Dust Extinction and Emission

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(平下 博之)

Dust Study Group

(1) Deepen the knowledge of dust for your individual studies (planets to cosmology)
(2) Start new studies or projects on dust
(3) Construct strategies for THz astronomy

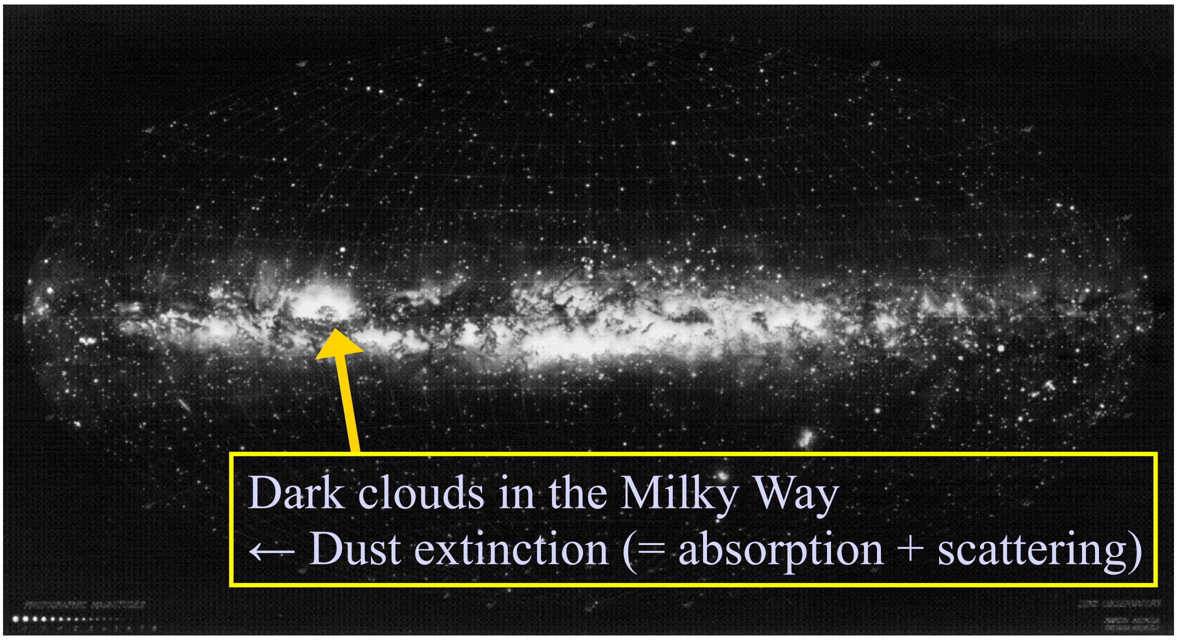
(1) Tutorials.
(2) Constant weekly/biweekly meeting to be decided.

Mailing list: dust@asiaa...
Please tell Ciska.

