Thermal radiation from cosmic dust

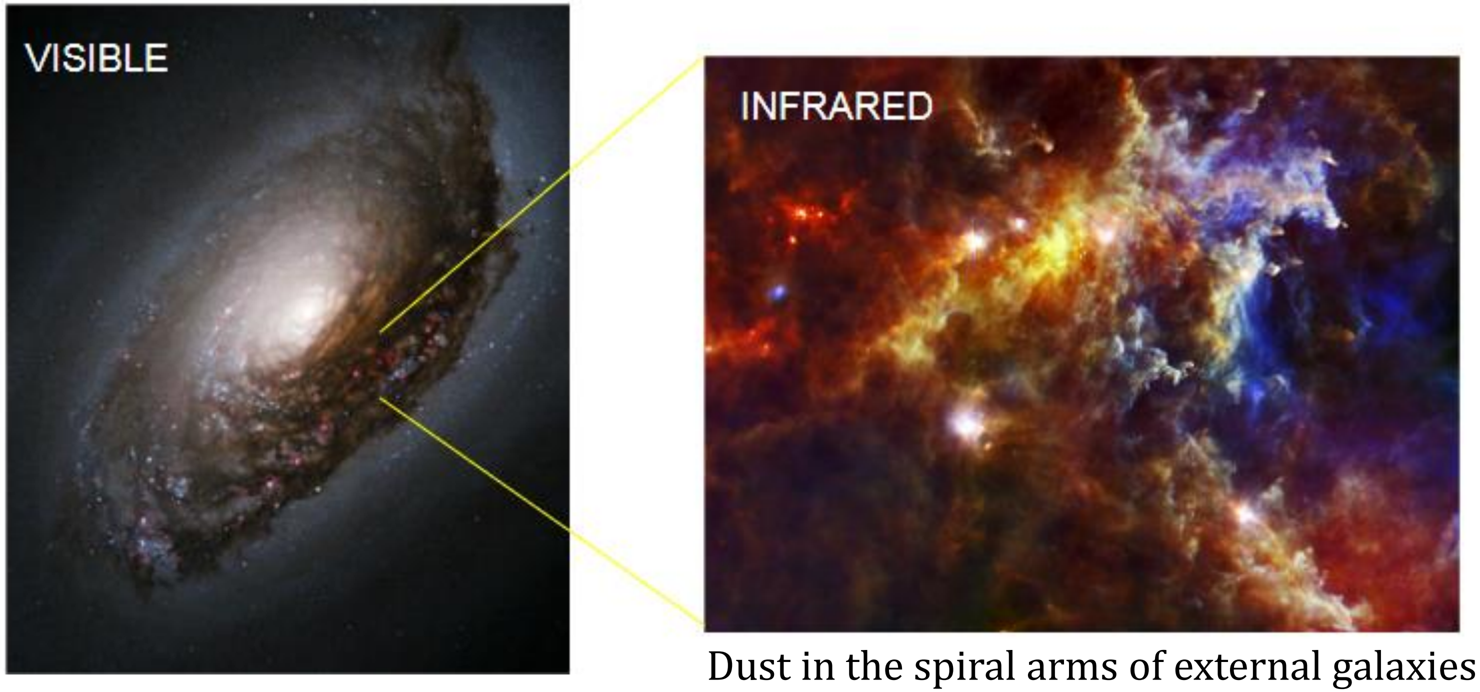
- Cosmic dust
- Dust extinction
- Interstellar reddening
- Heating and cooling of dust
- Thermal emission from dust

- Reference book: B.T. Draine, *Physics of the Interstellar and Intergalactic Medium*, Chapter 24

Cosmic dust

There are two major sources of submm radiation from galaxies: thermal continuum emission from dust grains, the solid phase of the interstellar medium (ISM), and line emission from atomic and molecular transitions in the interstellar gas. About 99% of the energy released by galaxies in the **submm and far-IR** wavebands is produced by **thermal emission from dust grains**; the remainder comes from fine-structure atomic and molecular rotational line emission.

