Theoretical Studies of Interstellar Dust

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"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Plan

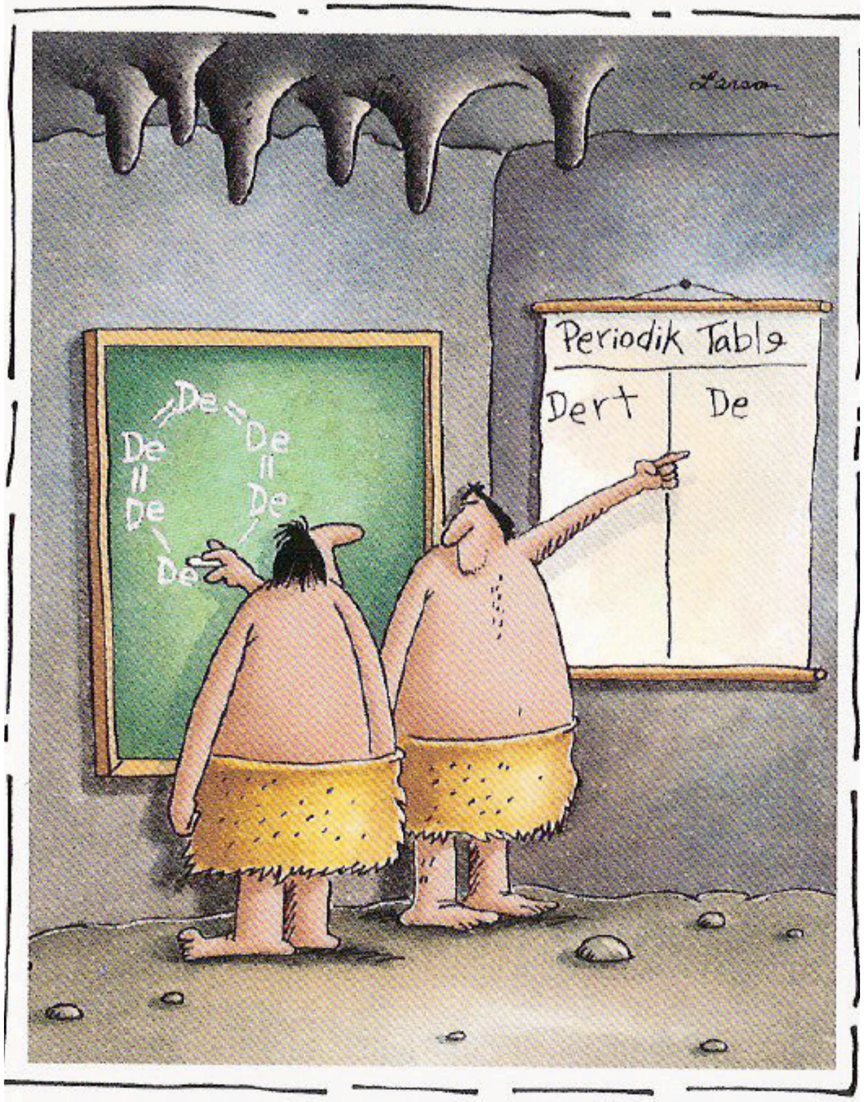
- Grain models: ingredients
- What can we calculate to compare to observations?
  - Interstellar Extinction
  - Interstellar Polarization
  - Scattering Properties of Dust
  - Heating/Cooling of Grains and Infrared Emission
  - Rotational Dynamics and "Spinning Dust" Emission
  - Magnetic Dipole Emission from Magnetic Dust?
- Grain Destruction in the ISM
- Grain Evolution in ISM of Milky Way and Other Galaxies

Some things I will *not* talk about:

- charging of interstellar grains
- role of grains in ionization balance
- heating by photoelectrons from grains
- deuteration of PAHs
- physics of grain alignment
- evolution of dust in dense clouds
- dynamics (and acceleration) of charged grains in interstellar shocks

I'm happy to discuss these or other dust physics matters any time – just stop by my office.

Dust Model Ingredients



Early chemists describe the first dirt molecule.

Dust in Diffuse Clouds (no ices present)

Essential Ingredients

- amorphous silicate material to account for 10μm and 18μm absorption
- Polycyclic aromatic hydrocarbon (PAH) material to account for IR emission features
- Additional carbonaceous material with significant aliphatic fraction to account for 3.4μm feature
- *Other stuff – stardust SiC, diamond, etc. – appears to have sufficiently low abundance that it can be ignored at the present stage of modeling.*

Extinction Curves

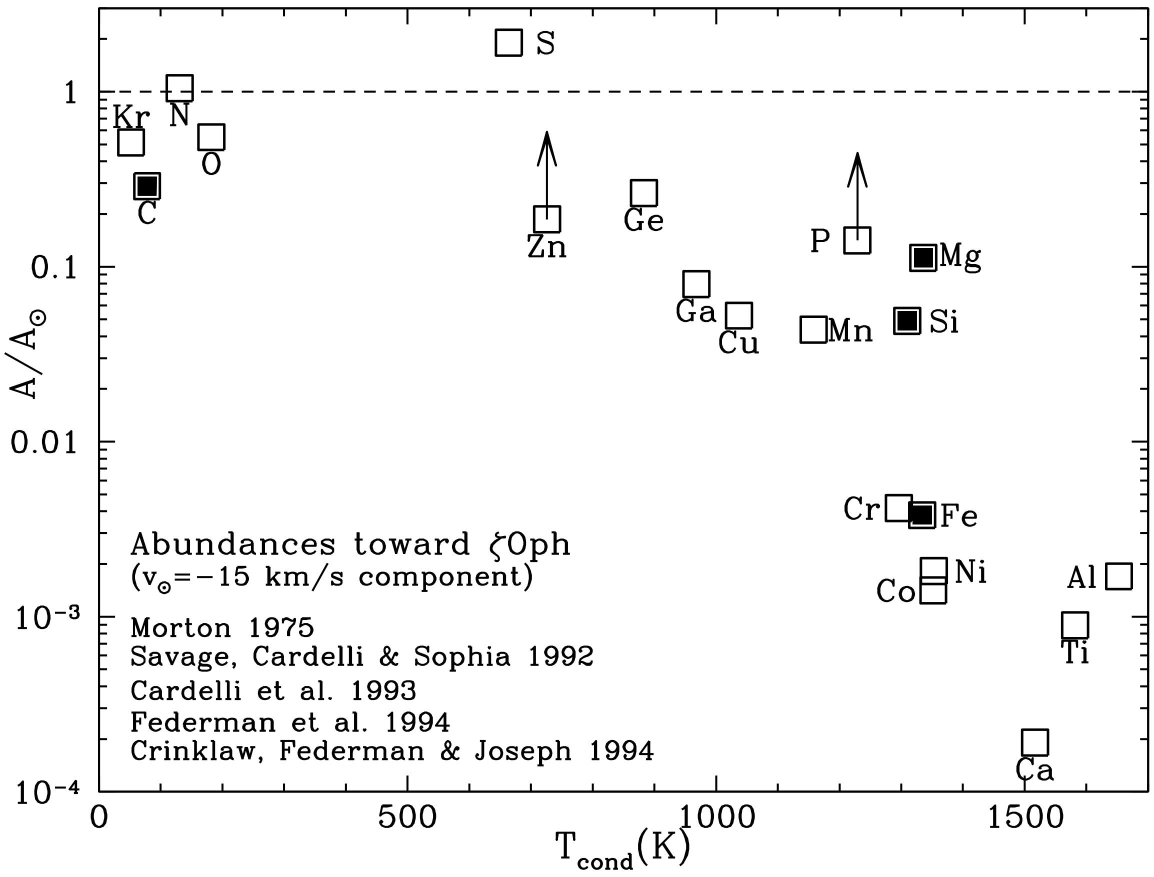
- Choose an observed extinction curve to reproduce
- specify components, e.g.,
  - population of silicate grains
  - population of carbonaceous grains
- Choose grain shape (e.g., oblate spheroid, axial ratio b/a)
- Fit extinction vs. λ by varying size distributions dn_j/da (e.g., $j =$ silicate , carbonaceous)
- Fit polarization vs. λ by varying
  $f_j(a)$ = degree of alignment for grains of composition j, size a

Also:

- Adjust size distribution of PAHs so that single-photon heating reproduces observed IR emission.
- Satisfy abundance constraints.

Abundance Constraints

Abundance in gas/solar abundance



Solid symbols = C, Mg, Si, Fe (major grain constituents) (Draine 2011).

- Sightline to nearby star ζ Oph (O9.5V, $D = 112 \pm 3$pc) has superb high-resolution absorption-line spectroscopy.
- If ISM is assumed to have solar abundances, then “depletions” of elements like C, Mg, Si, Fe indicate incorporation into solids.
- Total “missing mass”/H mass $= 0.0091 \pm 0.0006$
- **Challenge: to reproduce observed extinction without exceeding abundance constraints.**

Size Distribution of Interstellar Grains

- Observe extinction curve from $\sim 2\,\mu\mathrm{m} - 0.1\,\mu\mathrm{m}$
- Mathis et al. (1977) tried to reproduce average interstellar extinction curve using mixture of graphite and silicate spheres.
- Using non-parametric size distribution with upper and lower cutoffs, $a_{\rm min}$ and $a_{\rm max}$, they found best-fit size distributions dn/da.
- Their best-fit size distributions were very close to power-laws!!
- Therefore MRN proposed using power-laws

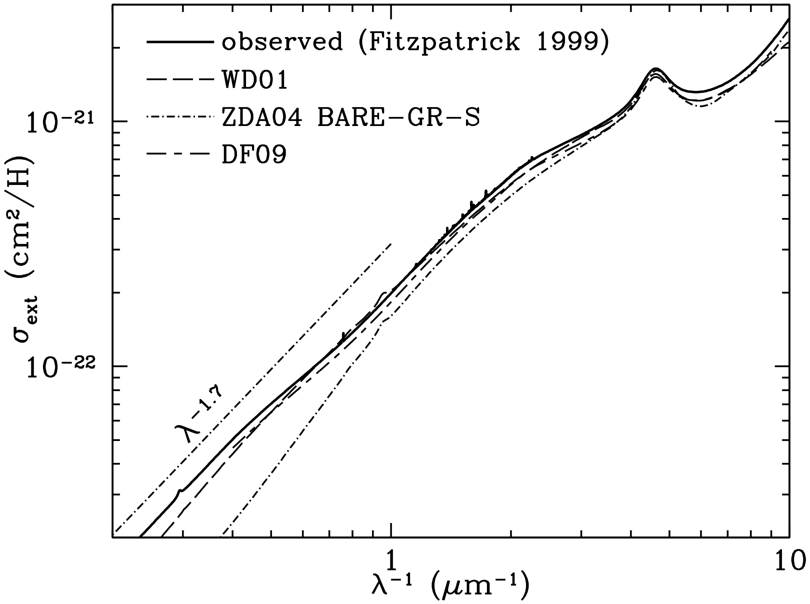
$$\frac{1}{n_{\rm H}}\frac{dn_{\rm gra,sil}}{da} = A_{\rm gra,sil}\, a^p \qquad \text{for } a_{\rm min} < a < a_{\rm max}$$

$$\begin{aligned} p &= -3.5 \\ a_{\rm min} &\approx 0.005\,\mu\mathrm{m} \\ a_{\rm max} &\approx 0.25\,\mu\mathrm{m} \end{aligned}$$

