Jupiter vs. ISM chemistry
how same + different? why different?
CO vs CH_4
C_4H_2 vs C_3H_8

Dust heating + cooling example - protoplanetary disk

Black pebble:

$P_{abs} = \pi a^2 F_* = \pi a^2 L_* / 4\pi d^2 = \pi a^2 \sigma T_*^4 \; R_*^2/d^2$

$P_{em} = 4\pi a^2 \sigma T^4$

equil: $T^4 = \frac{R_*^2}{4d^2} T_*^4 \implies T \propto d^{-0.5}$

Dust grain:

$4\pi R_*^2 \sigma T_*^4$

$P_{abs} = \pi a^2 \langle Q_{abs} \rangle F_* = \pi a^2 \int Q_{abs}(\nu) F_\nu \, d\nu$

$P_{em} = 4\pi a^2 \langle Q_{em} \rangle \sigma T^4 = 4\pi a^2 \int Q_{em}(\nu) \pi B_\nu(T) \, d\nu$

$= Q_{abs}(\nu)$

$T^4 = \frac{R_*^2}{4d^2} T_*^4 \frac{\langle Q_{abs} \rangle}{\langle Q_{em} \rangle}$

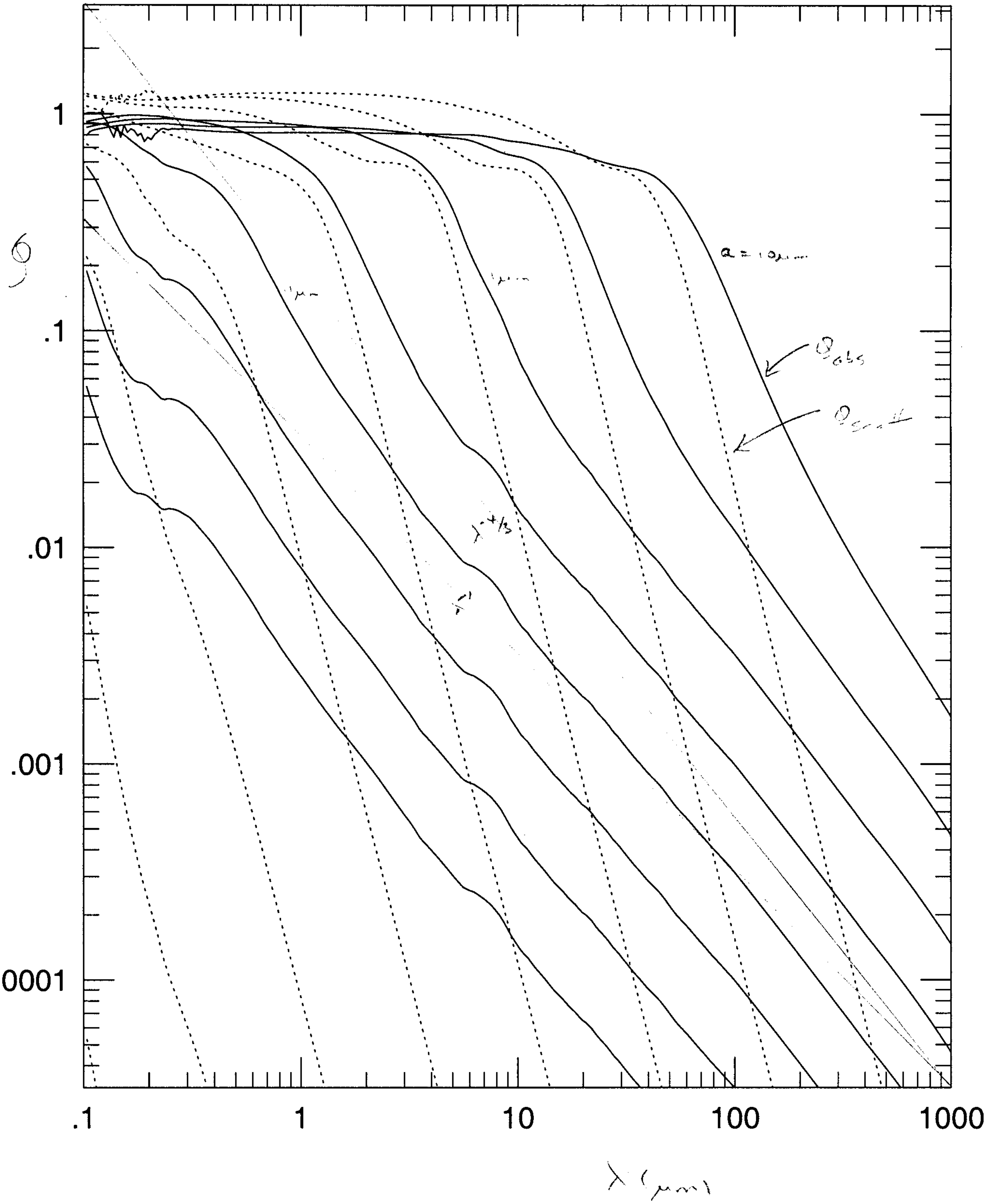
if $Q_{abs} \propto \nu$, $\langle Q \rangle \sim T$