Dust is a ubiquitous feature of the cosmos: it is formed in stars, then it is blown-off in a slow wind or a massive star explosion. The dust is then "recycled" in the clouds of gas between stars, and some of it is consumed when the next generation of stars begins to form. Even though dust is less than 1% of the baryonic mass of the Galaxy, it emits ~40% of the total luminosity.

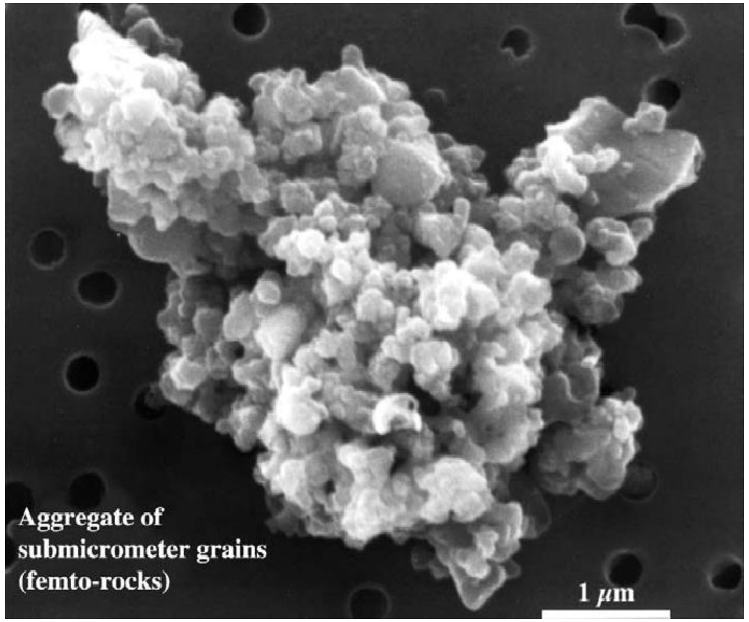


Dust in the spiral arms of external galaxies

Cosmic dust

Solid particles pervade interstellar space in the Milky Way and other galaxies, in many environments, from comets to giant molecular clouds, from circumstellar shells to galactic nuclei.

The dust is made of thin, highly flattened flakes of graphite (carbon) and/or silicates (rock-like minerals) often coated with water ice. Each dust flake is roughly the size of the wavelength of blue light or smaller: ~0.1 μm.



Model dust grain as a sphere of radius a. The extinction efficiency is the sum $Q_{ext} = Q_{abs} + Q_{scat}$ (ratios of cross sections to the geometrical , πa^2).

Mie theory (1908) solved Maxwell's equations to describe the scattering of electromagnetic radiation by a sphere.

Q_{ext} , Q_{abs} , Q_{scat} depend on size, composition (the complex refractive index of the grain material), temperature, and vary with wavelength: modifed BB spectrum.
Hot grains radiate at shorter wavelengths.

Dust extinction

Define a dimensionless **size** parameter $\mathbf{X = 2\,\pi\, \mathit{a}/\,\lambda}$ (proportional to frequency) **.**

Variation of extinction with $X \propto \lambda^{-1}$f or constant grain radius (or with grain radius varying for constant λ):

Q_{ext} increases monotonically with X for $0 < X < 4$: here extinction is dominated by scattering.

Q_{ext} becomes constant for large X.

When $X \ll 1$, $Q_{sca} \propto \lambda^{-4}$ and $Q_{abs} \propto \lambda^{-1} - \lambda^{-2}$: in the infrared, dust absorption (and also emission! Why? (*)) dominates over scattering.

For a given λ, the plots also show that small grains radiate less efficiently than large grains.

