Astronomical Dust:
“Everything” you “need” to know…

A671: Lecture 3
Jason Marshall & Terry Herter

See also the review articles:
- Draine, “Interstellar Dust Grains”, ARAA, 41, 241, 2003
- Draine, “Astrophysics of Dust in Cold Clouds”, 2004
  (http://www.astro.princeton.edu/~draine/bibl.rev.html)

A Brief Survey of Dust in Astronomy

- These three mosaics of the Milky Way plane illustrate several observational manifestations of dust
  - The *optical* image is dominated by patchy dust-extinguished photospheric emission
  - The *near-IR* image is dominated by relatively unobscured photospheric emission from disk stars
  - The *mid/far-IR* image is dominated by emission from dust, much of which is the same dust providing the optical obscuration (which is how it warmed up)

A Brief Survey of Dust in Astronomy

- Another example of dust absorption/emission is provided by M104: “The Sombrero Galaxy”

- Visible (HST) image shows dust silhouette
- Infrared (Spitzer) image shows
  - Planar dust ring (in red) encircling galaxy
  - Inner ring of stars (in blue) hidden in the visible image

A Brief Survey of Dust in Astronomy

- ...and perhaps someday, we’ll have a ridiculously high-resolution image of an AGN, revealing a dusty cocoon looking (probably nothing) like this fanciful artistic rendering...

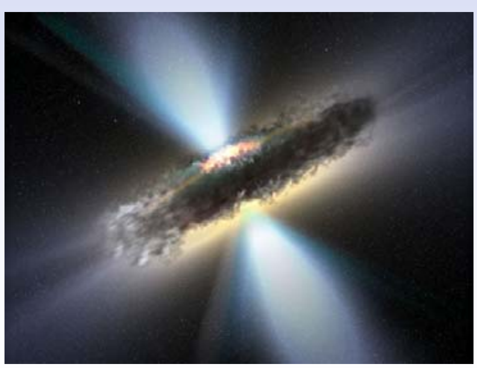

Image from APOD

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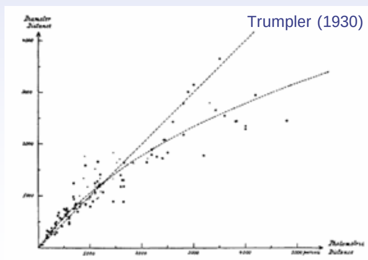
Dust Attenuation

- The presence of dust was established in the early 20th century through its obscuring effects
- Trumpler (1930) observed open star clusters and estimated their sizes using two methods:
  - Diameter distance: Calculated from the angular size of a cluster, assuming that all clusters are similar in size
  - Photometric distance: Calculated from the brightness of a cluster, assuming that all clusters have similar luminosities
- Clusters appear fainter than expected, indicating the presence of an intervening obscuring material



Dust Attenuation

- Long ago, star counts were used as a means of investigating our location within the Milky Way
  - Dust extinction in the optical creates an effective wall around the Solar System giving the appearance that it is centrally located within the galaxy
  - This was eventually sorted out by Shapley's observations of globular clusters...
- It is interesting to note a modern variant of this theme, in which cosmologists rely upon measuring the luminosity of distant Type 1a supernovae to measure the apparent acceleration of the expansion of the universe
  - Reddening could provide the same result (this, of course, has been taken into account in the analysis, but there is still much uncertainty about dust properties at high redshift...not to mention uncertainties with supernovae luminosities at high-z)

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Dust in the ISM

- Dust plays a significant role in the chemical and structural makeup of the ISM (many details of which were presented by Gordon in his lectures)
  - Catalyzing formation of H_2 & other molecules
    - Grains provide a location for atoms to meet
    - Grains provide a sink for the molecular binding energy
  - Depletion of the chemical elements
    - Many metals, such as Si and Fe, are bound in dust grains and are therefore depleted from the ISM
  - Cooling mechanism in dense clouds

