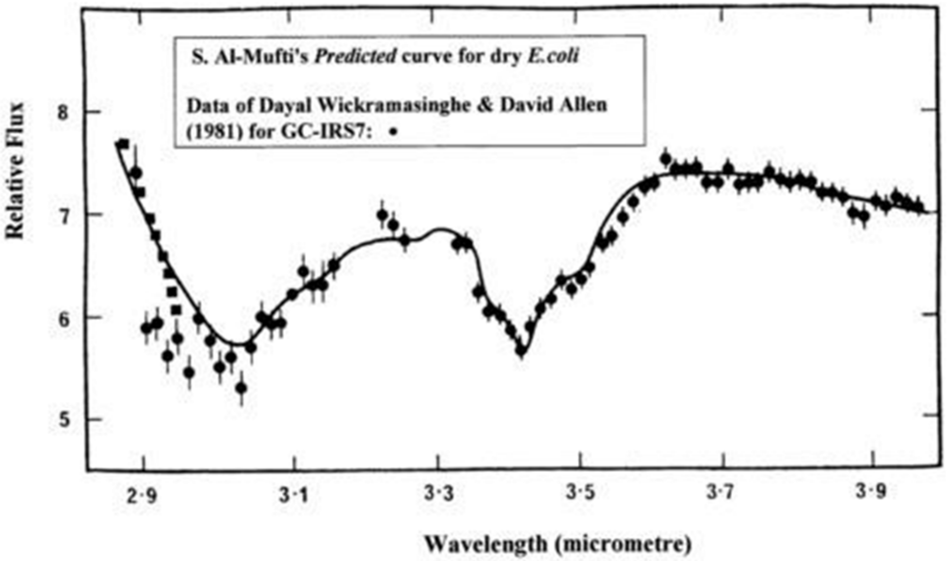
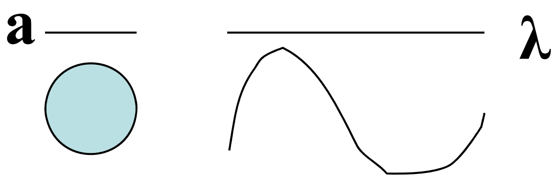
Canberra, ACT2600, Australia

Abstract: *The discovery of cross-linked hetero-aromatic polymers in interstellar dust by instruments aboard the Stardust spacecraft would confirm the validity of the biological grain model that was suggested from spectroscopic studies over 20 years ago. Such structures could represent fragments of cell walls that survive 30km/s impacts onto detector surfaces.* Astrophysics and Space Science, 2000



Scattering ….



Size of particles ≈ a

1. **$2\pi a \ll \lambda$ (radio) $\Rightarrow$ scattering $\leftrightarrow \lambda$**

   $I_{\text{scattering}} \propto \lambda^{-4}$ (Rayleigh scattering)

   ∴ **Blue** sky

2. **$2\pi a \gg \lambda$ $\Rightarrow$ scattering $\neq \lambda$**

   ∴ **Gray** sky in a cloudy day!

3. **$2\pi a \approx \lambda$ (dust, optical) $\Rightarrow$ $I_{\text{scattering}} \propto \lambda^{-1}$**

   $\Rightarrow$ Interstellar reddening (紅化)

Small particles **Large**

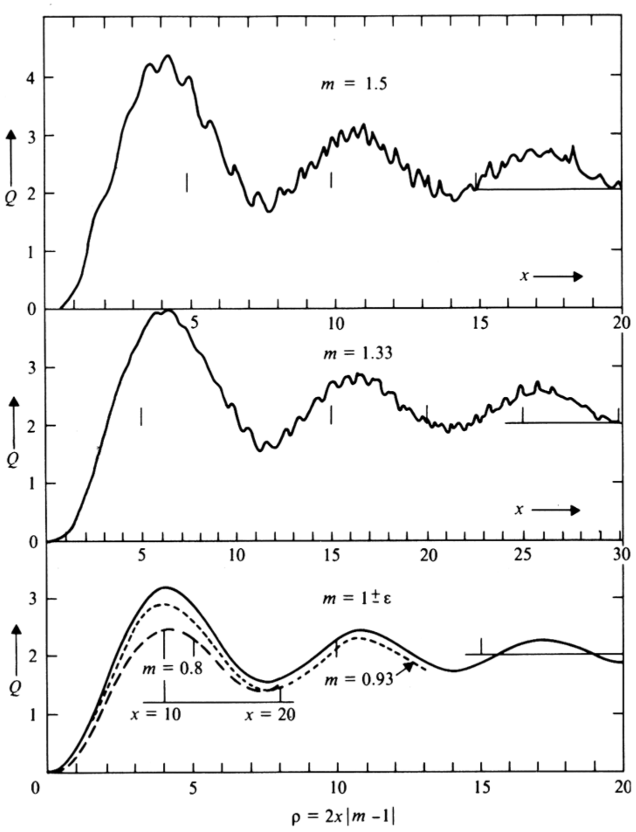


Figure 4.5. Extinction curves for spheres computed from Mie's formula for $m = 1.5$, 1.33, 0.93 and 0.8. The scales of x have been chosen in such a manner that the scale of $\rho = 2x|m-1|$ is common to these four curves and to the extinction curve for $m = 1+\varepsilon$. (From van de Hulst 1957.)