size

Increasing λ

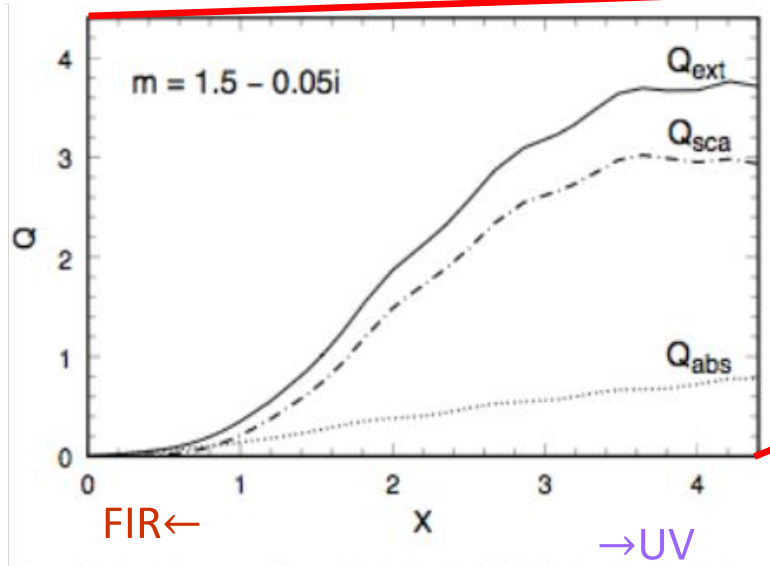


Figure 3.2. An enlargement of figure 3.1 showing the initial rise in extinction efficiency with X near the origin.

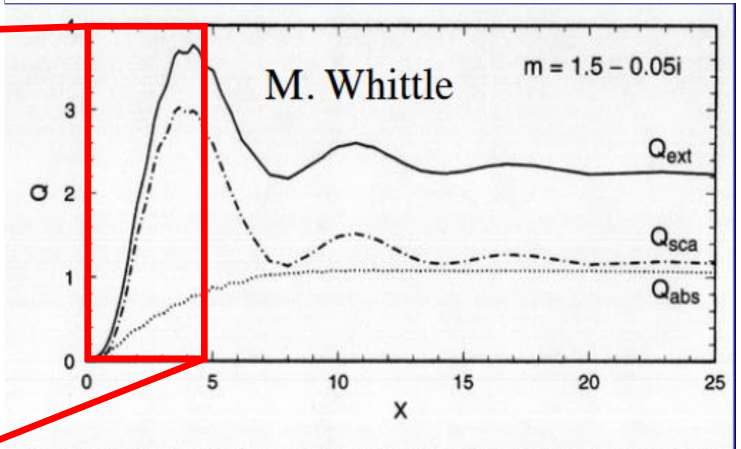


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext}, Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

To have an estimate:

since $X = 2\,\pi\, a/\,\lambda$, for grain size a= 0.1 μm, the FIR (10-1000 μm) is $X \sim 10^{-4}$ - 10^{-1} and the UV (100-400 nm) is $X \sim 6$

For detailed discussion: http://w.astro.berkeley.edu/~ay216/08/NOTES/Lecture05-08.pdf

