$(AGN)^2$

7. Interstellar Dust

Week 10

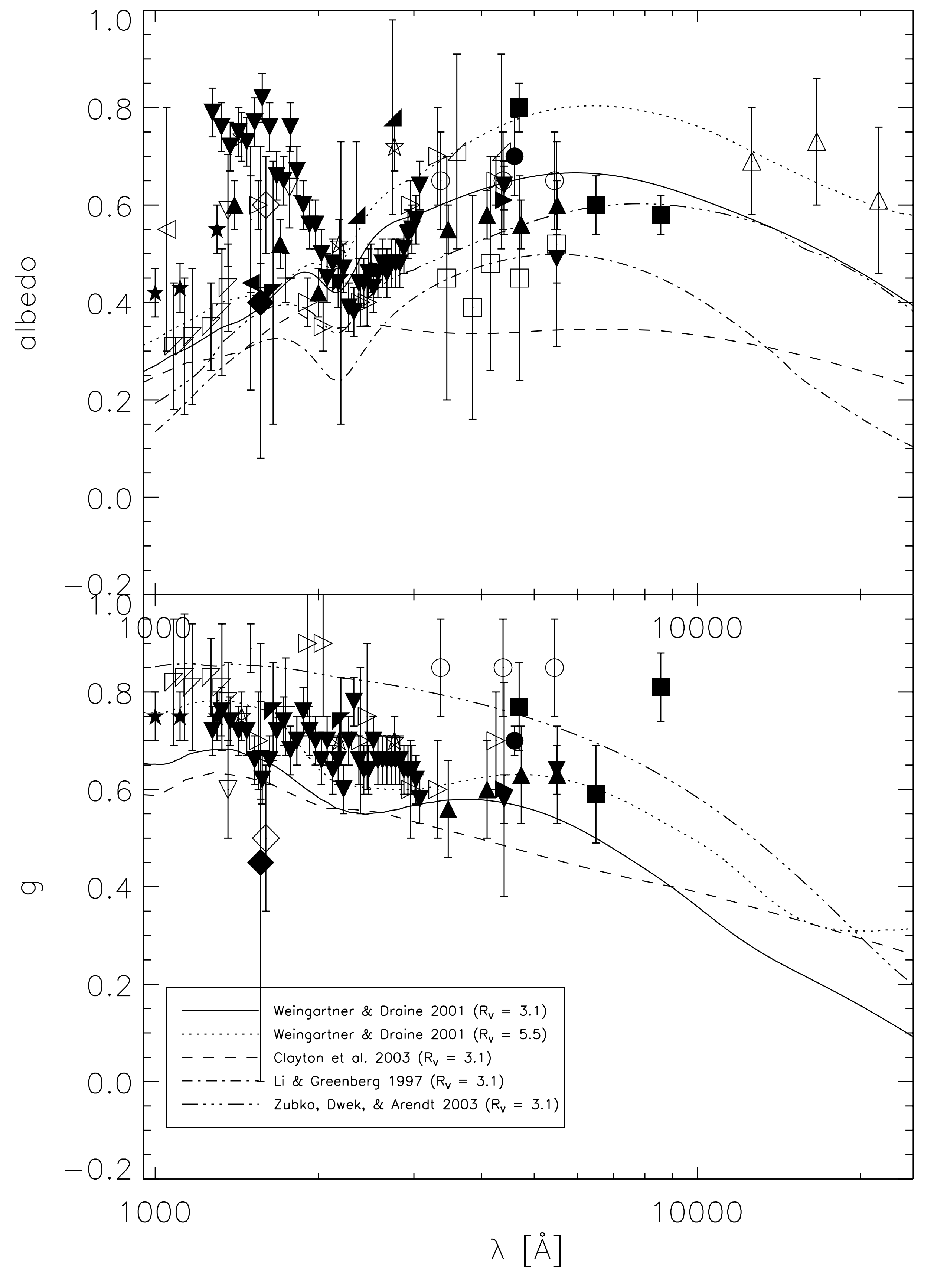
May 08 (Wednesday), 2024

updated on 05/10, 13:17

선광일 (Kwangil Seon)

