Astrofisica Generale II — 4

Maurizio Tomasi (maurizio.tomasi@unimi.it)

21 marzo 2025

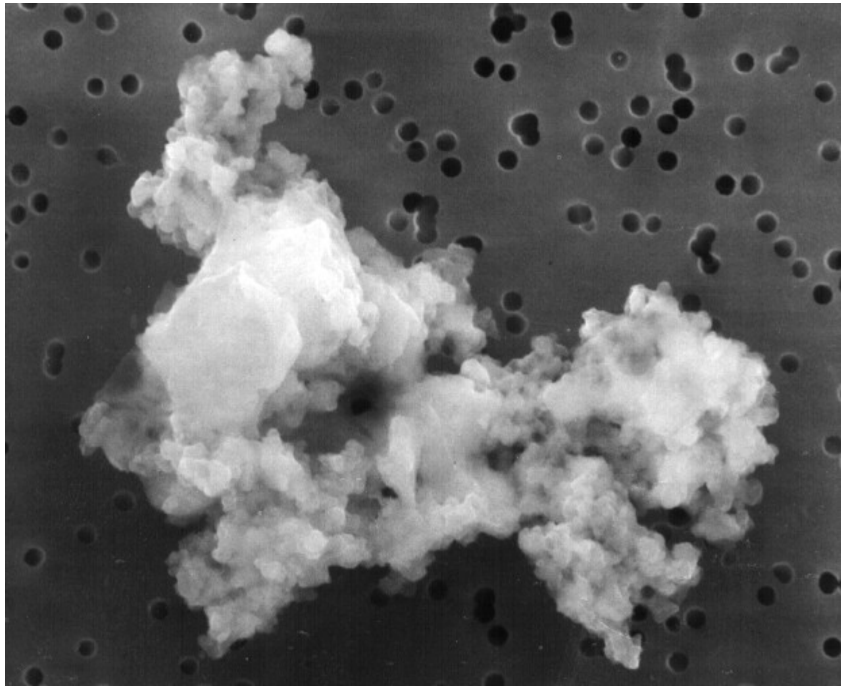
Characteristics of Dust in the ISM

Shape of Dust Grains

- Yesterday we saw that polarization suggests that the grains do not have spherical symmetry
- Can we get a more precise idea of their shape?

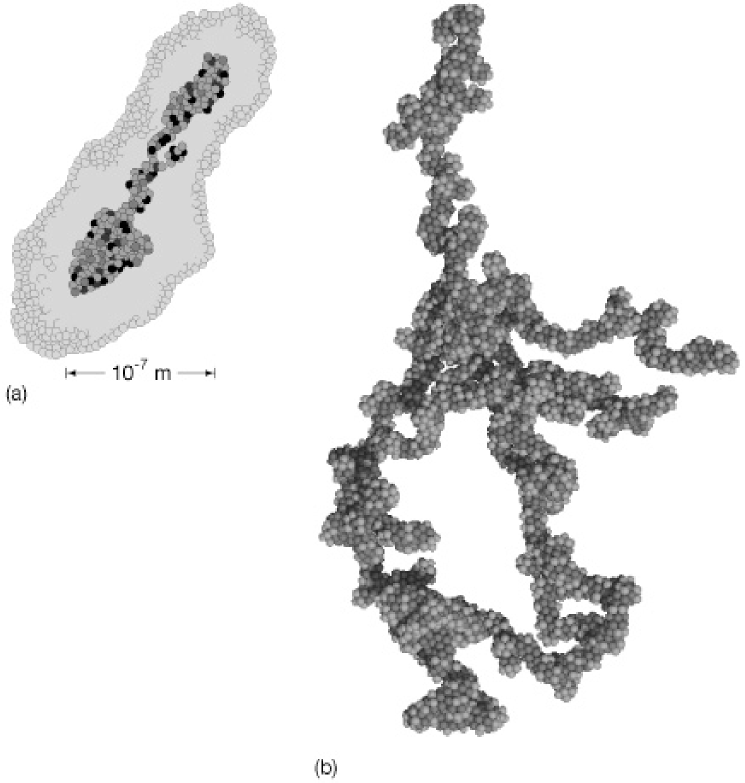
Shape of Dust Grains

Interplanetary dust particles can be captured by aircraft flying in the upper atmosphere.



Shape of Dust Grains

Dust grains (a) can collide with each other and aggregate into more complex structures (b).



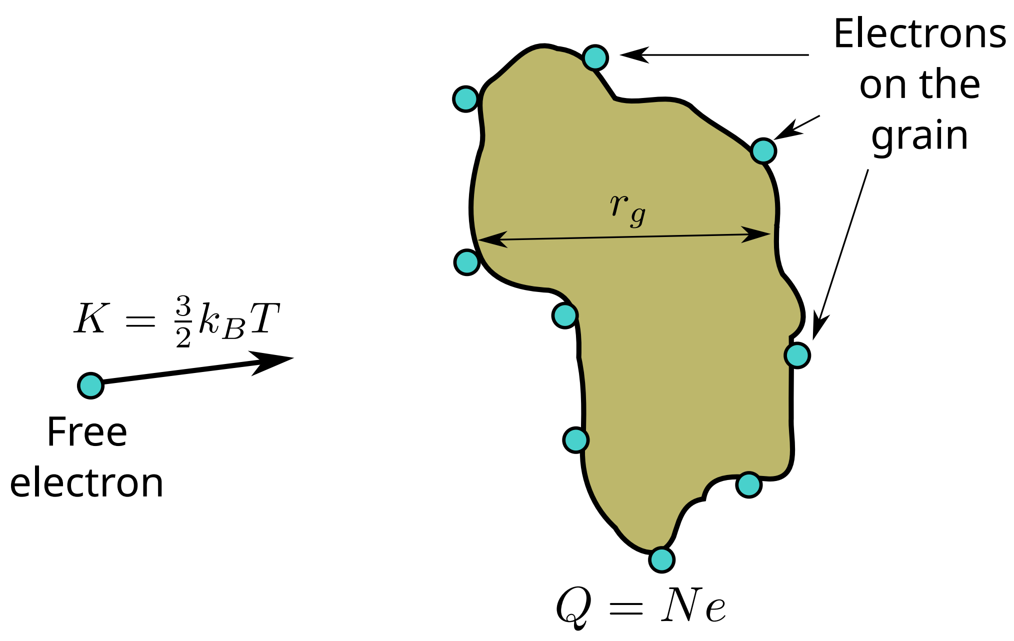
Electric Charge of Grains

- The interaction of grains with electromagnetic fields indicates that they are not electrically neutral (but the ISM is globally!).
- There are two mechanisms that allow charge to accumulate on the grains:

  1. “Slow” free electrons attach to the grain surface;
  2. Photoelectric effect caused by UV photons (not very important if A_V is large, because in that case the dust shields the photons).

- Let’s now consider the first case.

Electric Charge of Grains



Electrons can stick on the grain's surface if the kinetic energy of the electron is greater than the Coulomb potential of the grain (with r_g about 1μm). In this case, T is the temperature of the grain cloud.

Electric Charge of Grains

- The calculation is not very different from the one for the collision radius for globular clusters: we study when the potential energy is equal to the kinetic energy:

$$\frac{Ne^2}{4\pi\epsilon_0 r_g} = \frac{3}{2} k_B T, \quad \text{from which}$$

$$N = 6\pi\epsilon_0 k_B T \frac{r_g}{e^2} \approx 1.$$

- The high-velocity tail in the Boltzmann distribution for free electrons leads to $N \sim 10$.

Grain Temperature

- Let's now estimate the average temperature of a *single* dust grain. We can assume that they are heated by nearby stars.
- Suppose a grain is at a distance d from a star with radius R and temperature T, and that the star's luminosity is

$$L = 4\pi R^2 \sigma T^4$$

(spherically symmetric black body).

Grain Temperature

- The fraction of power hitting the grain is

$$f = \frac{\pi r_g^2}{4\pi d^2} = \frac{1}{4} \left(\frac{r_g}{d}\right)^2 .$$

- If the grain has albedo a, it absorbs a power

$$P_{\rm abs} = f\, L\, (1-a) = (1-a) r_g^2 \sigma T^4 \left(\frac{\pi R^2}{d^2}\right),$$

where $\pi R^2/d^2 \equiv \Omega_*$ is the solid angle of the star as seen from the grain.

Grain Temperature

- To calculate the grain's temperature at thermal equilibrium, we must also consider the power released by the grain.
- Let's assume it is spherical (horrible!), so that

$$P_{\rm rad} = 4\pi r_g^2 \sigma T_g^4,$$

where we use the so-called **effective temperature** T_g, i.e., the temperature of a black body that would emit the same amount of energy as the grain.

