The Dusty Universe

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Our Milky Way Galaxy: a spiral galaxy

M 83

NGC 4565

The Stellar Disk

Radius ≈ 15 kpc (50,000 light-years)

Most stars lie within ~ 300 pc of the midplane

$\sim 10^{11}$ stars with total mass $\sim 10^{11}\, M_{\odot}$

The Sun is about 8 kpc from the Galactic Center and 15 to 30 pc above the midplane.

Striking evidence of the plane geometry of our galaxy in the night sky: the Milky Way band

1610: Galileo discovers the Milky Way is made up of stars

1750: Thomas Wright suggests a plane geometry of stars

1755: Kant elaborates and suggests that spiral nebulae are distant, rotating systems like the Milky Way

The Interstellar Medium (ISM)

Total mass ≈ 10% of that in stars

Consists primarily of gas (dominated by H)

Average H number density at Sun's distance from Galactic Center:
$n_H \approx 1 \text{ cm}^{-3}$

Regions of the ISM are categorized by the form of H: atomic, ionized, molecular

2 phases of atomic H: cool ($T \sim 100$ K, $n_H \sim 30 \text{ cm}^{-3}$) and
warm ($T \sim 6000$ K, $n_H \sim 0.3 \text{ cm}^{-3}$)

Dust accounts for ≈ 1% of the mass of the ISM

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Household dust: dead skin cells, clothing and paper fibers, pollen and other plant material, soil particles, dust mites and their feces (particle sizes < 500 μm)

Interstellar dust: Solid grains < 1 μm in size; dominated by silicate and carbonaceous materials

The ISM is much less conspicuous than stars:

extremely low density => low surface brightness

ISM emits largely in radio, infrared

But, dust absorbs strongly in the visible; is responsible for the dark patches and rifts in the Milky Way (though not understood until the early 1900s).

Dust is nearly ubiquitous in the cosmos, but is generally a trace component. In the ISM near the solar system, there's one “typical” (0.1 μm) grain per million cubic meters.

So why do we care about dust?

- It blocks the light from stars, galaxies, …
- It plays important physical roles in star formation, …
- It's a useful diagnostic tool.

William Herschel (1738—1822) thought MW rifts were regions devoid of stars, “holes in the sky”. Actually, dust absorbs the starlight.

Late 1800's and early 1900's: E.E. Barnard photographs dark nebulae and gradually comes to consider these as due to obscuring matter.

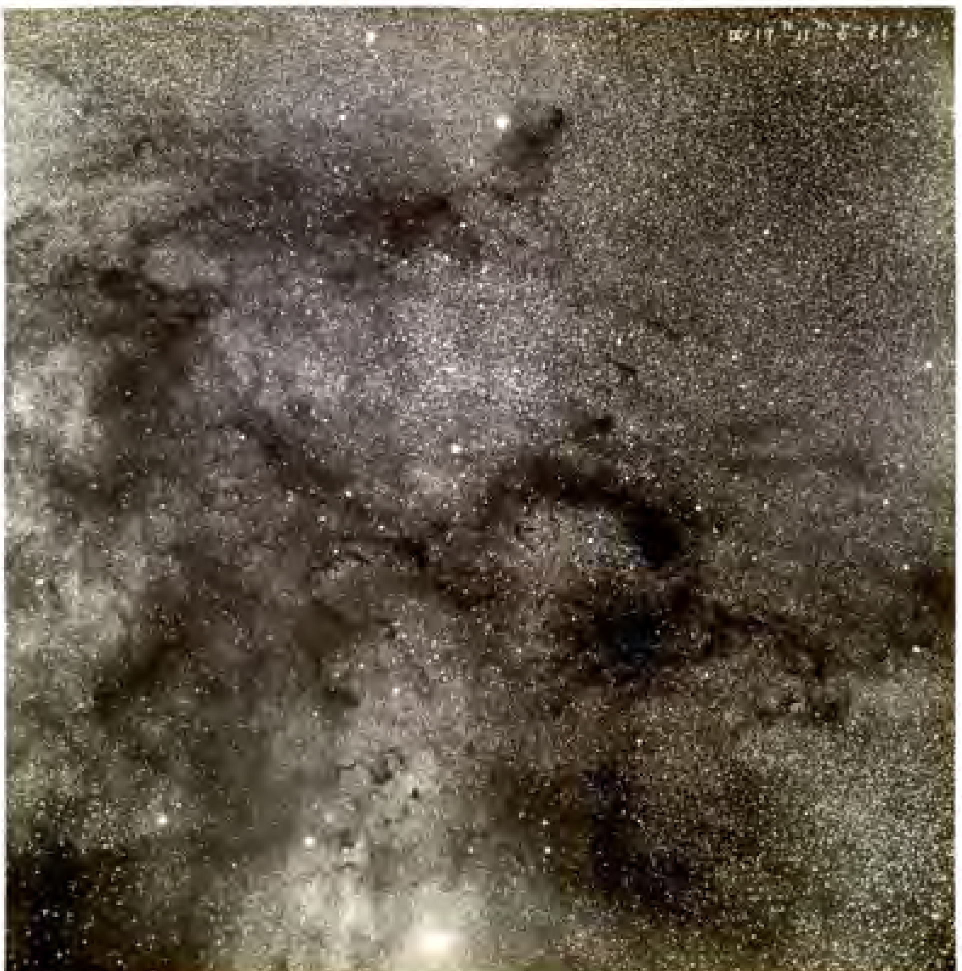


Plate 19 from Barnard's “Photographic Atlas of Selected Regions of the Milky Way” (region north of θ Oph)

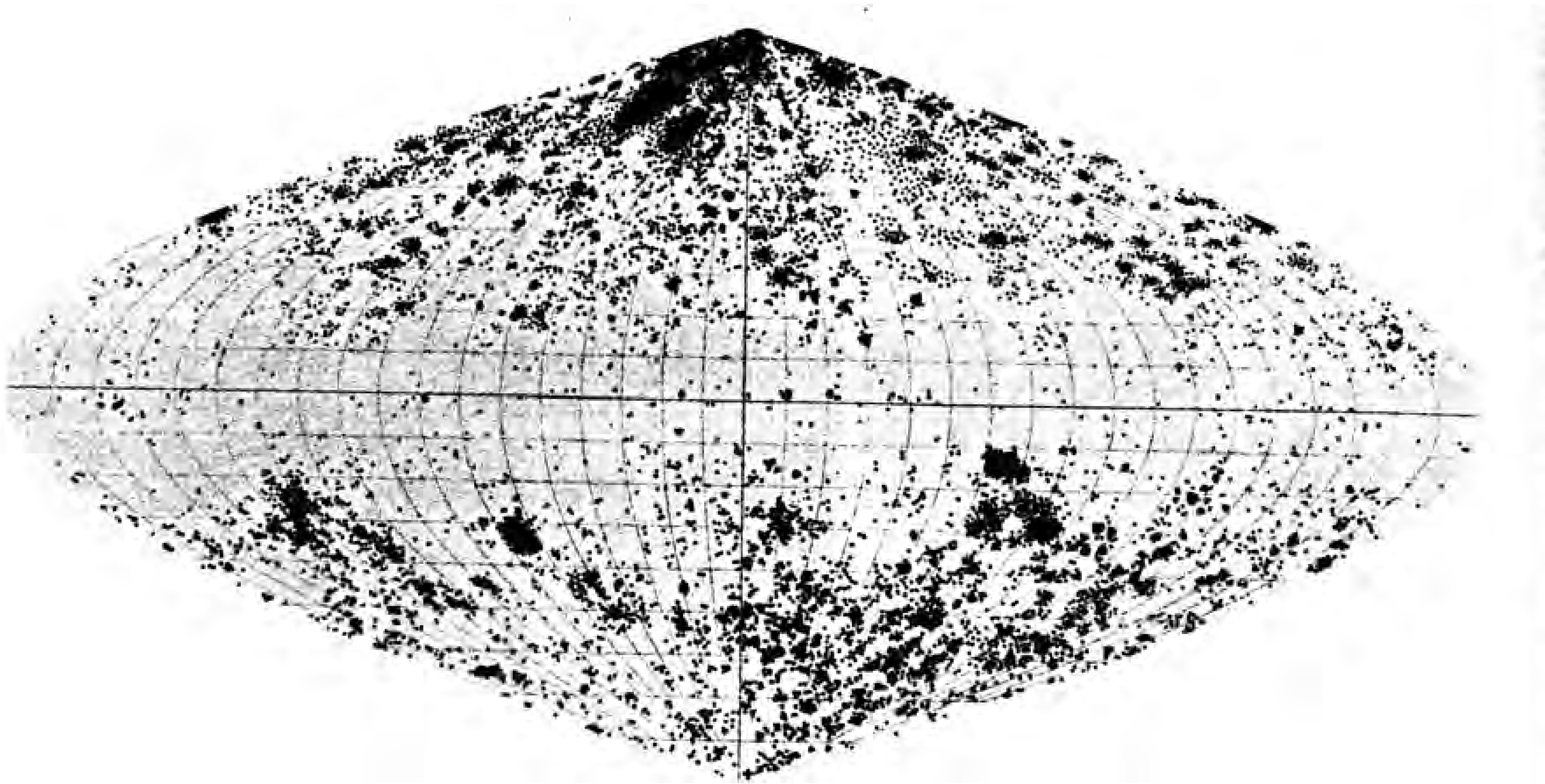
www.library.gatech.edu/barnard/

Other astronomers adopted Barnard's view around the same time, noting that holes in the sky would actually be long radial tunnels!