Dust Observations

- Extinction:

$$A_\lambda \equiv -2.5\log_{10}\left(\frac{f_\lambda^{obs}}{f_\lambda^{emit}}\right) = -2.5\log_{10}\left(e^{-\tau}\right) = 2.5\tau\log_{10} e \approx 1.086\tau$$

where A_λ is the extinction (in magnitudes) at wavelength λ as determined by comparing the observed flux with the emitted (unobscured) flux

- Selective extinction:

$$E(\lambda_2,\lambda_1) = A_{\lambda_2} - A_{\lambda_1}$$

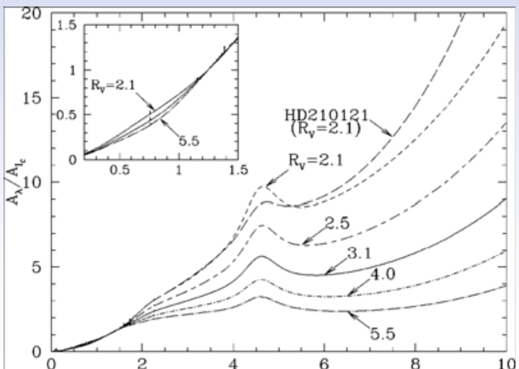
- Standard color excess:

$$E(\lambda_2,\lambda_1) \equiv E_{B-V}$$

λ_1 = 4350 A (Blue) and λ_2 = 5500 A (Visible)

Optical & Ultraviolet Extinction

- Extinction as a function of wavelength is mapped for various lines of sight in the Galaxy by measuring the selective extinction to stars of a known spectral type (with assumption that attenuation goes to zero at long wavelengths)



Draine, ARAA, 2003

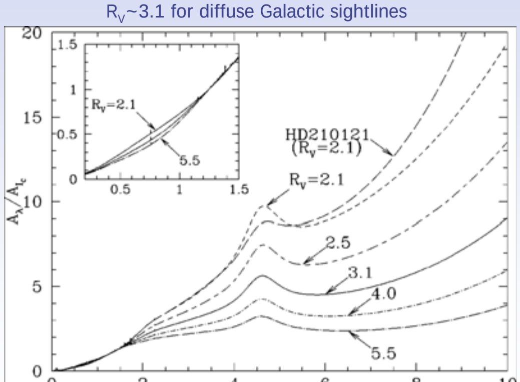
For λ > 912 A (λ^{-1} > 11 μm^{-1}), dust extinction cannot be measured due to H absorption

"Pair method" doesn't work for λ > few μm since stars are too faint there

Optical & Ultraviolet Extinction

- Observed extinction curves vary along lines of sight
- Variations form a one parameter family (Cardelli et al., 1989), defined by: $R_V \equiv \dfrac{A_V}{E_{B-V}}$

R_V~3.1 for diffuse Galactic sightlines



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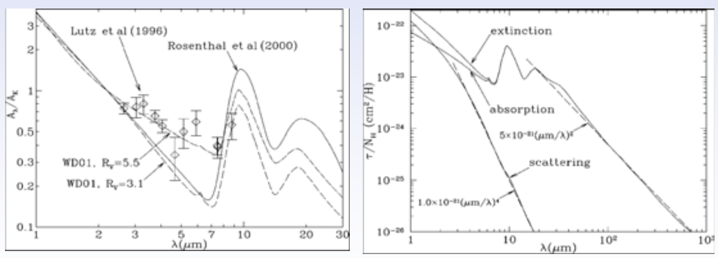
Infrared Extinction

- Infrared extinction curve dominated by prominent peaks at 10 and 18 μm due to silicates
- Note the difference between the observations towards Sgr A* (Lutz 1996) and OMC-1 molecular cloud (Rosenthal 2000)
- Moving from IR to optical, scattering begins to dominate the extinction



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Infrared Emission

- Observed emission from interstellar dust
  - Far-IR emission from cold dust
  - PAH emission from 3-12 microns