Grain Temperature

If the dust has reached the equilibrium temperature T_g, the emitted power must equal the absorbed power:

$$P_{\text{rad}} = P_{\text{abs}}$$

$$4\pi r_g^2 \sigma T_g^4 = (1-a) r_g^2 \sigma T^4 \left(\frac{\pi R^2}{d^2}\right)$$

$$T_g = T(1-a)^{1/4} \sqrt{\frac{R}{2d}}.$$

Grain Temperature

- The formula

$$T_g = T(1-a)^{1/4}\sqrt{\frac{R}{2d}}$$

  shows that the dust temperature does not depend on the size of the grains.
- This is the temperature of a *single* dust grain, but we can assume that at equilibrium it coincides with the temperature of the radiation emitted by the entire cloud of grains.

Grain Temperature

- In star-forming regions, the distances between cloud and star are on the order of a few AU ($\sim 10^{11}\,\mathrm{m}$), so $d/R \sim 10^3 \div 10^4$ and therefore $T_g \sim 10^{-2} T_*$.
- If $T_* = 10\,000\,\mathrm{K}$, then

$$T_g \sim 100\,\mathrm{K}.$$

- From Wien's law ($\lambda_{\mathrm{max}} T = 0.29\,\mathrm{cm\,K}$) we deduce that the peak of the emission is:

  1. 30 μm (IR) if $T = 100\,\mathrm{K}$;
  2. 0.3 mm (sub-mm) if $T = 10\,\mathrm{K}$.

Interstellar Dust

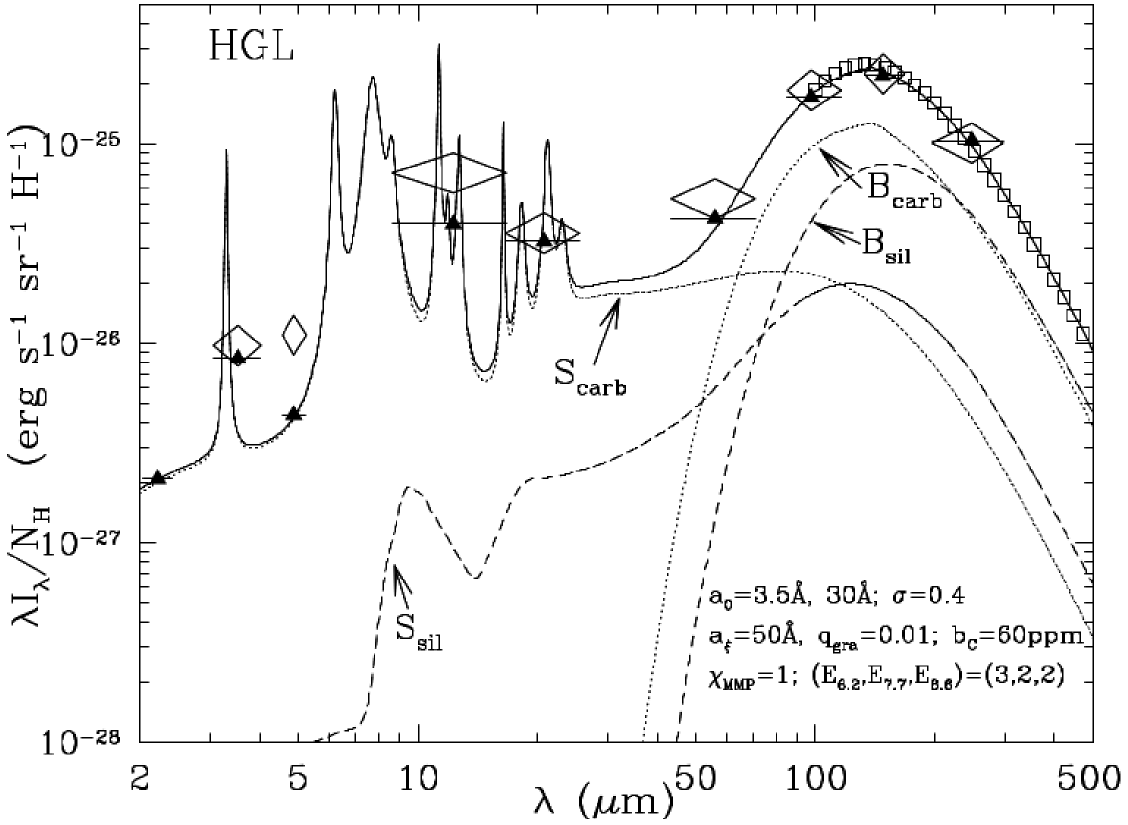
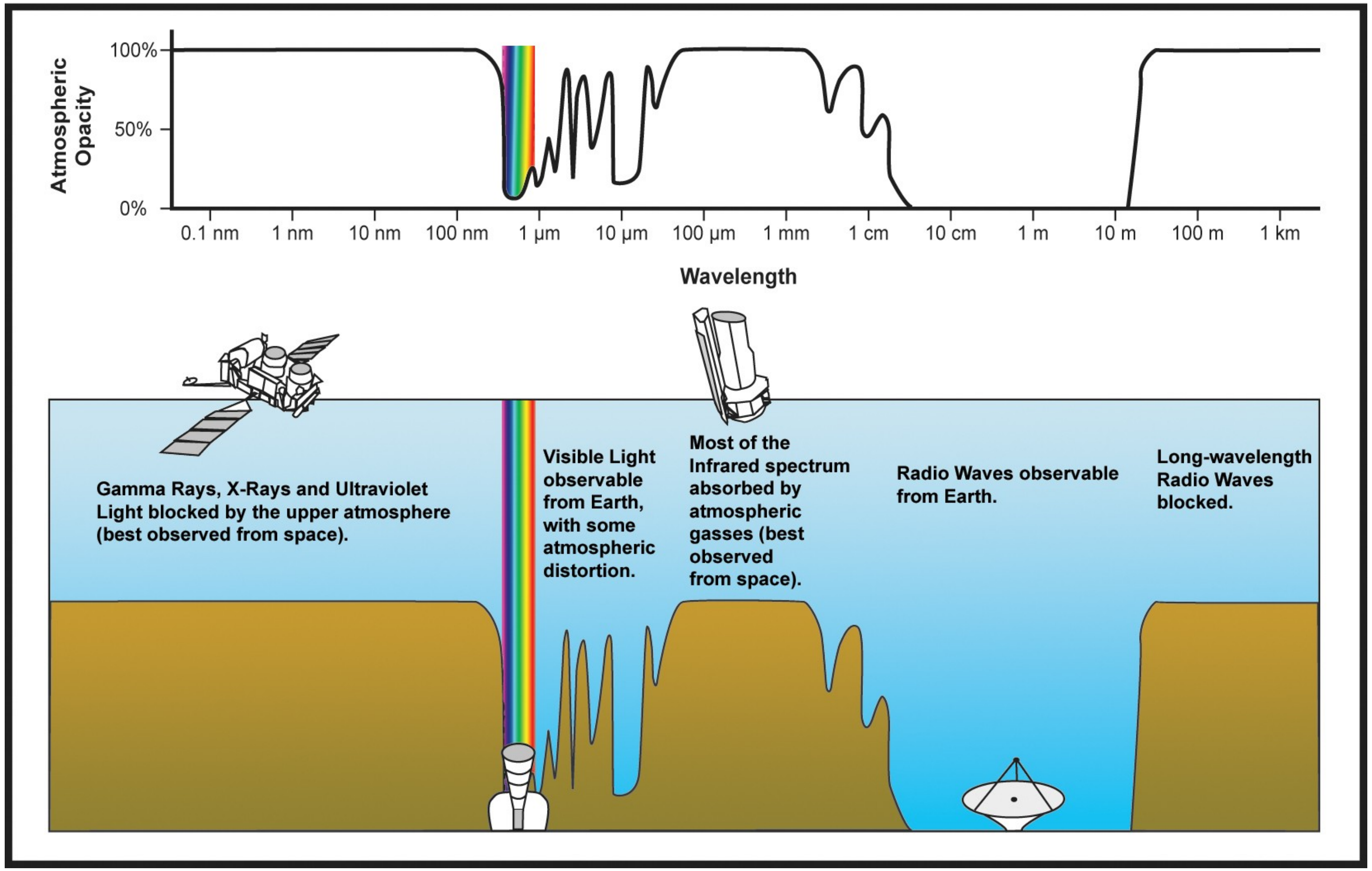
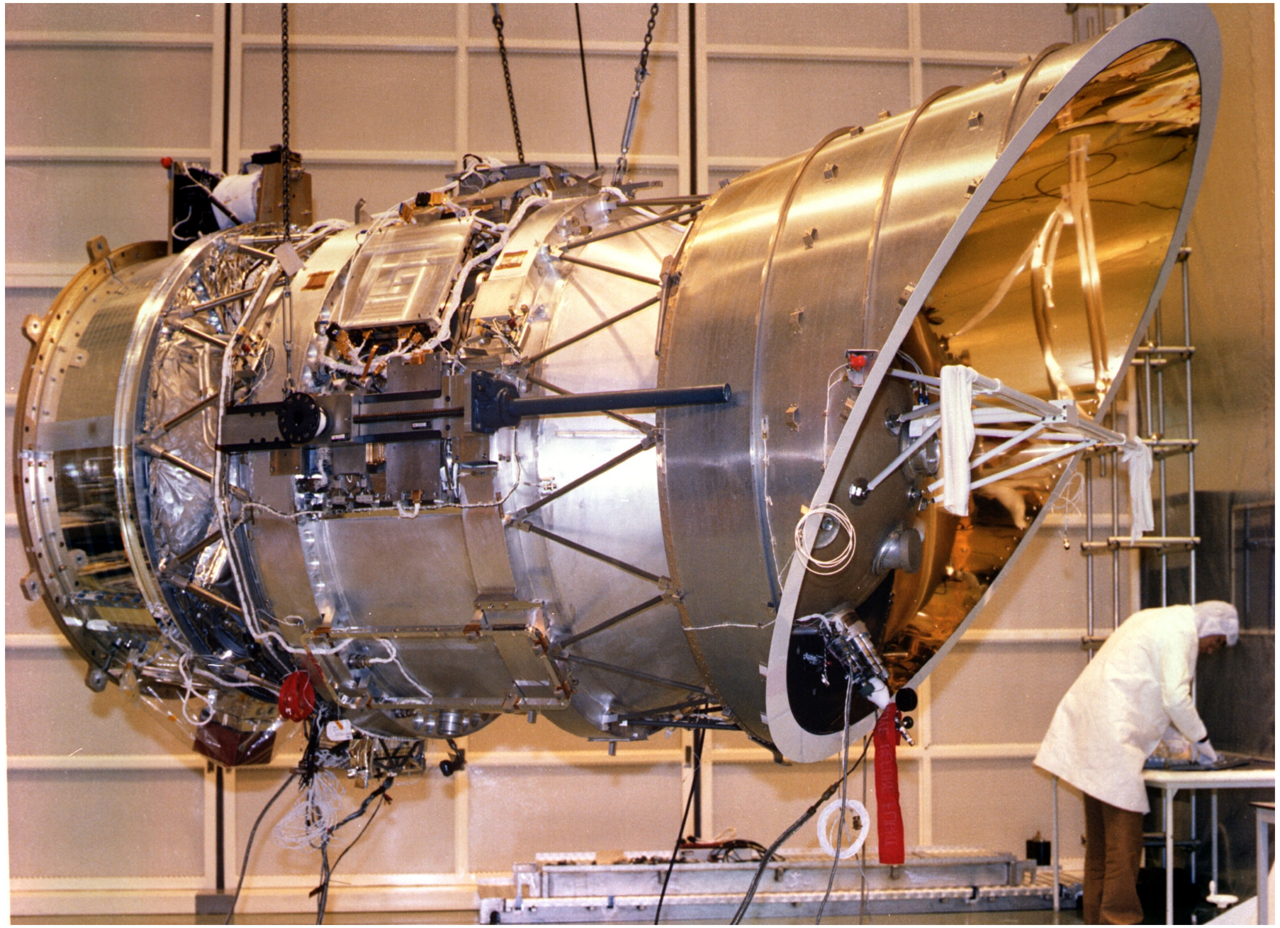