Heber D. Curtis (1918): Horsehead Nebula must be obscuring matter; otherwise random motions of stars would quickly obliterate sharp edges.

1914: Harold Spencer Jones suggests that dark lanes in edge-on spiral "nebulae" are due to obscuration.

1917: Curtis suggests that zone of avoidance (of globular clusters and spiral nebulae) is due to obscuring material in Galactic Plane. Also that spiral nebulae are other galaxies (hence dark lanes).

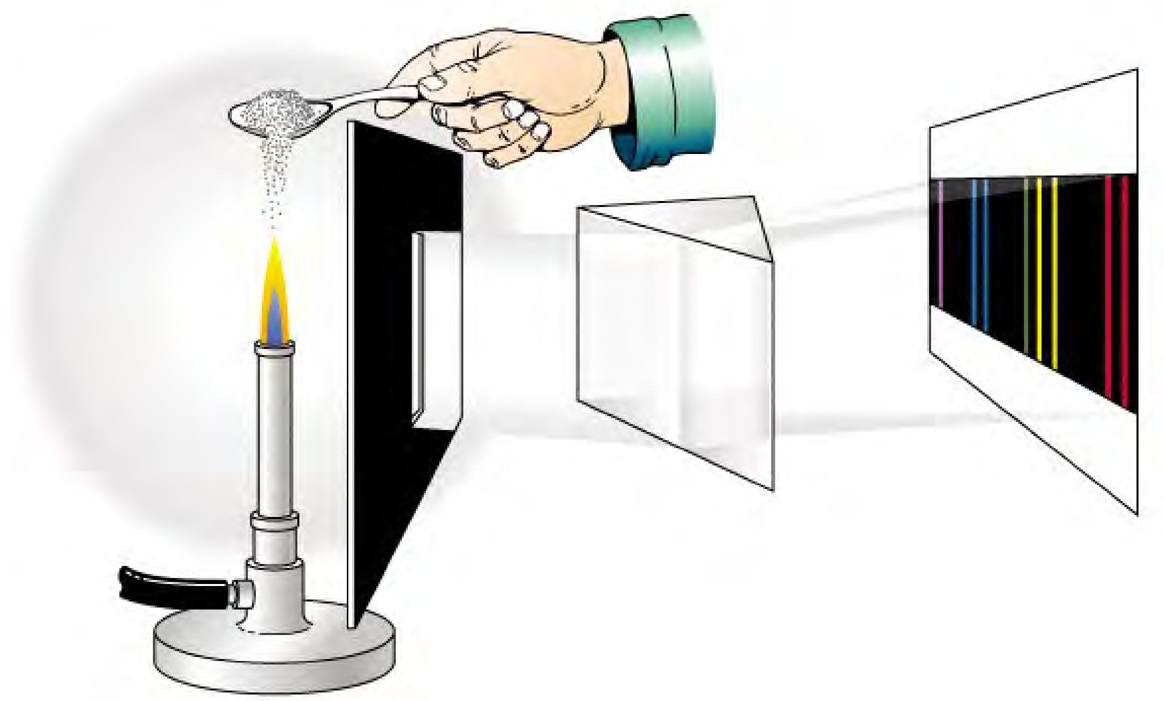


1930: R.J. Trumpler unambiguously demonstrated the existence of a distributed, attenuating interstellar medium. He used two different methods of measuring distances to open clusters.

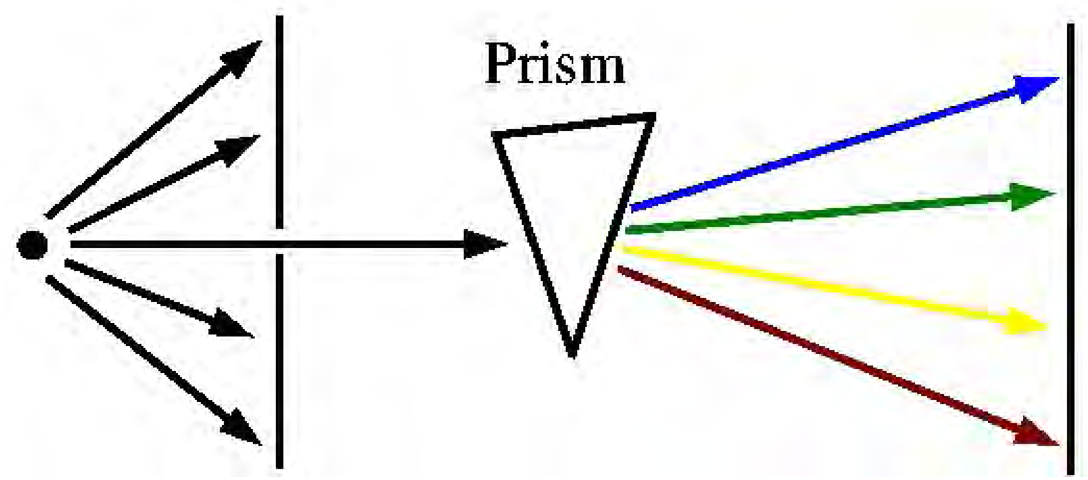
NGC 3293

Interlude on Stellar Spectra

a simple spectrometer:

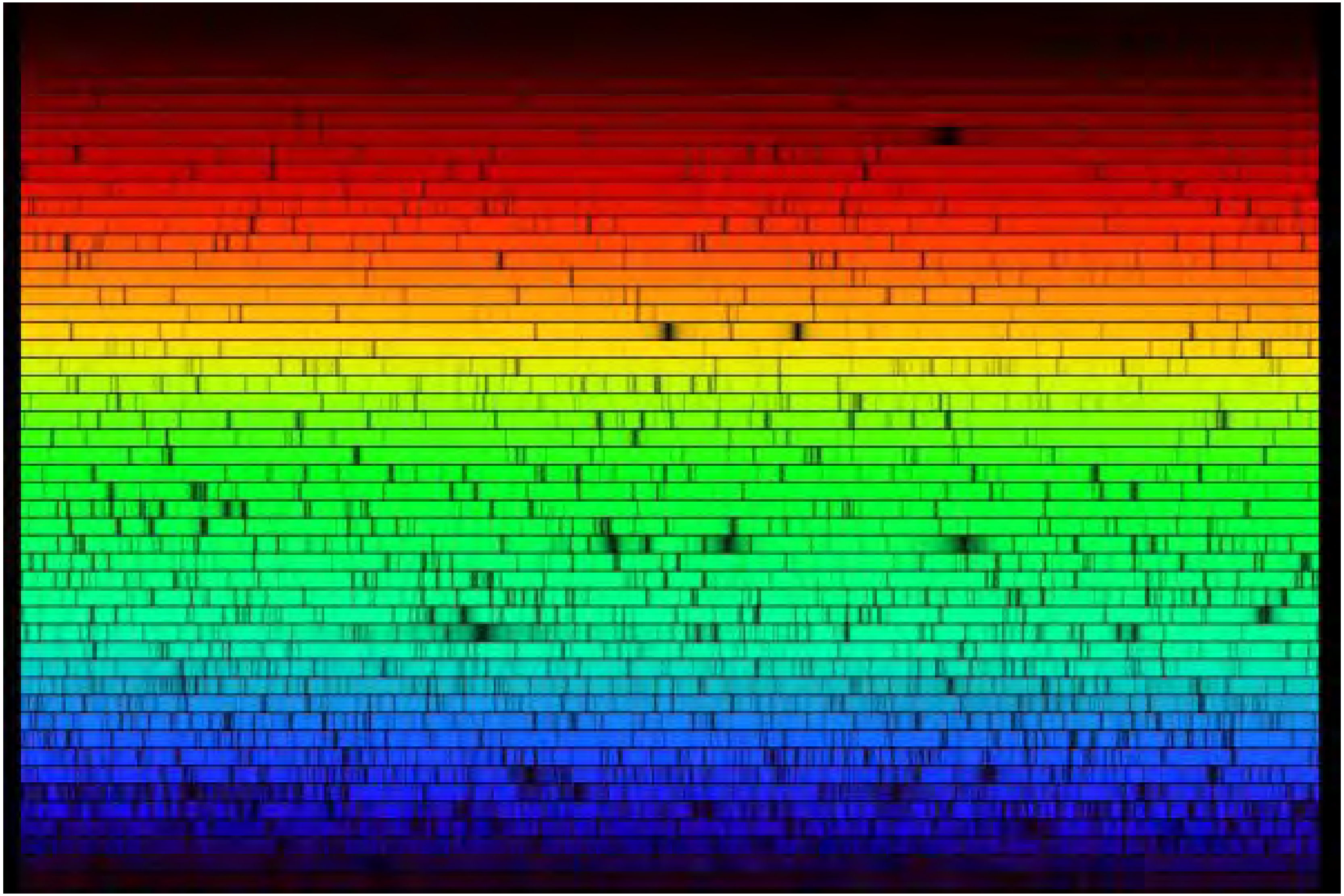


top view:



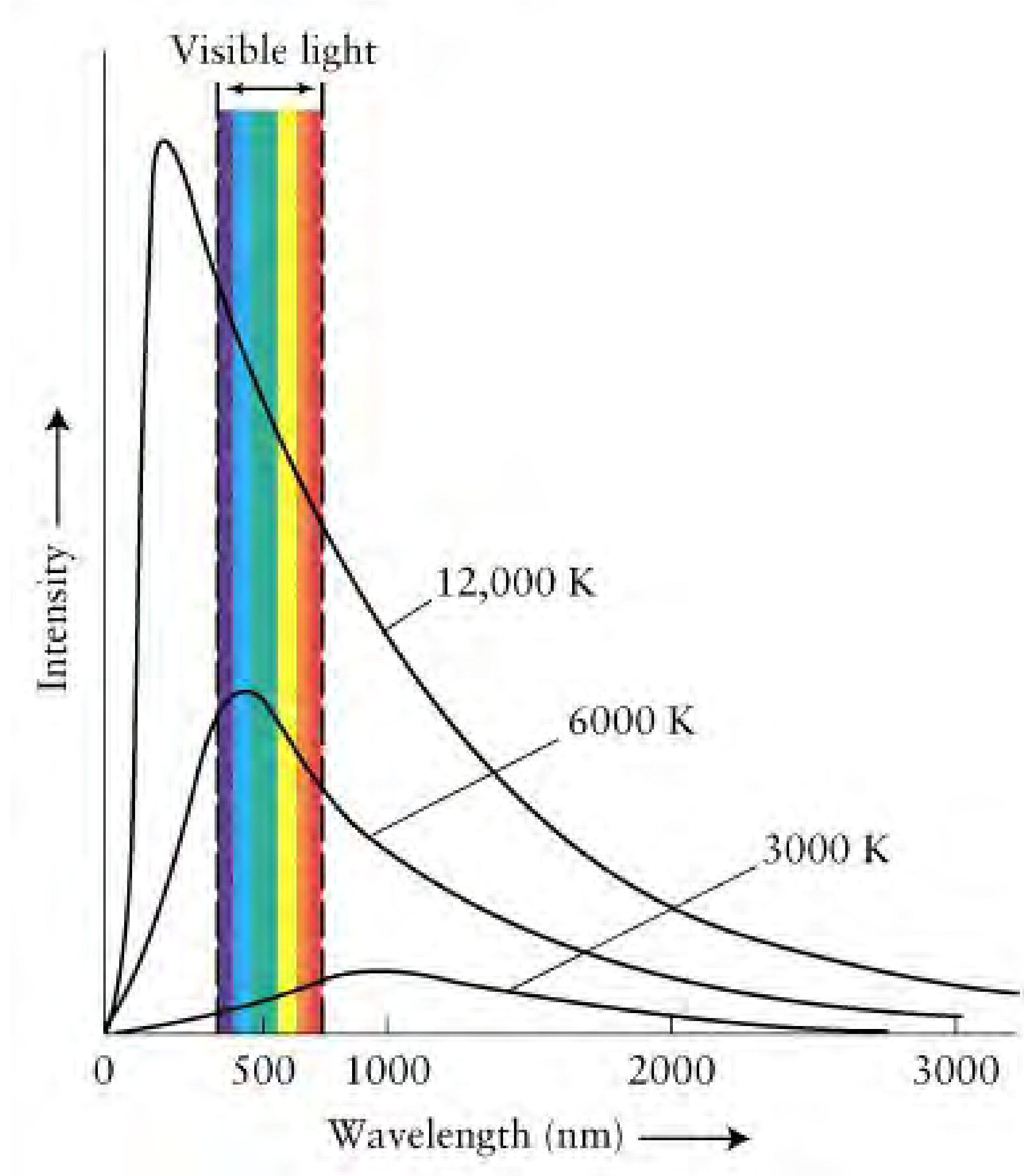
Stellar spectra are continuous with absorption lines.

The Sun's spectrum:



Continuous spectrum is approximately that of a blackbody (an object that absorbs all of the light incident on it).

For a blackbody, the intensity at all wavelengths, λ, depends only on the temperature of the blackbody.



Wien's Law:

$$\lambda_{max} = 0.29 \text{ cm} / T$$

Stefan-Boltzmann Law:

$$F = \sigma T^4$$

Absorption lines are due to atoms in the star's atmosphere.

Detailed analysis of the absorption lines yields info on composition, temperature, and luminosity of star—spectral type (and luminosity class).

Temperature derived from lines agrees with that from Wien's Law.

Now back to Trumpler's 2 methods for measuring the distance to an open cluster...

Method 1:

- Determine the spectral types / luminosity classes of stars in the cluster.
- This yields their luminosities, L (absolute magnitudes).
- Measure the fluxes, F, from the stars (apparent magnitudes).
- Comparison yields the distance, d: $F = L / 4\pi d^2$

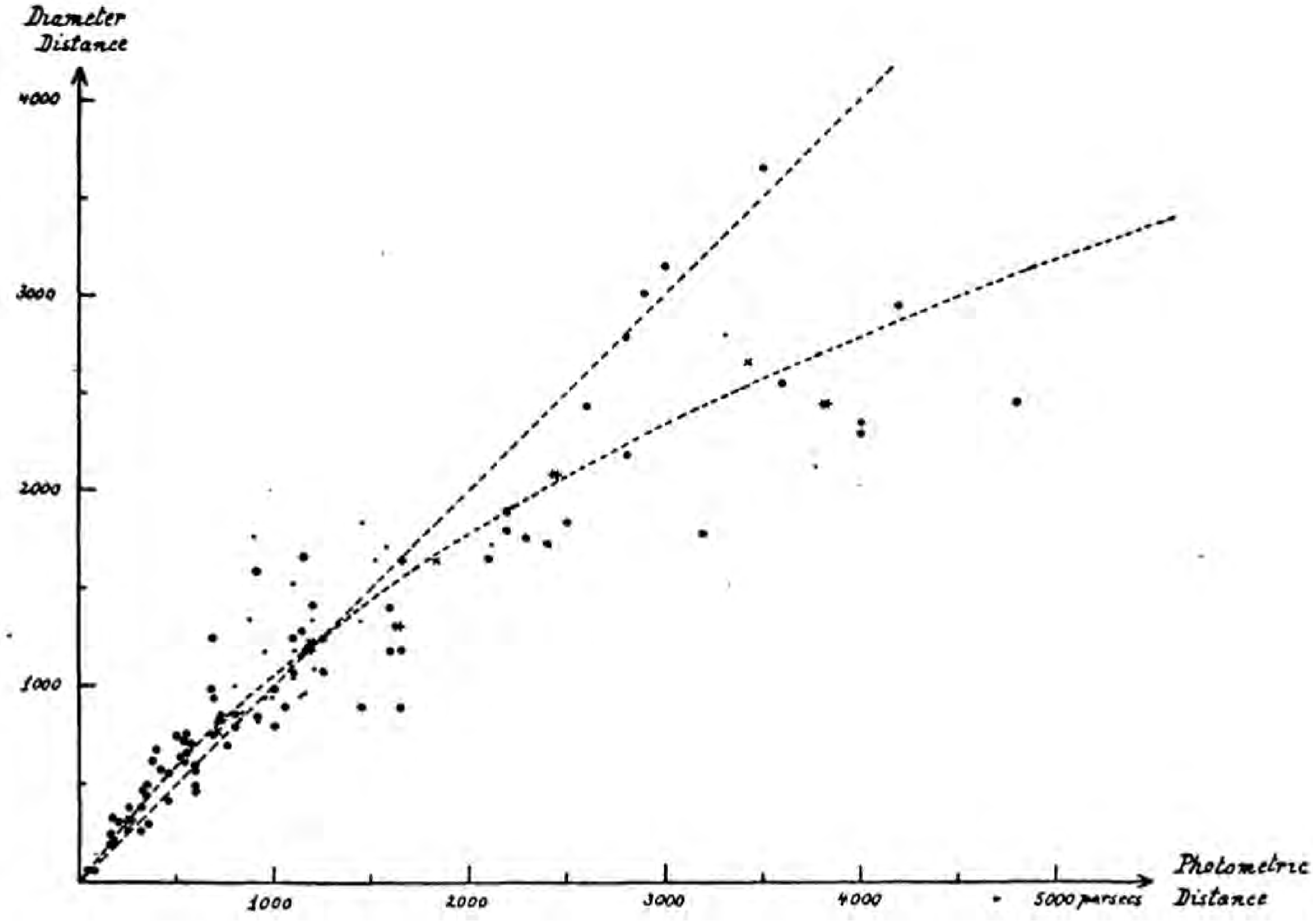
Method 2:

- Assume that cluster diameter is independent of distance, with a large scatter about a mean value, D.
- Measure the angular diameter of the cluster.
- Distance is determined geometrically: $\theta = D / d$

Plot the 2 independently determined cluster distances against one another.

Result should be a straight line with large scatter (though the slope may differ from 1, if D is mis-estimated).

Trumpler's result: not a straight line!



The farther the cluster, the greater the discrepancy between methods, with the luminosity distance exceeding the diameter distance.

=> flux drops off faster than expected from the $1/r^2$ law

=> attenuating material ($\approx$ 1 mag per kpc)

How do we know that the attenuation is due to dust (i.e., sub-μm grains)?

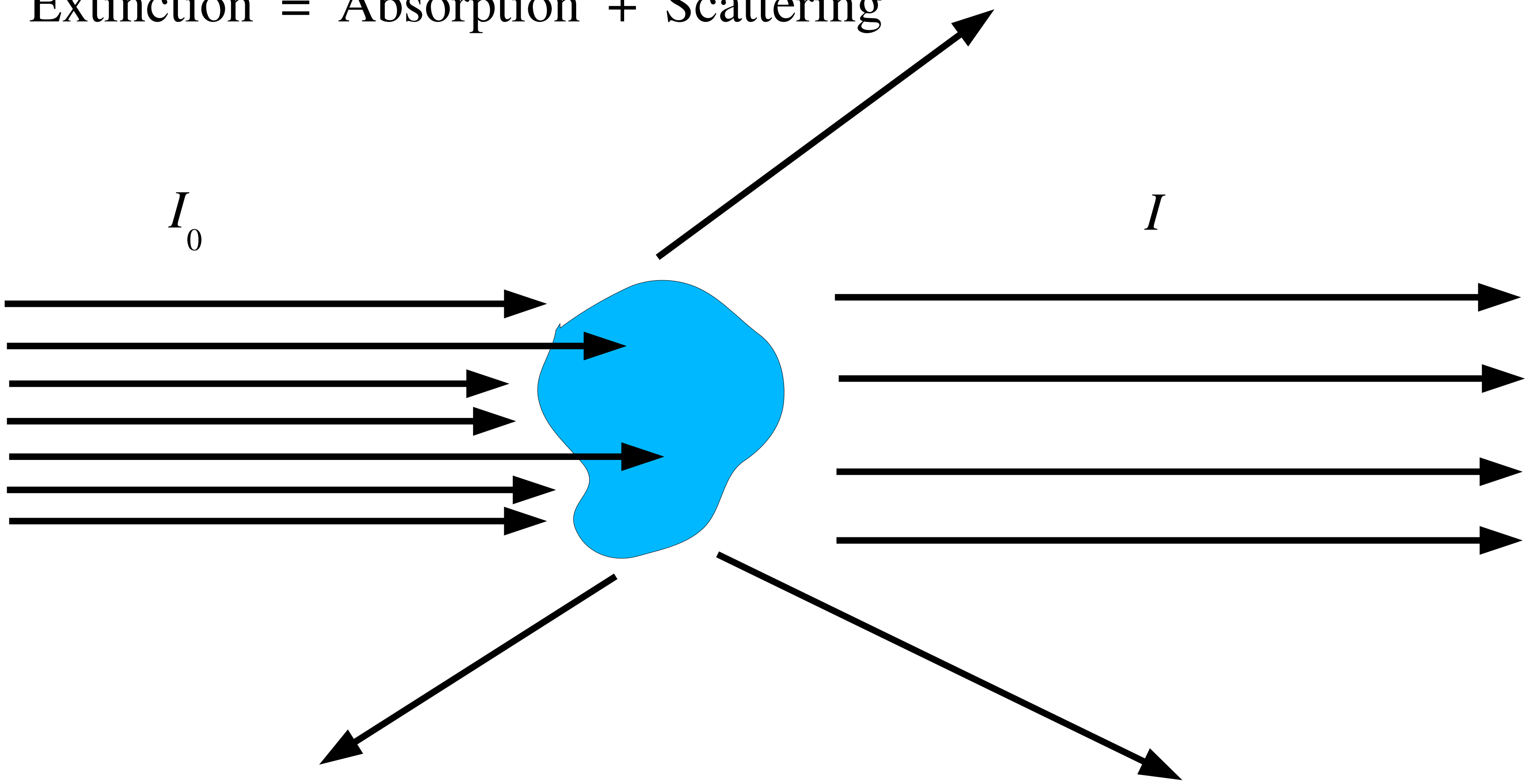
By looking at how the attenuation depends on wavelength, λ

Compare the spectra of 2 identical stars: one attenuated, the other not.

(the continuous spectrum of an unattenuated star is consistent with its spectral type)

Attenuation of radiation by dust is called extinction.