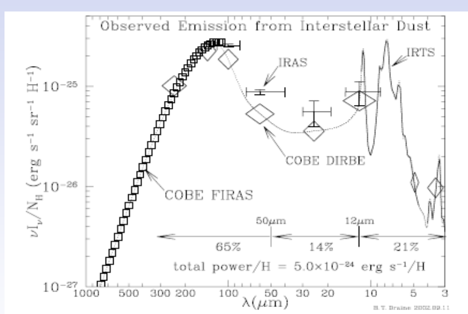

Fig. 8. Observed infrared emission per H nucleon from dust heated by the average starlight background (see text). Crosses: IRAS (Boulanger & Perault 1988); Squares: COBE-FIRAS (Wright et al. 1991); Diamonds: COBE-DIRBE (Arendt et al. 1998); Heavy Curve: IRTS (Onaka et al. 1996, Tanaka et al. 1996). The interpolated dotted line is used to estimate the total power.

Draine, ARAA, 2003

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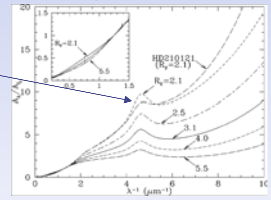
Chemical Composition

- Spectroscopic observations of features (i.e. those apparent in the extinction curve) provide information about the chemical composition of dust grains
  - 2175 Angstrom Feature

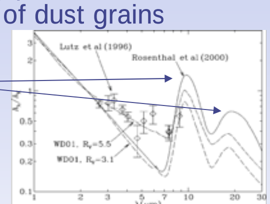


    - The feature is wide (implying a solid-state origin) and well fit by a Drude profile (similar to a Lorentzian)
    - Strength of the feature requires the responsible material to be abundant (i.e. made from H, C, N, O, Mg, Si, S, or Fe)
    - Graphite has an absorption peak near this frequency due to an electronic excitation in carbon sheets

Graphite is therefore a likely grain material

Chemical Composition

- Spectroscopic observations of features (i.e. those apparent in the extinction curve) provide information about the chemical composition of dust grains
  - 10 and 18 μm Features



    - Silicate minerals have strong absorption resonances at
      - ~9.7 μm due to the Si—O stretching mode
      - ~18 μm due to the O—Si—O bending mode
      - These features are seen in outflows from oxygen-rich stars, but not from carbon-rich stars

Silicates are therefore likely grain materials

- These two broad and smooth features are associated with 'amorphous' silicate grains, as opposed to crystalline silicate materials which have sharper and narrower features

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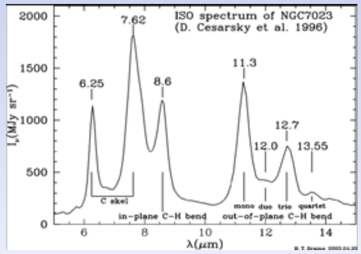
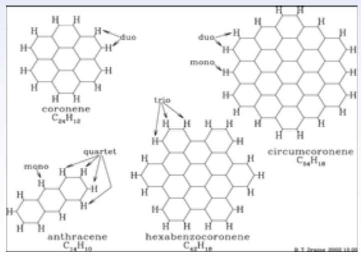
Chemical Composition

- "Unidentified" Infrared Features (UIFs, UIBs, PAHs, ...)
  - Planetary nebulae, HII regions, PDRs, reflection nebulae, and many galaxy spectra show characteristic band of "PAH" emission features
  - Up to 20% of starlight energy incident on a reflection nebula may be radiated in these bands
    - Particles must be abundant
  - Carriers believed to be polycyclic aromatic hydrocarbon molecules (extremely small grains)
    - Section of a graphite sheet with H atoms attached around the edges





Grain Sizes

- If the dust grains were large compared to the wavelength of incident light, the extinction would be independent of wavelength (geometric-optics limit)
  - Since the extinction continues to rise down to the shortest measured wavelengths, many grains smaller than this must contribute to the extinction
    - $2\pi a/\lambda<1$ for $\lambda=0.1$ μm requires many grains with $\mathbf{a<0.015}$ $\boldsymbol{\mu}$**m**
- In the optical, the dust albedo is ~0.5, so that scattering and absorption contribute equally to the extinction
  - Observations show grains are forward scattering, so they must be large enough that Rayleigh scattering isn't the process
    - $2\pi a/\lambda>1$ for $\lambda=0.6$ μm requires many grains with $\mathbf{a>0.1}$ $\boldsymbol{\mu}$**m**