FIG. 8.—Comparison of the model to the observed emission from the diffuse ISM at high Galactic latitudes ($|b| \geq 25°$). Curves labeled B_{sil} and B_{carb} show emission from "big" ($a \geq 250$ Å) silicate and carbonaceous grains; curves labeled S_{sil} and S_{carb} show emission from "small" ($a < 250$ Å) silicate and carbonaceous grains (including PAHs). Triangles show the model spectrum (*solid curve*) convolved with the DIRBE filters. Observational data are from DIRBE (*diamonds*; Arendt et al. 1998) and FIRAS (*squares*; Finkbeiner et al. 1999).

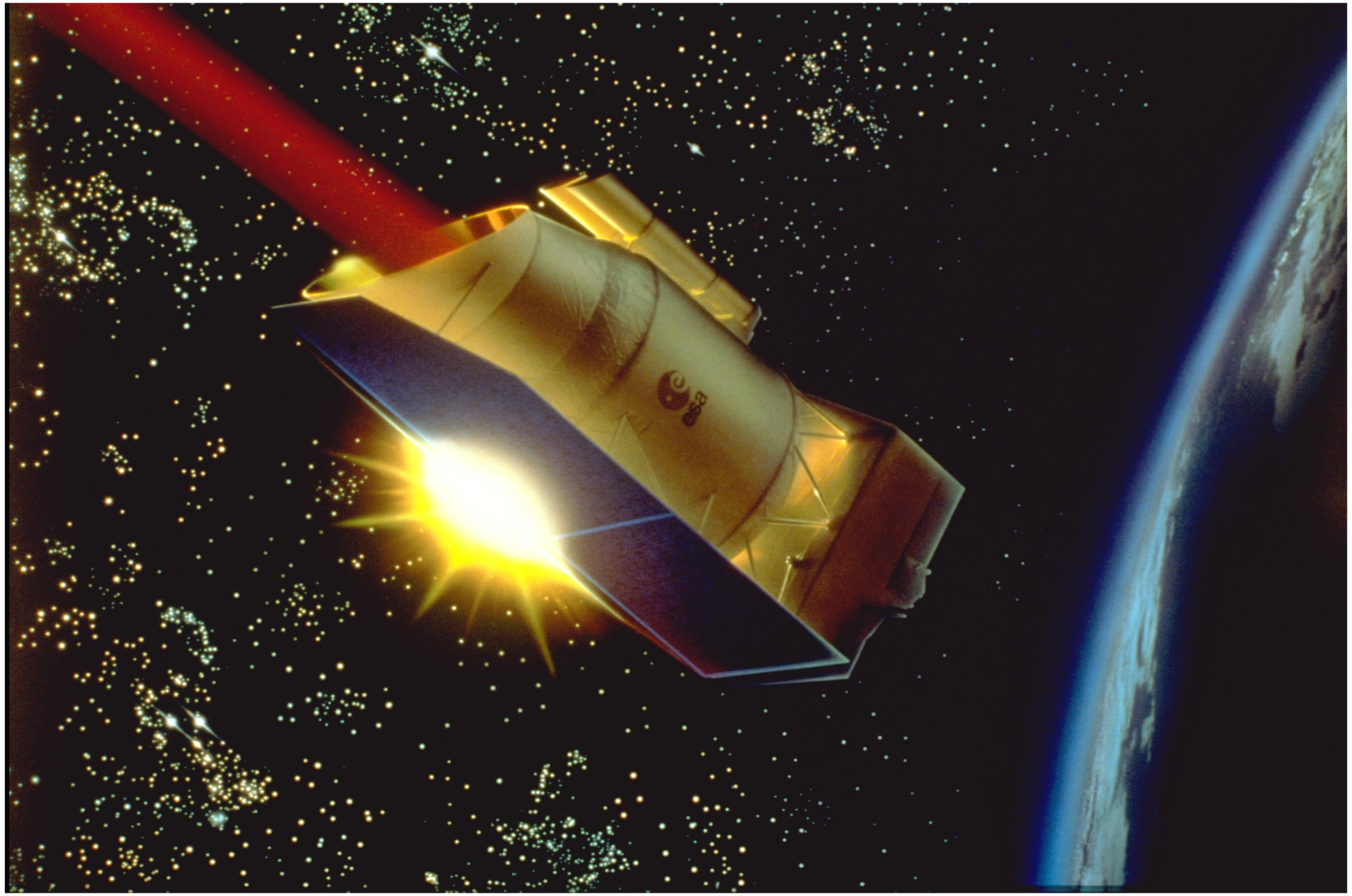
Li, A. & Draine, B. T. 2001, Astrophys. J., 554, 778–802