(*) See problem 5

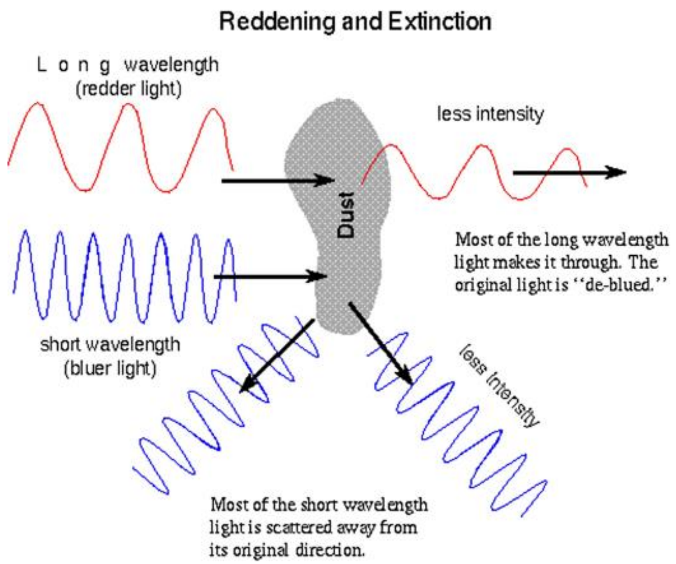
Interstellar reddening

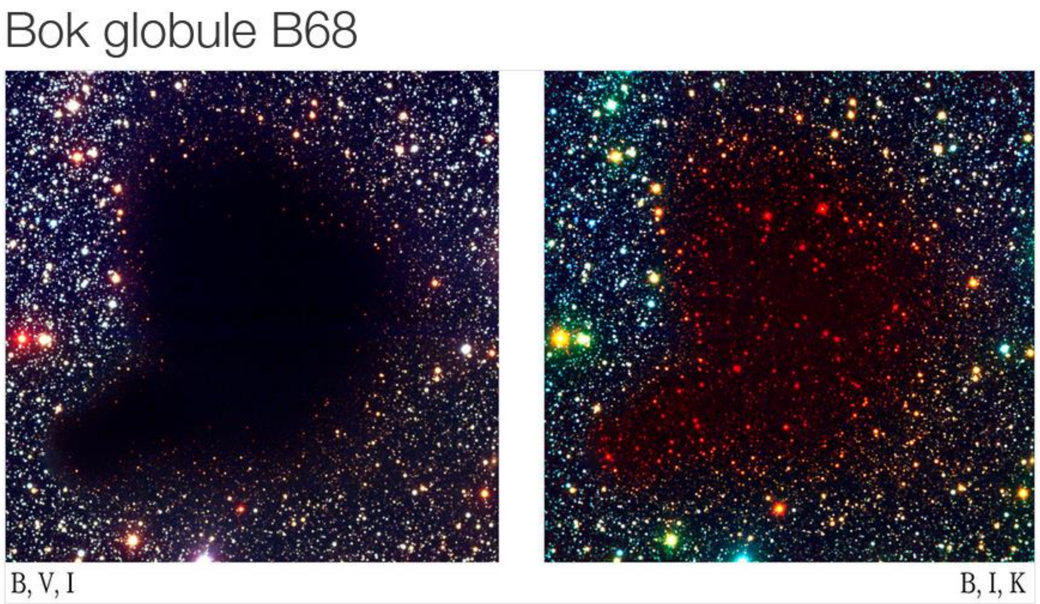
This has two consequences, one due to scattering, one due to absorption.

1) **Scattering** efficiency falls with increasing wavelength and becomes unimportant in the infrared where **absorption** dominates.

The wavelength of visible light is much the same size as many dust particles, so it is easily blocked (scattered) by the dust.

$\Rightarrow$ *interstellar reddening*





ESO Press Photo eso0102 shows a comparison of the central area of globule B68 in a colour composite of visible and near-infrared on the left and a false-colour composite based on a visible (here rendered as blue), a near-infrared (green) and an infrared (red) on the right.

Crediti: ESO

2) **Absorption**: the thermal emission is a blackbody spectrum modified by a wavelength-dependent emissivity: very inefficient absorbers/radiators at long wavelengths, with an emission efficiency of $Q_{em} = Q_{abs} \propto \lambda^{-\beta}$ (with β=1 or 2).

Remember: only absorption contributes to heating and to emission. This modifies the ISRF spectral distribution.

Heating and cooling of dust

What heats dust grains?

1. Absorb a photon of starlight
2. Collisions with atoms, electrons, cosmic rays, or other dust grains
3. Absorb energy from chemical reactions occurring on grain surfaces (e.g., H_2 formation)

Radiative heating of dust grains (1) important because of the large energy density of starlight ($\sim$0.5 eV cm $^{-3}$) and the grain's high opacity to starlight. A photon can leave the grain in an excited state, with a timescale of $\sim 10^{-7}$ s for spontaneous re-emission. Complex molecules making up grains have many excited states and can quickly (10^{-12} sec) redistribute that energy into internal vibrational states, heating the grain.

Emission timescale/vibrational redistribution timescale $\sim 10^{-5}$ $\Longrightarrow$ most photon absorptions will efficiently heat the grain.

How do grains cool?

1. Emit a thermal photon $\Leftarrow$ expected to dominate and setup LTE and radiative equilibrium in most ISM conditions
2. Collide with cold atoms or molecules
3. Ejection (sublimation) of atoms or molecules from the surface of the grain

Thermal emission from dust

Remember that the flux at the surface of an uniformly emitting sphere is $F_\nu = \pi I_\nu$ (CGS, erg s^{-1} Hz $^{-1}$ cm^{-2})

Consider a spherical dust grain with radius a immersed in the Galactic ISRF.