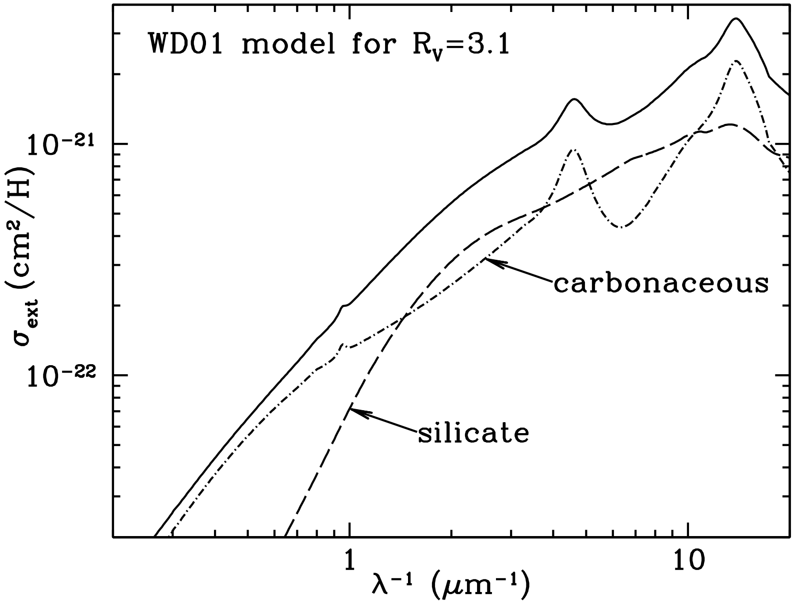
This is the famous "MRN" size distribution.

- $dn/da \propto a^{-3.5}$ has most of mass at large size end, most of area at small size end.
- $dn/da \propto a^{-3.5}$ is similar to size distribution of
  - ◇ $p \approx -3.25$ for asteroids with $5 < D < 300\,\mathrm{km}$ (Bottke et al. 2005)
  - ◇ steady-state coagulation/fragmentation models (Dohnanyi 1969; Weidenschilling 1997; Tanaka et al. 1996, 2005)
- **Problem: Because of PAHs, the MRN distribution can no longer be considered applicable to interstellar dust.**
  - ◇ Substantial mass in ultrasmall dust grains: $\sim 5\%$ of total dust mass is in particles with $< 10^3$ C atoms. This is *much* more than MRN extended to very small sizes.
  - ◇ PAHs contribute substantially to the UV extinction.
  - ◇ Non-PAH extinction not well-fitted by MRN distribution.

Modeling Extinction



Extinction: observed and modeled

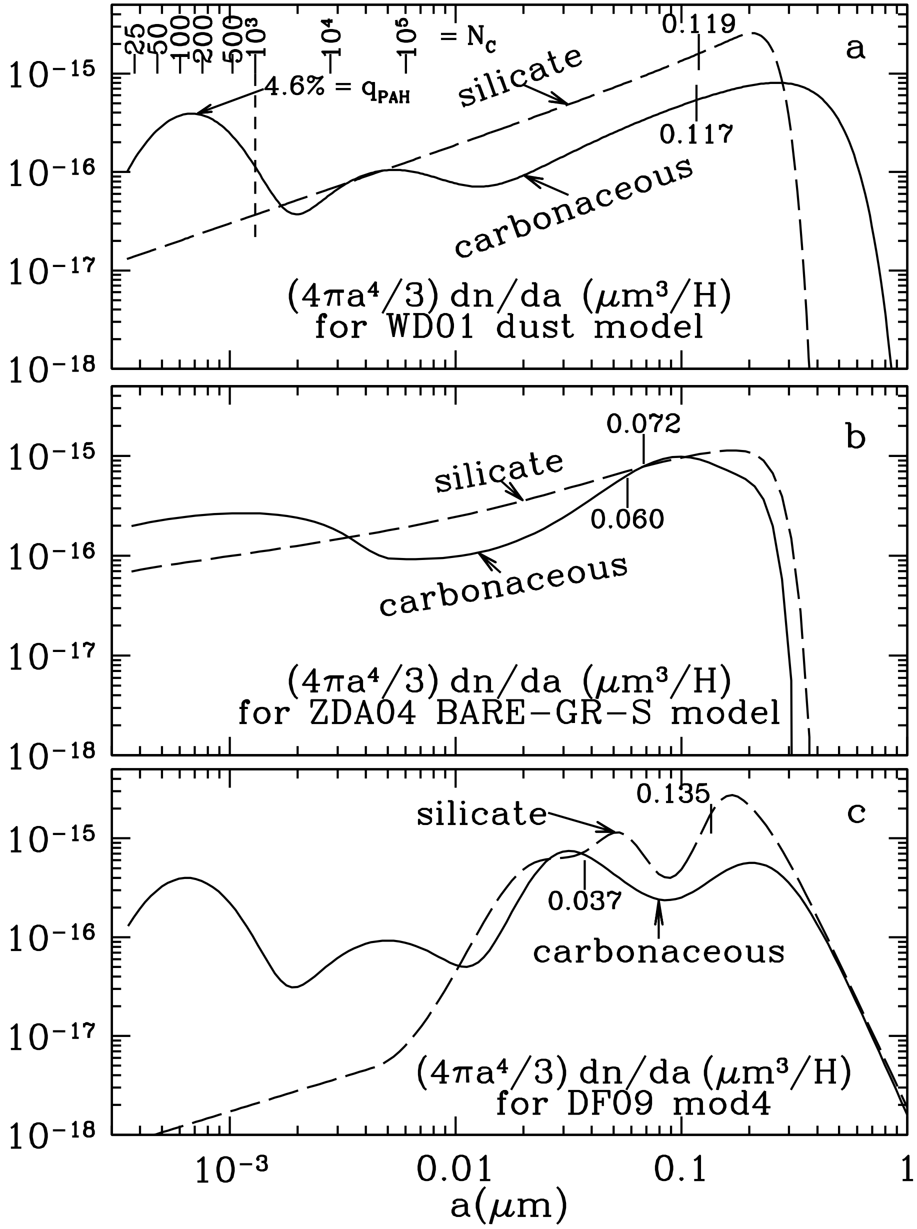


Extinction contributed by silicate and carbonaceous material in WD01 model.

- Dielectric functions for candidate materials are uncertain
- Calculation of $C_{\rm ext}(\lambda)$ is
  - easy if spheres are assumed
  - not so easy for spheroids
  - challenging for more complex shapes
- Models are not unique.

- "Observed" extinction in IR ($\lambda > 1\,\mu$m) is not well-determined – WD01 and ZDA04 models differ in what they adopt as "observed" IR extinction.
- In recent years there have been revisions to the "observed" extinction in the 3–8 μm region. Current models don't agree with observations in this region.

Dust Mass Distribution



Mass distributions for different grain models:
(a) WD01=Weingartner & Draine (2001) (b) ZDA04=Zubko et al. (2004); (c) DF09=Draine & Fraisse (2009).

figure from Draine (2011)

- Models not unique, but general agreement on overall distribution of grain mass.
- Most of grain mass at $0.05 < a < 0.5\,\mu$m.
- “Typical” (half-mass) grain radius $\sim$0.1 μm
- Size distribution is **not** a power-law.
- Significant mass in $a < 1$nm particles required to explain PAH emission.
- Models **not** consistent with claimed flux of $a > 0.3\,\mu$m particles entering heliosphere.

Regional Variations in Size Distribution

- Extinction curves are known to vary from one sightline to another.
- Denser regions tend to have
  - ◇ "flatter" extinction curves, i.e., higher values of $R_V \equiv A_V/E(B-V)$
  - ◇ increased R_V is attributed to tilt in size distribution to decrease numbers of small particles, increase numbers of larger particles.
  - ◇ grain growth is presumably due partially to accretion of atoms from gas, but this is only a minor effect (because unless ices can form, most depletable species are already depleted in diffuse clouds)
  - ◇ grain growth must be due primarily to coagulation.
- timescale for dust grain to collide with another dust grain is relatively short:

$$\tau_{dd} = \frac{1}{n_{\rm H}\,\Sigma_d\,(\Delta v)_{dd}} = 1\times10^7\,{\rm yr}\left(\frac{30\,{\rm cm}^{-3}}{n_{\rm H}}\right)\left(\frac{10^{-21}\,{\rm cm}^2/{\rm H}}{\Sigma_d}\right)\left(\frac{1\,{\rm km\,s}^{-1}}{\Delta v_{dd}}\right)$$

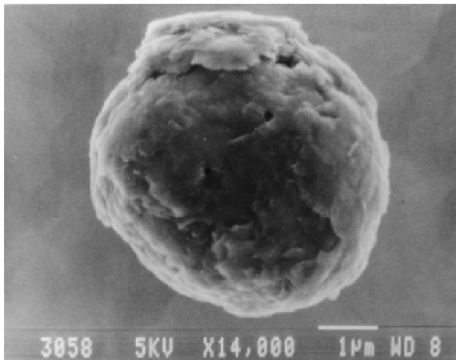
- dust-dust velocity differences $\Delta v_{dd} \sim 1\,{\rm km\,s}^{-1}$ are expected
  - ◇ radiation pressure and "recoil" effects can cause grains to drift through gas with speeds that depend on size and composition
  - ◇ ordinary fluid turbulence will give grains random velocities
  - ◇ MHD turbulence can pump energy into "orbital" motions of $\gtrsim 0.1\,\mu{\rm m}$ grains in diffuse clouds (Yan et al 2004)
- It is likely that coagulation modifies the grain size distribution. Presumably balanced by shattering in higher-velocity grain-grain collisions (Yan et al. 2004; Hirashita & Yan 2009; Hirashita et al. 2010)

