How to model interstellar dust…

Too soon for *ab initio* approach:

- Too much physics and surface chemistry that we don't understand
- Limited understanding of the time-dependent interstellar environment
- Limited knowledge of contribution of "stellar" sources (RG, AGB, PNe, novae, SNe) to the IS dust population

Observations must guide us.– Before we try to figure out the **evolution** of interstellar dust, we should first try to figure out what interstellar dust is today.

"Direct" Observations of Interstellar Dust

Scattering, absorption, emission of light:

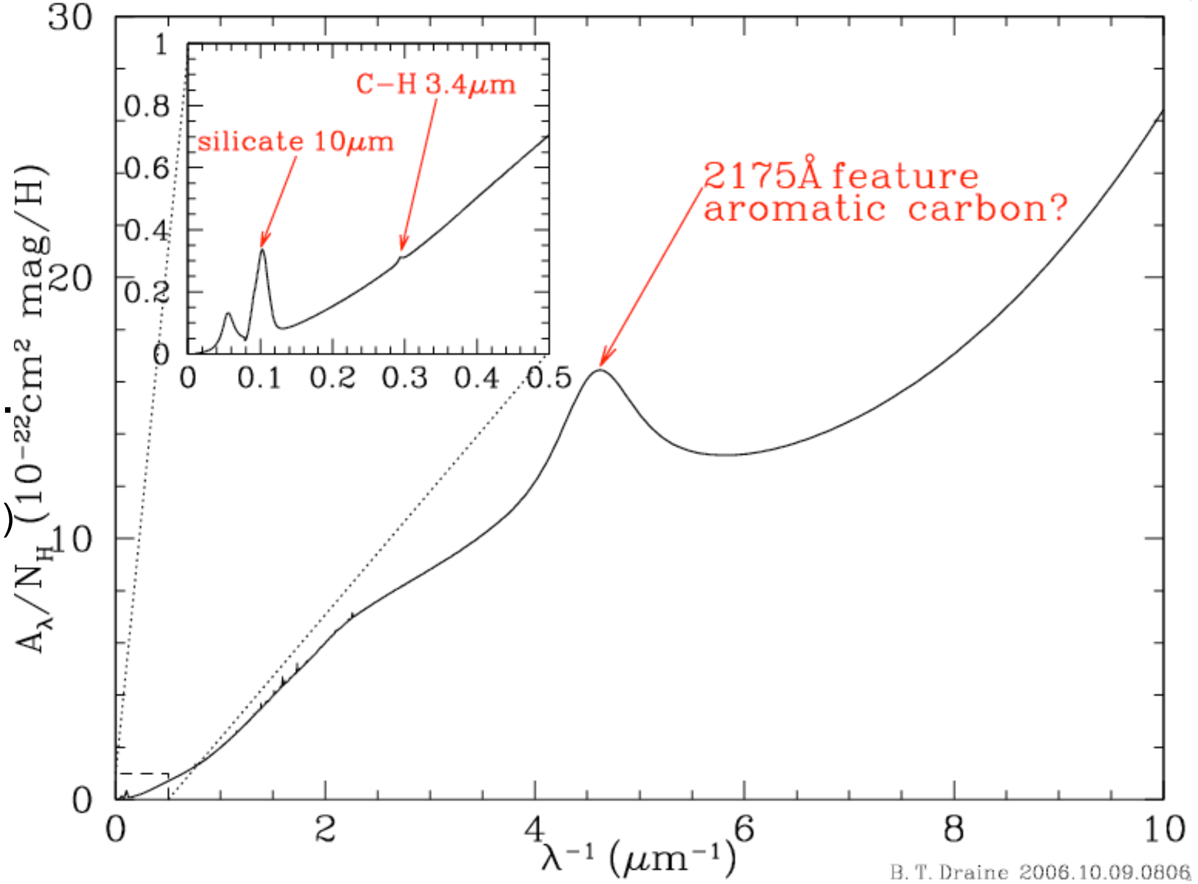
- extinction of starlight – A_λ/N_H
- variations of A_λ/N_H from one sightline to another
- polarization of starlight
- scattered light (reflection nebulae, DGL)
- small-angle scattering of X-rays by interstellar dust
- IR/submm emission from dust ($2\,\mu$m – 3mm), I_λ/N_H
  - PAH emission features
  - FIR/submm continuum
- polarization of IR emission
- microwave emission from interstellar dust
- luminescence from interstellar dust ("Extended Red Emission")