Observations from Space





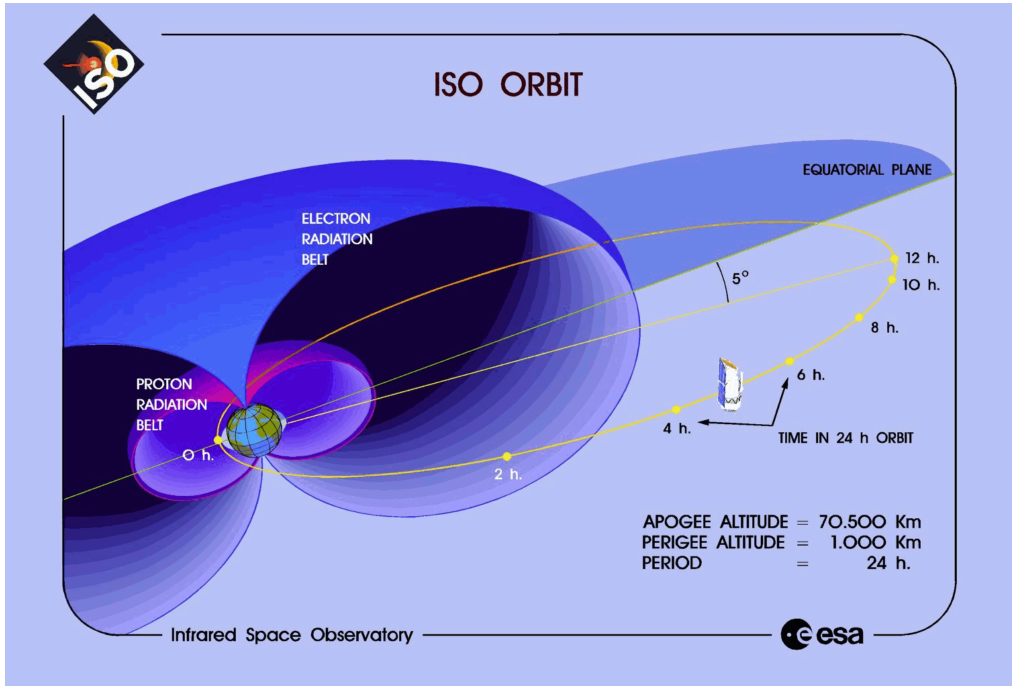
IRAS (Infrared Astronomical Satellite), 25/1/1983: First IR survey (12, 25, 60, 100 μm) of the whole sky. Geocentric orbit ($h \approx 900\ \mathrm{km}$).

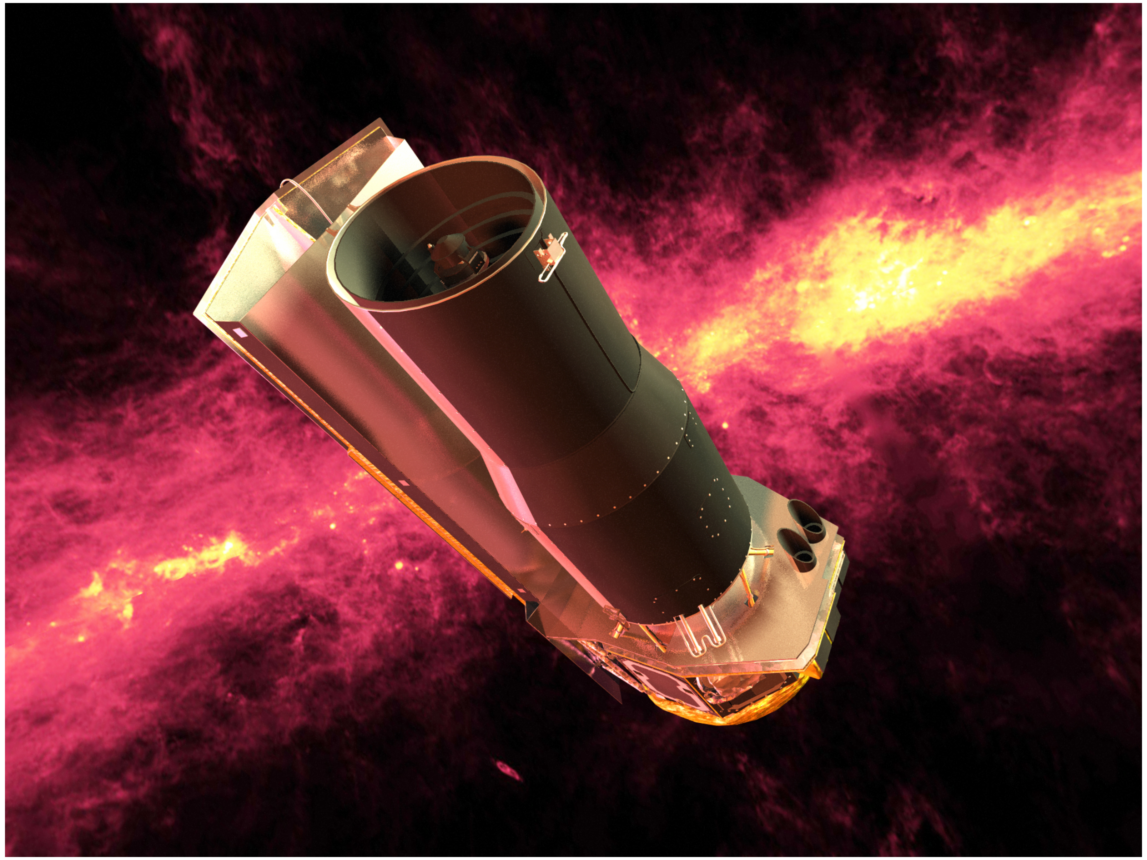


ISO (Infrared Space Observatory), 17/11/1995. Highly eccentric orbit (1000 km $\div$ 70 000 km).

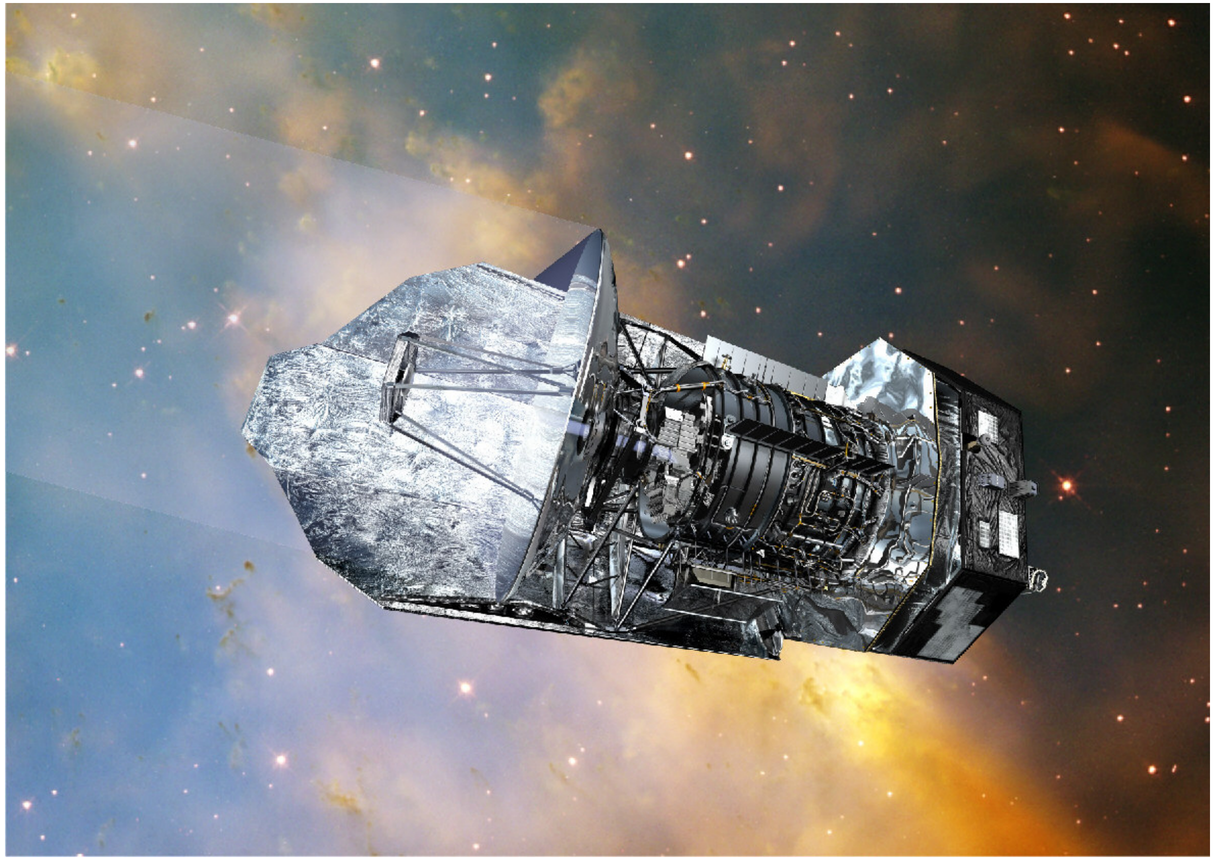
Eccentric orbits

- At apogee (maximum distance from Earth) the satellite moves very slowly: it is easier to make long observations
- The radiation belts are significant near perigee (minimum distance from Earth): ISO used to switch off its instruments for 7 hours each day.