Some Uncertainties

- **Separate populations of silicate and carbonaceous grains?**
  - It is natural for "stardust" to be segregated (silicate grains vs. carbon grains) but interstellar grains may be heavily affected by coagulation processes.
  - The 10 $\mu\mathrm{m}$ silicate feature is polarized therefore silicate-containing grains are aligned
  - **The $3.4\,\mu\mathrm{m}$ aliphatic C-H stretch shows no evidence of polarization** consistent with separate, non-aligned, population of carbonaceous grains.
  - But 3.4 $\mu\mathrm{m}$ feature is weak – few studies of polarization
  - Degree to which grain materials are segregated remains uncertain.
- **Grain geometry?**
  - Compact grains?
  - Fluffy grains resulting from agglomeration?
  - Models with compact grains can reproduce observations.
    What about fluffy grains? *We don't know – needs to be studied.*

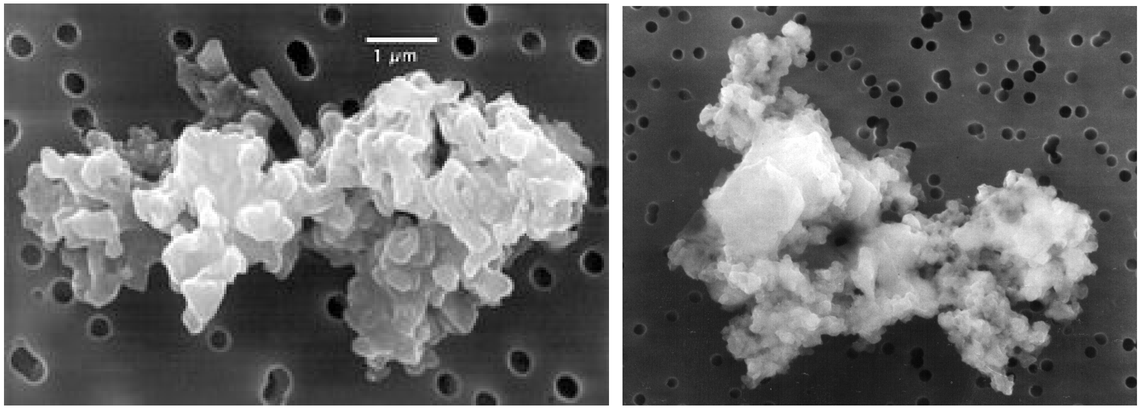
Grain Geometry: Uknown

- Are interstellar grains fairly smooth and compact?



Presolar onion-like graphite grain (diameter ~5 μm). Photo from S. Amari.

- Or are they typically loose aggregates of smaller particles, with a large "porosity"?



Two interplanetary dust particles collected from stratosphere (diameter ~10 μm). Elemental compositions similar to primitive meteorites: silicates + carbonaceous material.

Images courtesy E.K. Jessberger and Don Brownlee.

How Can We Determine Grain Geometry?

- **Direct capture?**
  - Stardust mission: (probably) destructive capture
  - Future mission: need to figure out how to capture incoming particles without destroying them...
- **Try to reproduce extinction and polarization observations**
  - Compact grains: OK
  - Fluffy grains – we don't yet know
  - Work in progress...
- **Try to reproduce X-ray halos**
  - Compact grains: OK
  - Fluffy grain models → more concentrated X-ray halos (Heng & Draine 2009). May be inconsistent with observations.
  - Work in progress...

Heating and Cooling of Grains: Infrared Emission

For given starlight radiation field u_ν, and grain of given composition c and radius a, calculate the probability distribution function dP/dE for internal energy E:

- ◇ define N energy bins E_j (we use $N = 500$)
- ◇ calculate transition matrix T_{ji} = probability per unit time of transition $i \to j$.
  upward transitions due to photon absorption
  downward transitions due to photon emission
- ◇ Let P_j = probability that grain will be in bin j
- ◇ Then

$$\frac{d}{dt}P_j = \sum_{i \neq j} T_{ji}P_i - \sum_{k \neq j} T_{kj}P_j$$

- ◇ Find steady state solution

$$0 = \sum_{i \neq j} T_{ji}P_i - \sum_{k \neq j} T_{kj}P_j$$

  with $\sum_j P_j = 1$.
- ◇ Repeat for many different sizes a.

Upward transition rates are calculated using absorption cross section $C_{\rm abs}(\nu)$ and radiation field u_ν.

How to calculate downward transition rates

$$T_{ji} \quad j < i \quad ?$$

See discussion in Draine & Li (2001).
A good approximation is to associate a temperature T_j with each energy bin E_j:

$$T_j = T \text{ for which } \langle E \rangle = E_j .$$

Thermal approximation: assume that grain with energy E_j has emission spectrum

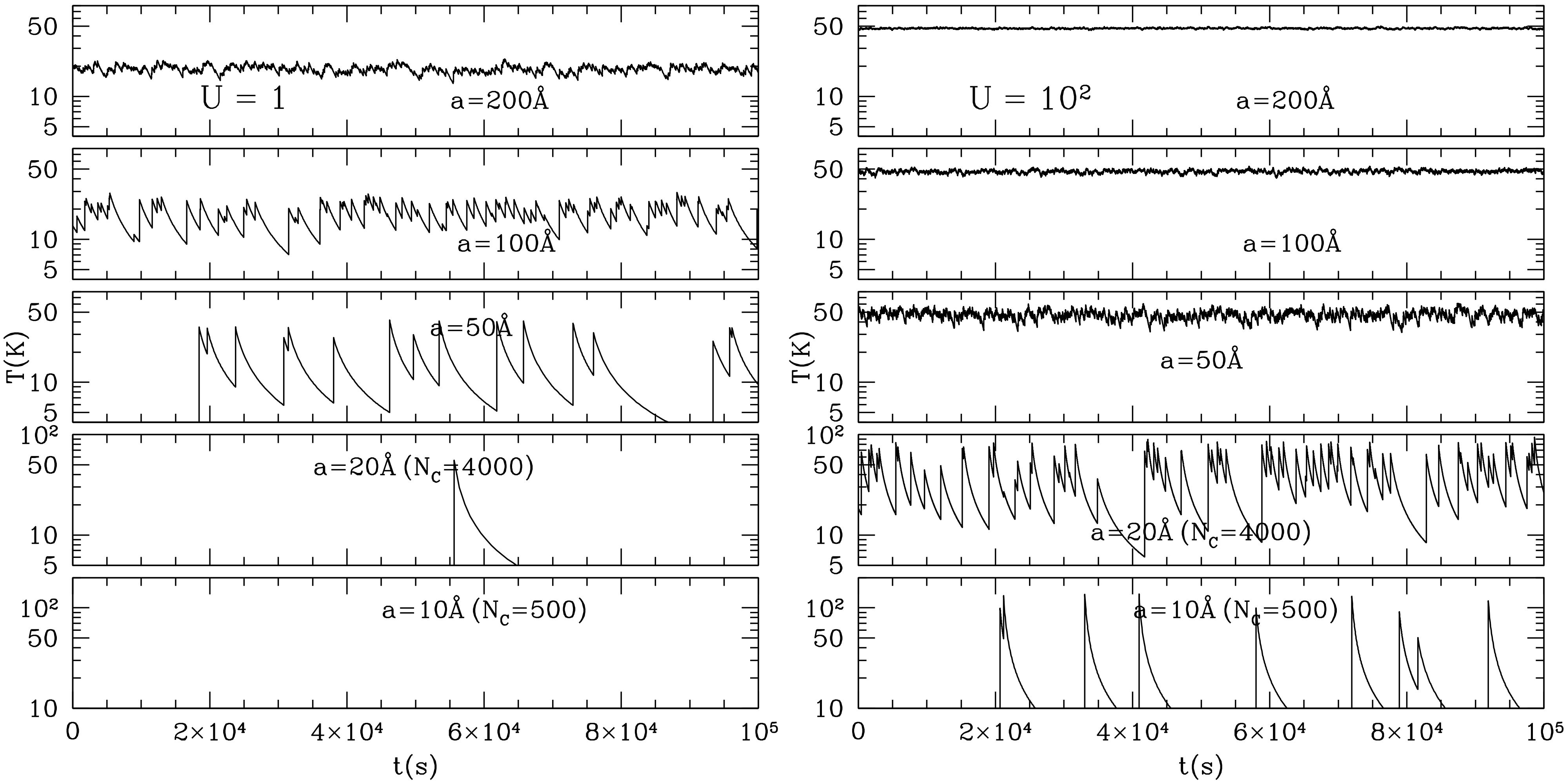
$$j_\nu = C_{\rm abs}(\nu) B_\nu(T_j)$$

where $B_\nu(T) =$ blackbody function.

Because energy bins have finite width, need to give some care to calculation of T_{ij}.

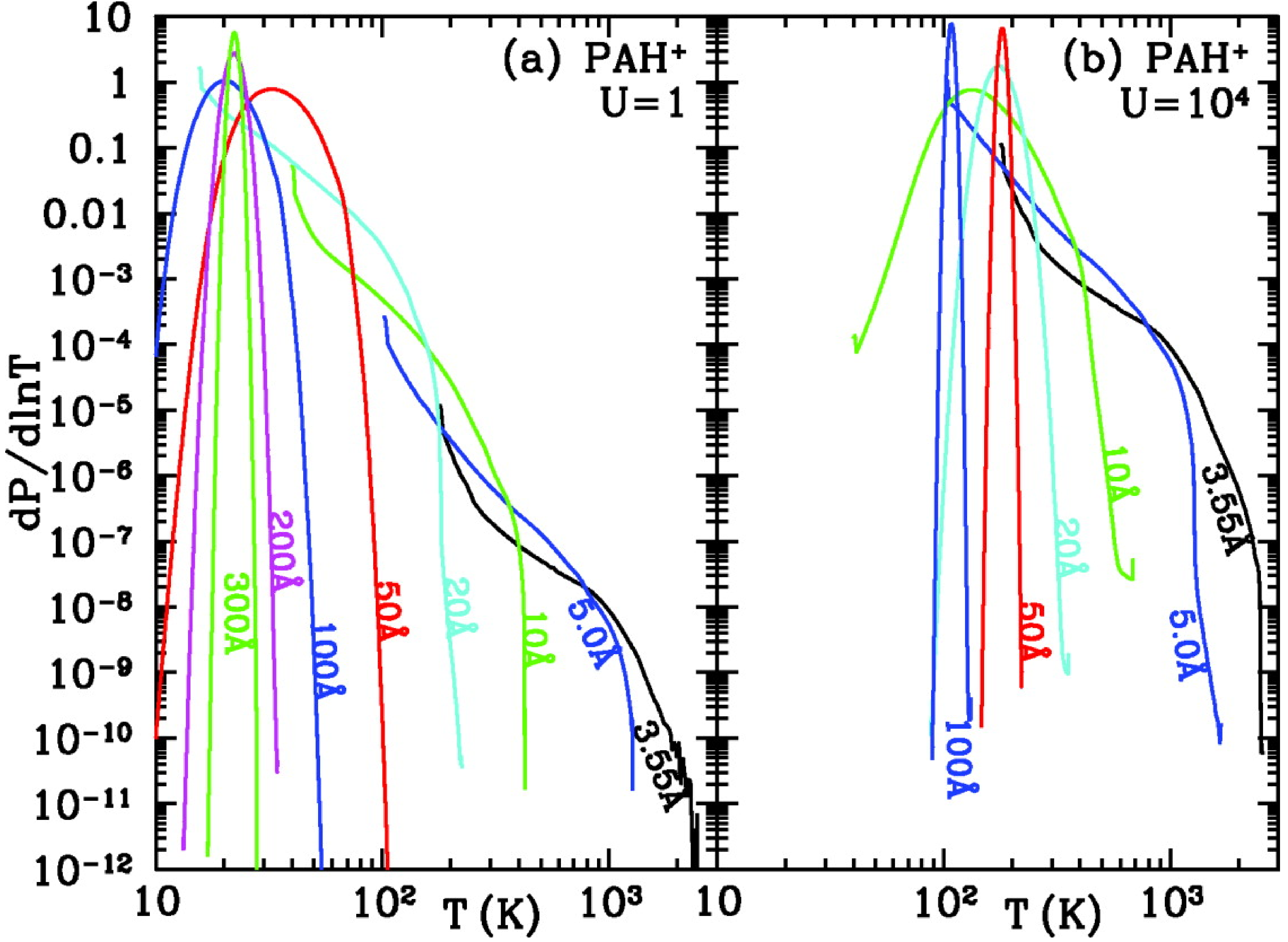
$$\boxed{\Longrightarrow (dP/dT)_{c,a}}$$