IR **UV**

Index of refraction

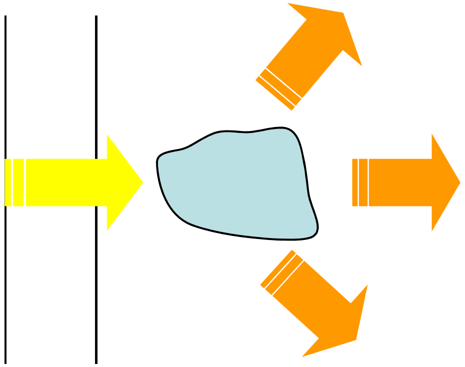
$$m = n - i\,k$$

$m = \infty$	Dielectric
$m = 1.33$	Ice
$m = 1.33 - 0.09\,i$	Dirty ice
$m = 1.27 - 1.37\,i$	Iron

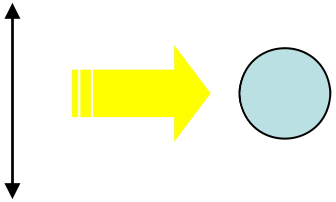
$x = 2\pi a/\lambda$ = dust size/wavelength

http://www.astro.spbu.ru/DOP/8-GLIB/ASTNOTES/node2.html

- In Earth's atmosphere, scattering
  $\sim\lambda^{-4}$ for small particles
  $\sim\lambda^{0}$ for large particles
- In ISM at visible wavelength, scattering
  $\sim\lambda^{-1}$ particle size ≒ wavelength ~ 0.5 μm
- For large particles, Q ~ 2,
  i.e., σ~ 2 times geometric cross section, because light diverges over larger extent



Rayleigh Scattering by Small Particles



Dielectric sphere, *a*,
2πa << λ

Polarization of
plane wave, λ

Sphere will oscillate with the **E** field
➔ sphere radiates like an electric dipole

Power radiated in all directions

$$P = \frac{2}{3}\frac{e^2}{c^3}|a|^2$$

where a is acceleration

$$x = x_0\, e^{-j\omega t}$$

$$a = \ddot{x} = -x_0\omega^2\, e^{-j\omega t}$$

$$P = \begin{cases} \frac{2}{3}\,\frac{e^2}{c^3}|x_0\omega^2|^2 \leftrightarrow \lambda^{-4} \\ \sigma\, S \end{cases}$$

Poynting vector $S = \frac{c}{8\pi}\,\mathbf{EB}^* = \frac{c}{4\pi}\mathbf{E^2}$

$$Q_{sca} = \sigma/\,\pi\, a^2$$

…

$$\boxed{Q_{sca} = \frac{8}{3}\,x^4\,|\frac{m^2-1}{m^2+2}|^2}$$ $\rightarrow \lambda^{-4}$