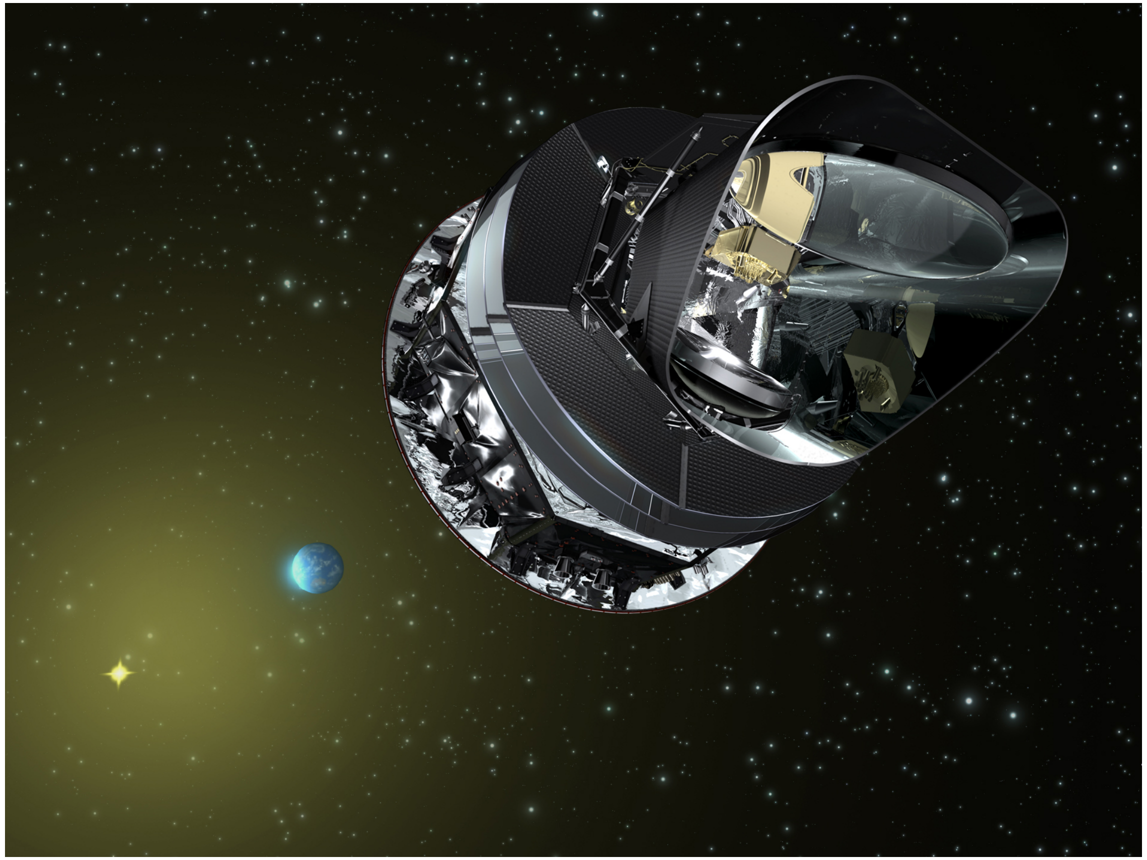




Spitzer Space Telescope (USA), 25/8/2003. Heliocentric orbit (IRrelevant astronomy)

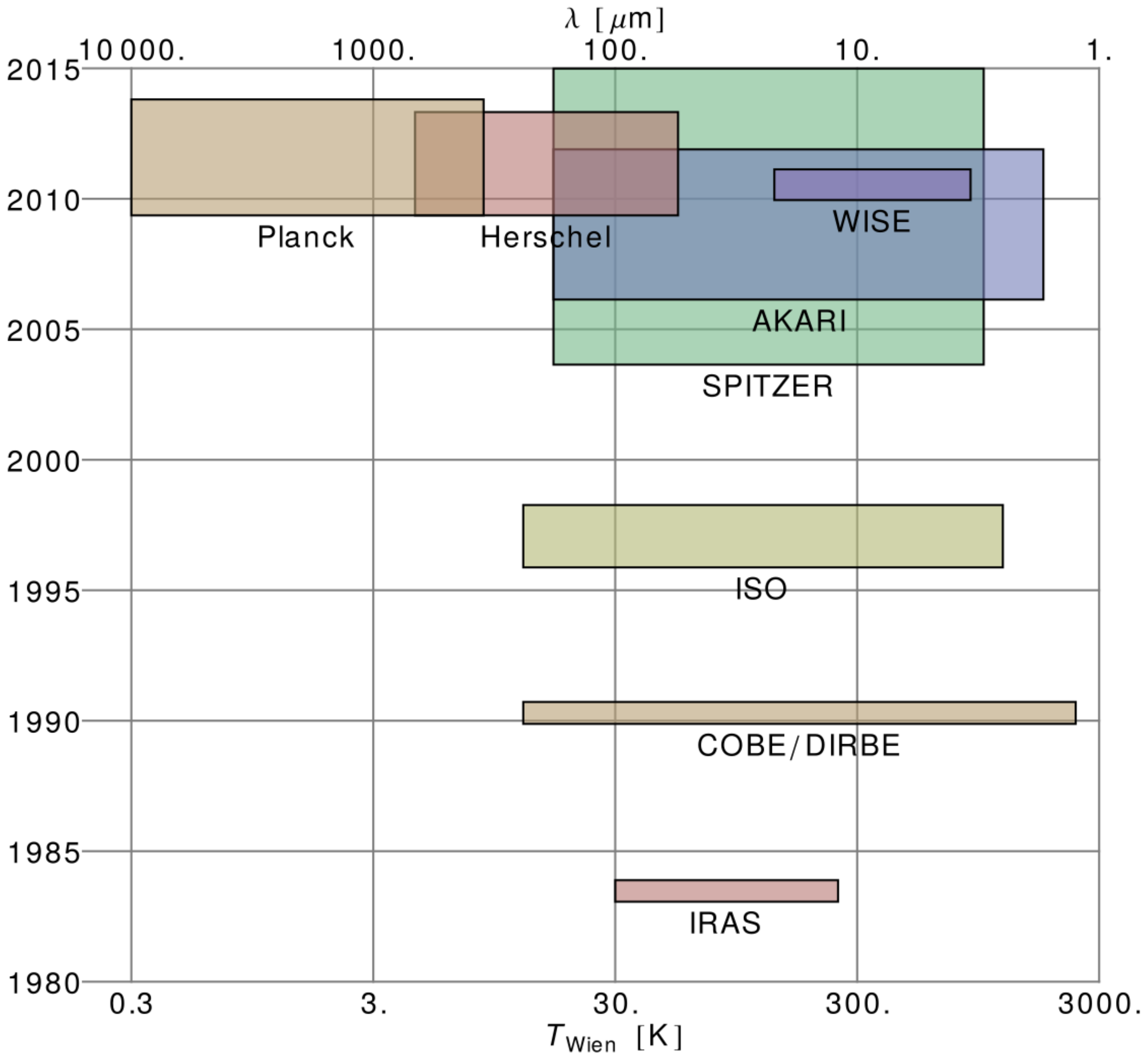


Herschel (ESA), 14/5/2009. Heliocentric orbit around L_2 ($d = 1.5 \times 10^9\ \mathrm{m}$).



Planck (ESA), 14/5/2009. Heliocentric orbit around L_2 ($d = 1.5 \times 10^9\,\mathrm{m}$).

Mostly mm, but up to 350 μm.


λ [μm]
10 000.
1000.
100.
10.
1.
2015
2010
2005
2000
1995
1990
1985
1980
Planck
Herschel
WISE
AKARI
SPITZER
ISO
COBE/DIRBE
IRAS
0.3
3.
30.
300.
3000.
T_{Wien} [K]

Grain Properties: Summary

Characteristic	Source	Result
Shape	Star polarization, interplanetary dust	Asymmetric
Size	Trend of $A(\lambda)$	$\mathrm{nm} < r_g < \mu\mathrm{m}$
Composition	Spectrum, shape of $A(\lambda)$	Silicates, carbonates, ice, ferrite, hydrocarbons
Electric charge	Star polarization, energy conservation	$N = \frac{3}{2} k_B T \frac{r_g}{e^2} \sim 10$
Temperature	Illumination from stars	$T_g = T_* \sqrt{\frac{R}{2d}} \sim 10 \div 100\,\mathrm{K}$

Grain Rotation and Anomalous Emission

Grain Rotation

Why do grains tend to align their rotation axis?