A Day in the Life of 5 Interstellar Grains



- grain with 50 C atoms in local starlight ($U = 1$): ∼1 absorption/100 days

Temperature Distribution Functions



from Draine & Li (2007)

Temperatures of "Classical" Grains

For large grains,

$$(dP/dT)_{c,a} \quad \Longrightarrow \quad \delta(T - T_{\rm ss}(c,a))$$

Steady-state temperature $T_{\rm ss}(c,a)$ is solution to **heating** = **cooling**

$$\int d\nu \, C_{\rm abs}(\nu) \, u_\nu c = \int d\nu \, C_{\rm abs}(\nu) \, B_\nu(T_{\rm ss})$$

If $C_{\rm abs} \propto \nu^\beta \propto \lambda^{-\beta}$ in IR, then

$$\int d\nu \, C_{\rm abs}(\nu) \, B_\nu(T_{\rm ss}) \propto T_{\rm ss}^{(4+\beta)}$$

and

$$T_{\rm ss} \propto u_\star^{1/(4+\beta)}$$

If

$$\begin{aligned} C_{\rm abs} &\propto a^2 \ \ \text{for starlight absorption} \quad (a \gtrsim 0.1\,\mu{\rm m}) \\ C_{\rm abs} &\propto a^3 \ \ \text{for IR emission} \quad (a \lesssim 10\,\mu{\rm m}) \end{aligned}$$

then

$$T_{\rm ss} \propto u_\star^{1/(4+\beta)} \, a^{-1/(4+\beta)}$$

Bigger grains are slightly cooler.

Typically $\beta \approx 2 \Longrightarrow T_{\rm ss} \propto u_\star^{1/6} a^{-1/6}$

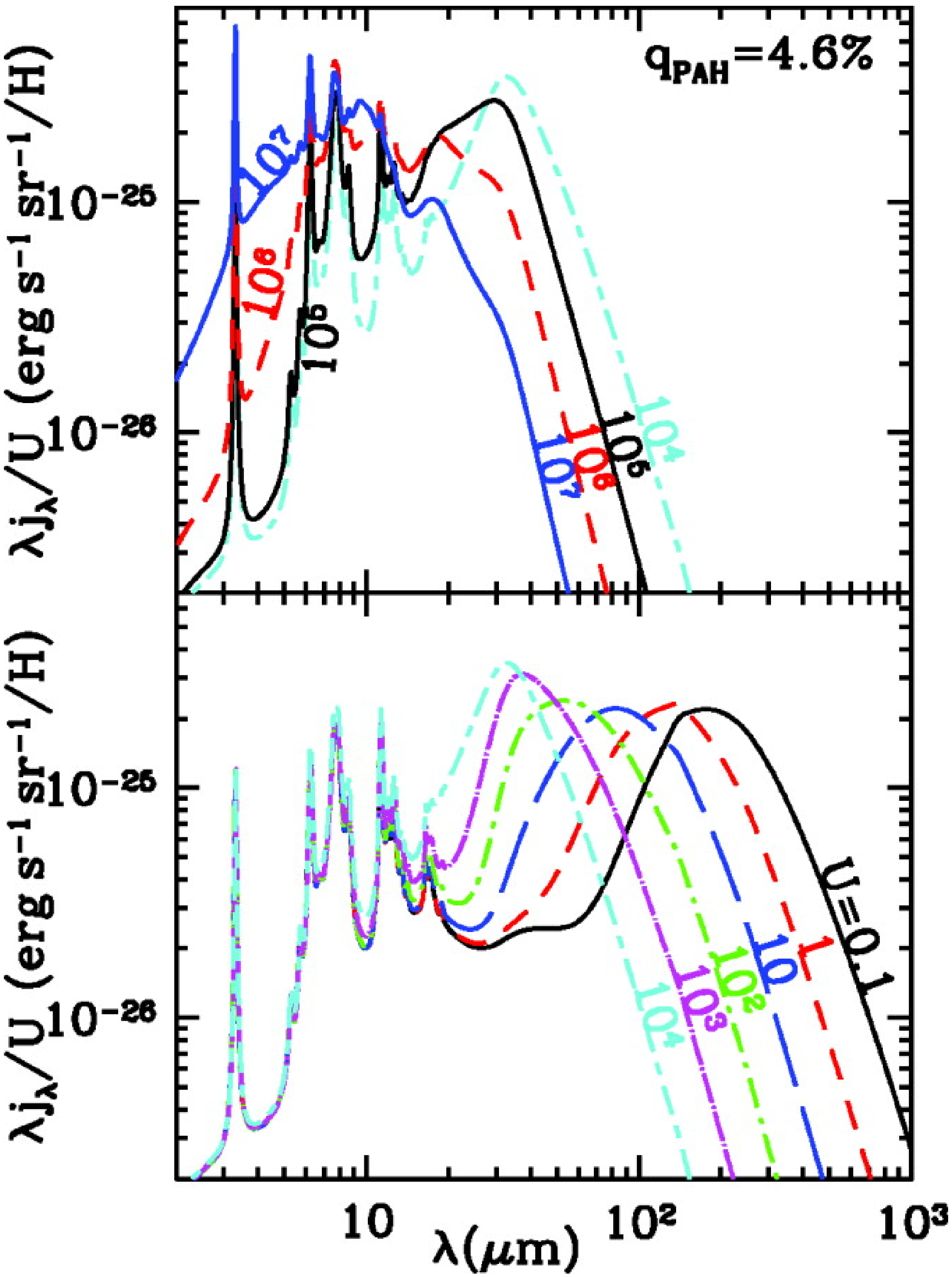
Emission Spectra

Sum over compositions c, integrate over size a to get emission spectrum:

$$j_\nu = \sum_c \int da \left(\frac{dn}{da}\right)_c \times \int dT \left(\frac{dP}{dT}\right)_{c,a} C_{\rm abs}(a,\lambda) B_\nu(T)$$

$\lambda \lesssim 15\,\mu$m emission spectrum (PAH features) independent of U for $U \lesssim 10^4$

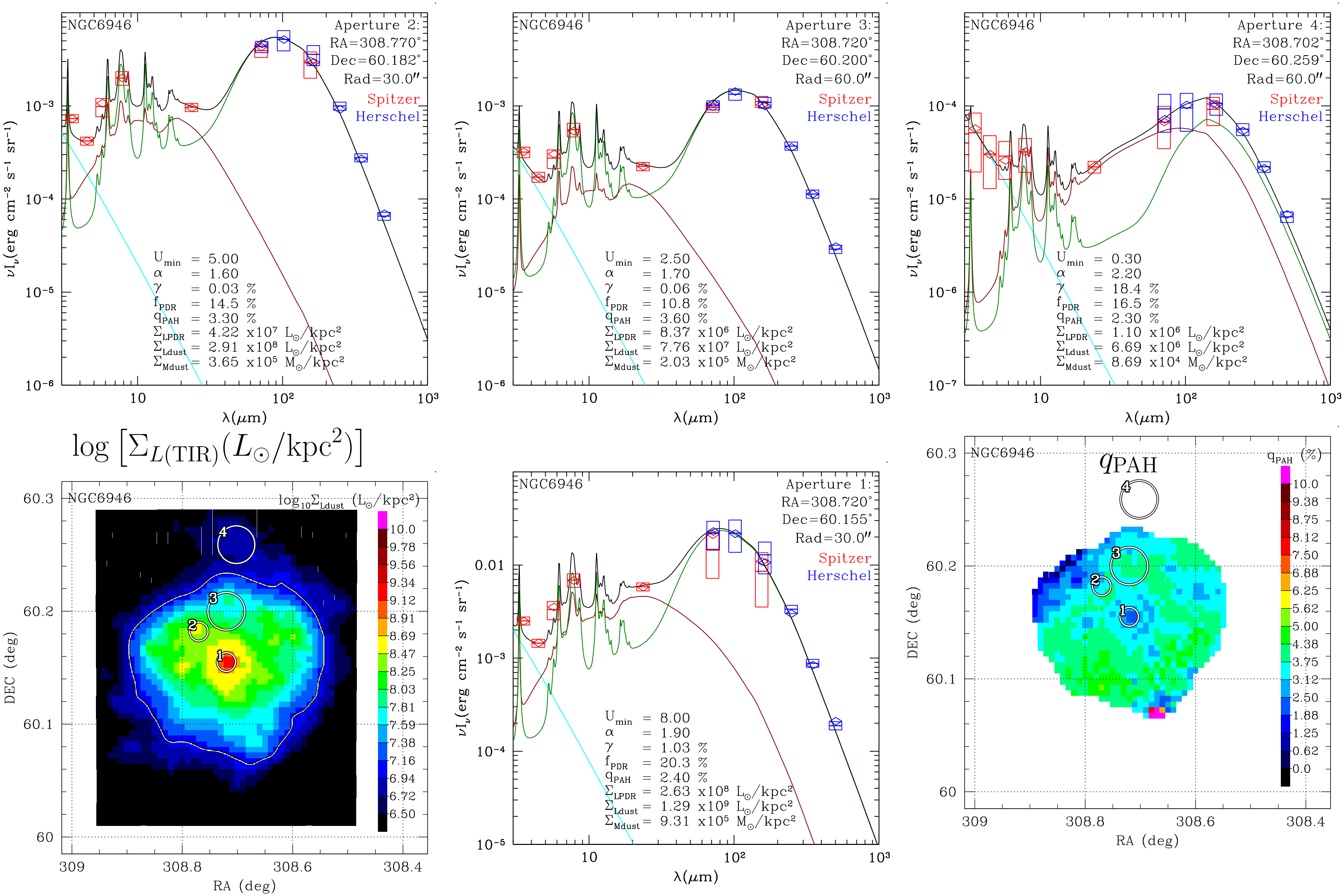
emission following single-photon heating events



from Draine & Li (2007)