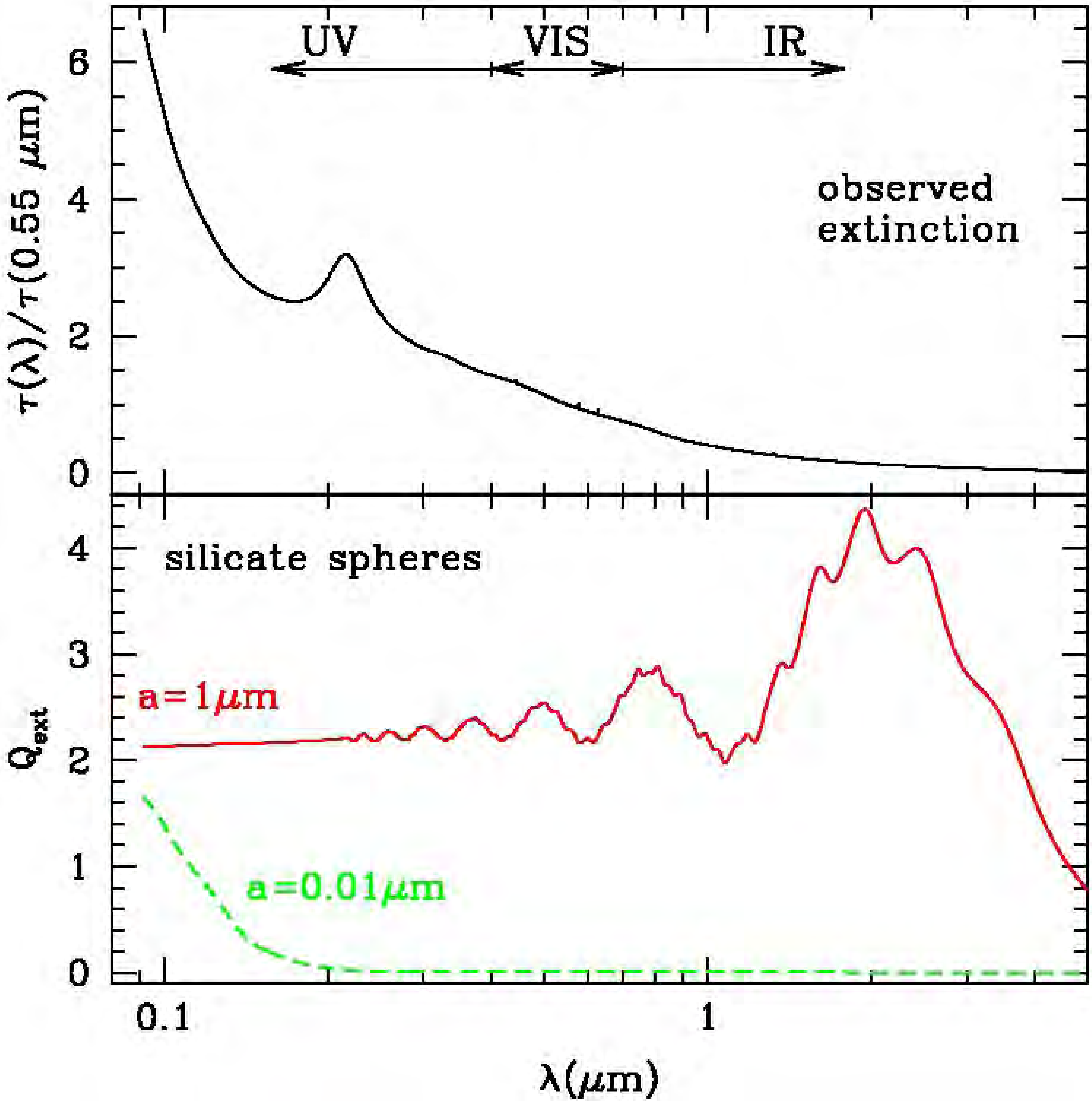
Extinction = Absorption + Scattering



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

$$\tau = \pi a^2 Q_{ext} N$$

Q_{ext} depends on wavelength and grain size and composition; extinction mostly yields info on grain size.



UV
VIS
IR
observed
extinction
τ(λ)/τ(0.55 μm)
6
4
2
0
silicate spheres
a=1μm
a=0.01μm
Q_ext
4
3
2
1
0
0.1
1
λ(μm)

Analysis of the entire extinction curve => grains as large as ≈ 0.3 μm

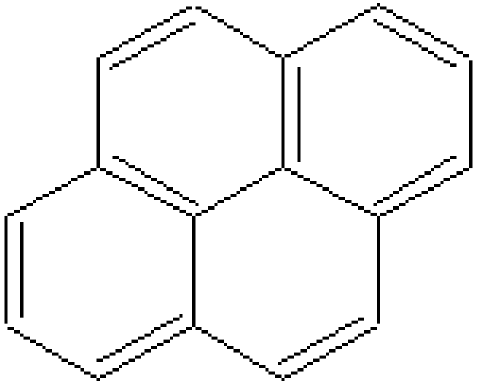
Reflection nebulae => efficient scattering at visible wavelengths; requires grains with $a \approx 0.1$ μm

Witch Head Nebula (reflection of light from Rigel, located to the right)

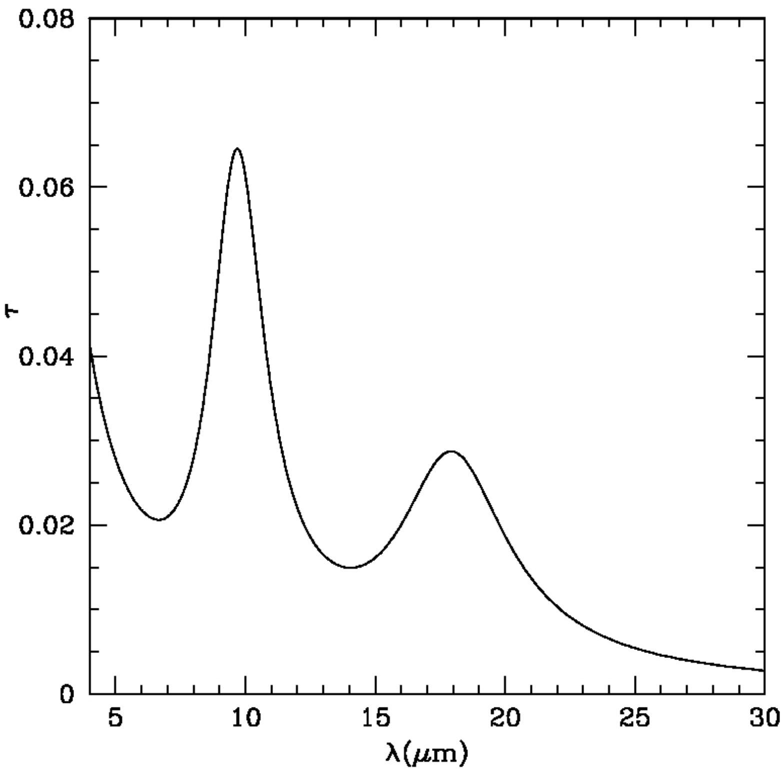
Pleiades (a young star cluster wandered close to a dusty cloud)