The balance between energy absorbed by the grain and thermal energy emitted (over 4π sr) by the grain is:

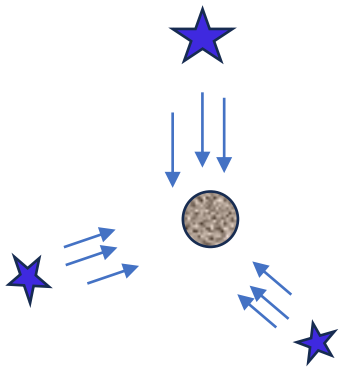
$$\left(\frac{dE}{dt}\right)_{abs} = \int_0^\infty \frac{u_\nu d\nu}{h\nu} \, \underline{c\, h\nu} \; Q_{\rm abs}(\nu)\, \underline{\pi a^2} = \underbrace{4\pi a^2}_{\text{Grain area}} \int_0^\infty \underline{Q_{\rm abs}(\nu)\, \pi B_\nu(T_{grain})}\, d\nu = \left(\frac{dE}{dt}\right)_{emit}$$

Number density of photons of frequency ν, ν+dν

Photons move at speed c and carry energy hν

Geom. cross section

Flux emitted at the grain surface per unit grain area and frequency



We used Kirchhoff's law $Q_{abs}(\nu) = Q_{em}(\nu)$

Left side: integral of the incident flux per unit frequency × effective absorption cross-section of the grain (geometric cross-section of the grain multiplied by Q_{abs}, the absorption efficiency). (Heating)

Right side: surface area of the grain × emitted spectrum, which is a blackbody with temperature T_{gr} modified by an emission efficiency Q_{em}. (Cooling)

Heating.

Stars emits primarily at UV, visible and near-IR wavelengths:

$Q_{abs} \sim \nu\text{-}\nu^2$ => most grain **absorption is preferentially in the UV/visible/near-IR.**

Inefficient absorber at longer λ.

Starlight energy density $u^* \sim 1.05 \times 10^{-12}$ erg cm^{-3} (Mathis et al.1983)

The spectrum-averaged absorption cross section is:

$$\langle Q_{abs} \rangle_* \equiv \frac{\int Q_{abs}(\nu) u_*(\nu) d\nu}{\int u_*(\nu) d\nu}$$

$$\langle Q_{abs} \rangle_* \sim 0.18 \left(\frac{a}{0.1\ \mu m}\right)^{0.6} \quad \text{for silicate} \quad 0.01 \le a \le 1\ \mu m$$

$$\langle Q_{abs} \rangle_* \sim 0.8 \left(\frac{a}{0.1\ \mu m}\right)^{0.85} \quad \text{for graphite} \quad 0.005 \le a \le 0.15\ \mu m$$

Cooling.

We average $\langle Q_{abs} \rangle$ over the Planck function at T_{grain} :

$$\langle Q_{abs} \rangle_T = \frac{\int B_\nu(T) Q_{abs}(\nu) d\nu}{\int B_\nu(T) d\nu} \approx 2\times 10^{-3} \left(\frac{a}{\mu m}\right) T_{grain} \qquad \text{if } \beta = 1$$

or

$$\langle Q_{abs} \rangle_T \approx 4\times 10^{-6} \left(\frac{a}{\mu m}\right) T_{grain}^2 \qquad \text{if } \beta = 2$$

E.g. amorphous carbon has $Q \propto \lambda^{-1}$ and $\langle Q_{abs} \rangle_T \approx 7 \times 10^{-4}\ a/\mu m\ T_{gr}$ /K