Plus a few more direct approaches:

- dust grains entering the heliosphere today
- presolar grains trapped in meteorites 4.5Gyr ago

Observational Constraints on Dust: *Observed Extinction*

- **10μm feature:** probably **amorphous silicate**
- **2200A “bump”:** probably aromatic **C** (probably PAHs…)
- 3.4μm feature: **C-H** stretch. aromatic/aliphatic ratio ?
  ~85/15 (Pendleton & Allamandola 02)
  <15/85 (Dartois et al. 04)
- λ dependence requires **size distribution from a<0.01μm to a>0.3μm**


Extinction per H nucleon

Indirect constraints on interstellar dust

- Dust models limited by abundances of elements such as C, Mg, Si, Fe...:
  $(X \text{ in dust}) = (X \text{ total}) - (X \text{ in gas})$
- **Variable** depletions of heavy elements – atoms must be able to accrete onto dust, and to return from dust to gas
- Catalysis of H_2 on grains
- photoelectric heating of ISM
- Variable depletion of D from gas phase (!!)

How do we use observations to figure out what dust is?

Unable to "invert" observations → model

Instead:

- adopt hypothetical model
- calculate as many observable properties as we can
- compare to observations

If model agrees with observations, continue to use it.

If model does not agree.... **change the model**

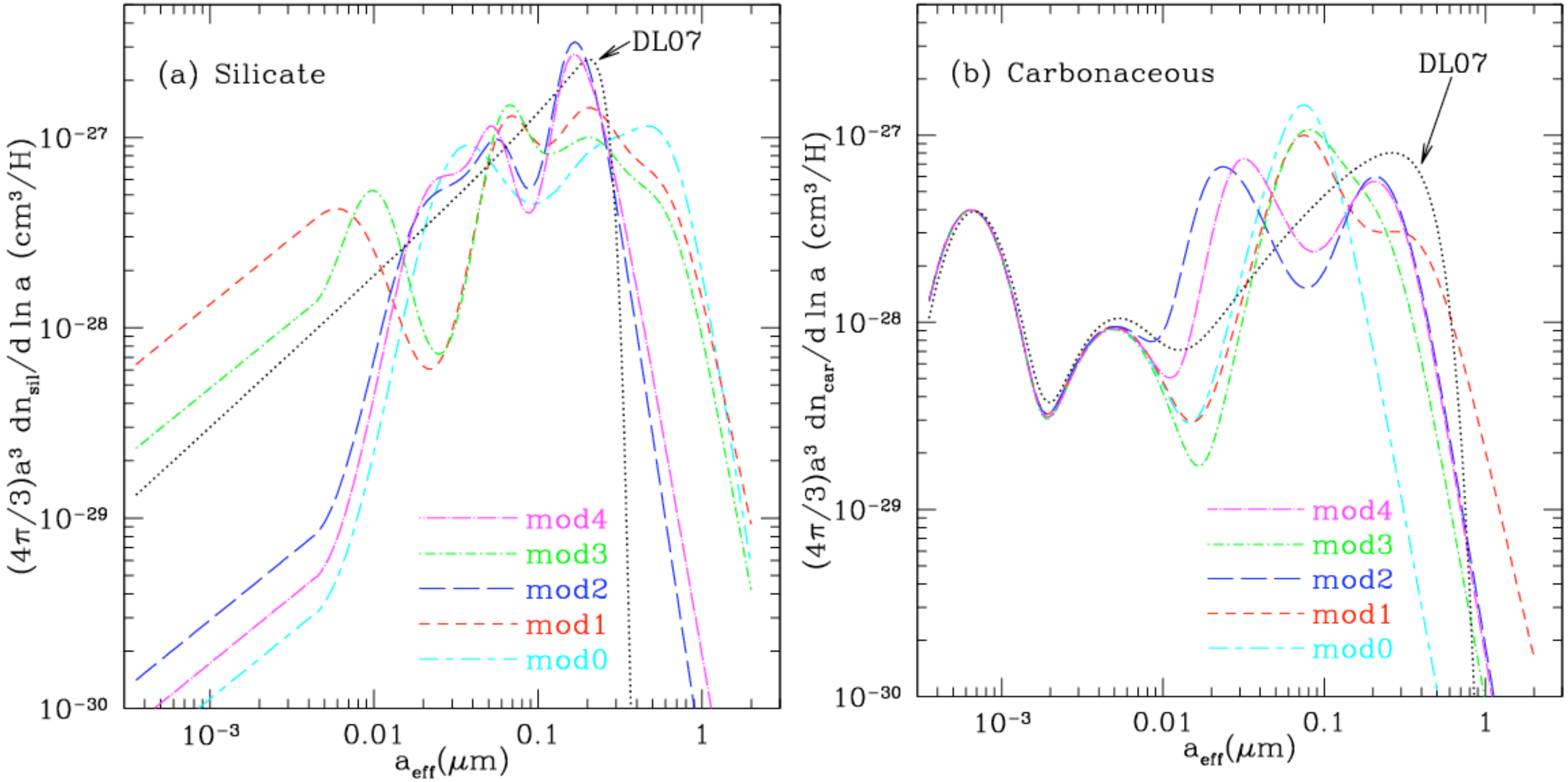
One Tentative Model

(Draine & Li 2007; Draine & Fraisse 2009)

- Ingredients:
  - amorphous silicate grains (tentative dielectric function)
  - PAHs, with estimated absorption cross sections
  - larger carbonaceous grains. Try graphite (tentative dielectric function)
- Shape
  - for silicate and larger carbonaceous grains: oblate spheroids.
  - experiment with different axial ratios.
  - (if not studying polarization, OK to assume spheres)
- Size distribution dn/da
  - vary dn/da to try to reproduce observed A_λ
- Alignment with magnetic field (alignment fraction $f(a)$)
  - adjust $f(a)$ to reproduce observed starlight polarization

Size Distributions

(models are not unique…)