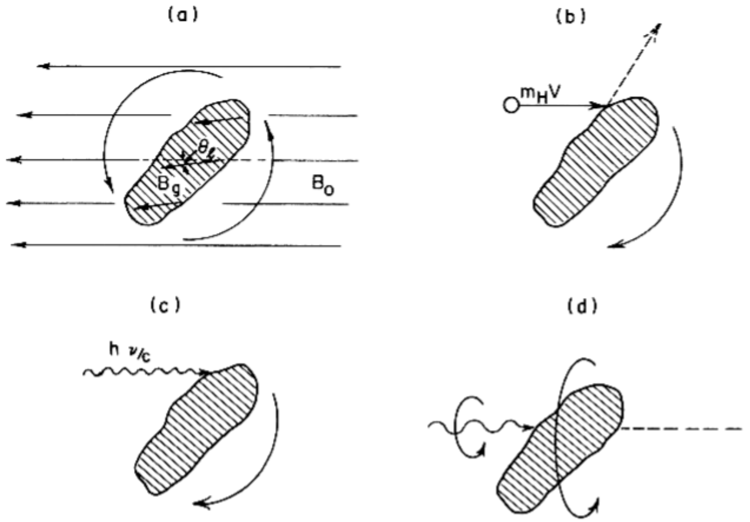


Fig. 9.14. Alignment mechanisms for interstellar grains: (a) process of paramagnetic relaxation; (b) alignment by streaming through gas, or (c) through a photon field. In process (c) the photon's linear momentum causes the grain to spin; in process (d) the photon's intrinsic spin angular momentum is of importance (see text).

Harwit, *Astrophysical concepts* (4th edition), Springer (2006)

Grain Rotation

- If the grain is paramagnetic, the Galactic field $\vec{B}_{\mathrm{Gal}}$ induces a magnetic moment $\vec{\mu}_B \propto \vec{B}_{\mathrm{Gal}}$ parallel to it, which causes a mechanical torque $\vec{\tau} = \vec{\mu}_B \times \vec{B}_{\mathrm{Gal}}$. Then:

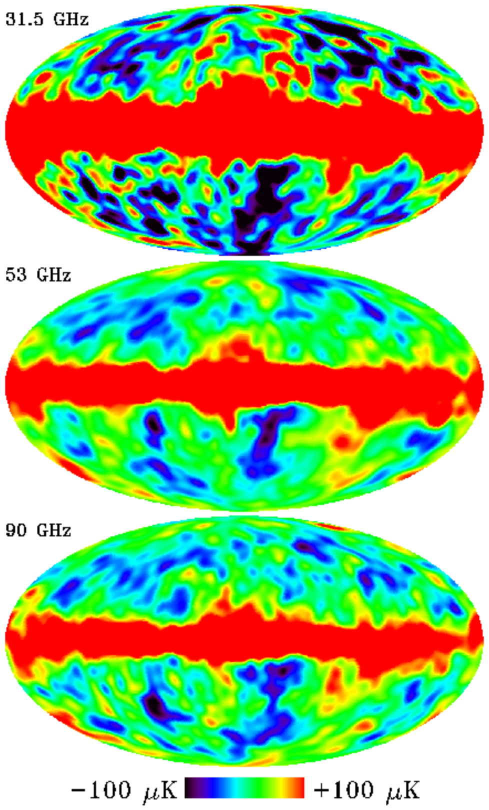
  1. If the grain rotates as in case *a* of the previous figure, the rotation leads $\vec{B}_{\mathrm{Gal}}$ and $\vec{\mu}_B$ to misalign. To realign, $\vec{\mu}_B$ induces an opposing torque.

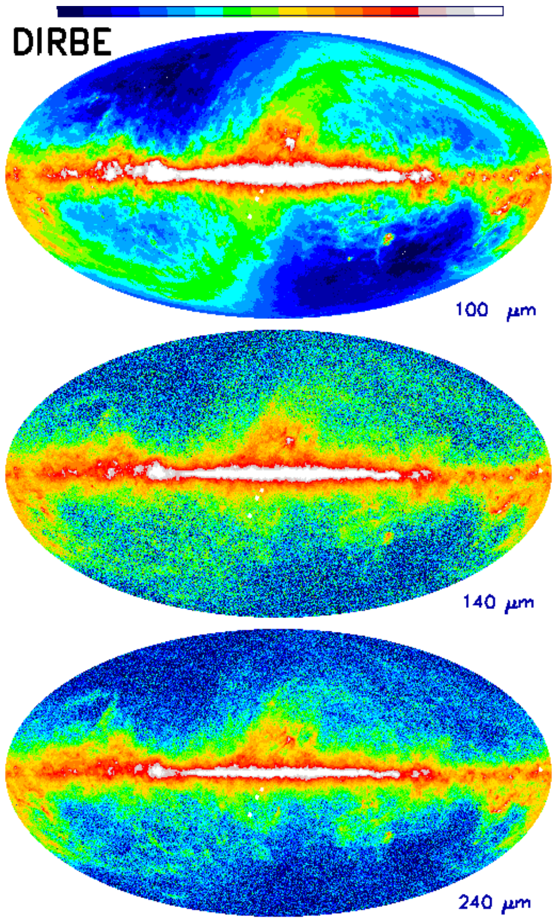
  2. If the rotation axis is parallel to $\vec{B}_{\mathrm{Gal}}$, there is no torque.

- Therefore, the rotation axis tends to align with $\vec{B}_{\mathrm{Gal}}$ (**paramagnetic relaxation**).

Anomalous Emission

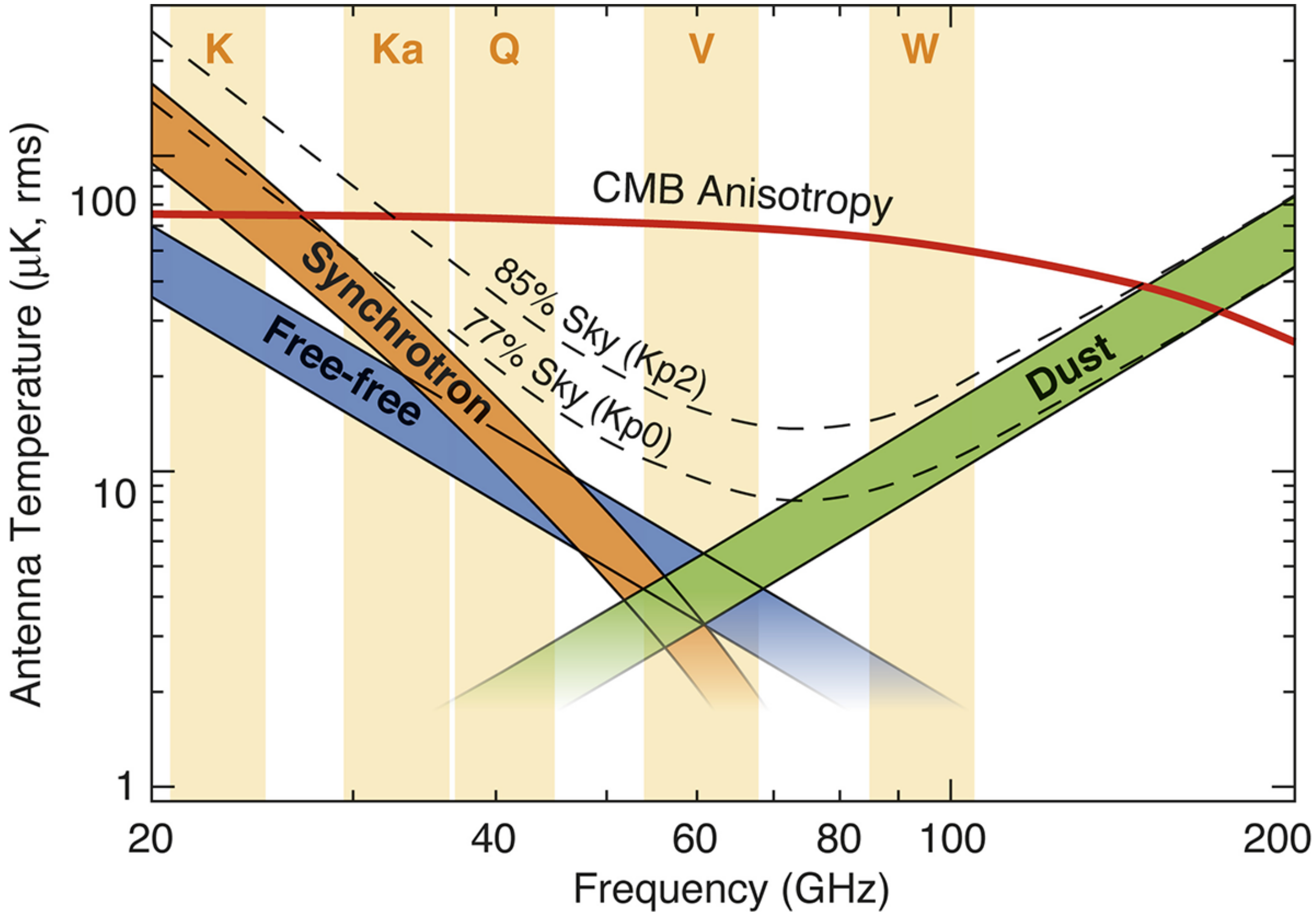
- In 1995, Kogut *et al.* published a paper measuring the correlation between the sky emission at 140 μm (measured by COBE-DIRBE) and at 31.5 GHz (measured by COBE-DMR).
- These studies sought to characterize the relative contribution of different emissions around the microwave region, in order to better isolate the CMB signal (which we will see in more detail in the last part of the course).