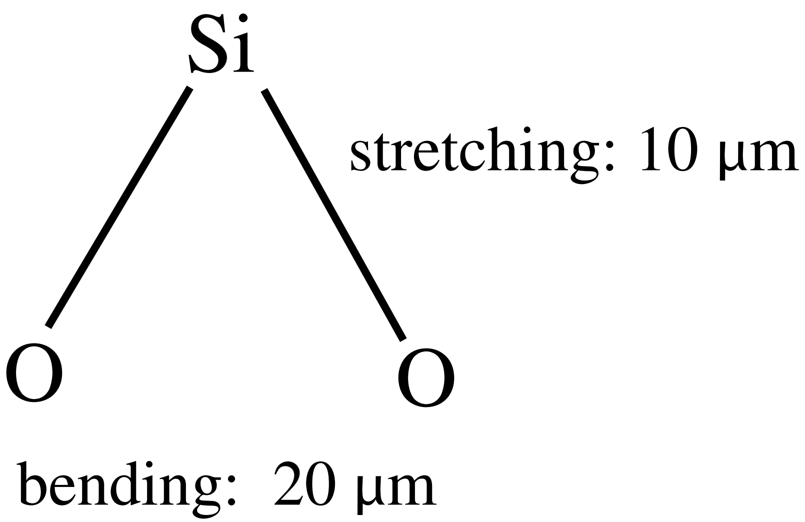
Dust Spectroscopy

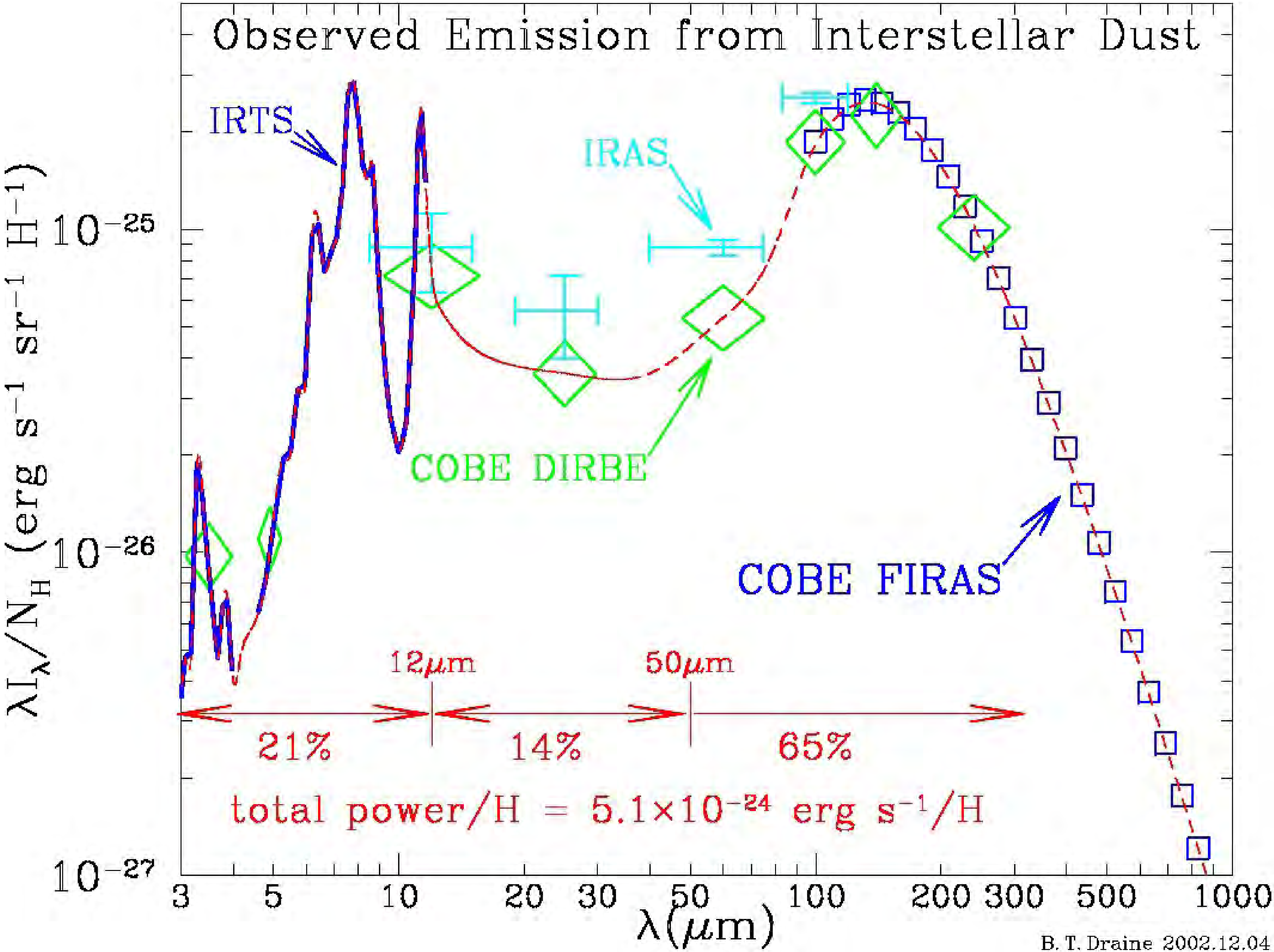
0.22 μm feature: probably due to aromatic carbon (graphite or polycyclic aromatic hydrocarbon—PAH)



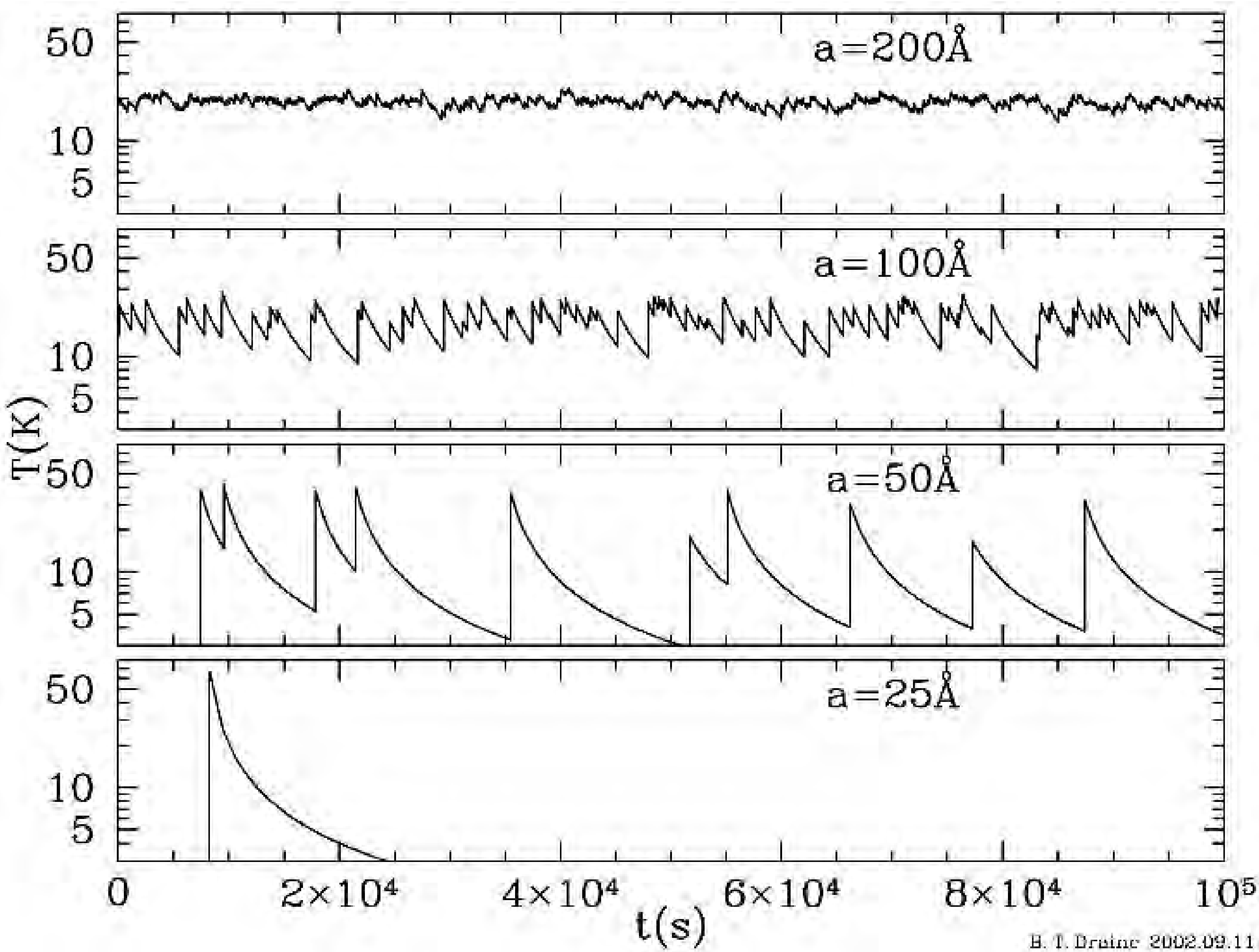
10 and 20 μm features: silicates






Observed Emission from Interstellar Dust
IRTS
IRAS
COBE DIRBE
COBE FIRAS
$\lambda I_\lambda / N_H$ (erg s^{-1} sr^{-1} H^{-1})
10^{-25}
10^{-26}
10^{-27}
12μm
50μm
21%
14%
65%
total power/H = 5.1×10^{-24} erg s^{-1}/H
3
5
10
20
30
50
100
200
300
500
1000
λ(μm)
B. T. Draine 2002.12.04

A day in the life of 4 carbonaceous grains



Interstellar grains in meteorites

identified by anomalous isotopic ratios; not representative!

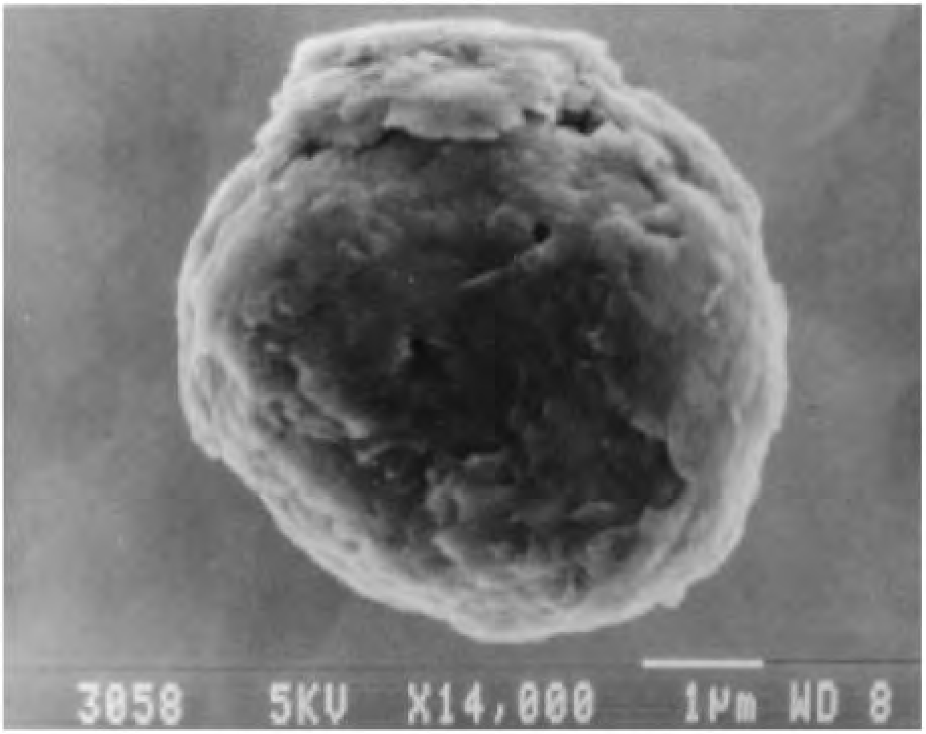
0.001 μm diamonds
0.5—10 μm graphite
0.2—10 μm SiC
0.3—1.5 μm Al_2O_3 (corundum)
0.5 μm Si_3N_4