Milky Way in the Optical

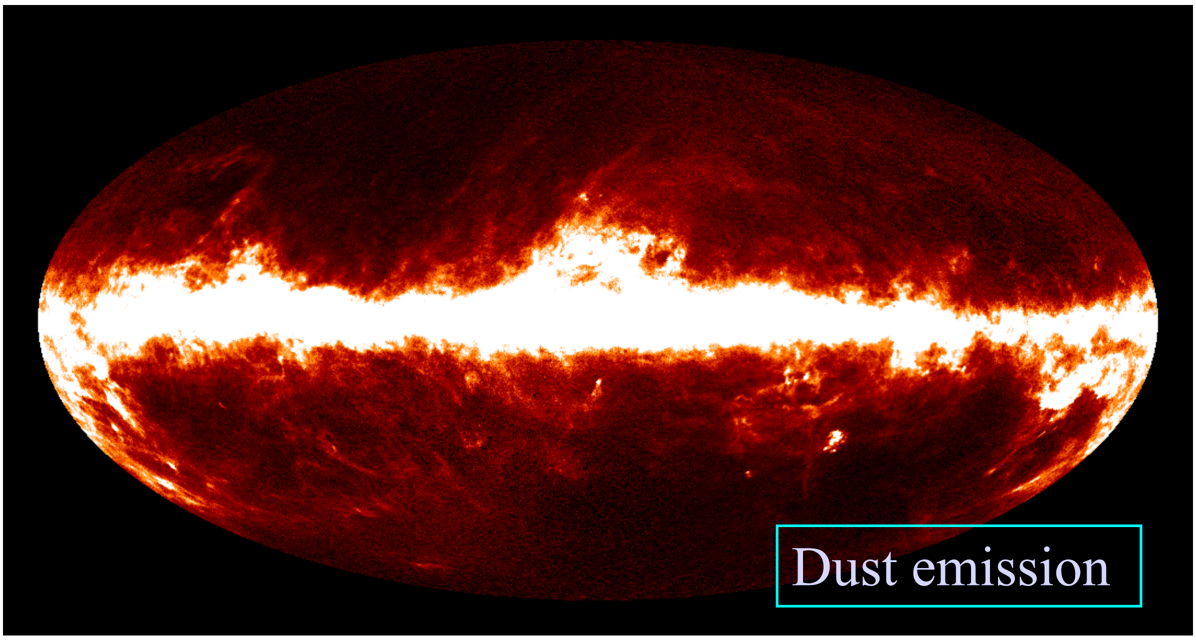
Optical ($\lambda \sim 0.5\ \mu m$)

Lund Observatory



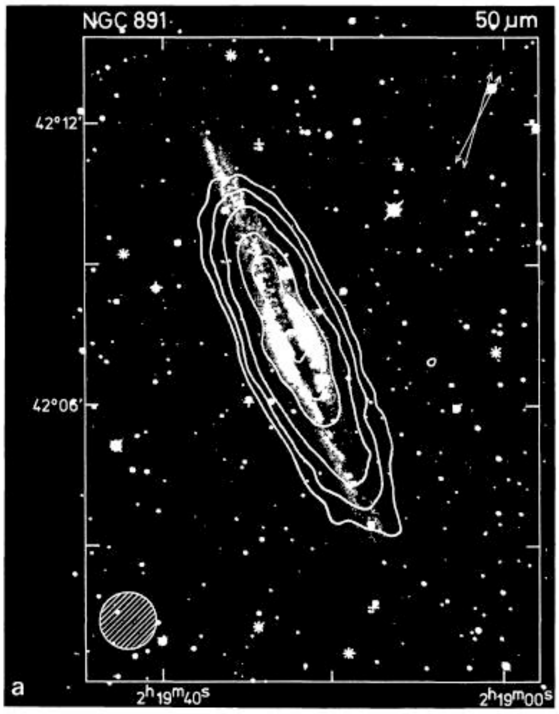
Milky Way in Far-Infrared (FIR)

COBE 140 μm

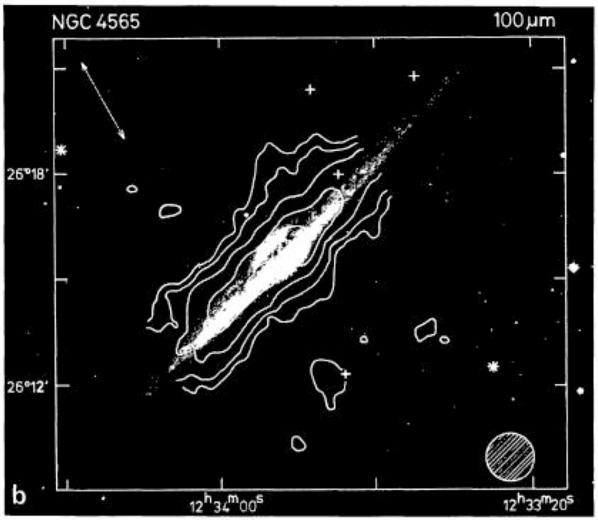


Spiral Galaxies (Edge-on)