(The correlation is between the 31.5 GHz map and the 140 μm map).

Emission types



Origin of the Correlation

- The synchrotron signal is generated by cosmic rays, which should not be correlated with dust.
- Yet this is what is observed! Three possibilities:

1. Dust also emits at synchrotron frequencies;
2. Cosmic rays also emit at dust frequencies;
3. Something else (what?) emits at both synchrotron and dust frequencies.

Rotating Grains

- In 1998, A. Lazarian and B. T. Draine proposed that the grains of polycyclic aromatic hydrocarbons (PAHs) emit in the spectral region around 30 GHz, due to their rotation.
- The physical model is simple, even if the details are extremely complicated!

Rotating Grains

- Suppose that the grains have an electric dipole moment $\vec{\mu} = q\vec{r}$ and that they are rotating with angular velocity ω
- We then expect them to emit photons with frequency $\nu = \omega/2\pi$.
- If the grains are in thermal equilibrium, have angular momentum $L \gg h$ and are set in rotation mainly by collisions, then

$$\frac{1}{2}I\left\langle\omega^2\right\rangle \approx \frac{3}{2}k_BT, \qquad \text{with } I = \frac{2}{5}Ma^2 = \frac{8}{15}\pi\rho a^5.$$

Caveats

- The assumption that all the collision energy is converted into rotational energy is an approximation: in reality it is estimated that part of the energy (10–20 %) is converted into vibrational modes.
- The assumption that the angular momentum L is much greater than h allows the use of classical physics, where the angular momentum is not quantized: this is always true, because the smallest grains have $L/h \sim 70$.

Rotating Grains

The solution can be written in this form:

$$\nu = \frac{\sqrt{\langle\omega^2\rangle}}{2\pi} = 32\,\mathrm{GHz} \times \left(\frac{T}{100\,\mathrm{K}}\right)^{1/2} \times$$

$$\times \left(\frac{2\,\mathrm{g/cm^3}}{\rho}\right)^{1/2} \times \left(\frac{5\,\mathrm{\mathring{A}}}{a}\right)^{5/2}.$$

(Only grains with $a \lesssim 10\,\mathrm{\mathring{A}}$ contribute to this emission, see Fig. 7 of Draine & Lazarian, 1998). The predicted emission peak is around 30 GHz: encouraging!

Rotating Grains

For a realistic model, other effects must also be taken into account:

1. Ion collisions (Coulomb forces);
2. Coupling between $\vec{\mu}$ and the electromagnetic field;
3. Absorption/emission of photons (due to their angular momentum);
4. H_2 formation;
5. Etc.

Rotating Grains

- A more detailed model predicts that

$$\langle \omega^2 \rangle \lesssim 3 k_B \frac{T}{I}.$$

  The result is still that the predicted spectrum has an emission peak around a few tens of GHz.

- Obviously, detailed models also estimate the **intensity**, in order to compare it with the measured one. (A complete model must therefore take into account the average surface of the grains, their emissivity, their shape, etc.)

THE ASTROPHYSICAL JOURNAL, 508:157–179, 1998 November 20

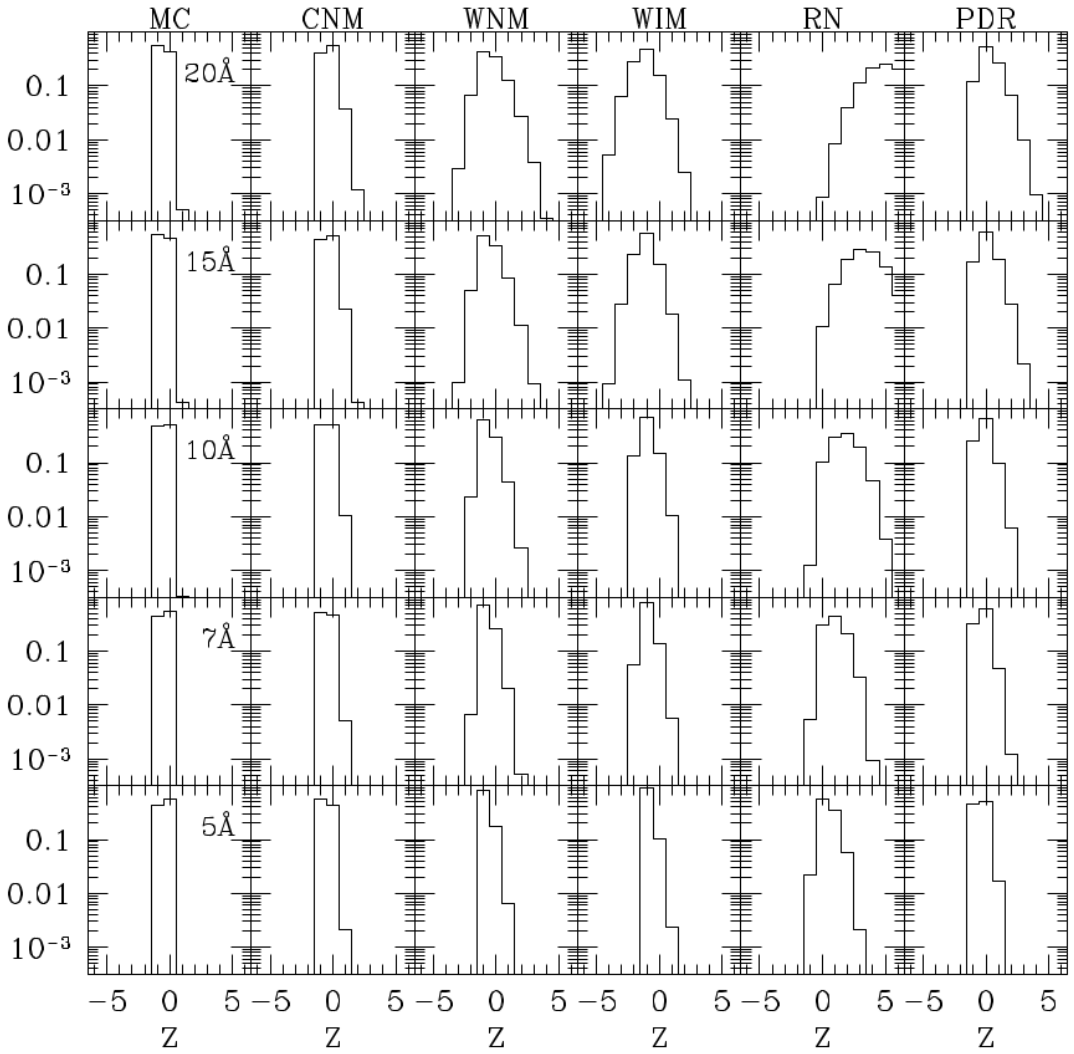
ELECTRIC DIPOLE RADIATION FROM SPINNING DUST GRAINS

B. T. DRAINE AND A. LAZARIAN
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544
Received 1998 February 18; accepted 1998 June 25

ABSTRACT

We discuss the rotational excitation of small interstellar grains and the resulting electric dipole radiation from spinning dust. Attention is given to excitation and damping of grain rotation by collisions with neutrals, collisions with ions, "plasma drag," emission of infrared radiation, emission of electric dipole radiation, photoelectric emission, and formation of H_2 on the grain surface. Electrostatic "focusing" can substantially enhance the rate of rotational excitation of grains colliding with ions. Under some conditions, "plasma drag"—due to interaction of the electric dipole moment of the grain with the electric field produced by passing ions—dominates both rotational damping and rotational excitation. Emissivities are estimated for dust in different phases of the interstellar medium, including diffuse H I clouds, warm H I, low-density photoionized gas, and cold molecular gas. Spinning dust grains could explain much, and perhaps all, of the 14–50 GHz background component recently observed by Kogut et al., de Oliveira-Costa et al., and Leitch et al. Future sensitive measurements of angular structure in the microwave sky brightness from the ground and from space should detect this emission from high-latitude H I clouds. It should be possible to detect rotational emission from small grains by ground-based pointed observations of molecular clouds, unless these grains are less abundant there than is currently believed.