$$\boxed{Q_{abs} = -4\,x\,Im(\frac{m^2-1}{m^2+2})}$$ $\rightarrow \lambda^{-1}$

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

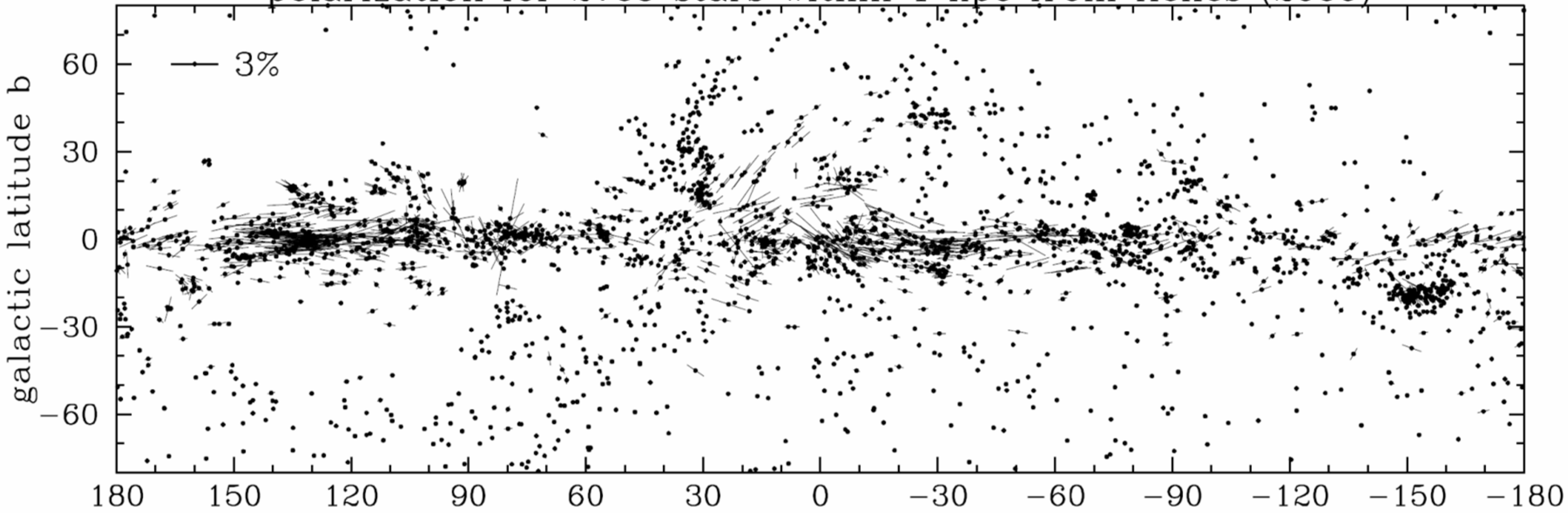
$$m = n - i\,k$$

$x=2\pi a/\lambda$ = dust size/wavelength

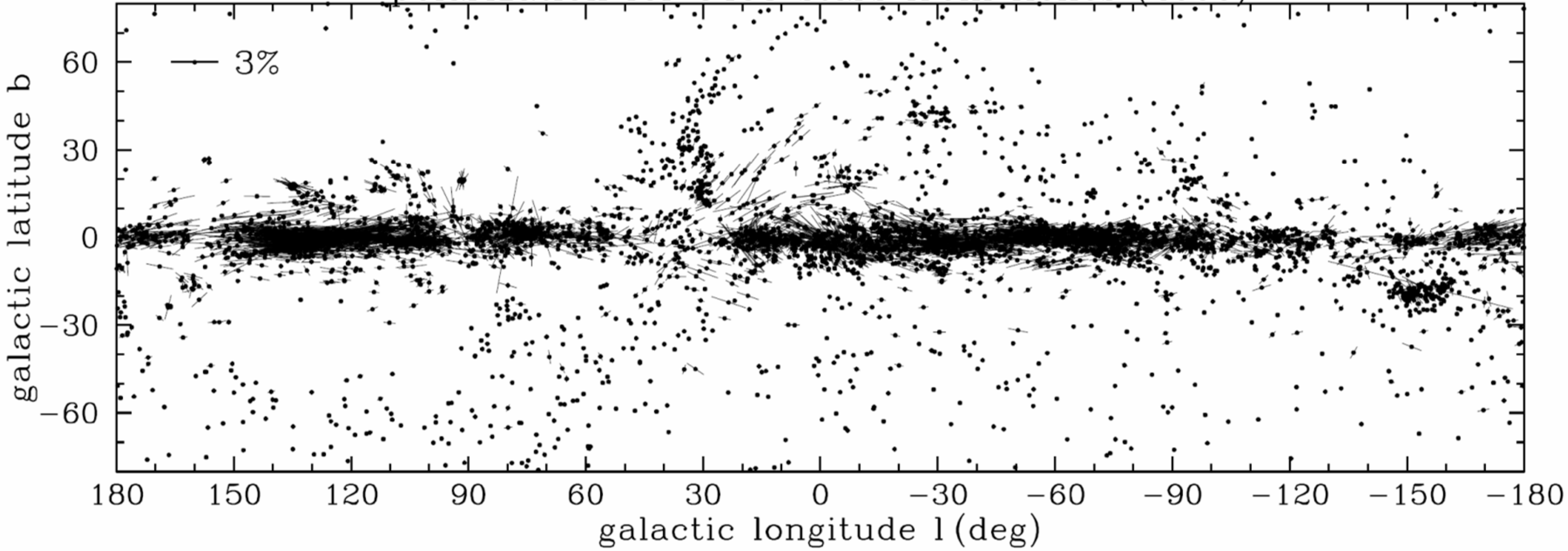
Note:

- When *m* is real, i.e., no imaginary part
  → no absorption
- With the imaginary part, most extinction at small *x* comes from absorption → Q_{ext} increases
- For pure ice, transmitted and refracted signals interfere
  → large scale oscillation
- If there is impurity (internal absorption)
  → oscillation is reduced

polarization for 2765 stars within 1 kpc from Heiles (2000)



polarization for 5453 stars from Heiles (2000)



References

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  Galactic center study
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