KASI / UST

- Comparison with Observations



Karl D. Gordon (2004)
Astrophysics of Dust
(ASP Conference Series, Vol. 309, 77)

https://www.stsci.edu/~kgordon/Dust/Scat_Param/scat_data.html

7.7 Effects of Grains on Surrounding Gas

- Grains seem to be about as important as He in their effects on the ionization and temperature structure of a nebula.
  - Grains absorb some of the ionizing continuum and their photoionization can heat the gas.
- Electric Charge of a dust grain in a nebula
  - The charge results from the competition between (1) photoejection of electrons from the solid particle by the UV photons, which tends to make the charge positive, and (2) captures of positive ions and electrons from the nebular gas, which tend to make the charge more positive and negative, respectively.
  - Typical grain materials have work functions (ionization potential) between 4 and 10 eV.
- Equilibrium equation for the charge on a grain

Photoelectric Emission:

- The rate of increase of the charge Ze due to photoejection of electrons can be written

$$\left(\frac{dZ}{dt}\right)_{\rm pe} = \pi a^2 \int_{\nu_{\rm K}}^{\infty} \frac{4\pi J_\nu}{h\nu} Q_\nu^{\rm abs} \phi_\nu d\nu$$

where ϕ_ν is the photodetachment probability ($0 \le \phi_\nu \le 1$) for a photon that strikes the geometrical cross section of the particle.

- **[Threshold]** If the dust particle is electrically neutral or has a negative charge, the effective threshold is $h\nu_{\rm K} = h\nu_{\rm c}$ (the threshold of the material). If the particle is positively charged, the lowest energy photoelectrons cannot escape. Therefore, the threshold is

$$\begin{aligned} h\nu_{\rm K} &= h\nu_{\rm c} + Ze^2/a & Z &< 0 \\ &= h\nu_{\rm c} & Z &\le 0 \end{aligned}$$

Here, $-Ze^2/a$ = the potential energy at the surface of the particle.

Collisional Charging:

See Chap. 25 in "Physics of the Interstellar and Intergalactic Medium" (Draine) for the derivation of the formulae

Chap 4 in "The Physics of the Interstellar Medium" (Dyson and Williams)

- The rate of increases of the charge due to capture of electrons is

$$\left(\frac{dZ}{dt}\right)_{\rm ce} = -\pi a^2 n_e \sqrt{\frac{8kT}{\pi m_e}}\xi_e Y_e$$

$$\langle v \rangle = \int_0^\infty v f(v) dv = \sqrt{\frac{8kT}{\pi m_e}}$$ = mean speed for the Maxwell distribution of speed.

ξ_e = the electron-sticking probability ($0 < \xi_e < 1$)

$$Y_e = 1 + \frac{Ze^2}{a}\frac{1}{kT} \qquad Z > 0$$

$$= \exp(Ze^2/akT) \qquad Z \le 0$$

Y_e is the factor due to the attraction or repulsion (Coulomb focusing) of the charge on the particle.

- The rate of increases of the charge caused by capture of protons is

$$\left(\frac{dZ}{dt}\right)_{\rm cp} = \pi a^2 n_p \sqrt{\frac{8kT}{\pi m_{\rm H}}}\xi_p Y_p$$

$$Y_p = 1 - \frac{Ze^2}{a}\frac{1}{kT} \qquad Z \le 0$$

$$= \exp(-Ze^2/akT) \qquad Z > 0$$

Equilibrium Equation

- Thus, the charge on a particle can be found from the solution of the equation:

$$\frac{dZ}{dt} = \left(\frac{dZ}{dt}\right)_{\rm pe} + \left(\frac{dZ}{dt}\right)_{\rm ce} + \left(\frac{dZ}{dt}\right)_{\rm cp} = 0$$

  In this equation, the factor πa^2 cancels out, but the dependence on a through the surface potential remains.

  The equation can be solved numerically for a model nebula for which the density and the radiation field are known.

- [General result] In the inner part of an ionized nebula, photoejection dominates and the particles are positively charged. In the outer parts, where the UV flux is smaller, the collision with electrons dominate and the particles are negatively charged because more electrons strike the particle.

• Grain Temperature

Heating is caused by absorption of the local radiation field and collisions with gas

- The radiation field is usually most important and the heating rate is given by

$$\dot{E}_{\rm heat} = \pi a^2 \int_0^\infty \frac{4\pi J_\nu}{h\nu} Q_\nu^{\rm abs} (1 - \phi_\nu) d\nu$$ for the radiation field J_ν incident upon dust grains.

  For $\nu < \nu_{\rm K}$, $\phi_\nu = 0$ (all the energy of absorbed photons heat the grain). For $\nu > \nu_{\rm K}$, $\phi_\nu \neq 0$ (some of the energy goes into the photoelectron, with much goes into heating the grain)

Cooling is predominantly due to emission in the IR continuum.