Wainscoat et al. (1987)



$L_{\rm FIR}/L_{\rm opt} = 1.05$



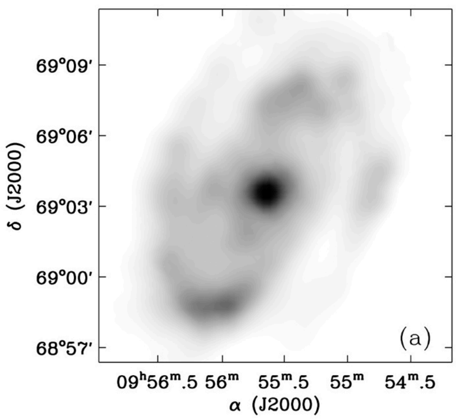
$L_{\rm FIR}/L_{\rm opt} = 0.22$

Contour: Far-infrared intensity
Image: Optical

M81 (Face-on)

Optical: **stars**

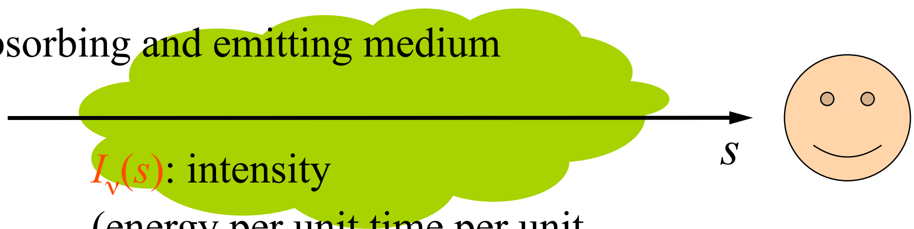
FIR: **dust**



Sun & Hirashita (2011)

What to Understand?

Radiation Transfer Equation



(energy per unit time per unit area per unit solid angle)

$$\boxed{dI_\nu/ds = -\rho\kappa_\nu I_\nu + j_\nu}$$

absorption

emission

κ_ν: mass absorption coefficient

ρ: density

j_ν: emissivity

Optical Depth

Definition: $d\tau_\nu = \rho\kappa_\nu ds$ ($= n\sigma_\nu ds$)

$s = 1/n\sigma_\nu$ (mean free path)

$\Leftrightarrow \tau_\nu = 1$ (photons are absorbed once *on average*)

Radiation transfer equation:

$dI_\nu/d\tau_\nu = -I_\nu + S_\nu$

$dI_\nu/ds = -\rho\kappa_\nu I_\nu + j_\nu$

$S_\nu = j_\nu/(\rho\kappa_\nu)$: source function

Local Thermodynamic Equilibrium (LTE):

$S_\nu = B_\nu(T)$

The Cross Section of Grains

$\sigma_{\nu,\,ext} = \sigma_{\nu,\,abs} + \sigma_{\nu,\,sca}$

$\sigma_{\nu,\,abs} = \pi a^2 Q_{abs}(a, \nu)$

$\sigma_{\nu,\,sca} = \pi a^2 Q_{sca}(a, \nu)$

Mie theory $\rightarrow$ $Q_{abs}(a, \nu)$, $Q_{sca}(a, \nu)$ under $\varepsilon = \varepsilon_1 + i\varepsilon_2$

<u>General properties about Q_{abs} and Q_{sca}</u>

$x = 2\pi a/\lambda$

- $Q_{abs} \sim 1$and $Q_{sca} \sim 1$ for $x \sim> 1$
- $Q_{abs} \sim 4\pi x(3\varepsilon_2/|\varepsilon + 2|^2)$ and