Lower emission/abs at long wavelengths

Rahul Shetty *et al* 2009 *ApJ* **696** 2234

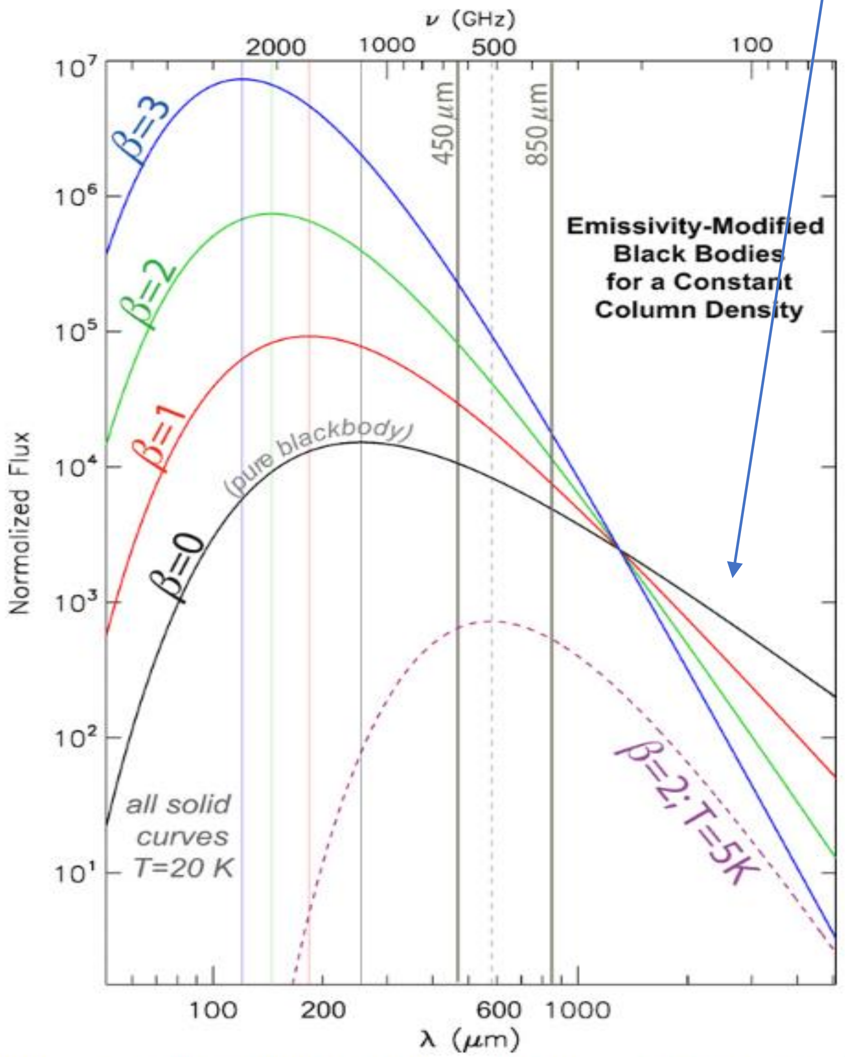


Figure 1. Emissivity-modified blackbodies with different spectral indices β, but constant column density from a 20 K source. Dashed SED is from a 5 K source with $\beta = 2$. Thin solid vertical lines indicate the peak wavelength of the SEDs.

Thermal emission from cosmic dust

So, we found $\langle Q_{abs}\rangle_T \propto T_{gr}^{\beta}$

To within an order of magnitude the equation of **thermal balance** becomes:

$u_* c\, \langle Q_{abs}\rangle_* = 4\, \langle Q_{abs}\rangle_T\, \sigma\, T_{gr}^{\,4}$ (σ = Stefan-Boltzmann constant; $u_* \sim 10^{12}$ erg cm^{-3})

scales as $T_{gr}^{4+\beta}$, much steeper than the $T_{gr}^{\,4}$ scaling of a blackbody

T_{grain} will depend *critically* on the assumed emissivity law:

$T_{grain} \propto u_*^{1/(4+\beta)} \langle Q_{abs}\rangle_*^{1/(4+\beta)}$ (Typically, few 10s to few 100s K)