- The cooling rate is given by Kirchhoff's law.

  The cooling due to a spherical grain of radius a is

  $$\dot{E}_{\rm cool} = n_{\rm D}(\pi a^2)\int_0^\infty Q_\nu^{\rm abs} 4\pi B_\nu(T_{\rm D})d\nu$$ where $T_{\rm D}$ is the dust temperature.

  The cooling mainly occurs in the IR, where $\lambda \gg a$ and $Q_\lambda^{\rm abs} \propto \lambda^{-1}$. As a result,

  $$T_{\rm D} \propto \left(\frac{L}{4\pi r^2 a}\right)^{1/5}$$

- For a representative particle with $a = 3.0 \times 10^{-5}$ cm, the dust temperature is $T_{\rm D} \approx 100$ K at $r = 3$ pc from the star (with the 40,000 K blackbody radiation).

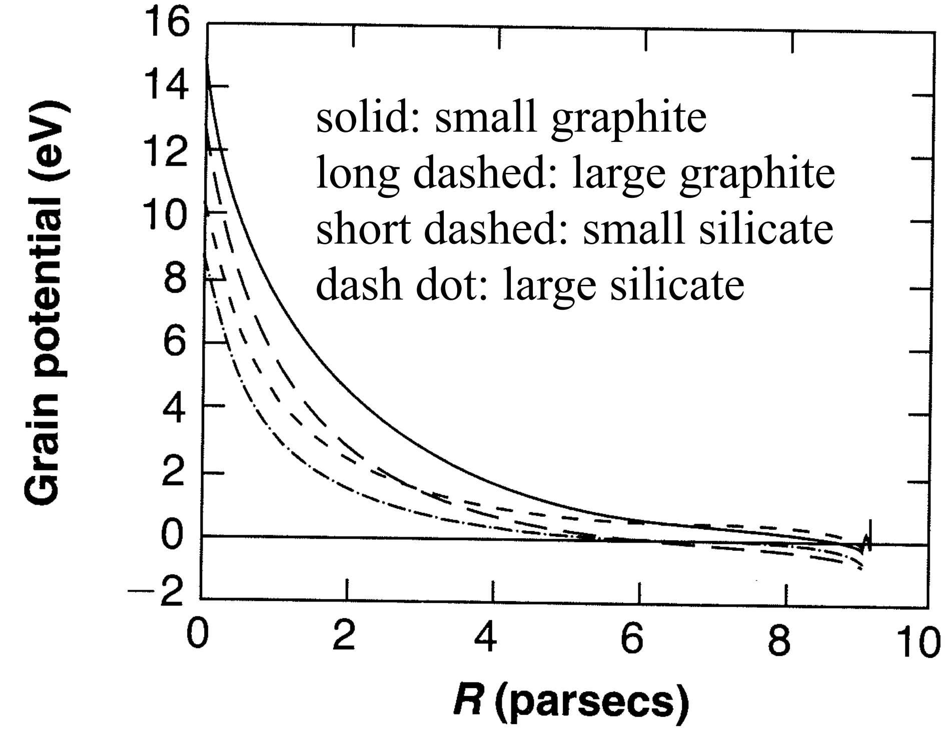
- In H II regions,
  - The ionization region is smaller than the dust-free case due to dust absorption of the LyC.

Near the central star

- The ionizing radiation field creates a positive charge, which then creates the attractive Coulomb force.
- The grain "ionization potential" is this Coulomb potential + the work function.
- Grain photoionization accounts for ~ 30% of the total heating in these regions.
- Smaller grains tend to have a larger potential and to be hotter, due to their smaller radius.
- Graphite is more highly charged than the silicates due to the larger cross section at higher energies.