IR Emission: Models vs. Observations

(Aniano et al. 2012)

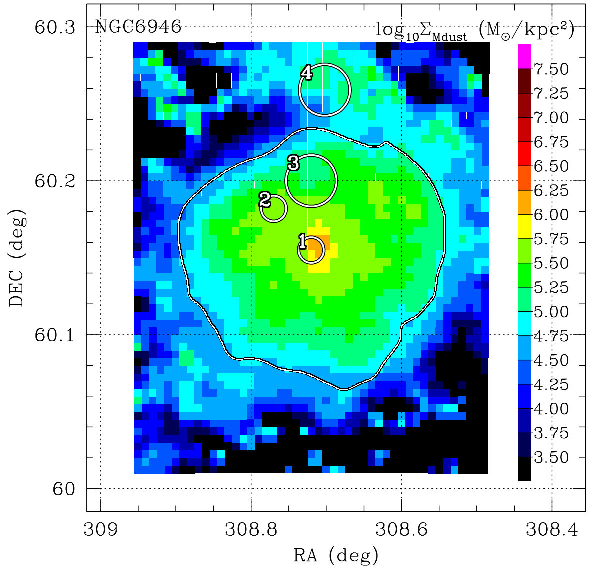


$\log\left[\Sigma_{L(\mathrm{TIR})}(L_\odot/\mathrm{kpc}^2)\right]$

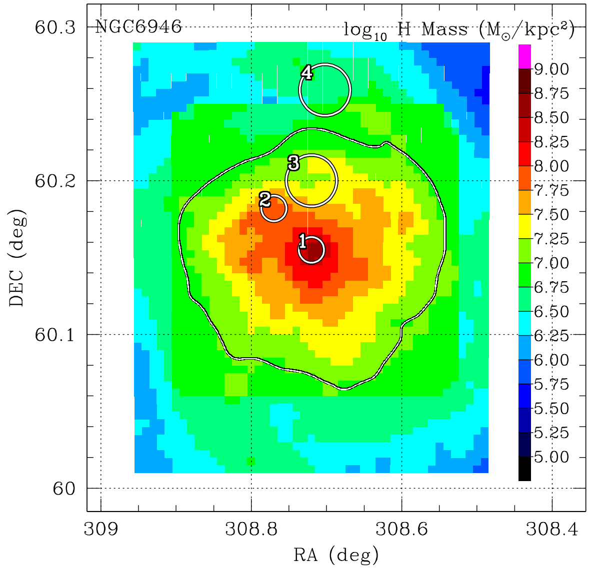
q_{PAH}

Dust-to-Gas Ratio in NGC 6946 at MIPS 160 resolution

$\Sigma_{\rm dust}$

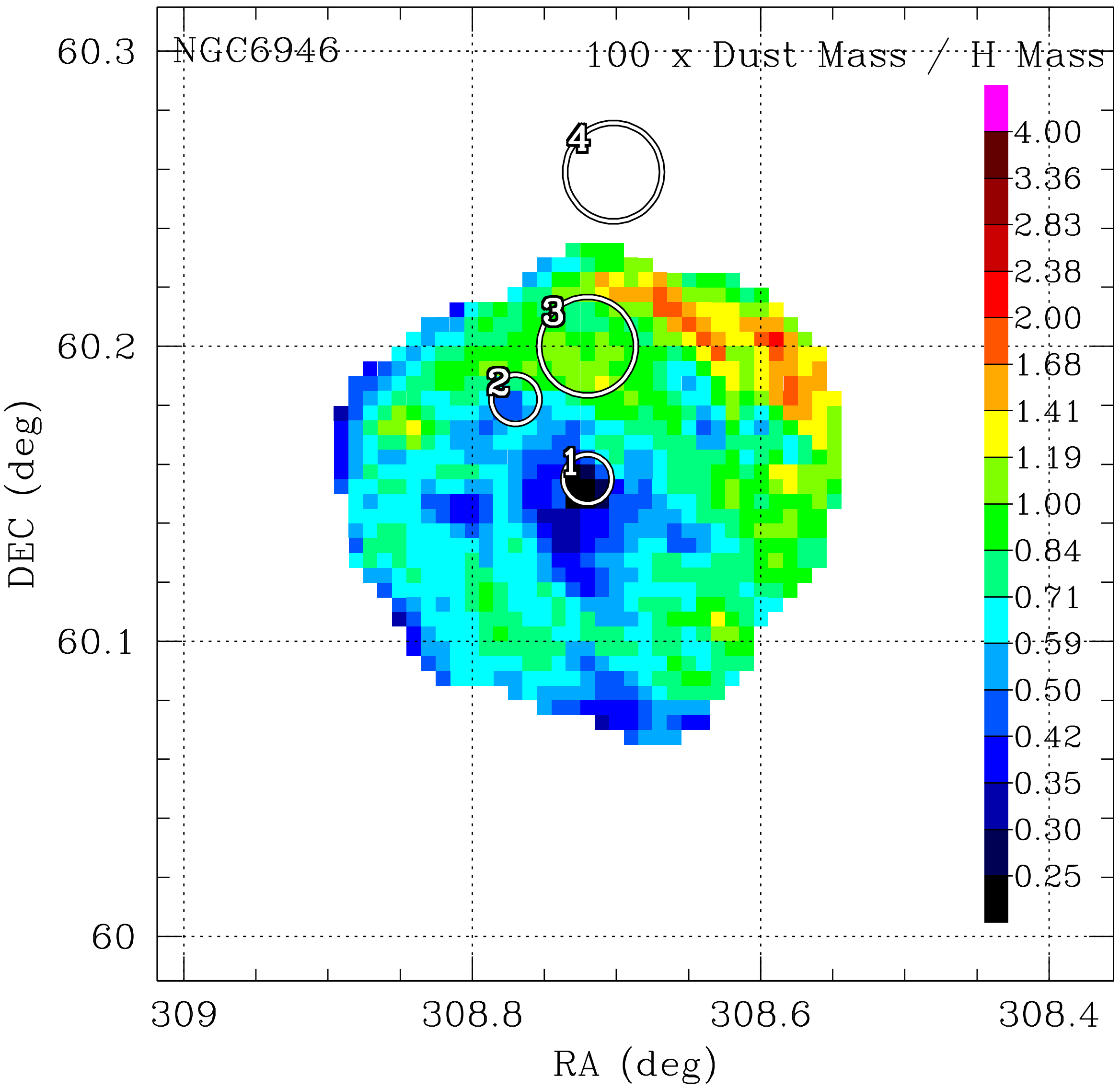


$\Sigma_{\rm H\,I+H_2}$



$$X_{\rm CO} = 4\times10^{20}\,{\rm H_2\,cm^{-2}}/({\rm K\,km\,s^{-1}})$$

$\Sigma_{\rm dust}/\Sigma_{\rm HI+H_2}$ *(Aniano et al. 2012)*

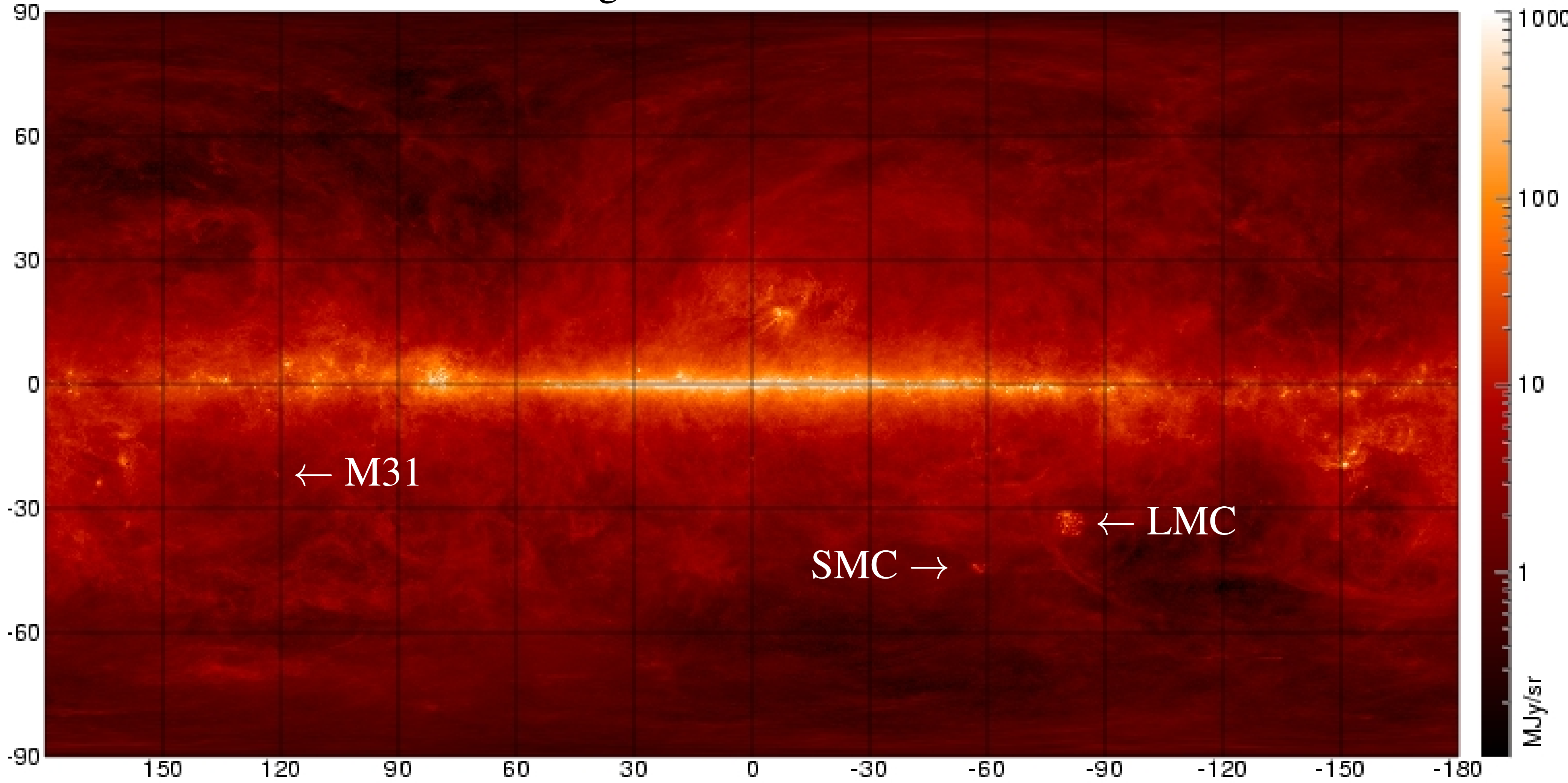


- Low dust/gas ratio within ~2 kpc of center: $X_{\rm CO}$ **should be lower near center** (Meier & Turner 2004; Donovan Meyer et al. 2012)
- $M_{\rm dust}/M_{\rm H} \approx 0.010 \pm 0.004$ over most of disk
- A few places with high $M_{\rm dust}/M_{\rm H}$ – bad data?