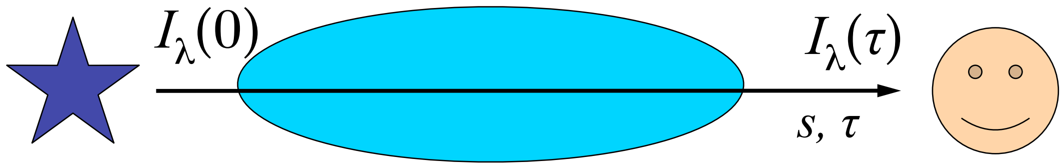
$Q_{sca} \sim (8x^4/3)|(\varepsilon - 1)/(\varepsilon + 2)|^2$ for $x << 1$

$\rightarrow$ In FIR, $Q_{abs} >> Q_{sca}$, and $Q_{abs} \propto \nu^\beta$ ($\beta = 1 - 2$)

Material properties through ε

Dust Extinction

Extinction Only (UV, Opt, NIR)



Extinction = Absorption + Scattering

τ: optical depth for extinction

$dI_\lambda/d\tau_\lambda = -I_\lambda(\tau_\lambda)$

$\rightarrow I_\lambda(\tau) = I_\lambda(0)\ e^{-\tau_\lambda}$

Magnitude: $m_\lambda = -2.5 \log I_\lambda + \text{const.}$

Extinction: $A_\lambda = m_\lambda(s) - m_\lambda(0)$

$= 2.5[\log I_\lambda(0) e^{-\tau_\lambda} - \log I_\lambda(0)]$

$= (2.5 \log e)\ \tau_\lambda$

Measurement of Extinction (Color Excess/Reddening)

Difference of magnitudes in two wavelengths: λ_1, λ_2

(1) We observe a star with a known stellar type in two wavelengths, λ_1 and λ_2 (= V = 0.55 μm).

(2) Since we know the stellar type, the difference of extinctions in two wavelengths can be measured.

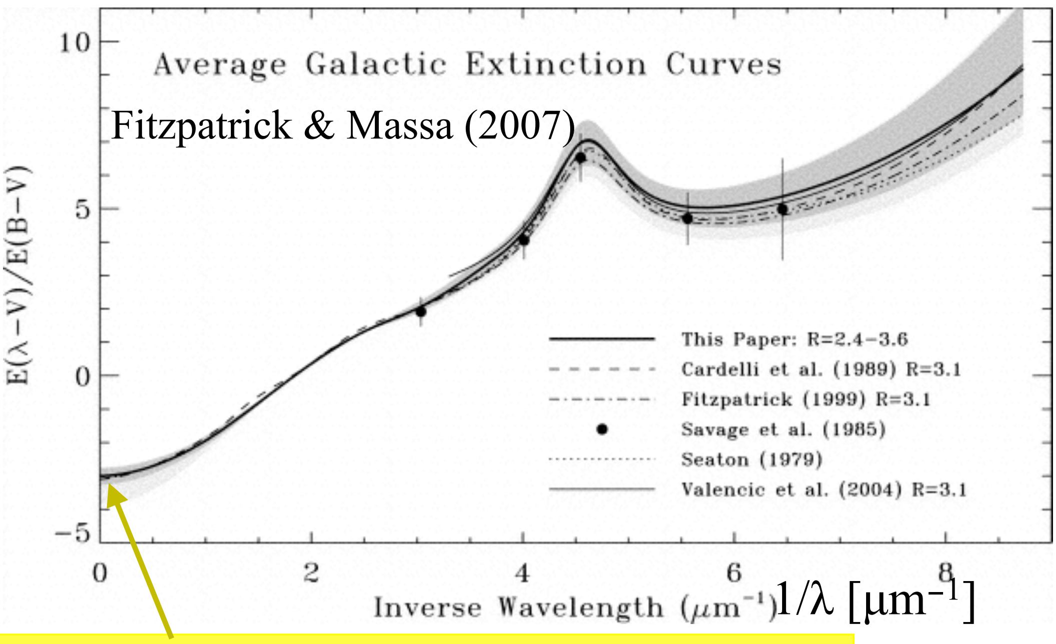
$$(m_{\lambda 1} - m_V) = \boxed{(M_{\lambda 1} - M_V)} + (A_{\lambda 1} - A_V)$$

$E(\lambda_1 - V) \equiv (A_{\lambda 1} - A_V)$: color excess / reddening

Observed. Known from the spectral type.