Subject headings: atomic processes — diffuse radiation — dust, extinction — ISM: clouds — plasmas — radiation mechanisms: thermal


MC
CNM
WNM
WIM
RN
PDR
20Å
15Å
10Å
7Å
5Å
0.1
0.01
10^{-3}
−5
0
5
Z

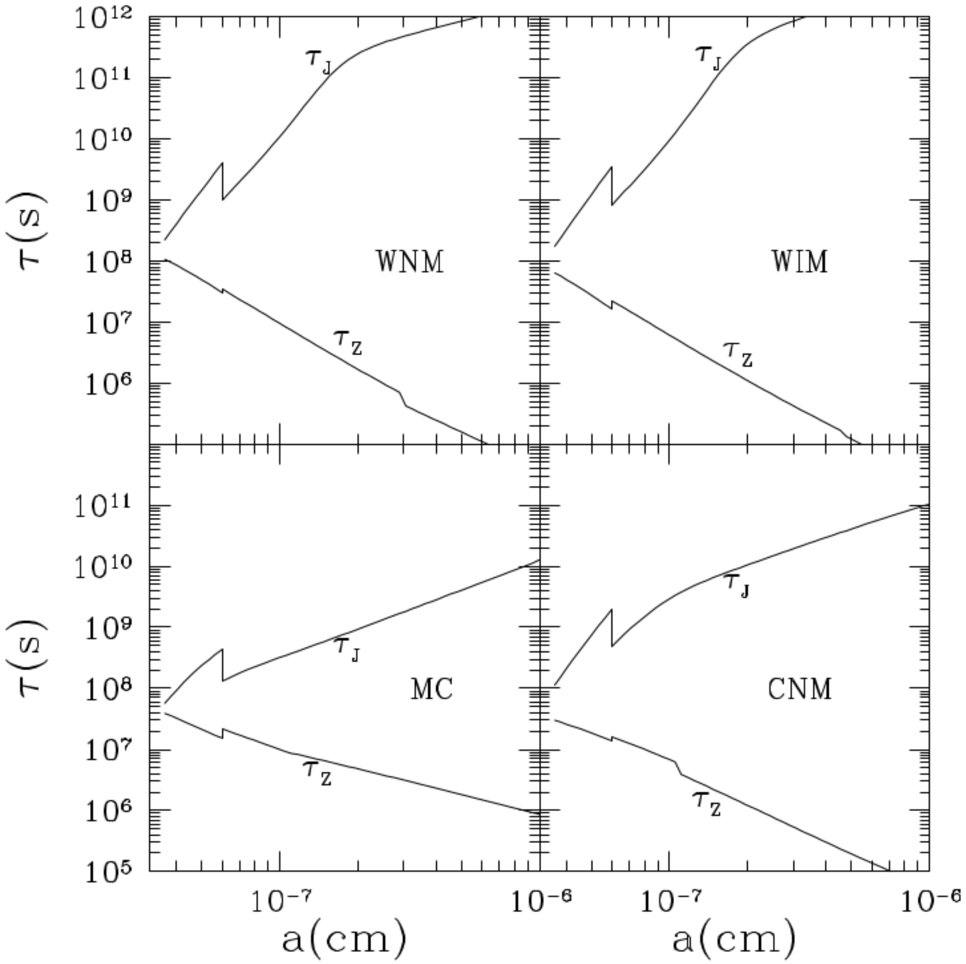
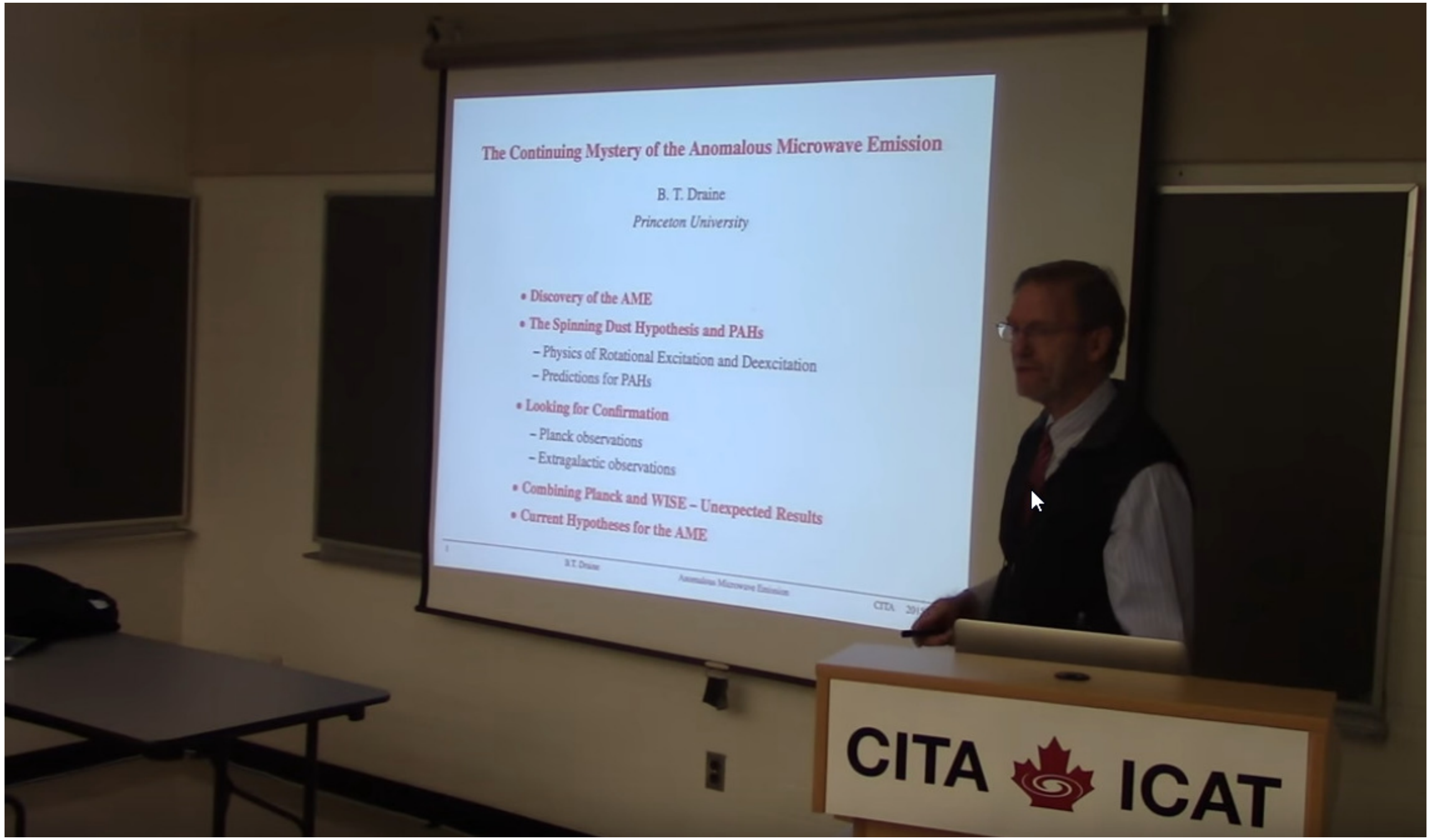


FIG. 3.—Characteristic timescale τ_Z (see eq. [5]) for changes in the grain charge Ze. Also shown is the characteristic rotational damping time τ_J (see eq. [58]) for a grain with charge $Z_m e$. It is apparent that the approximation $\tau_Z \ll \tau_J$ is excellent for all except the smallest ($a < 4$ Å) grains.



See *The continuing mistery of the Anomalous Microwave Emission*, a 2015 talk by B. Draine.

Anomalous Emission