How about Nearby Galaxies?

100 μm IRAS/COBE Map of Sky (after zodi subtraction)

Image credit: D. Finkbeiner

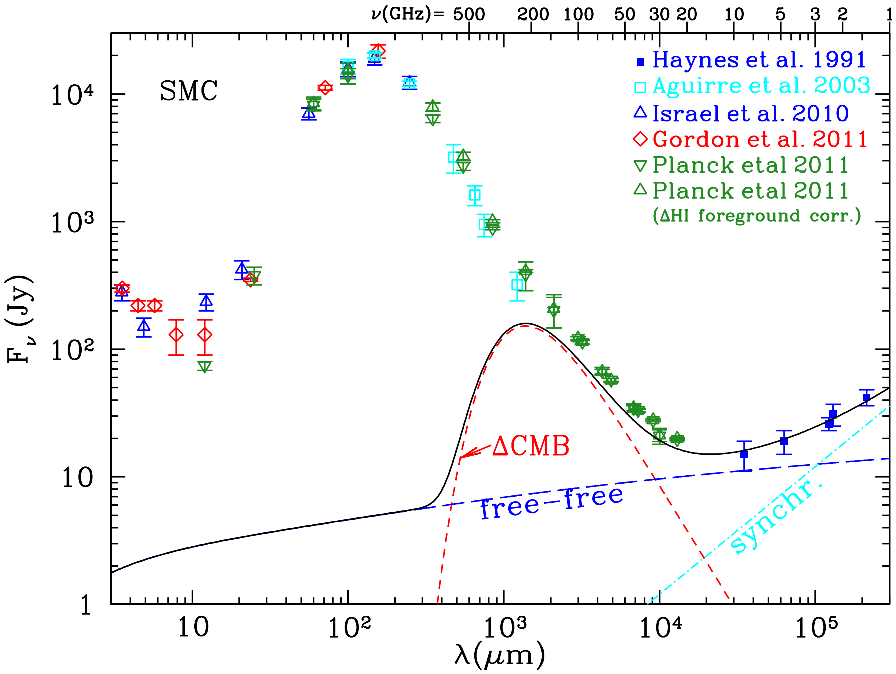


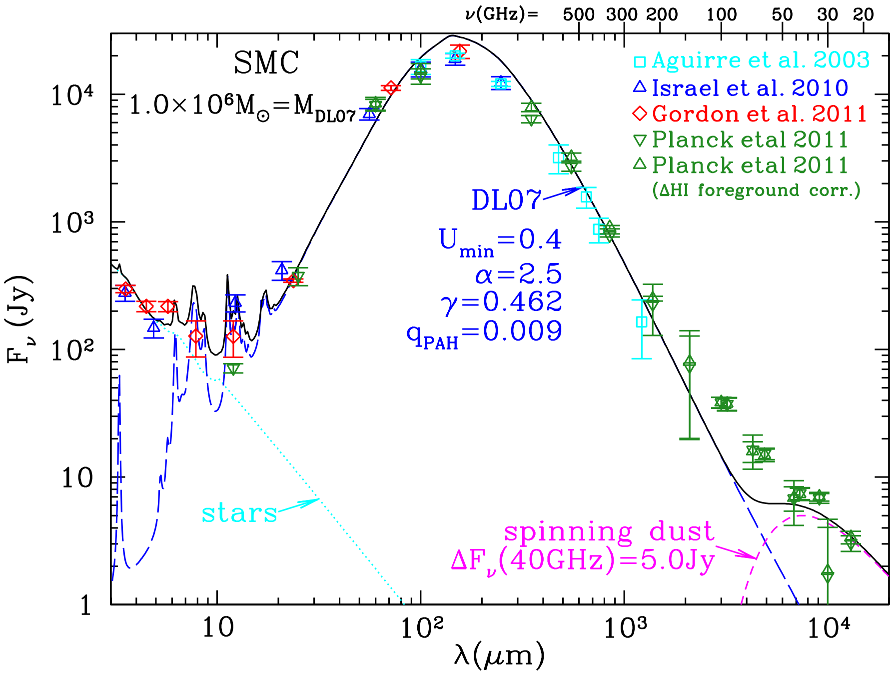
galactic longitude (deg.)

The Small Magellanic Cloud (SMC)

- Interstellar gas less enriched with heavy elements (C,N,O,...,Fe) formed in massive stars
  SMC metallicity ∼25% "solar"
- Composition of dust appears to differ from dust in the Milky Way.
  2175Å "bump" is weaker

Dust in the SMC: Excess 50–300 GHz Emission





- Photometry: Israel et al. (2010) and Planck Collaboration et al. (2011)
- $M_{\rm H}(SMC) \approx 4.8 \times 10^8 M_\odot$
- $Z(SMC) \approx 0.25 Z_\odot$
- $M_{\rm dust,max}(SMC) \approx 1.2 \times 10^6 M_\odot$
- After subtracting
  - *synchrotron emission*
  - *free-free (bremstrahhlung)*
  - *chance upward fluctuation of CMB*

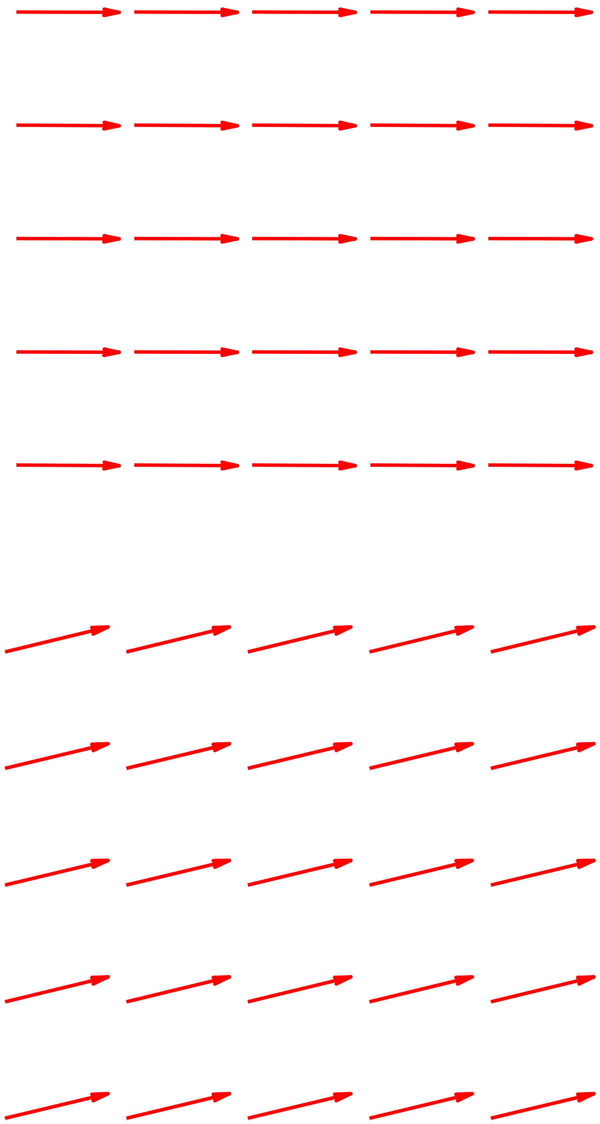
Can dust model + starlight reproduce the observed emission?

- Model with acceptable mass of dust, but severe 50–200 GHz shortfall.
- **Dust in SMC is more emissive at mm wavelenths than MW dust**... why?
- At long wavelengths (particle size $\ll$ λ), it is usually assumed that emission comes from *thermal fluctuations in the electric dipole moment*.

Perhaps this isn't the only source of emission from dust....

Magnetic Dipole Emission from Magnetic Dust

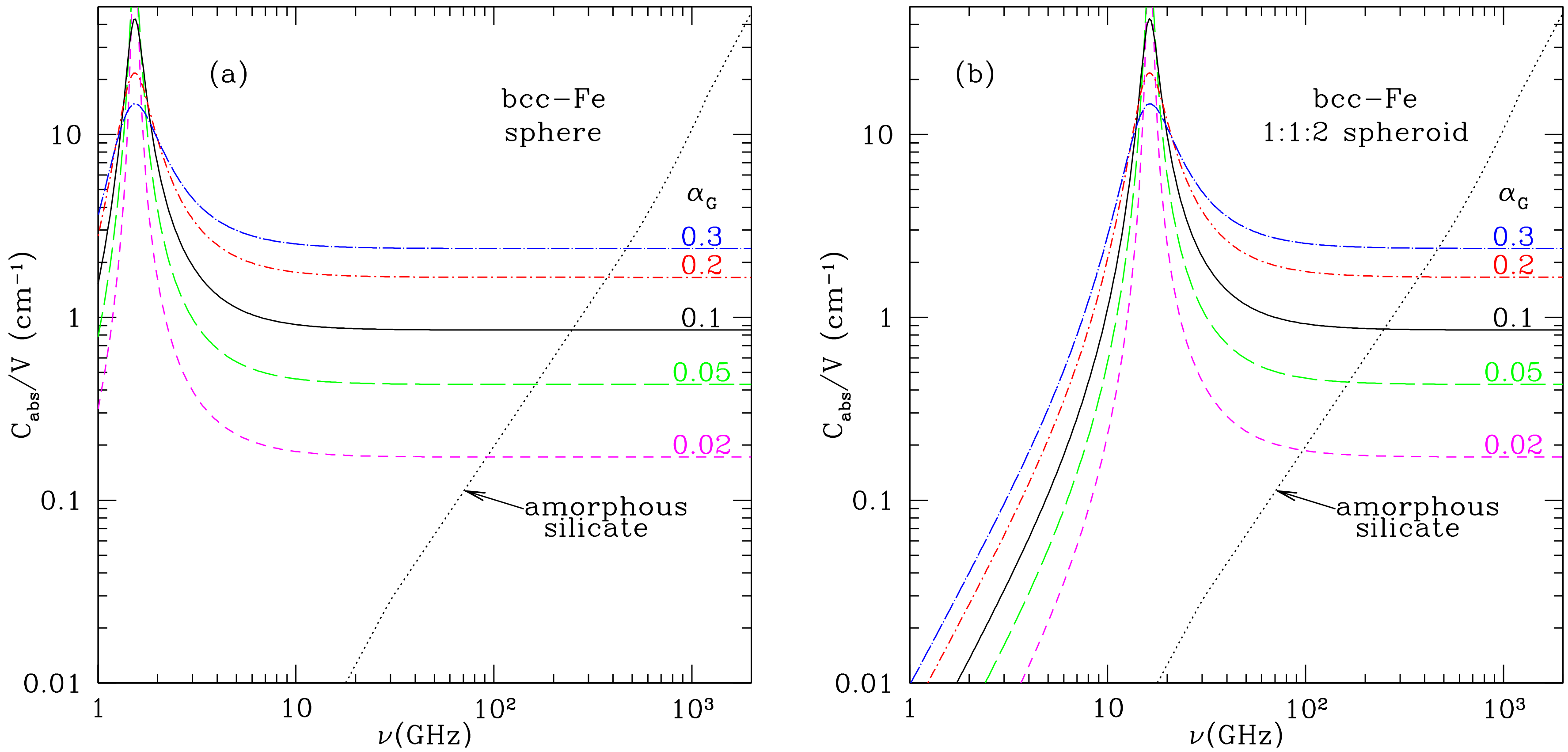
(Draine & Lazarian 1999; Draine & Hensley 2012b)