We can obtain $E(\lambda - V)$ as a function of λ.

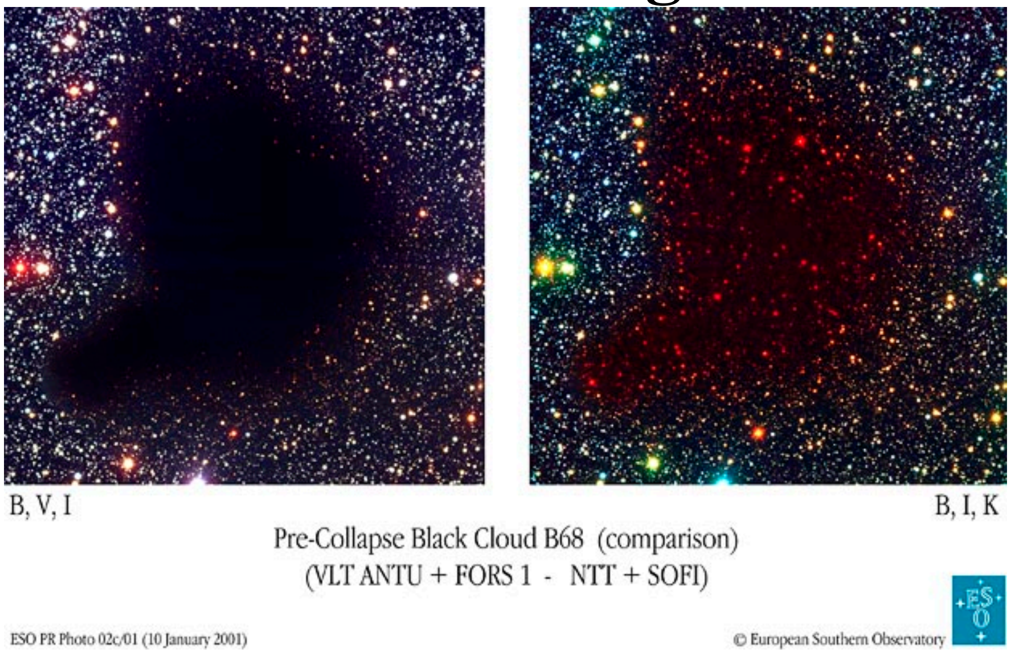
Extinction Curve in the MW



$-R_V \equiv E(\infty - \mathrm{V})/E(B - V) = -A(V)/E(B - V)$

$R_V = 3.1$

Reddening



Extinction depends on the wavelength (selective extinction).
⇒ The size of dust grains should be less than ~ 1 μm.

Extinction Curves in Nearby Galaxies

Pei (1992)