$T^4 = \frac{R_*^2}{4d^2} T_*^4 \frac{T_*}{T} \implies T = T_* \left(\frac{R_*}{2d} \right)^{0.4}$

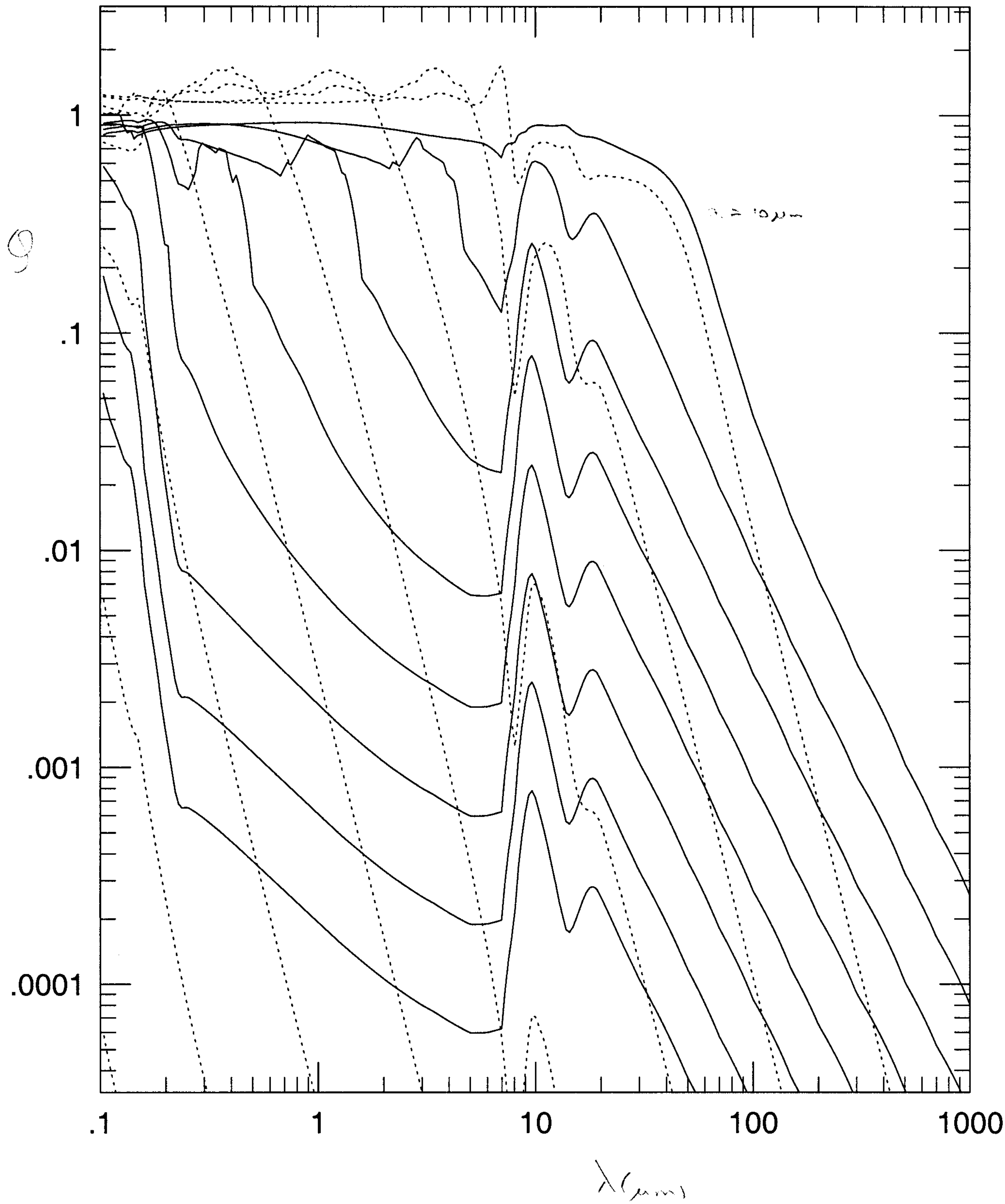
at 1 AU from Sun: $\frac{R_*}{2d} = 2.3 \times 10^{-3}$ $\quad T = 0.088 T_*$