- Suppose much of the Fe is in magnetic material (e.g., metallic Fe, magnetite Fe_3O_4, or maghemite γ–Fe_2O_3)
- Lowest energy state of metallic Fe:
  - spins are parallel (magnetized),
  - magnetization $\vec{M}$ is aligned with one of the crystal axes
- Excited state: spins parallel, but oriented away from crystal axis
- Oscillations in magnetization → magnetic dipole emission
- Finite temperature → **thermal** magnetic dipole emission

Magnetic Dipole Absorption Cross Section for Fe Nanoparticles

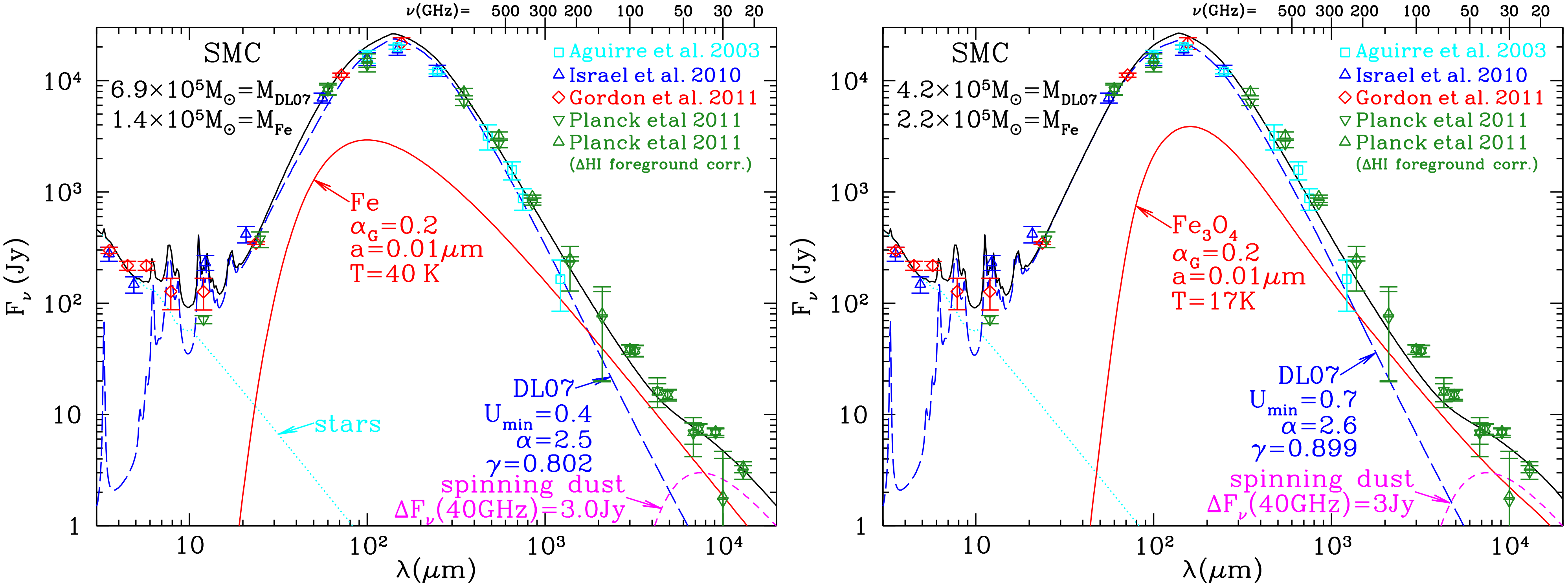
(Draine & Hensley 2012b)



- Magnetization dynamics: use **Gilbert equation**
  (*not* Landau-Lifshitz eq. or Bloch-Bloembergen eq.)
- For metallic Fe: ferromagnetic resonance frequency depends on particle shape.
- Absorption depends on uncertain "Gilbert damping parameter" α_G.
  $\alpha_G \approx 0.2$ may be realistic.

SMC Dust Models With Iron or Magnetite (Fe$_3$O$_4$) Nanoparticles

(Draine & Hensley 2012a)

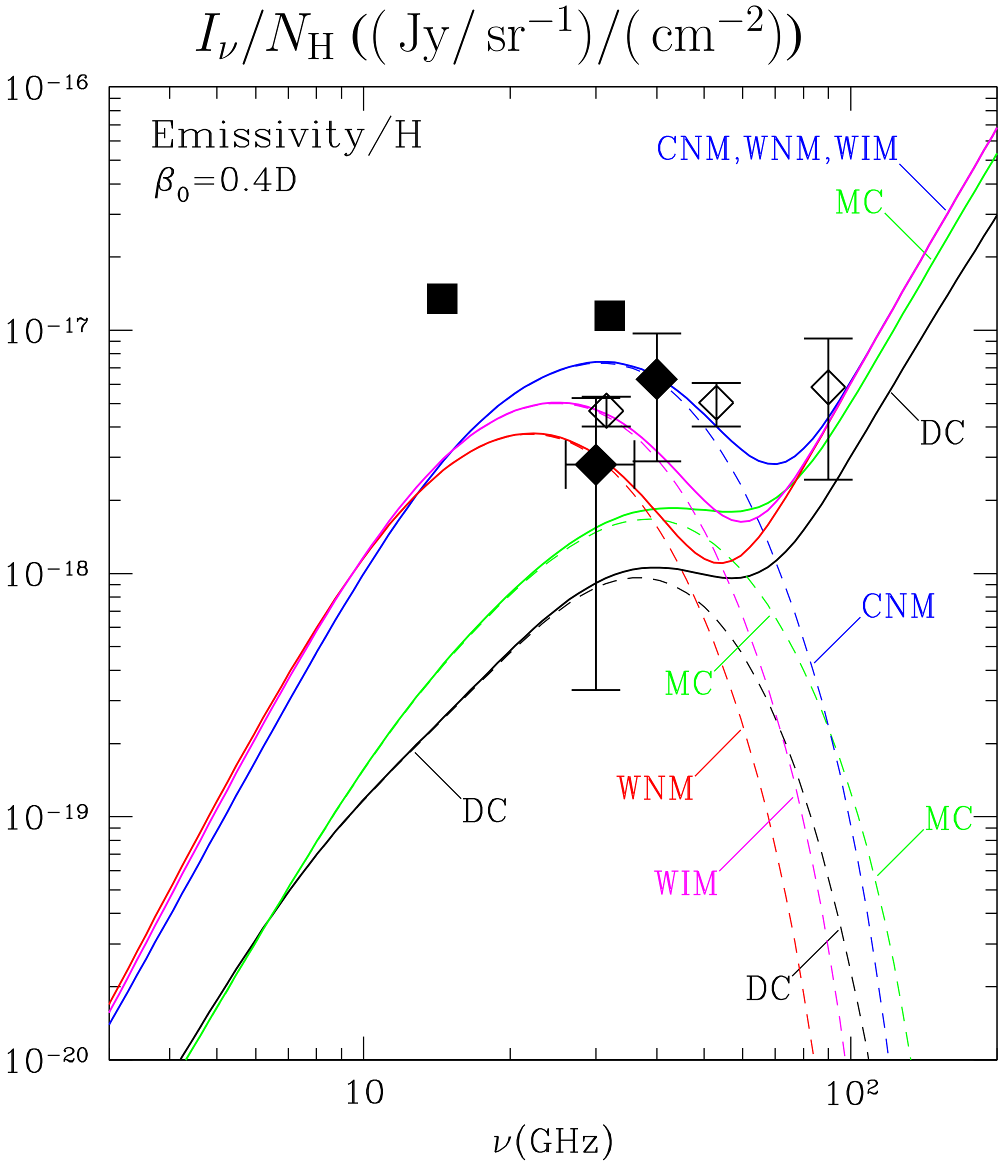


- $M_{\rm dust} = 8.4 \times 10^5 M_\odot$ or $6.4 \times 10^5 M_\odot$ (both $< M_{\rm dust,max} = 1.2 \times 10^5 M_\odot$)
- magnetic dipole emission dominates for $\nu \lesssim 200\,{\rm GHz}$
- spinning dust component:
  - normal spectrum (peaking near 40 GHz)
  - has ∼expected strength (scaled with PAH abundance in SMC)

Rotational Dynamics: Spinning Dust

- Large population of PAHs needed to produce observed IR emission features
- IR emission comes from *vibrations* but PAHs will also be *rotating*
- Estimate rotational frequency as function of PAH size
- Processes that change angular momentum:
  - collisions with atoms or ions
  - “plasma drag”: coupling to ions that do not physically impact PAH
  - absorption of starlight photons
  - emission of IR photons
  - radiation from spinning electric dipole [for assumed dipole moment]

  sub-thermal rotation: $\langle E_{\rm rot}\rangle < 1.5kT_{\rm gas}$
- Integrate over PAH size distribution