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Grain Sizes

- Mathis, Rumpl, & Nordsieck (MRN) [ApJ, 217, 1977] were able to fit the observed UV/optical extinction curve with a combination of graphite and silicate grains distributed in size according to

$$\frac{1}{n_H}\frac{dn_i(a)}{da} = \xi_i a^{-3.5}$$

for 50 A < a < 0.25 μm. n_H is the number density of hydrogen nuclei (in both atoms and molecules) and ξ_i sets the abundance of each grain type (log ξ_{gra}=-25.13 & log ξ_{sil}=-25.11 cm$^{2.5}$)

Grain Sizes

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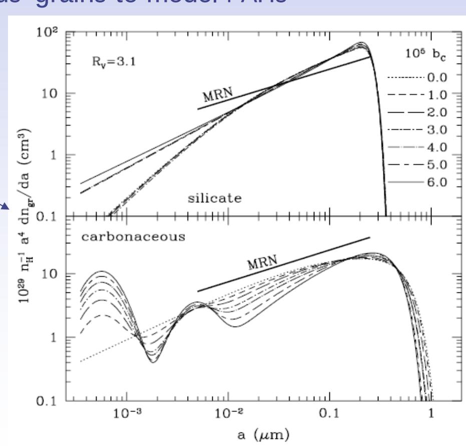
- Weingartner & Draine [ApJ, 548, 2001] modified the simple MRN power-law to a slightly more complicated functional form and included additional small 'carbonaceous' grains to model PAHs

Proportional to dust volume per logarithmic size interval



Grain Shapes

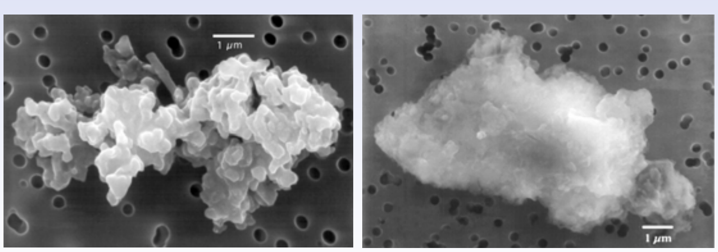
- It was discovered in 1949 that starlight was polarized
  - Degree of polarization tended to be higher for stars with greater reddening
  - Stars in a given region have similar polarization vectors

  Dust grains must be somewhat **non-spherical** so that they can be partially aligned by B-fields, thereby polarizing starlight

- Many/most calculations are performed assuming spherical grains, for which analytic solutions are available using Mie theory
- A fair bit of effort is currently going into exploring the dependencies of grain emission as a function of grain shape and porosity

Grain Shapes

- These are examples of interstellar grains
- Note that these grains are much larger than the grains that dominate the mass of the ISM
- They're clearly complicated structures and are certainly not spheres



Images from Wikipedia ("Cosmic dust")

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Grain Optical Properties

Definitions

a = grain radius

$$Q_{ext} = \frac{\sigma_{optical}}{\sigma_{geometric}} = \frac{\sigma_{opt}}{\pi a^2}$$

$Q_{scat} = \sigma_{scat} / \sigma_{geo}$ Scattering efficiency

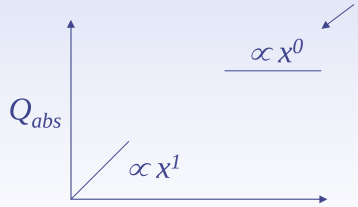
$Q_{abs} = \sigma_{abs} / \sigma_{geo}$ Absorption efficiency

$Q_{ext} = Q_{scat} + Q_{abs}$ Total extinction efficiency

Grain Optical Properties

- Mie (1908) derived the behavior of Q_{abs}
  - For a ~ λ: Q_{abs} ~ a / λ
  - For a < λ: Q_{abs} ~ 0
  - For a > λ: Q_{abs} ~ constant