$= 513$ K

Amorphous carbon



Amorphous Silicates



color difference.
is; viz.

(5.88)

straightforward.
alized extinction
is

(5.89)

color excess as,

(5.90)

into the infrared,

(5.91)

by extrapolating
on ratio A_λ/A_V

n, this parameter

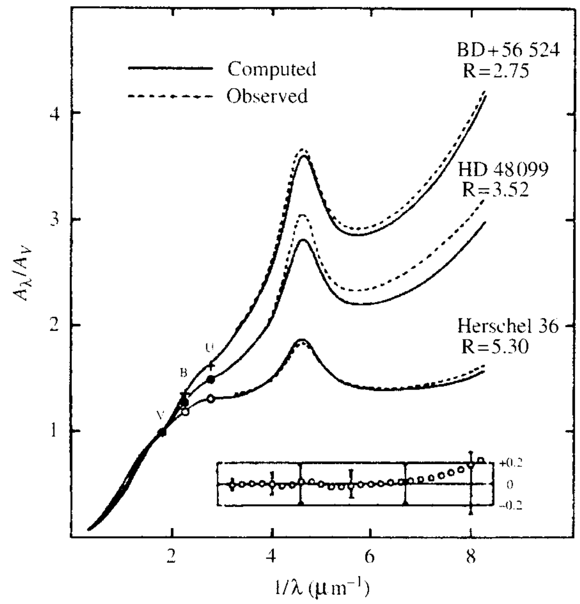


Figure 5.7 Three observed extinction curves are shown as a function of λ^{-1}. These curves show the range in wavelength behavior of the extinction laws in the interstellar medium. The solid lines show, for comparison, the computed parameterized extinction. The insert shows the deviations. Figure courtesy of J. S. Mathis; reprinted with permission from *Ann. Rev. Astron. Astrophys.*, **28**, p. 37, ©1990 by *Ann. Rev.* (www.annualreviews.org).

For a diffuse rad'n field : ... :

$$P_{abs} = 4\pi a^2 \int Q_{abs}(\nu)\, \pi J_\nu \, d\nu$$

↑ heated from all sides

Is this consistent w/ $\pi a^2 \int Q_{abs}(\nu) F_\nu \, d\nu$?

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

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

$$= 4\pi J_\nu \quad ✓ \quad \text{(as desired)}$$

What if $J_\nu = B_\nu(T_*)$?

$$4\pi a^2 \int Q_{abs}(\nu)\, \pi J_\nu \, d\nu = 4\pi a^2 \int Q_{em}(\nu)\, \pi B_\nu(T) \, d\nu$$

$$\Rightarrow T = T_* \quad ✓ \quad \text{(as required)}$$

How to set up program to calculate T inside an optically thick dust disk?