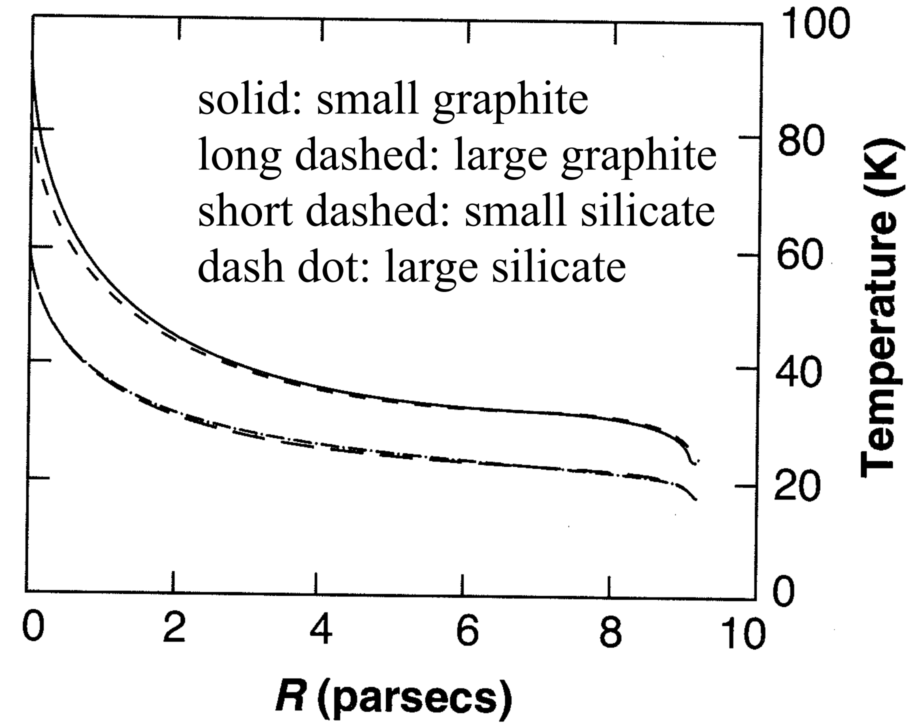
In outer regions

- The radiation field is extinguished and grains recombine more rapidly than they are ionized, creating a negative charge



[Figure 7.10]
A 40,000 K black body source is assumed.
Here, small = 0.03 μm, large = 0.2 μm.

- Grain temperature
  - The temperature is not strongly affected by the grain composition but the grain size is important.
  - Small grains are hotter than large grains because Q^{abs} is smaller and they cool less efficiently in the IR.
  - The total emission originating from large grains can be approximated by a single equilibrium temperature. However, it is not the case for small grains.
  - Grains are hotter near the star.
  - The total emission is the volume integral of the cooling rate and is strongly weighted to warmer regions due to the temperature dependence of the Planck function.



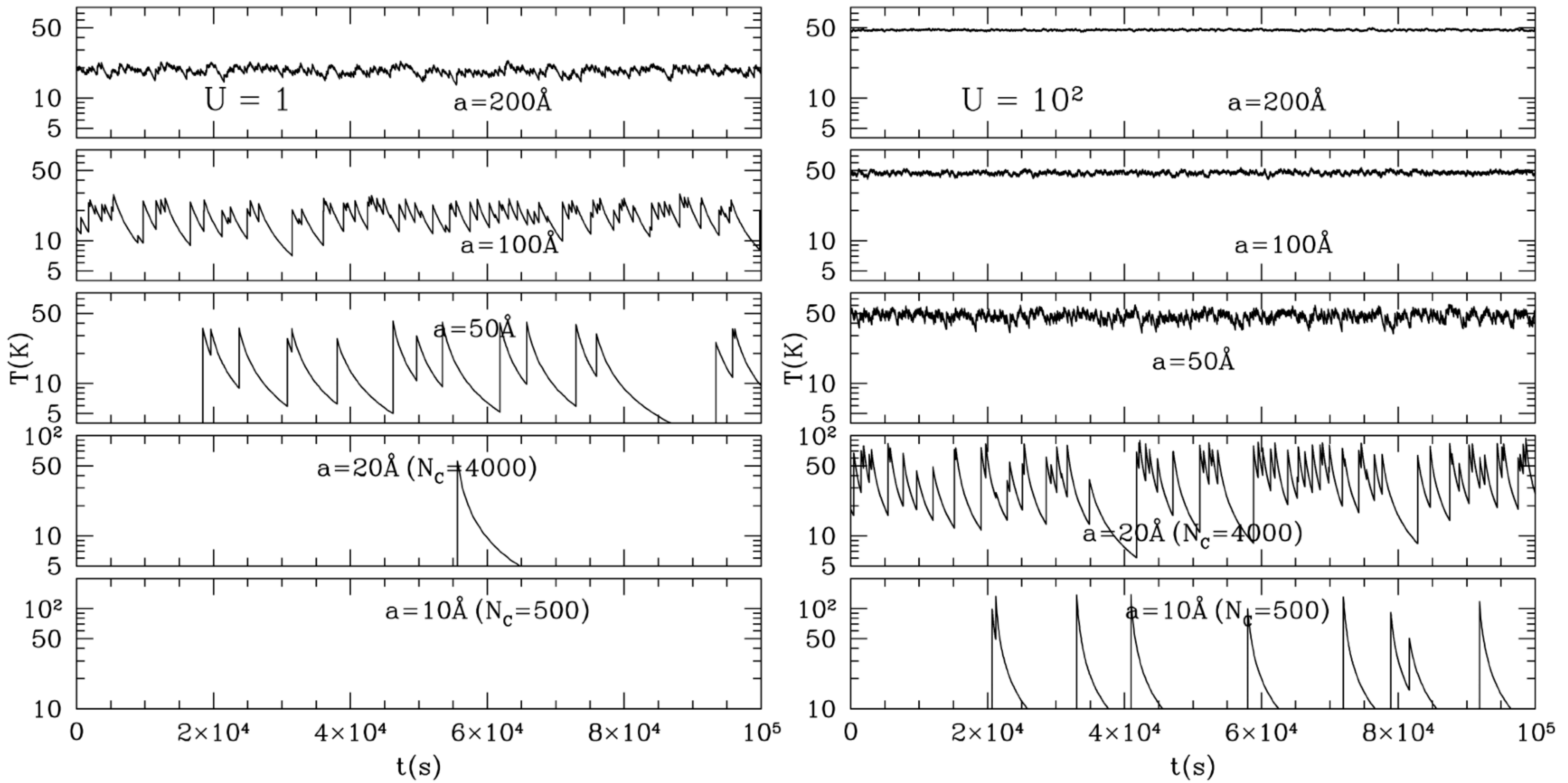
[Figure 7.10]
A 40,000 K black body source is assumed.
Here, small = 0.03 μm, large = 0.2 μm.