Note that this large grain behavior is identical to that of a blackbody



$$x = \frac{2\pi a}{\lambda}$$

Grain Absorption

- The total absorption cross section (which is equal to the extinction curve in the infrared—since scattering is negligible) is obtained by integrating over the optical properties of each grain-size, weighted by the grain-size distribution function, and summed over grain species (graphite and silicate)

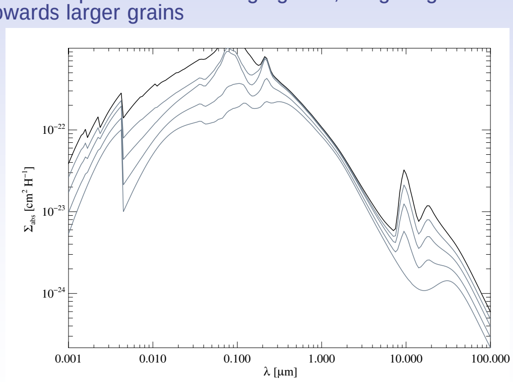
$$\Sigma_{abs} = \Sigma_{abs}^{gra} + \Sigma_{abs}^{sil}$$

where

$$\Sigma_{abs}^{i}(\lambda) = \int_{a_-}^{a_+} \frac{1}{n_H} \frac{dn(a)}{da} \pi a^2 Q_{abs}^{i}(a,\lambda)\, da$$

Grain Absorption

- From bottom to top, the curves show the total absorption cross section of dust embedded in increasingly 'hotter' radiation fields
  - The hottest dust (bottom curve) is completely depleted of silicate grains (silicate grains sublimate at a lower temperature than graphite grains)
  - The hotter dust has fewer small grains since they sublimate at lower temperatures than large grains, weighting the distribution towards larger grains



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Equilibrium Heating

- Dust particles in the ISM absorb photons:
  - Absorption in UV or visible (highest cross-section)
  - Radiate in the infrared
- Consider a particle a distance *d* from an illuminating radiation source (it could be a star, an AGN, etc) with spectral energy distribution L_ν. The flux from the illuminating source at the particle is

$$f_\nu = \frac{L_\nu}{4\pi d^2}$$

- For example, a star radiating as a blackbody at temperature T_* produces a flux

$$f_\nu^* = \pi B_\nu(T_*)\frac{4\pi R_*^2}{4\pi d^2} = \pi B_\nu(T_*)\frac{R_*^2}{d^2}$$

Equilibrium Heating

- The rate at which energy is absorbed is

$$P_{abs} = \int_0^\infty Q_{abs}\pi a^2 \frac{L_\nu}{4\pi d^2} d\nu$$

- The emitted power by the dust is

$$P_{emit} = \int_0^\infty Q_{emit} 4\pi a^2 \pi B_\nu[T_d(a)] d\nu$$

$T_d(a)$ = grain-size dependent dust temperature

- By Kirchhoff's law, $Q_{emit} = Q_{abs}$
  - Strictly this law states that at thermal equilibrium, the emissivity of a body (or surface) equals its absorptivity

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Equilibrium Heating

- In equilibrium $P_{abs} = P_{emit}$ so that

$$\int_0^\infty Q_{abs} \frac{L_\nu}{4\pi d^2} d\nu = \int_0^\infty Q_{abs} 4\pi B_\nu [T_d(a)] d\nu$$

- For a very large grain, $a >> \lambda$, $Q_{abs} \rightarrow$ constant (i.e. behavior equivalent to a blackbody), so that