$A_\lambda/A_{0.44\mu m}$

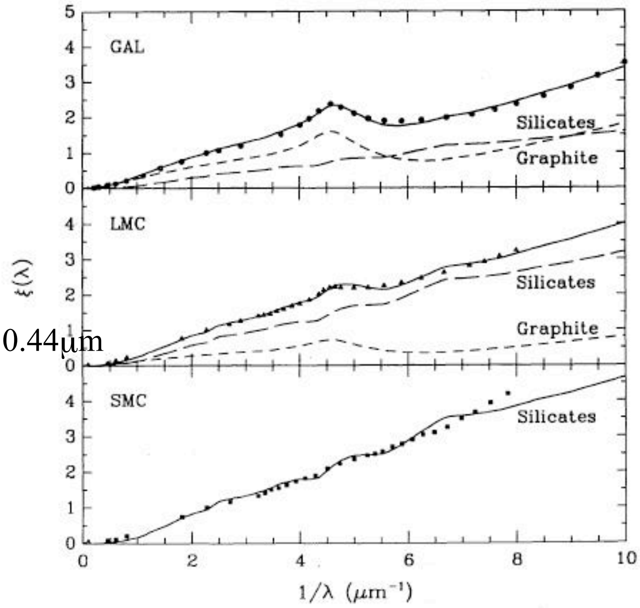


FIG. 5.—Comparisons between the model and empirical extinction curves in the Milky Way, LMC, and SMC. The short and long-dashed lines show, respectively, the relative contributions from graphite and silicate grains, with the sum of the two shown as the solid lines.

Fitting:
Grain size distribution
$n(a) \propto a^{-3.5}$
(Mathis et al. 1977)

$a_{min} = 0.005\ \mu m$
$a_{max} = 0.25\ \mu m$

Calzetti Extinction Curve for Starbursts

Calzetti et al. (1994)

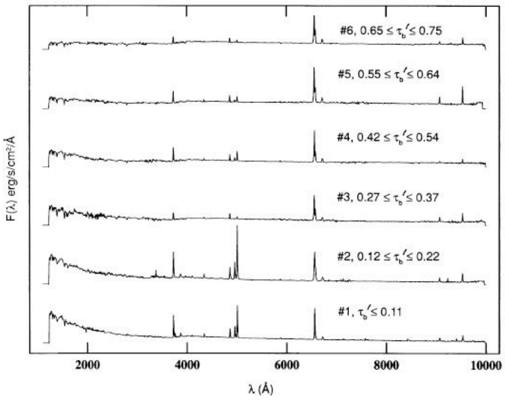


FIG. 17.—The spectra of the six templates are shown for increasing values of the extinction parameter τ_B', from the bottom to the top of the figure.