Draine & Fraisse 2009

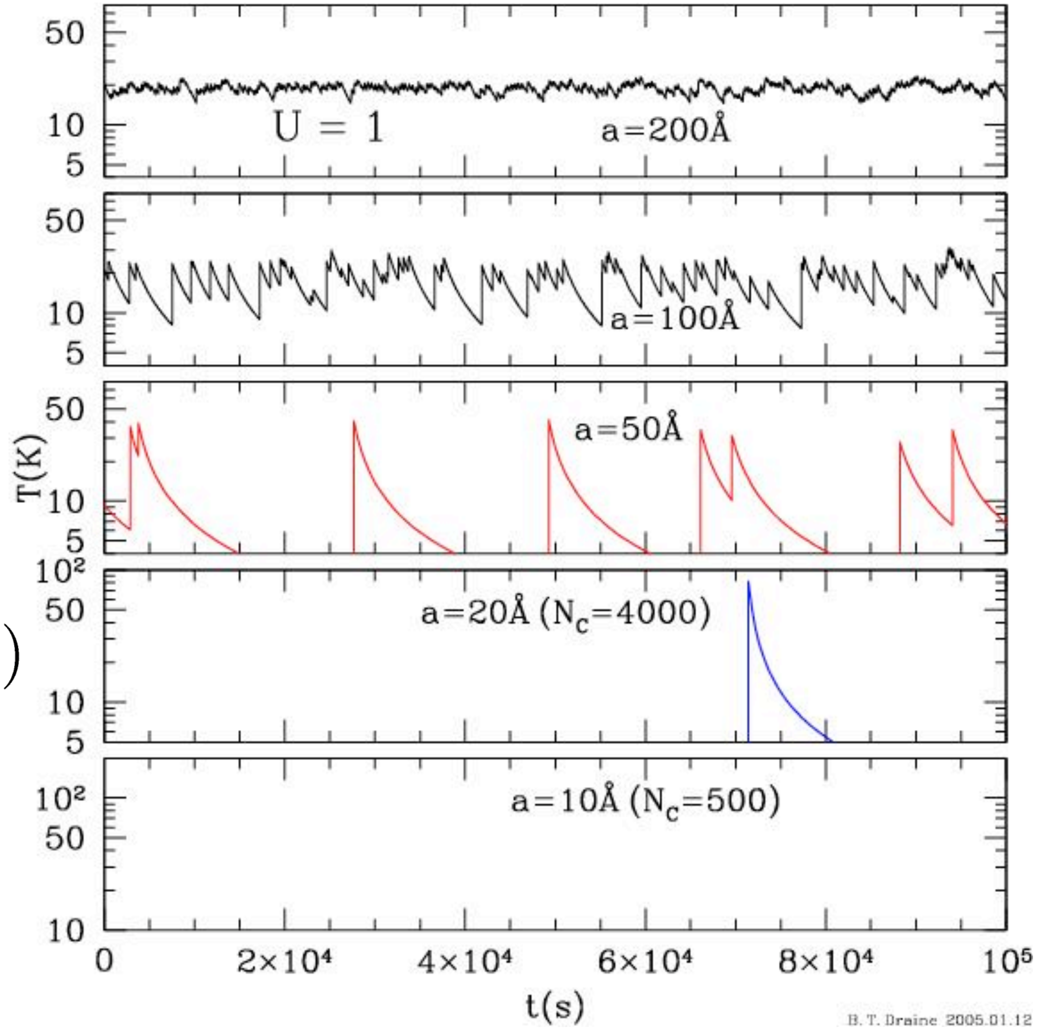
Modeling IR Emission

- Physical grain model: for each grain, calculate $C_{abs}(\nu)$, heat capacity
- **Stochastic heating: Find p(T; comp,size) for each composition, size**
- Time-averaged IR emission:

$$P_\nu = \int dT \frac{dP}{dT} C_{abs}(\nu) 4\pi B_\nu(T)$$

- Sum over compositions, size distribution

A day in the life…



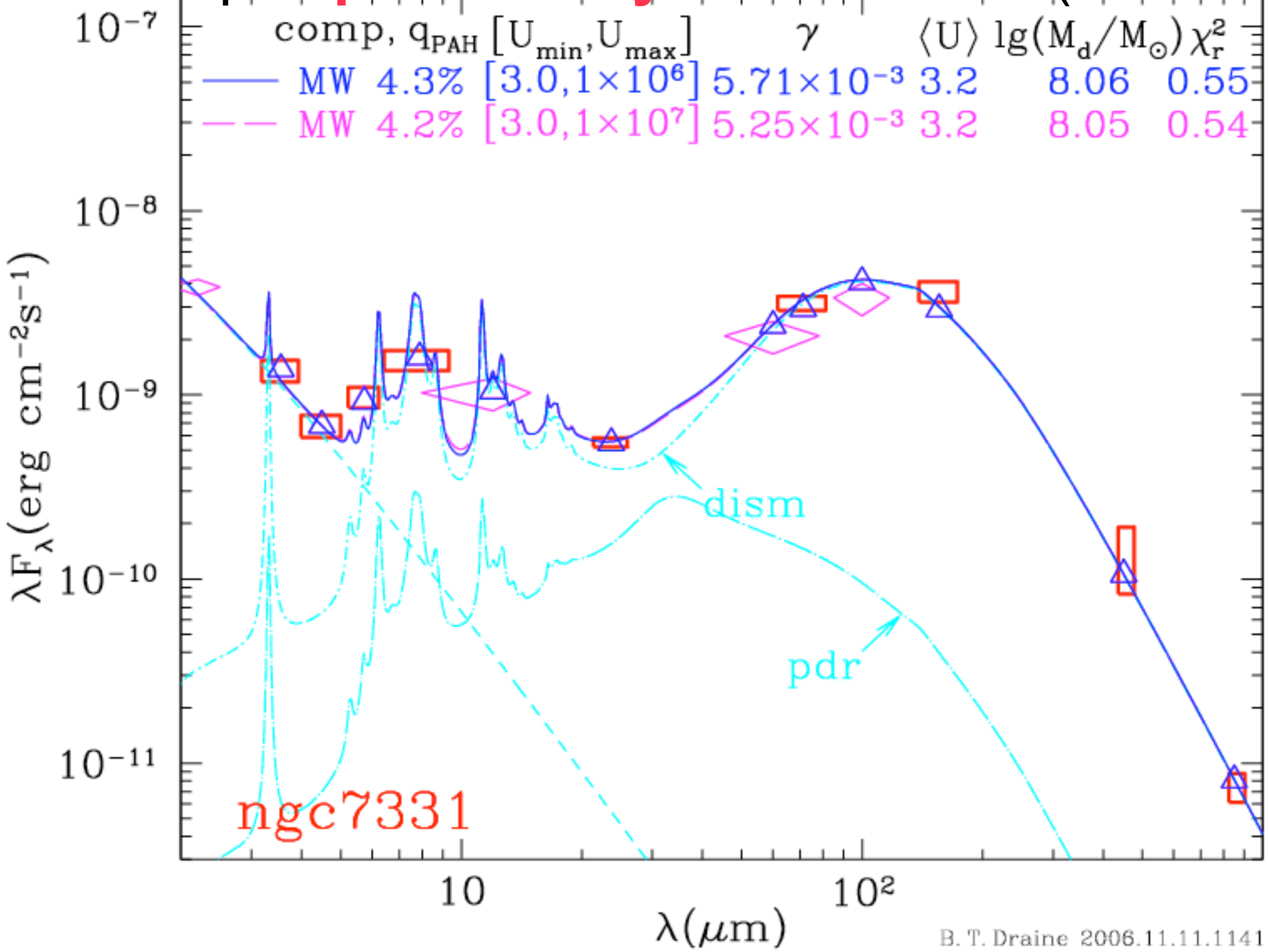
Modeling IR Emission

$$U \equiv \frac{starlight\ intensity}{local\ ISRF}$$

- For each U, find T distribution function dP/dT
- Adopt suitable mix of U values for dust in region (entire galaxy, or part of galaxy)
- Calculate IR emission from model.
  - determine **dust mass** $M_{\rm dust}$
  - determine **intensity of starlight** heating dust

How well does the dust model do?

Example: **photometry** of NGC 7331 (SINGS data)



$$
\begin{aligned}
M_{\rm dust} &= 1.1\times10^{8}\,M_\odot \\
M(\mathrm{HI}) &= 1.0\times10^{10}\,M_\odot \\
M(\mathrm{H_2}) &= 1.6\times10^{10}\,M_\odot
\end{aligned}
\quad\longrightarrow\quad
\frac{M_{\rm dust}}{M_{\rm H}} = 0.0043
$$