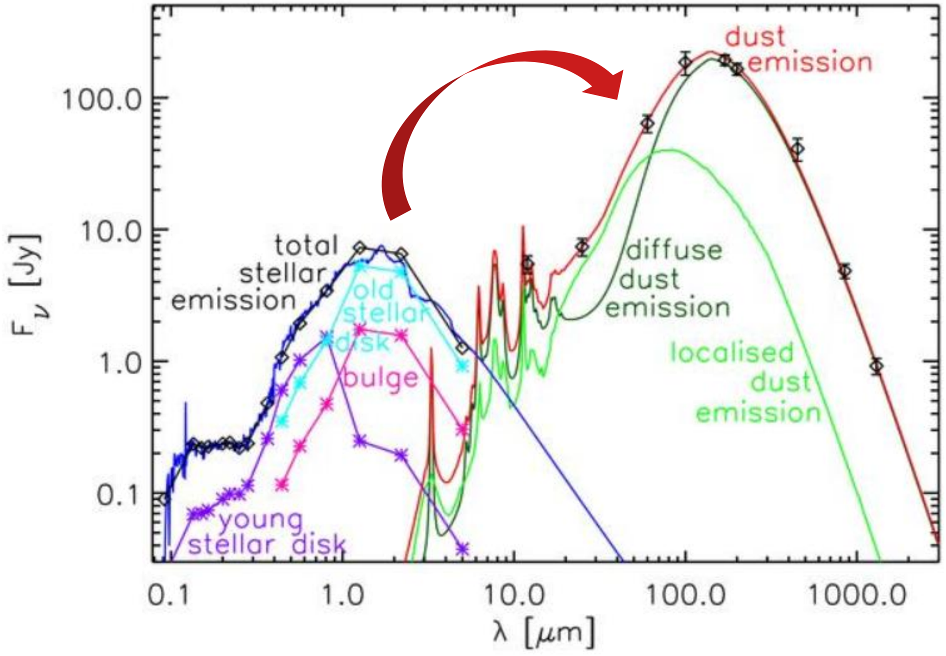
Implications:

1) Grains will have an equilibrium temperature **hotter** ($\langle Q_{abs}\rangle_* < 1$) than the temperature of a perfect blackbody ($Q_{abs} = 1$) immersed in the same radiation field. Increasing β, increases T_{grain}.

2) The most used SED is $f_\nu \propto Q_{abs}(\nu) B_\nu(T_{grain})$.

The spectrum will be a Planck function at T_{grain}, convolved with $Q_{abs}(\nu)$

The absorbed UV radiation field is then reradiated to in the mid- to far-IR.



The best fit model SED of NGC 891, Popescu+ A&A 527, A109 (2011)

Problem 10

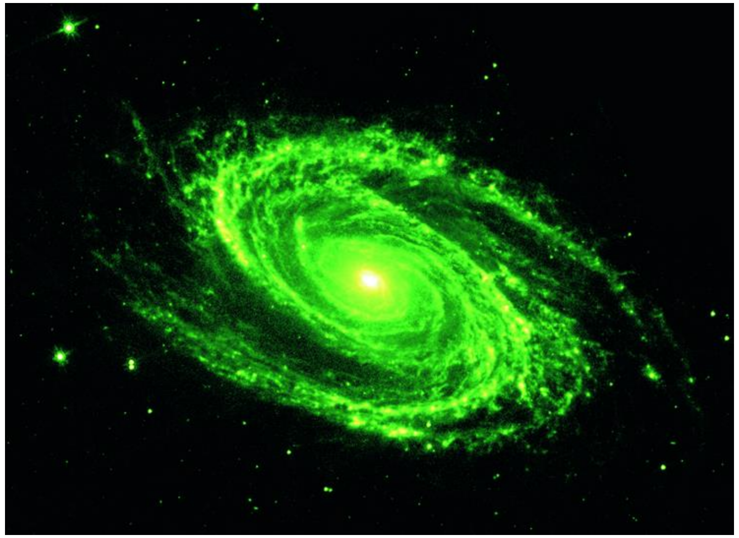
The dust "temperature" derived from the observed spectrum depends critically on the form of assumed emissivity law.

Suppose the power law index of Q_{abs} steepens (e.g., $\beta = 1$ to $\beta = 2$). How will the emergent spectrum plausibly change?

Panchromatic view of M81

Optical view: young, massive blue stars in the spiral arms, as well as the old red stars of the bulge. From Kitt Peak Observatory.

Near infrared light from old stars, like red giants, with surface T ~3,000 K



Mid infrared: emission from hot dust, with T from 300 to 1,000 Kelvin (*)

Far infrared : dust at 30–100 K , where the thermal emission from dusty galaxies tends to peak.

(*) Note that silicate, graphite etc vaporize at T>2000 K. The "dust destruction radius" depends on the source SED. For the Sun, R~0.023 A.U.