Balmer decrement Hα/Hβ: indicator of extinction

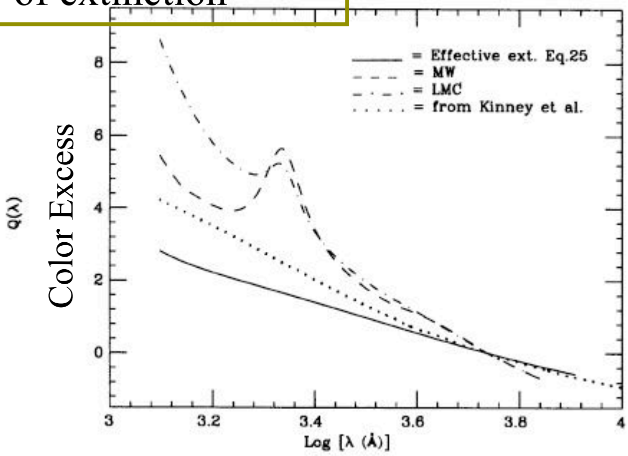


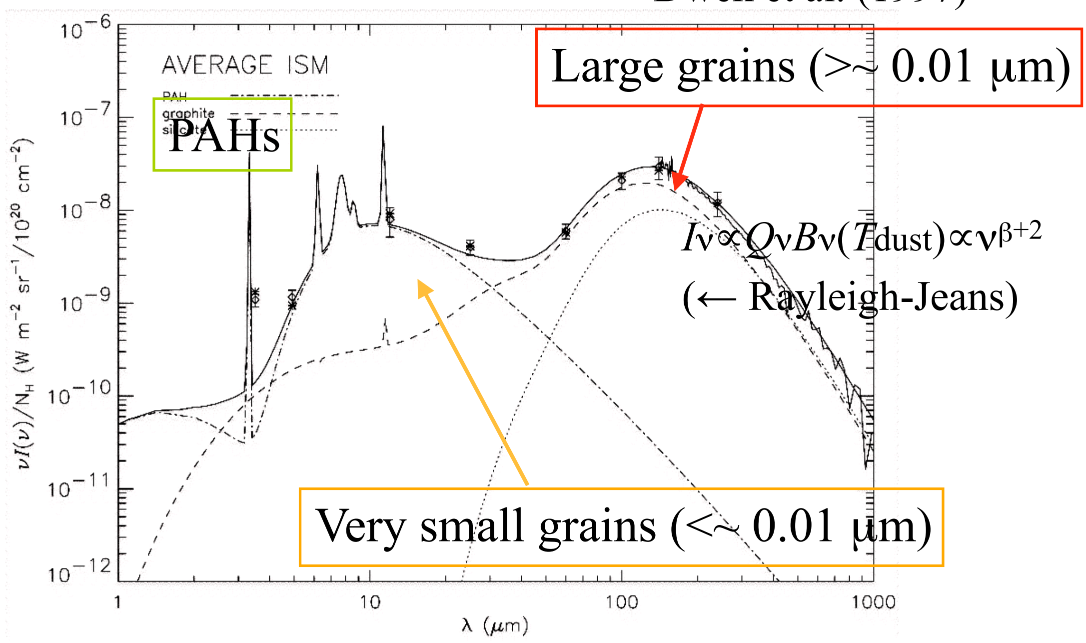
FIG. 21.—The extinction law derived in this work (eq. [25], *continuous line*) is compared with the Milky Way (*dashed line*) and the LMC (*dot-dashed line*) extinction laws. The extinction law derived by Kinney et al. (1994b) is also shown (*dotted line*). The zero point of the four curves is arbitrary and has been chosen to be the value $Q(5500) = 0.0$.

Relative geometry between star and dust distribution is important (e.g., Inoue 2005)

Dust Emission

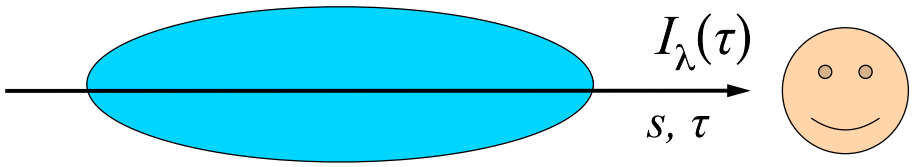
Infrared Spectrum of the Milky Way

Dwek et al. (1997)



COBE data + Model

Emission Only (FIR, sub-mm)



Emission from large grains with a constant $T_{\rm dust}$

τ_ν: optical depth for absorption

$dI_\nu/d\tau_\nu = B_\nu(T_{\rm dust}) \longrightarrow I_\nu(\tau_\nu) = \tau_\nu B_\nu(T_{\rm dust})$

$\tau_\nu \propto \nu^\beta$ ($\beta = 1 - 2$)

Wien's displacement law

$h\nu_{\rm max} = 2.82\, kT$ ⟶ Peak of the emission ~ 100 – 200 μm means a temperature ~ 30 – 15 K.

In fact, $\tau_\nu \propto \nu^\beta$ ($\beta = 1 - 2$), so the peak is slightly different.

What Determines the Temperature?

Radiative Equilibrium

$$\int_0^\infty \sigma(\lambda,a) J_\lambda \, d\lambda = \int_0^\infty \sigma(\lambda,a) B_\lambda(T) \, d\lambda$$