(Temperatures of Interstellar Grains)

- Large Grains
  - Grains with radii $a \gtrsim 0.03\,\mu$m, can be considered "classical." These grains are macroscopic - *absorption or emission of single quanta do not appreciably change the total energy in vibrational or electronic excitations*.
  - The temperature of a large dust grain can be obtained by equating the heating rate to the cooling rate.
- Very Small Grains
  - For ultra-small particles, ranging down to large molecules, quantum effects are important (this include the "spinning" dust grains responsible for microwave emission).
  - When a dust particle is very small, its temperature will fluctuate. The happens because whenever an energetic photon is absorbed, *the grain temperature jumps up by some not negligible amount* and subsequently declines as a result of cooling.
  - To compute their emission, *we need their optical and thermal properties (dielectric function and specific heat capacity c_V)*.
    - The optical behavior depends in a sophisticated way on the the complex index of refraction and on the particle shape.
    - The thermal behavior is determined more simply from the specific heat.
  - We need to calculate the distribution function of temperature.

(The Stochastic Time Evolution of Grain Temperature)

Monte-Carlo simulations of the temperature fluctuation:
See Draine & Anderson (1985, ApJ, 292, 494) and Krugel (The Physics of Interstellar Dust, IoP).



Temperature versus time during 10^5 s (~1 day) for five carbonaceous grains in two radiation fields: the local starlight intensity (U = 1; left panel) and 10^2 times the local starlight intensity (U = 10^2; right panel). The importance of quantized stochastic heating is evident for the smallest sizes.

[Fig 24.5, Draine]

- Sublimation Temperature of ices
  - $T_{sub} = 20\,K$ for CH_4 (methane), $T_{sub} \approx 60\,K$ for NH_3 (ammonia), $T_{sub} \approx 100\,K$ for H_2O (water).

    CH_4 cannot be held anywhere in the nebula.

    NH_3 vaporizes except in the outer parts.

    H_2O evaporates only in the innermost parts.
  - $T_{sub} \approx 10^3\,K$ for graphite, silicate, and silicon carbide particles

    Hence, they are less sublimated.
- Polarization
  - Most of studies assume that grains are spherical, for simplicity. However, scattered light by grains and transmitted light through grains is found to be polarized.
  - This indicates that grains are (1) not non-spherical and (2) aligned with the galactic magnetic field ($B \sim 5\,\mu G$).
  - Grains are thought to be composed of paramagnetic materials, interacting with magnetic fields. (1) Gas-grain collisions and the recoil caused by emitted or absorbed photons and (2) the radiative torque cause the grain to spin.
  - An interaction between the galactic magnetic field and the spinning grain help align it with the field.
  - Observations of polarization can give information on the geometry and strength of the galactic magnetic field.