Need to know J_ν

I followed many rays through disk, integrating eqn. of rad. xfer

$$\frac{dI_\nu}{ds} = -\left[\sum_i \pi a_i^2 Q(a_i,\nu)\, n_i\right] I_\nu + \sum_i \pi a_i^2 Q(a_i,\nu)\, n_i\, B_\nu(T_i)$$

or for finite Δs :

$$\Delta I_\nu = e^{-\alpha(\nu)\Delta s} I_\nu + \left(1 - e^{-\alpha(\nu)\Delta s}\right) S_\nu$$

$$S_\nu = \sum_i \pi a_i^2 Q(a_i,\nu)\, n_i\, B_\nu(T_i) \Big/ \sum_i \pi a_i^2 Q(a_i,\nu)\, n_i$$

By averaging rays through each grid cell in disk
I calculated J_ν
Then I recalculated T and repeated until it converged

How to include scattering?
Negligible for emitted radiation in IR
Important for star light:

$$\frac{dI_\nu}{ds} = -\sum_i \pi a_i^2 (Q_{abs} + Q_{sca}) n_i I_\nu$$
$$+ \sum_i \pi a_i^2 Q_{abs} n_i B_\nu(T)$$
$$+ \sum_i \pi a_i^2 Q_{sca} n_i J_\nu$$

or $S_\nu = \dfrac{\alpha_{abs} B_\nu + \alpha_{sca} J_\nu}{\alpha_{abs} + \alpha_{sca}}$

What next?
To calculate the disk structure, I need T_{gas} so I can solve the eqn. of hydrostatic equil.

$$\frac{dP}{dz} = -g\rho$$

where $P = nkT$, $\rho = \langle m \rangle n$

At high n, $T_{gas} = T_{dust}$
At low n, w/ other heating sources, need to calculate T_{gas} by balancing heating + cooling.

Small grains + PAHs

Grain size distribution:

MRN : $\frac{dn}{da} \propto a^{-3.5}$ up to $a_{max} \sim 0.1\mu m$

$\pi a^2 \frac{dn}{d\ln a} \propto a^{-0.5}$: τ_{UV} dominated by small grains

$\frac{4\pi}{3} a^3 \frac{dn}{d\ln a} \propto a^{+0.5}$: τ_{FIR} dominated by a_{max}

grain T falls w/ a b/c ϵ_{FIR}/τ_{UV} increases

Sellgren : reflection nebulae w/ NIR albedo > 1

explanation : emission w/ T > T_{equil}

$\Rightarrow$ v. small grains

Similar effect: 3.3 μm emission from dust illuminated by UV — PAHs

PAHs: carbon bonds, benzene sp^3, $sp^2 + p$

Excitation: $\pi \rightarrow \pi^*$ electronic excitation

followed by radiative or non-radiative xition to excited vib. state in another electronic state