Absorption of stellar light $=$ Thermal emission

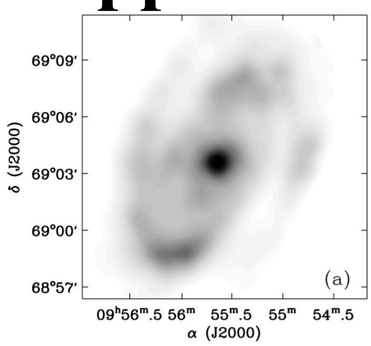
J_λ: interstellar radiation field

$B_\lambda(T)$: Planck function

$\sigma(\lambda, a)$: cross section for emission

a: radius of the grain

Application: Dust Mass Estimate



$$L_\nu = 4\pi D^2 F_\nu = \kappa_\nu M_{\rm dust} B_\nu(T_{\rm dust})$$

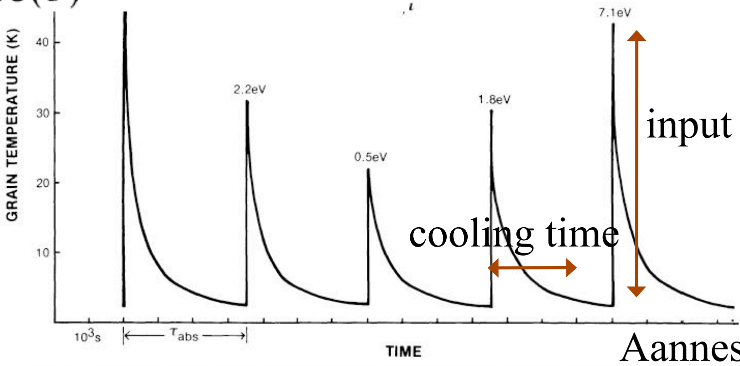
$$\kappa_\nu = \frac{\pi a^2 Q_{\rm abs}(a,\,\nu)}{\frac{4}{3}a^3 s} = \frac{3Q_{\rm abs}(a,\,\nu)}{4as}$$

($Q_{\rm abs}(a, \nu)/a$: independent of a for $a >\sim \lambda$)
Dust mass is insensitive to the grain size distribution
(as long as $a << \lambda$)

Very Small Grains

large surface/volume ratio → easy to cool
small cross section → large interval of photon injection
⇒ Small grains show large temperature fluctuation (stochastic heating).

$$\frac{dT}{dt} = \frac{3}{aC(T)}\left[H - \langle Q_{\rm abs}\rangle_T \sigma T^4\right]$$

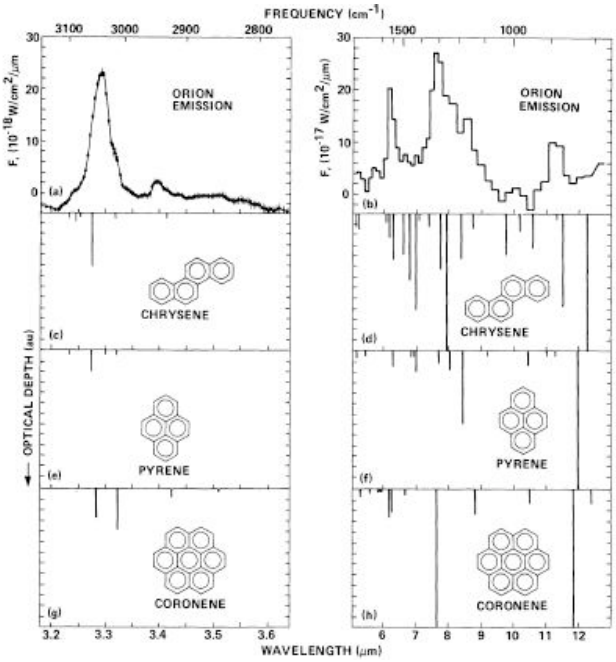


Aannestad et al. (1979)

Fig. 1. Typical temperature fluctuations of an interstellar grain of radius 0.005 μ due to absorption of various starlight photon energies at a mean interval of 3.5 × 10³ s.

PAHs

Unidentified Infrared (**UIR**) features



PAH=Polycyclic Aromatic Hydrocarbon

Allamandola et al. (1989)

Further Reading

• Evans, A. 1995, “The Dusty Universe”, (Wiley: New York)
• Krügel, E. 2003, “The Physics of Interstellar Dust”, (IoP: Bristol)
• Rybicki, G. B., & Lightman, A. P. 1979, “Radiative Processes in Astrophysics”, (Wiley: New York)