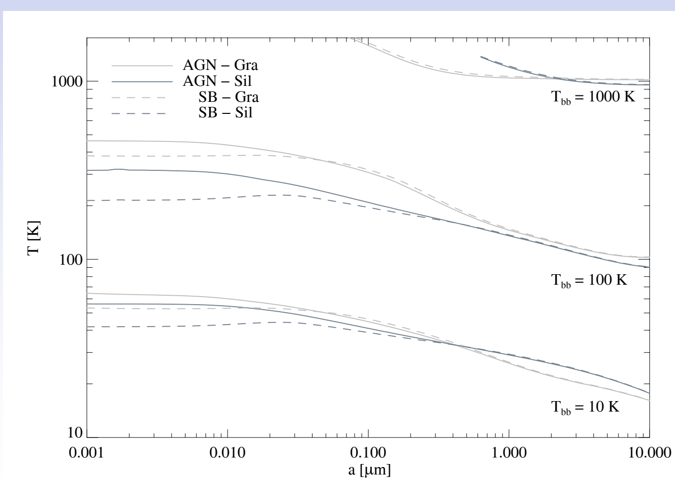
$$\frac{1}{4\pi d^2} \int_0^\infty L_\nu d\nu = \int_0^\infty 4\pi B_\nu (T_{bb}) d\nu \longrightarrow \frac{L_{bol}}{4\pi d^2} = 4\sigma T_{bb}^4$$

- Taking the ratio of these, we find an implicit expression for the temperature of a grain of size a embedded in a radiation field that heats a blackbody to T_{bb}

$$\int_0^\infty Q_{abs} \pi B_\nu [T_d(a)] d\nu = \sigma T_{bb}^4 L_{bol}^{-1} \int_0^\infty Q_{abs} L_\nu d\nu$$

Equilibrium Heating

- Equilibrium temperatures of grains as a function of grain-size and radiation field:



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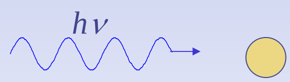
Stochastic Heating

- What if a photon strikes a very small particle?
  - It may cause it to heat up significantly…



$$\Delta E = \frac{\partial E}{\partial T}\Delta T \quad \Rightarrow \quad h\nu = C_v \Delta T$$

- In general C_v, the heat capacity of the particle will depend on T. The peak T, T_p is given by

$$h\nu = \int_0^{T_p} C_v(T)\,dT$$

Stochastic Heating

- At the lowest temperatures we have the Debye law

$$C_v \propto T^3$$

- While at high temperatures

$$C_v = 3Nk$$

- Where $3N$ is the number of degrees of freedom

- Debye temperature (θ_D)
  - dividing line between low and high T cases
  - θ_D ~ 200 - 500 K for typical grain materials

- These properties are used to create simplified grain models with ‘realistic’ vibrational mode spectra

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Stochastic Heating

- Numerical techniques exist to calculate the energy distribution function of small grains as a function of their size and environment
  - P(E) is the probability that a grain has a vibrational energy E' > E
  - For large grains, P(E) becomes a delta function, which is why they are well described with equilibrium physics

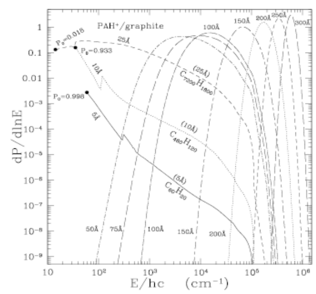

Fig. 18. Energy distribution functions for charged carbonaceous grains with radii $a = 5, 10, 25, 50, 75, 100, 150, 200, 250, 300$Å in the interstellar radiation field. The discontinuity in the 5, 10, and 25Å curves is an artifact due to a change in the method of estimating the cooling when the energy is equal to the 20th vibrational mode. For 5, 10, and 25Å, a dot indicates the first excited state, and the probability P_0 of being in the vibrational ground state is given. Taken from Li & Draine (2001).

Stochastic Heating

- The time averaged emission spectrum from a grain is then calculated from

$$f_\lambda = 4\pi \int dE \frac{dP(E)}{dE} \pi a^2 Q_{abs} B_\lambda [T(E)]$$

- With results

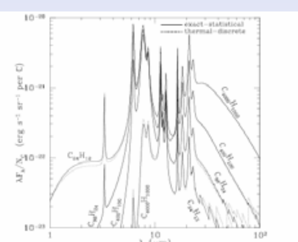

Fig. 19. IR emissivity per C atom for PAH+ molecules of various sizes illuminated by the average ISRF. Solid line: "exact-statistical" calculation, which uses transition probabilities which do not involve the thermal approximation. Dotted line: "thermal-discrete" calculation where the spontaneous emission rates are calculated using a thermal approximation, as discussed in the text. The two methods are in excellent agreement, indicating that the thermal approximation can be used to calculate the transition rates. Taken from Draine & Li (2001).