describe vibrational excitation by $\frac{1}{2}kT = E$/mode

not quite right: Canonical vs. microcanonical ensembles

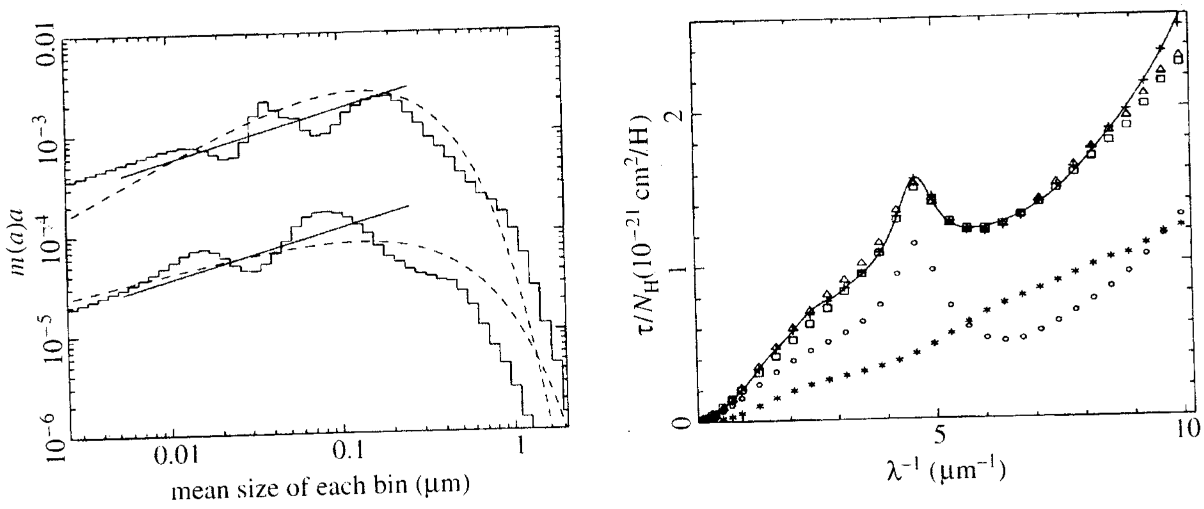


Figure 5.15 The interstellar grain size distribution – plotted as mass fractions – derived from different types of fits to the observed extinction curve (left panel). The top histogram and dashed line show silicates; the bottom histogram and dashed line shows graphite, displaced downwards by factor 10. The solid lines show for comparison the simple MRN power law size distributions. The calculated extinction curve is compared to the observations in the right panel. The contributions due to silicates (∗) and graphite (∘) are shown separately. Figure reprinted with permission from S.-H. Kim, P. G. Martin and P. D. Henry, 1994, *Ap. J.*, **422**, p. 164.

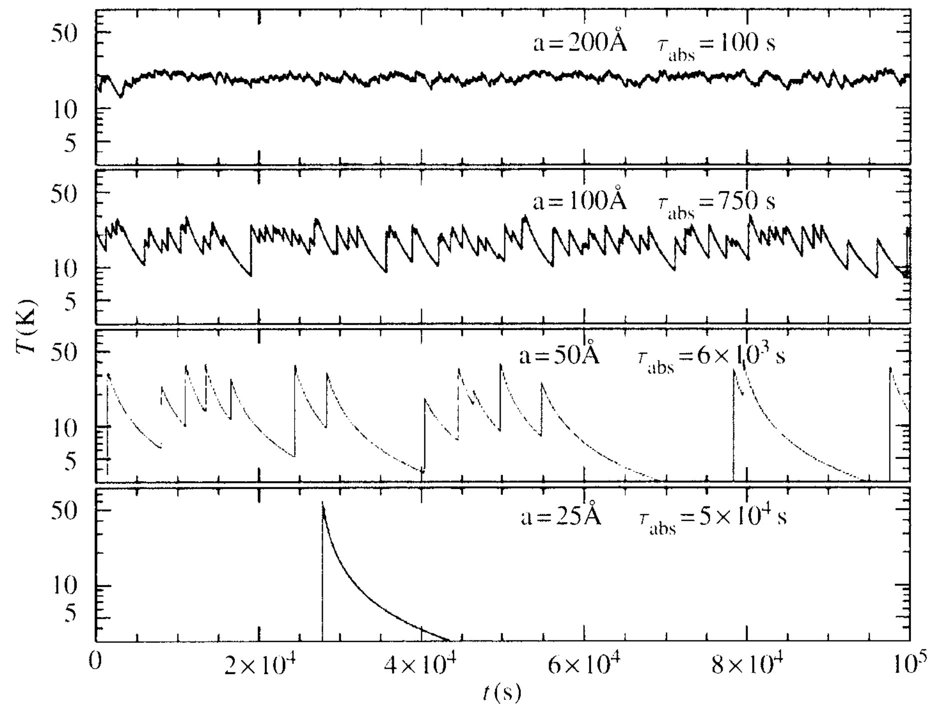


Figure 6.5 The time-dependent behavior of the temperature for various sizes of the species. The time axis corresponds to approximately one day. These calculations pertain to the diffuse ISM. Figure courtesy of B. T. Draine; reprinted, with permission, from the *Ann. Rev. Astron. Astrophys.*, **41**, p. 241 ©2003 by *Ann. Rev.* (www.annualreviews.org).