IR Spectroscopy

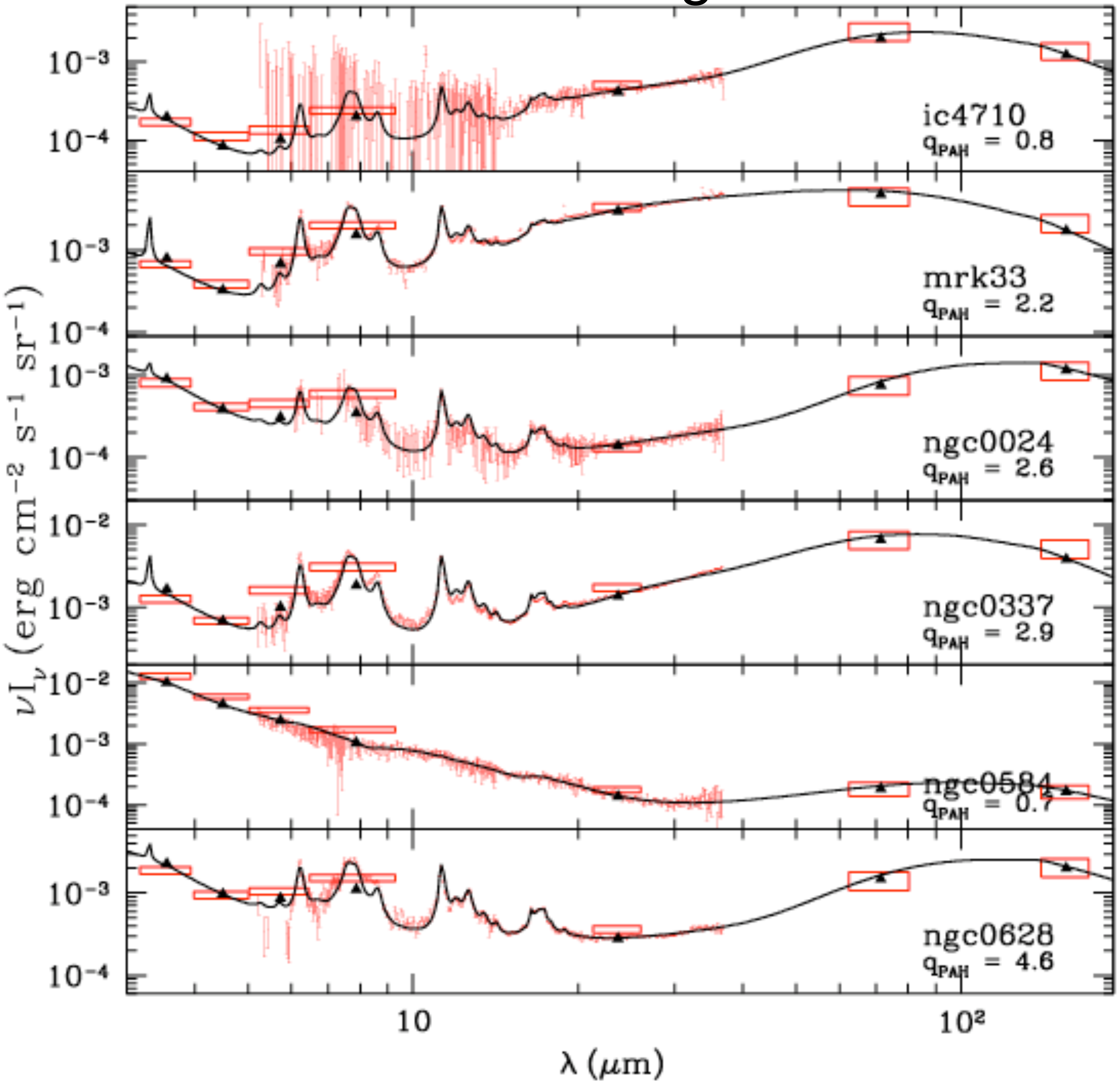
red: observations

black: model

model = dust mix heated by suitable mix of starlight intensities