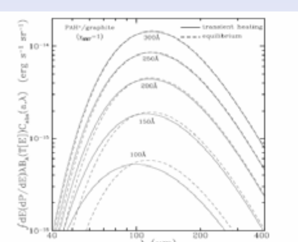

Fig. 20. IR emission per grain for carbonaceous grains of various sizes illuminated by the average ISRF. Solid line: full stochastic heating calculation. Broken line: assuming steady-state temperature T_{ss}. For $a \gtrsim 200$Å in the ISRF we see that stochastic heating has little effect on the emission spectrum, but for $a \lesssim 150$Å it significantly modifies the emission spectrum. Taken from Li & Draine (2001).

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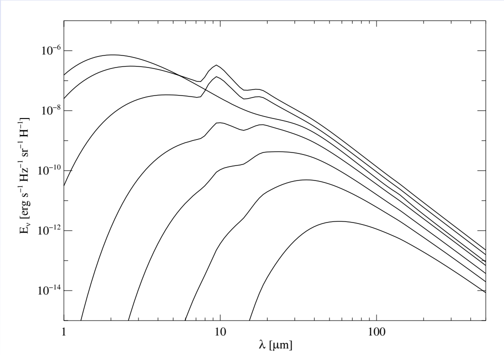
Grain Emission

- From bottom to top, the curves show the emissivity of dust embedded in increasingly 'hotter' radiation fields
  - The hottest dust (top curve) is completely depleted of silicate grains (silicate grains sublimate at a lower temperature than graphite grains)
  - The hotter dust has fewer small grains since they sublimate at lower temperatures than large grains, weighting the distribution towards larger grains



Production & Destruction of Grains

- Grain Production
  - Some grains form in stellar outflows
    - Dust emission is observed from outflows in red giants, carbon stars, and planetary nebulae
    - Silicates are observed in outflows from oxygen rich stars (O/C > 1) and are absent from carbon rich stars (O/C < 1)
    - Dust is believed to condense out of initially dust-free gas
  - There is evidence that many (if not most) dust grains form in the ISM (Draine & Salpter, 1979; Draine, ARAA, 2003)
    - The problem is that dust in the ISM has a "mean residence time"—the timescale on which grains are destroyed
    - The rate at which dust is pumped into the ISM from stellar outflows is less than the destruction rate
    - Additional dust must therefore be forming in the ISM

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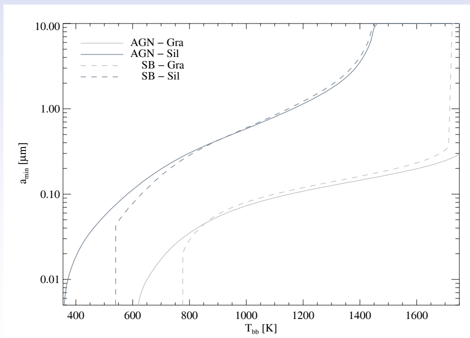
Production & Destruction of Grains

- Grain are destroyed by many processes
  - Shattering in low-velocity grain-grain collisions
  - Vaporizations in high-velocity grain-grain collisions
  - Grains sublimate when they get too hot:



Dust Abundances

- It is found that

$$A_V/N_H = 5.3\times10^{-22}\ \text{mag-cm}^2$$

where

$$I = I_0 10^{-A_V/2.5}$$

$$N_H = \int n_H\, dr \approx n_H D$$

$$\tau_V = 0.92 A_V$$

$$\left(e^{-\tau_V} = 10^{-A_V/2.5}\right)$$

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Dust Abundances

- We have

$$\tau_v = Q\pi a^2 n_d D \qquad \text{and} \qquad N_H = n_H D$$

$$\Rightarrow \frac{\tau_v}{N_H} = \frac{Q\pi a^2 n_d}{n_H} \quad \Rightarrow \frac{n_H}{n_d} = Q\pi a^2 \frac{N_H}{\tau_v}$$