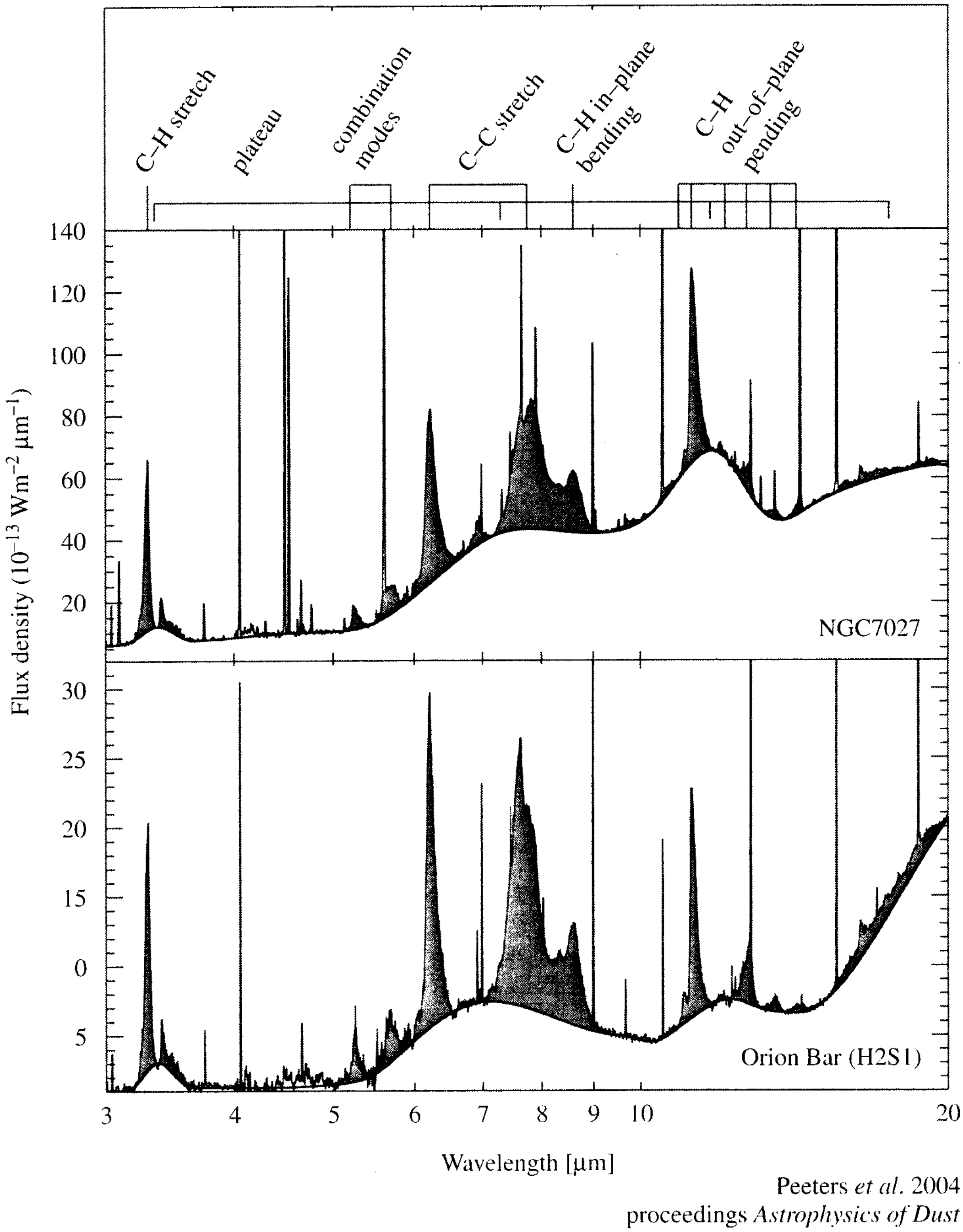


Figure 6.16 The 3–15 μm spectra of the PDRs associated with the Orion Bar and NGC 7027, illustrating the ubiquitous nature as well as the richness of the IR emission features. The IR emission features are shaded. The narrow lines are HI recombination lines, H_2 pure rotational and rotational–vibrational lines, and atomic fine-structure lines. The top panel indicates the PAH vibrational modes associated with each feature. Note the presence of broad plateaus underneath the narrow emission features. Figure adapted from E. Peeters, *et al.*, 2002, *A. & A.*, **390**, p. 1089.

These modes "measure" nearest-neighbor interactions to a large extent. Hence, the infrared signatures of carbonaceous solids with an abundant aromatic component – such as coal, amorphous carbon soots, and charcoals – also bear a general