7.8 Dynamical Effects of Dust in Nebulae

- Radiation Force
  - Dust particles in a nebula are subjected to radiation pressure from the central star.
  - However, the coupling between the dust and gas is very strong, so the dust particles do not move through the gas to any appreciable extent, but rather transmit the central repulsive force of radiation pressure to the entire nebula.

Radiation force on a dust particle of radius a by the central star is

$$F_{\rm rad} = \pi a^2 \int_0^\infty \frac{F_\nu}{c} Q_\nu d\nu = \pi a^2 \int_0^\infty \frac{L_\nu}{4\pi r^2 c} Q_\nu d\nu, \text{ where } Q_\nu = Q_\nu^{\rm abs} + Q_\nu^{\rm scatt}(1-g).$$

Most of the radiation from hot stars has $\lambda \ll a$. Then, $Q_\nu \approx 1$. In this case, $F_{\rm rad} \approx \dfrac{a^2 L}{4r^2 c}$.

However, this is not true for very small particles or for very cool stars.

- The diffuse radiation field is more isotropic and its effect can be neglected in the radiation force.

Drag force: The force tends to accelerate the dust particle, but its velocity is limited by the drag on the particle due to its interaction with the gas.

- If the dust particle is neutral, this drag results from direct collisions of the ions with the grain, and the resulting force is

$$F_{\rm coll} = \frac{4}{3} n_p \pi a^2 \left(\frac{8kTm_{\rm H}}{\pi} \right)^{1/2} w \qquad \langle v \rangle = \int_0^\infty v f(v) dv = \sqrt{\frac{8kT}{\pi m_{\rm H}}}$$

where w is the velocity of the particle relative to the gas, assumed to be smaller than the mean thermal velocity.

Epstein drag: the regime where the particle size is less than the mean-free-path of the gas.
Refer to Baines et al. (1965, MNRAS, 130, 63) for the derivation of the formula.
See also Chap. 4, Astrophysics of Planet Formation (Armitage, 2nd Ed.) and Chap. 26, Draine (2011)

Thus, the particle is accelerated until two forces are balanced, and reaches a terminal velocity

$$F_{\rm rad} = F_{\rm coll} \Rightarrow w_t = \frac{3L}{16\pi r^2 c n_p}\left(\frac{\pi}{8kTm_{\rm H}}\right)^{1/2}$$, which is independent of the particle size.

For instance, for a particle at a distance of 3.3 pc from an O star, $w_t = 10\,{\rm km\,s^{-1}}$. The time required for a travel of 1 pc is about 10^5 yr.

- For charged dust particles, the Coulomb force increases the interaction between the positive ions and the particle significantly, and the drag on a charged particle has an additional term,

$$F_{\rm Coul} \approx \frac{2n_p Z^2 m_{\rm H}}{T^{3/2}} w$$

Comparison of $F_{\rm coll}$ with $F_{\rm Coul}$ shows that Coulomb effects dominate if $|Z| \geq 50$. In most regions of the nebula, the particles have a charge greater than this, the terminal velocity is even smaller and the particle motion relative to the gas is smaller yet.

Typical values are under 1 km s^{-1}. Under these conditions the dust particles are essentially frozen to the gas.

- Therefore, the radiation pressure on the particles acts on the nebular material, and the equation of motion of fluid contains this extra term:

$$\rho\frac{Du}{dt} = -\nabla P - \rho\nabla\phi + n_D\frac{a^2L}{4r^2c}\mathbf{e}_r$$ where $\mathbf{e}_r$ is the unit vector in the radial direction.

This acceleration can be appreciable, and the radiation-pressure effects should be taken into account in a model of an evolving H II region.

- Calculations showed that old nebulae will tend to develop a central “hole” that has been swept clear of gas by the radiation pressure upon the dust.

  An example of a real nebula is the Rosette Nebula (NGC 2244).