Grains flowing through the solar system

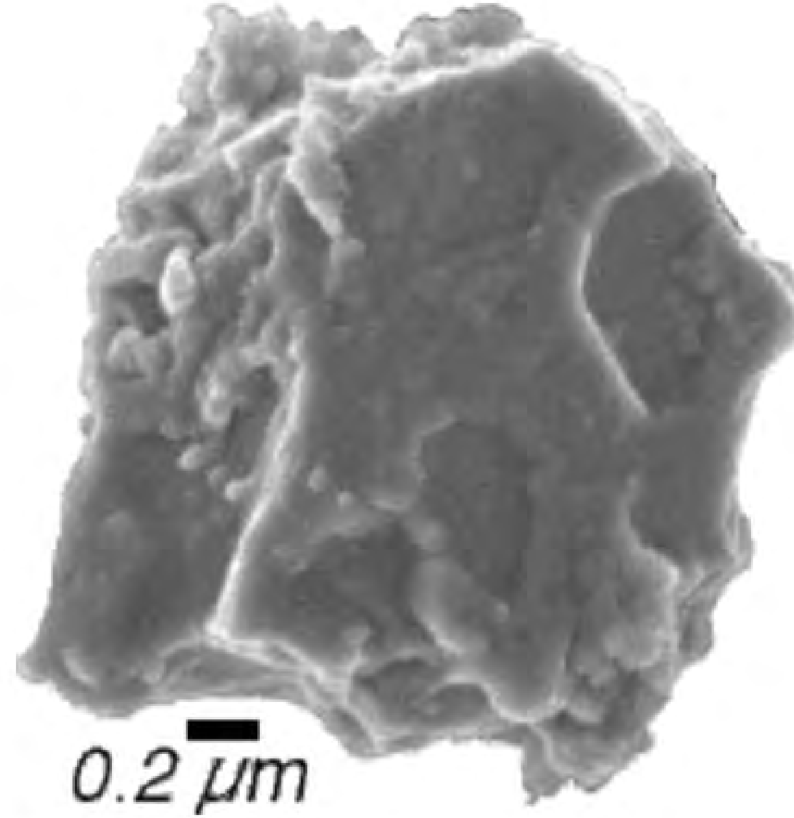
Impact detectors on Ulysses, Galileo: 0.3—1 μm grains

Radar detection of extrasolar meteors: 8, 25 μm grains

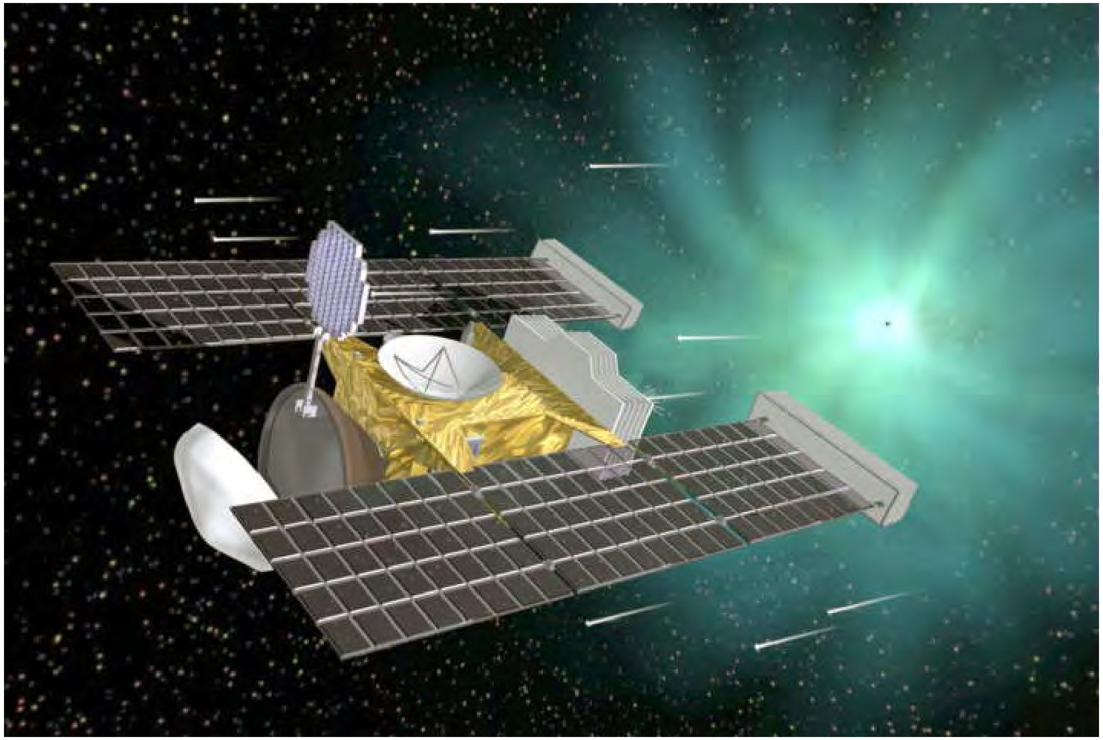
Abundances of "metals" in large grains in the local ISM seems too large, given solar system abundances. Is the local dust unusual?



presolar graphite grain



presolar SiC grain



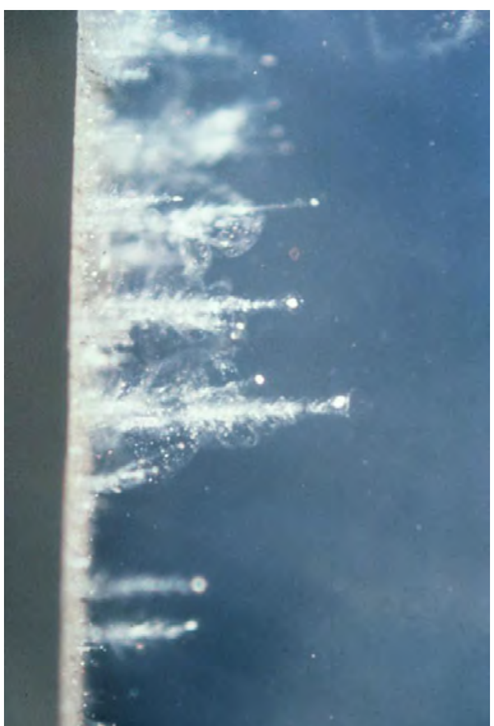
The Stardust Mission

launched Feb 7, 1999

encountered Comet Wild 2
on Jan 2, 2004

Earth return on Jan 15, 2006

stardustathome.ssl.berkeley.edu



Aerogel

silicon-based, but 1000 × less dense than glass

99.8% of the volume is vacuum

Physical Roles

In dense clouds: formation and protection of molecules (e.g., H_2)

In star-forming clouds: grains radiate away heat
=> cloud can collapse

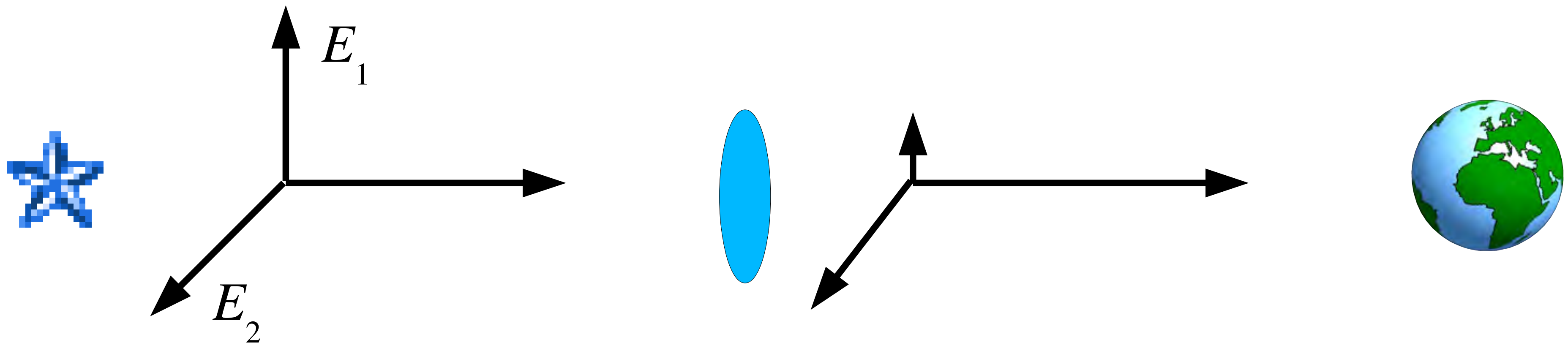
In the diffuse ISM: photoelectric emission from dust heats the gas