- Now

$$\rho_d = 4\pi a^3 \rho_{gr} n_d / 3$$

$$\rho_H = m_H n_H$$

ρ_d = dust mass/cm^3
ρ_{gr} = density of material in the grain

Dust Abundances

- Putting this all together

$$\frac{\rho_H}{\rho_d} = \frac{3m_H}{4\pi a^3 \rho_{gr}} \frac{n_H}{n_d}$$

$$= \frac{3m_H}{4\pi a^3 \rho_{gr}} Q\pi a^2 \frac{N_H}{\tau_v}$$

$$= 1.09 \frac{3}{4} \frac{m_H Q N_H}{a \rho_{gr} A_v}$$

$$\sim 130$$

Taking $Q \sim 1$, $a \sim 0.1$ μm, $\rho_{gr} \sim 2$, $m_H = 1.67\times10^{-24}$ g

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Dust Abundances

Expected Gas-to-Dust Ratio

Element	N_x/N_H	AW	$(N_x/N_H)\times$AW
C	4×10^{-4}	12	0.0048
N	10^{-4}	14	0.0014
O	8×10^{-4}	16	0.0128
Mg	3×10^{-5}	24	0.0007
Si	3×10^{-5}	28	0.0008
S	1.6×10^{-5}	32	0.0005
Fe	2.5×10^{-5}	56	0.0014
			0.0225

$$\Rightarrow \quad (\rho_H / \rho_d)_{min} = 1/0.0225 = 45$$

- Not bad, considering the approximations we made such as using only a single grain-size/Q_{abs} value (instead of integrating over the grain-size distribution)

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A Day in the Life of a Grain

Time Between Photon Hits

- The rate at which photons hit the grain is

$$R_{hit} \approx \frac{L_*}{h\nu} \frac{1}{4\pi d^2} Q_a \pi a^2$$

which for a grain with radius 300 Angstroms absorbing UV photons (λ~0.2 mm) at a distance of 1.5 AU from a 1 L_{sun} star, gives a rate ~0.00408 s^{-1}

- The time between hits is $1/R_{hit}$ ~ 250 seconds

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Radiative Cooling Timescale

- The cooling timescale, Δt, is very short

$$\Delta t \sim \frac{E}{dE\ / dt} = \frac{3Nk}{4\pi a^2 \sigma T^3}$$

$$E = 3NkT$$

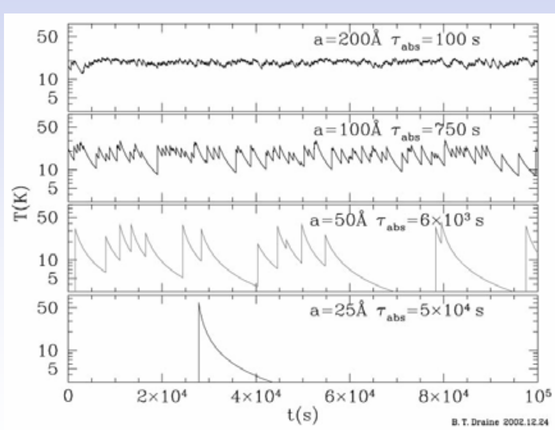
$$\frac{dE}{dt} \approx 4\pi a^2 \sigma T^4 Q_{IR}$$

$$\Delta t \sim \frac{3 \cdot 50 \cdot 1.38\times10^{-16}\ \mathrm{ergs\,K^{-1}}}{4\pi\,(3\times10^{-8}\mathrm{cm})^2 \cdot 5.67\times10^{-5}\ \mathrm{ergs\,K^{-4}} \cdot (1000\mathrm{K})^3}$$

$$\sim \frac{2\times10^{-5}}{Q_{IR}}\ \text{seconds}$$

A Day in the Life of a Grain

- A day in the life of four carbonaceous grains, heated by the local interstellar radiation field
- τ_{abs} is the mean time between photon absorptions



Draine, ARAA, 2003

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