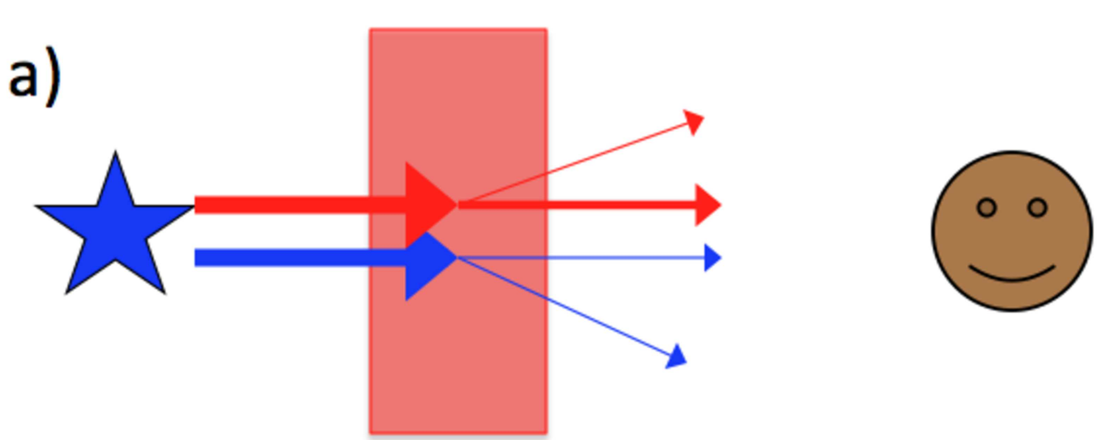
credit: Shawn Nielsen, VisibleDark

- Concluding Remarks
  - Observations clearly show that dust exist in nebulae, but its optical and physical properties are still not accurately know.
  - Models and calculations carried out to date must be considered schematic and indicative rather than definitive.

(extinction vs. attenuation)

extinction

individual point source



extinction = intrinsic property of dust

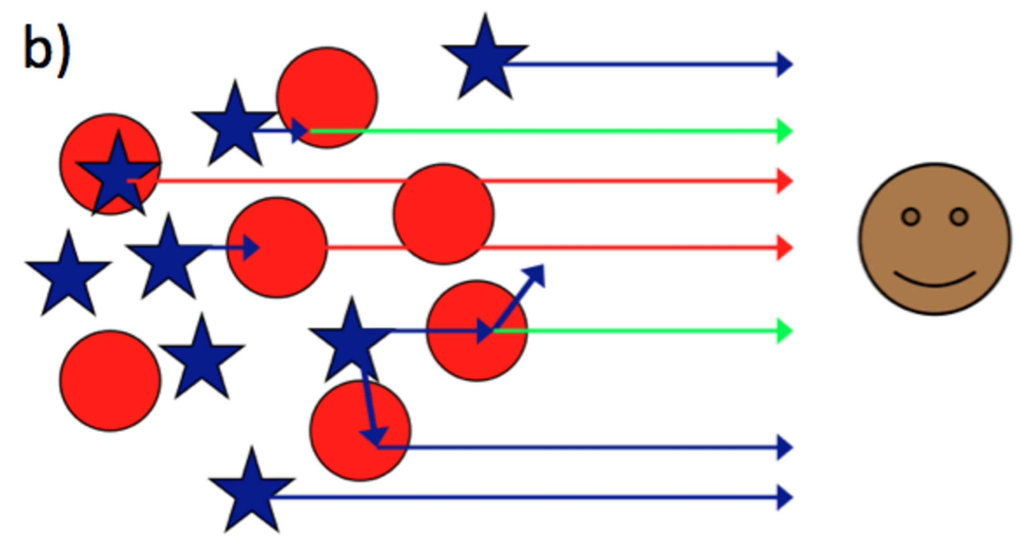
$$F_\lambda = F_\lambda^{\rm star} e^{-\tau_\lambda^{\rm ext}}$$

$$\tau_\lambda^{\rm ext} = -\ln\left(\frac{F_\lambda}{F_\lambda^{\rm star}}\right)$$

attenuation (or effective extinction)

extended source

Calzetti (2013)