In protoplanetary disks: grains collide and stick => growth of larger objects; building blocks of planets

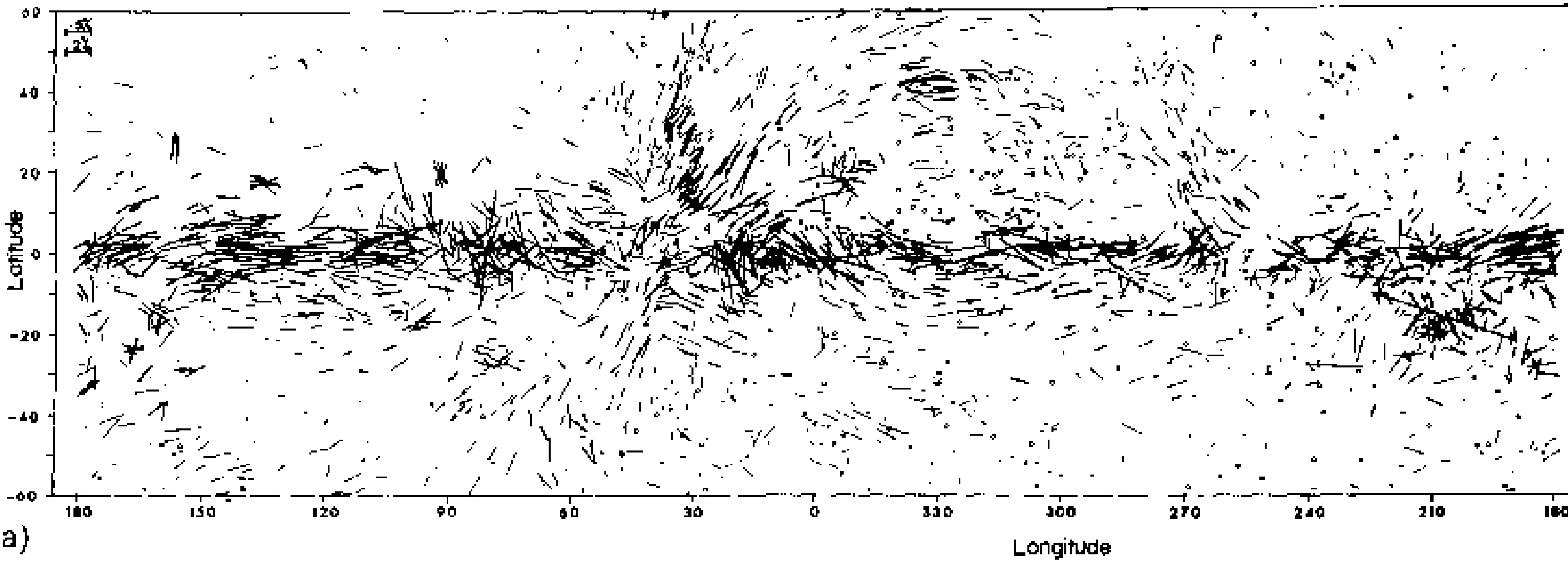
In stellar envelopes: grains condense; radiation pressure pushes them out; gas is dragged along
=> winds from stars

Diagnostic Roles

Aligned, non-spherical grains polarize starlight:



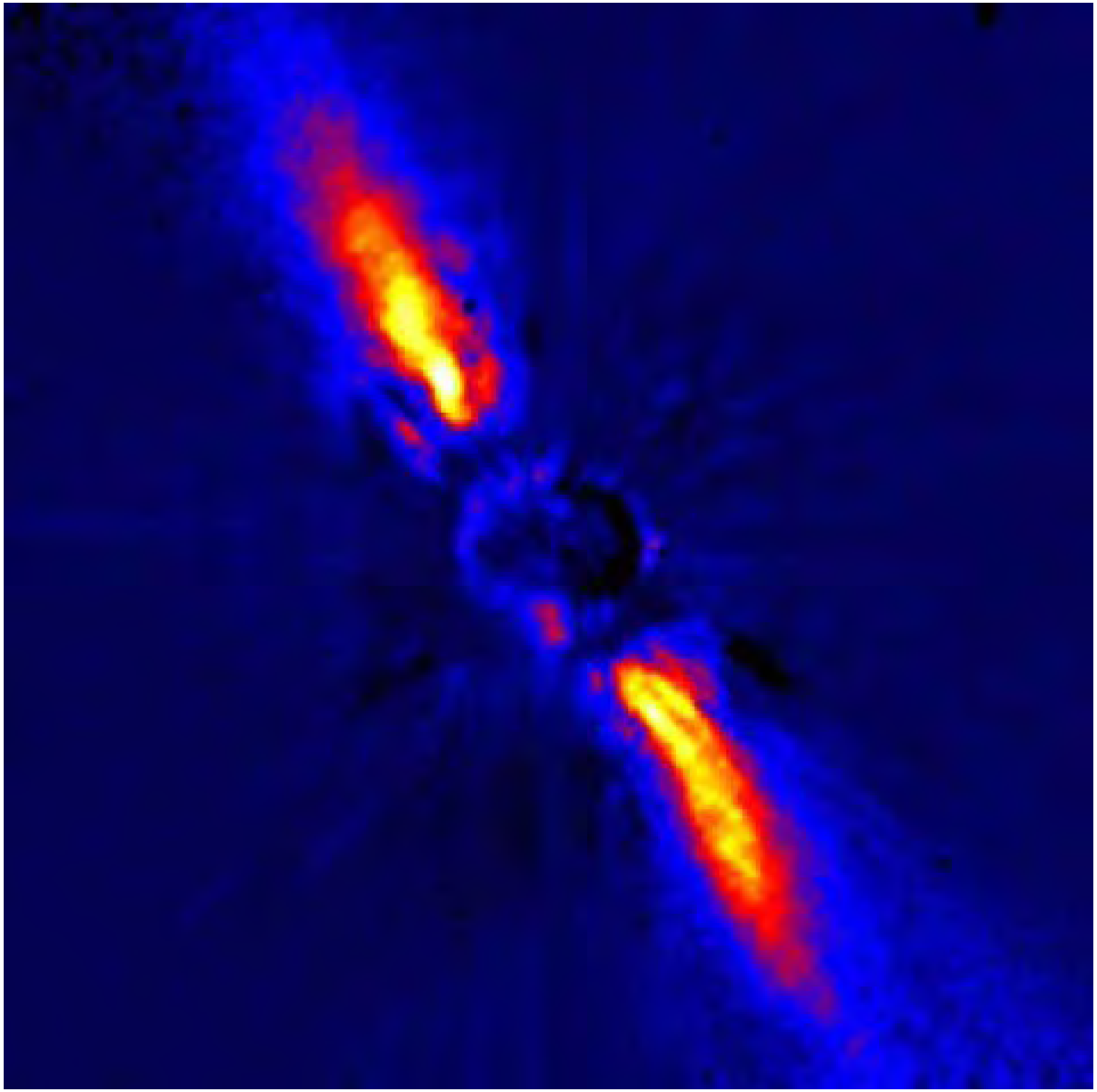
Grain is like an antenna—electric intensity in 1-direction is preferentially attenuated.



(a)

Grains align with respect to the Galactic magnetic field!

Structure in debris disks => presence of planets?



IR image of
β Pictoris

Some Mysteries

Detailed structure of interstellar dust: X-ray spectroscopy

Formation of dust: estimated formation rate in stellar winds and supernovae is slower than estimated destruction rate in supernova shocks

=> Dust forms in low-density ISM. How?

How do grains align with the magnetic field of the Galaxy?

Planet formation: How do grains grow from sub-micron to km size?
Severe time constraints!

For further reading:

Interstellar Matters, G.L. Verschuur (history of ISM discovery)

The Fullness of Space: Nebulae, Stardust, and the Interstellar Medium, G. Wynn-Williams (popular-level overview)

Dust in the Galactic Environment, D.C.B. Whittet (a textbook)