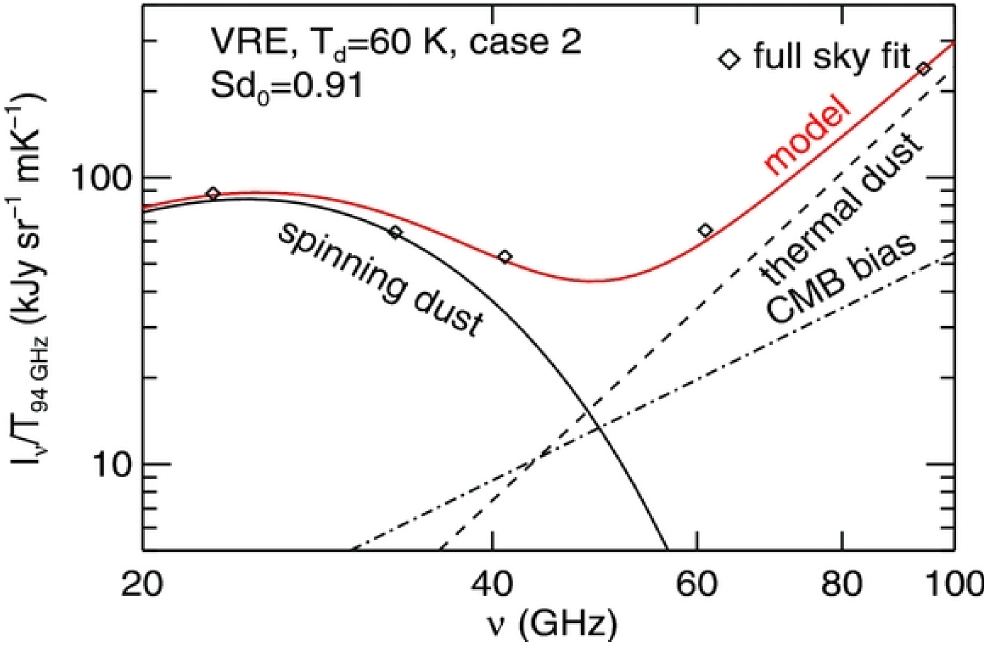
Draine & Lazarian (1998)

Rotational Dynamics: Spinning Dust

Recent Refinements

- Will spinning dust emission be polarized?
  NO: pol $< 1\%$ **at** $\nu > 30\,\mathrm{GHz}$
  (Lazarian & Draine 2000)
- Factor of two correction to rotational excitation by photon emission (Ali-Haïmoud et al. 2009)
- Analytic solution to Fokker-Planck equation (Ali-Haïmoud et al. 2009)
- Polarized IR emission from PAHs in reflection nebulae (Sironi & Draine 2009)
- Allow for rotation around non-principal axis (Hoang et al. 2010; Silsbee et al. 2011)
- Include effects of high-ΔJ impacts with ions (Hoang et al. 2010)
- Wobbling for general asymmetric grains (moment-of-inertia tensor with 3 non-degenerate eigenvalues) (Hoang et al. 2011)
- Include internal relaxation (coupling of vibrational and rotational modes) with transient heating (Hoang et al. 2011)

Comparison with WMAP 5yr data



(Hoang et al. 2011)

Grain Destruction in the ISM

Principal Mechanisms for solid → gas in SN Blastwaves

- Sputtering (removal of single atoms following impact of H or He ions)
- Vaporization in grain-grain collisions
- SN shock will destroy dust if $v_s \gtrsim 250\,\mathrm{km\,s^{-1}}$.
  $M v_s^2 \approx 2.7E$ (Sedov)

$$M = \frac{2.7\times 10^{51}\,\mathrm{ergs}}{(250\,\mathrm{km\,s^{-1}})^2} = 2200 M_\odot$$

- 1 SN/50 years:

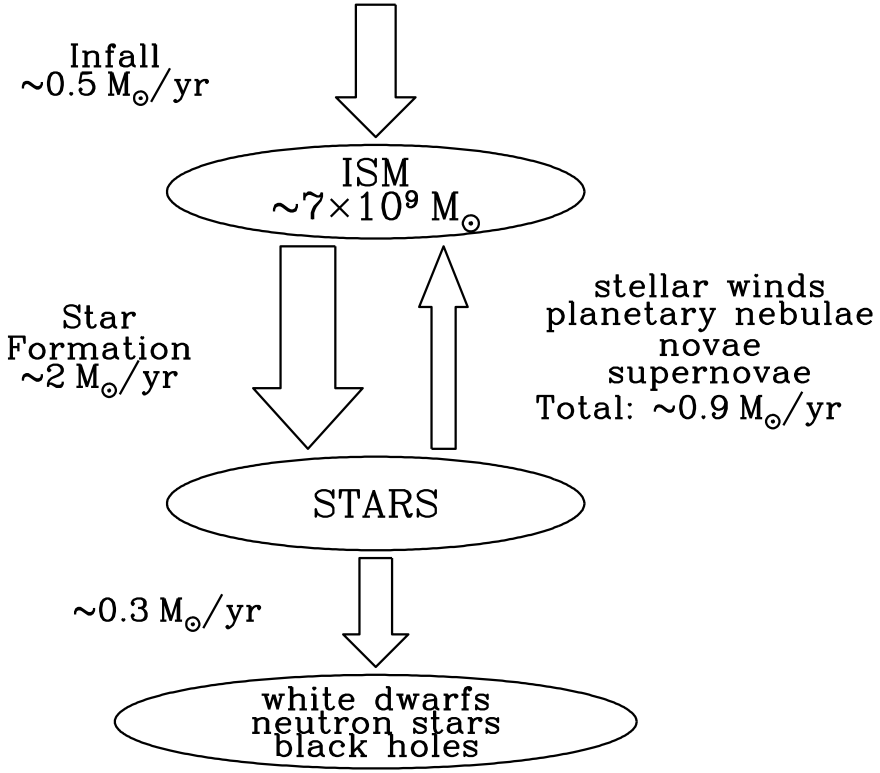
$$\tau_{\rm dest} = \frac{M_{\rm ISM}}{2200 M_\odot / 50\,\mathrm{yr}} = 1.6\times 10^8\,\mathrm{yr}$$

Complications:

- additional (partial) destruction in lower-velocity shocks
- ISM is inhomogeneous (but does mix rapidly)
- SN are correlated
- $\tau_{\rm dest} \approx 4\times 10^8\,\mathrm{yr}$
- Problem revisited a number of times (e.g., Barlow 1978; Draine & Salpeter 1979; Dwek & Scalo 1979; Jones et al. 1994) with similar conclusions (but see Jones & Nuth 2011, for dissenting view).

Grain Destruction and Reformation in the ISM

Mass Budget for the MW ISM



Infall
$\sim$0.5 $M_\odot$/yr

ISM
$\sim 7\times10^9\ M_\odot$

Star
Formation
$\sim$2 $M_\odot$/yr

stellar winds
planetary nebulae
novae
supernovae
Total: $\sim$0.9 $M_\odot$/yr

STARS

$\sim$0.3 $M_\odot$/yr

white dwarfs
neutron stars
black holes

Production of stardust

Injection of Gas and Stardust from Stellar Sources

gas ($M_\odot$/yr)	dust ($M_\odot$/yr)	Stellar Source
0.33	0.0016	Planetary Nebulae ($\sim$0.3/yr)
0.20	0.0010	RG, Red AGB, C star winds
0.06	<0.0001?	OB, WR, other warm/hot star winds
0.27	0.0002?	SNe (1/50 yr, $\sim 10^{-2} M_\odot$ dust/SN?)
	0.001 ?	*if* $0.5 M_\odot$ *dust/SN*
0.01	0.00001	Novae (100/yr, $10^{-7} M_\odot$ dust/nova?)
$\sim$0.9	**$\sim$0.003**	**All stellar sources**
	$\sim$0.004	*if* $0.5 M_\odot$ *dust/SN*

$$M_{\rm dust,inj} \approx 0.0035 M_\odot\,{\rm yr}^{-1}$$

- ISM "lifetime"
  $M_{\rm ISM}/({\rm SFR} - \dot{M}_{\rm in} - \dot{M}_{\rm return}) = 1.2\times10^{10}\,{\rm yr}$
- $\tau_{\rm SFR} = M_{\rm ISM}/{\rm SFR} = 3.5\times10^9\,{\rm yr}$
- $\tau_{\rm dest} \equiv$ lifetime of dust against destruction
  $\approx 4\times10^8\,{\rm yr}$
- dust formation $\approx$ removal+destruction
  $\dot{M}_{\rm dust,inj} = M_{\rm dust} \times (\tau_{\rm SFR}^{-1} + \tau_{\rm dest}^{-1})$

- **Predicted mass of surviving stardust:**
  $M_{\rm dust} = \dot{M}_{\rm dust,inj}/(\tau_{\rm SFR}^{-1} + \tau_{\rm dest}^{-1}) =$ $\mathbf{1.3\times10^6 M_\odot}$
- **But observe**
  $M_{\rm dust} \approx 0.007 \times M_{\rm ISM} = \mathbf{5\times10^7 M_\odot}$
- **Must be some other source of dust!**

Implications for Grain Evolution in the ISM

- Stardust expected to account for only ∼3% of observed dust mass.
- Bulk of dust mass must be **grown in the ISM**.
- In dense regions, time scale for atom to collide with grain surface is short:

$$\tau_{\rm acc} = \frac{1}{n_{\rm H}\sigma_{\rm dust}\Delta v} = 1\times10^7\left(\frac{30\,{\rm cm}^{-3}}{n_{\rm H}}\right)\left(\frac{{\rm km\,s}^{-1}}{\Delta v}\right)\,{\rm yr}$$

  for $\sigma_{\rm dust} = 10^{-21}\,{\rm cm}^2/{\rm H}$ = geometric cross section/H

- Challenge: understanding how to form separate populations of **carbonaceous material** and **amorphous silicates**
  Must be the result of UV photolysis (see discussion in Draine 2009)

- Dust in young galaxies at high z (e.g., J1148+5251 @ $z = 6.42$, with $M_{\rm dust}/M_{\rm gas} \gtrsim 0.004$) can be the result of injection of small amount of stardust from SNe and high-mass stars, followed by growth in dense regions of the ISM.

Many Challenges Remain...

- The geometry of interstellar grains.
- The composition of interstellar dust – both “stardust” and the materials grown in the ISM.
- The formation/destruction of PAHs
- The size distribution, and changes in the size distribution.
- The physical processes responsible for alignment of interstellar dust.
- The velocity distribution of interstellar dust in presence of MHD turbulence.
- Opacities of interstellar grain materials, from X-ray to microwave.
- Charging of interstellar grains
- Heating of gas by photoelectrons from grains
- Chemistry on grain surfaces
- Your idea here..

THANK YOU

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