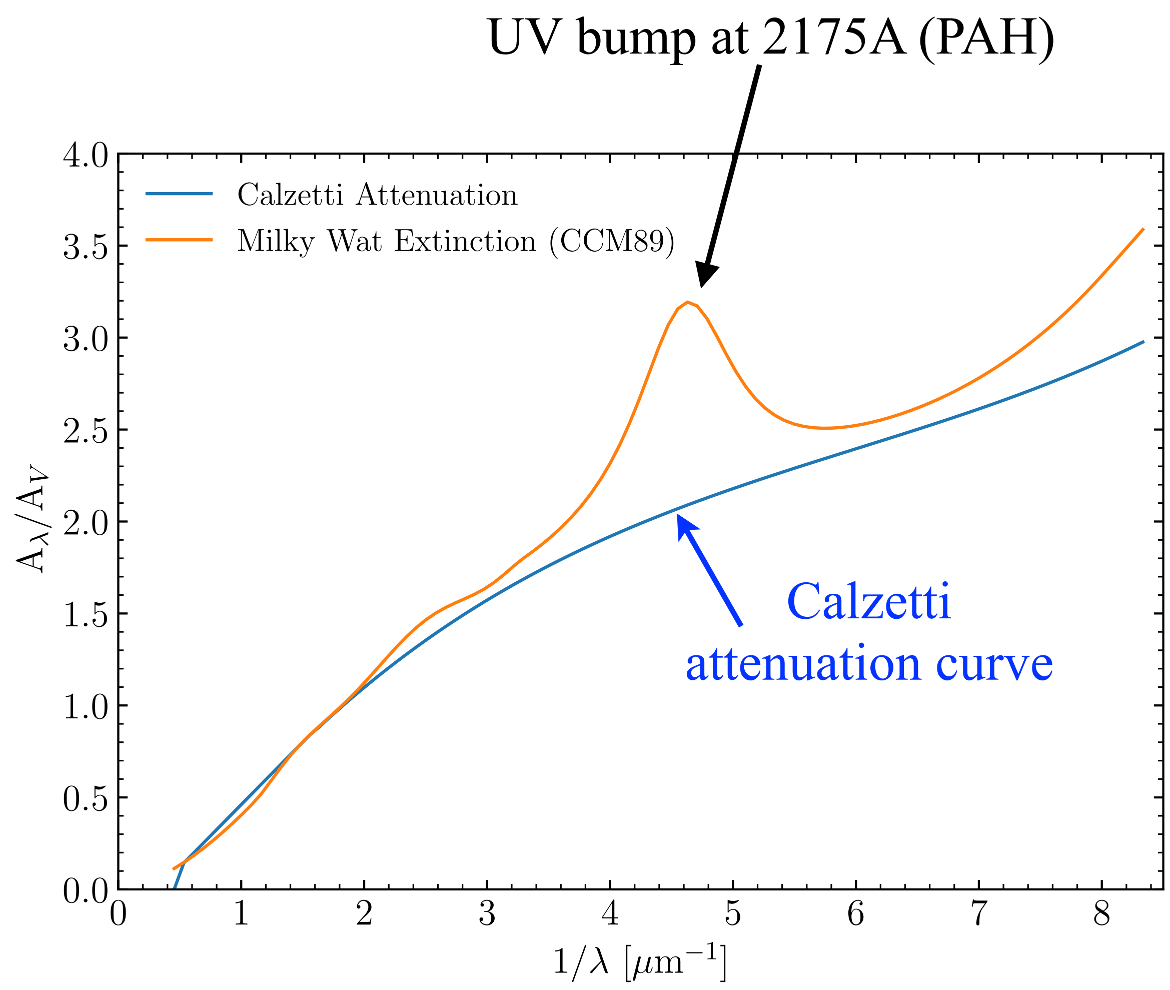
attenuation = intrinsic property of dust
+ radiative transfer effect

$$F_\lambda = F_\lambda^{\rm galaxy} e^{-\tau_\lambda^{\rm att}}$$

$$\tau_\lambda^{\rm att} = -\ln\left(\frac{F_\lambda}{F_\lambda^{\rm galaxy}}\right)$$

(Calzetti Law)

- Calzetti curve (1994, 2000) was derived from the IUE observations of local starburst galaxies.



Three Questions:

1. Why no UV bump?
2. Why shallower than the MW extinction
3. Is it universal?

- Witt & Gordon (2000) - **the SMC dust is attributed to be responsible to the Calzetti curve**, mainly because of no UV bump feature in the Calzetti curve.
- Seon & Draine (2016) - an extensive analysis on the Calzetti curve

Discussion

- https://gitlab.nublado.org/cloudy/cloudy/-/wikis/home

(1) Read the above website and Download the cloudy source code (version 23.01)

(2) Compile and Install the code

(3) Install the stellar atmosphere grids (Atlas, Tlusty, WMbasic)

(4) Go to the test suite directory “tsuite/auto.” Copy “h_otspp.in" and “h_otssp.in” into your own directories. Run the two models. (The purposes of the test suite models are explained at the end of the input file.)

(5) Plot temperature, heating, H density, electron density, H I fraction, and H II fraction as functions of radius or depth. Ensure correct physical units are labeled on the *x*- and *y*-axes. Please plot radius or depth in units of parsec (pc).

(6) Explain the differences between the two models.

To learn about the meanings of the input parameters and output file contents, read “hazy1.pdf” under the directory “docs”