Dust Extinction and Emission

Hiroyuki Hirashita
(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

Dark clouds in the Milky Way
← Dust extinction (= absorption + scattering)

Milky Way in Far-Infrared (FIR)

$COBE$ 140 $\mu m$

Dust emission
Spiral Galaxies (Edge-on)

Wainscoat et al. (1987)

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

Contour: Far-infrared intensity
Image: Optical

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

M81 (Face-on)

Optical: stars

FIR: dust

Sun & Hirashita (2011)
What to Understand?

Radiation Transfer Equation

absorbing and emitting medium

\[ \frac{dI_\nu}{ds} = -\rho \kappa_\nu I_\nu + j_\nu \]

\(I_\nu(s)\): intensity
(energy per unit time per unit area per unit solid angle)

\(\kappa_\nu\): mass absorption coefficient
\(\rho\): density
\(j_\nu\): emissivity

absorption
emission
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:

\[
dI_\nu/d\tau_\nu = -I_\nu + S_\nu
\]

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

Local Thermodynamic Equilibrium (LTE):

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

The Cross Section of Grains

\[ \sigma_{\nu, \text{ext}} = \sigma_{\nu, \text{abs}} + \sigma_{\nu, \text{sca}} \]

\[ \sigma_{\nu, \text{abs}} = \pi a^2 Q_{\text{abs}}(a, \nu) \]

\[ \sigma_{\nu, \text{sca}} = \pi a^2 Q_{\text{sca}}(a, \nu) \]

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

General properties about \( Q_{\text{abs}} \) and \( Q_{\text{sca}} \)

\( x = 2\pi a/\lambda \)

- \( Q_{\text{abs}} \sim 1 \) and \( Q_{\text{sca}} \sim 1 \) for \( x \sim 1 \)
- \( Q_{\text{abs}} \sim 4\pi x(3\varepsilon_2/|\varepsilon + 2|^2) \) and \( Q_{\text{sca}} \sim (8x^4/3)|(|\varepsilon - 1|/(\varepsilon + 2)|^2 \) for \( x << 1 \)

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

Material properties through \( \varepsilon \)
Dust Extinction

Extinction Only (UV, Opt, NIR)

Extinction = Absorption + Scattering

$\tau$: optical depth for extinction

$\frac{dI_\lambda}{d\tau_\lambda} = -I_\lambda(\tau_\lambda)$

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

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: $\lambda_1, \lambda_2$

(1) We observe a star with a known stellar type in two wavelengths, $\lambda_1$ and $\lambda_2$ ($= V = 0.55 \, \mu m$).

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

\[
(m_{\lambda_1} - m_V) = (M_{\lambda_1} - M_V) + (A_{\lambda_1} - A_V)
\]

\[
E(\lambda_1 - V) = (A_{\lambda_1} - A_V): \text{color excess / reddening}
\]

Observed. Known from the spectral type.

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

---

**Extinction Curve in the MW**

Fitzpatrick & Massa (2007)

\[-R_V \equiv E(\infty - V)/E(B - V) = -A(V)/E(B - V)\]

$R_V = 3.1$
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)

Fitting:
Grain size distribution
\[ n(a) \propto a^{-3.5} \]
(Mathis et al. 1977)
\[ a_{\text{min}} = 0.005 \ \text{µm} \]
\[ a_{\text{max}} = 0.25 \ \text{µm} \]
Relative geometry between star and dust distribution is important (e.g., Inoue 2005)

Balmer decrement Hα/Hβ: indicator of extinction

Dust Emission
Infrared Spectrum of the Milky Way

Dwek et al. (1997)

Large grains (>~ 0.01 µm)

Very small grains (<~ 0.01 µm)

\[ I \propto Q_B(T_{dust}) \propto \nu^{\beta+2} \]

\[ \tau_I \approx \frac{dI}{d\tau} \]

\[ \frac{\tau_I}{\tau} = B_{\nu}(T_{dust}) \]

\[ \tau_{\nu} \propto \nu^\beta (\beta = 1 - 2) \]

Wien’s displacement law

\[ h\nu_{\max} = 2.82 \, kT \]

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

- \( J_\lambda \): interstellar radiation field
- \( B_\lambda(T) \): Planck function
- \( \sigma(\lambda, a) \): cross section for emission
- \( a \): radius of the grain

Application: Dust Mass Estimate

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

\[ \kappa_\nu = \frac{\pi a^2 Q_{abs}(a, \nu)}{\frac{4}{3} a^3 s} = \frac{3 Q_{abs}(a, \nu)}{4 a s} \]

\( Q_{abs}(a, \nu)/a \): independent of \( a \) for \( a \gg \lambda \)

Dust mass is insensitive to the grain size distribution (as long as \( a \ll \lambda \))
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).

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

Fig. 1. Typical temperature fluctuations of an interstellar grain of radius 0.005 μm due to absorption of various starlight photon energies at a mean interval of 3.3 × 10^{-6} s.

PAHs

Unidentified Infrared (UIR) features

PAH = Polycyclic Aromatic Hydrocarbon

Allamandola et al. (1989)
Further Reading

• Krügel, E. 2003, “The Physics of Interstellar Dust”, (IoP: Bristol)