(BTD, R. Reyes, J.D. Smith, & SINGS team…)

Centers of galaxies:

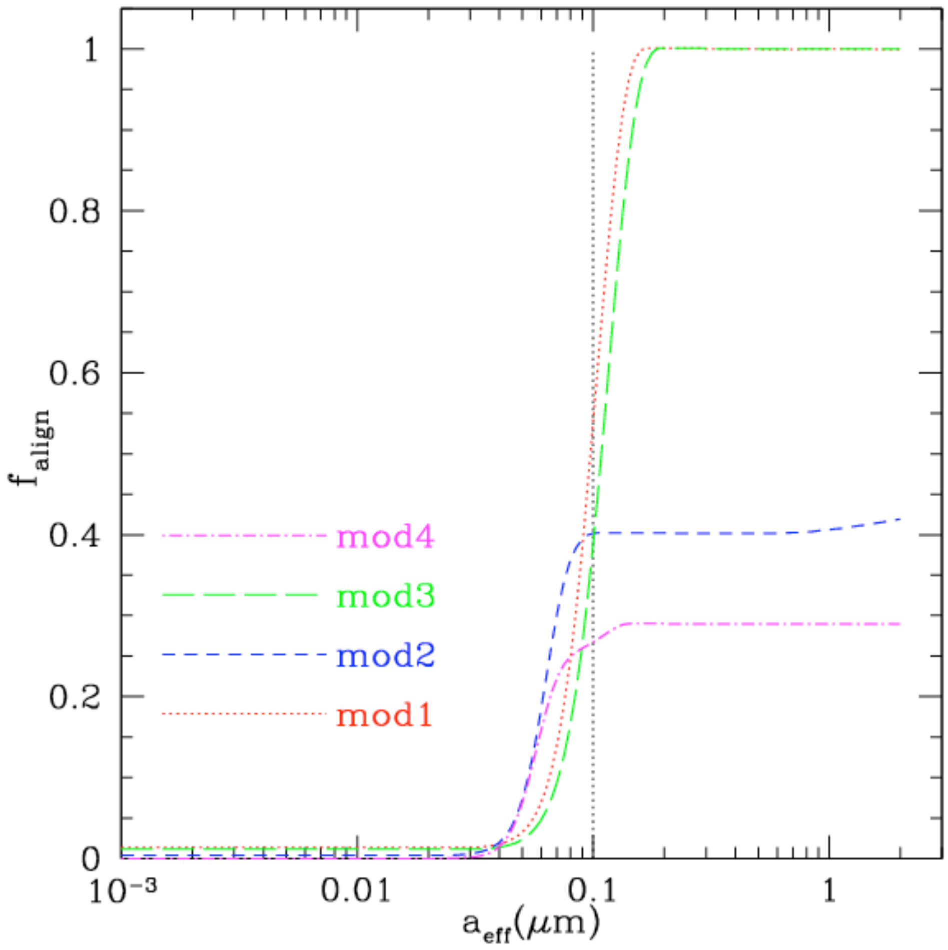


Polarization of Starlight in Milky Way

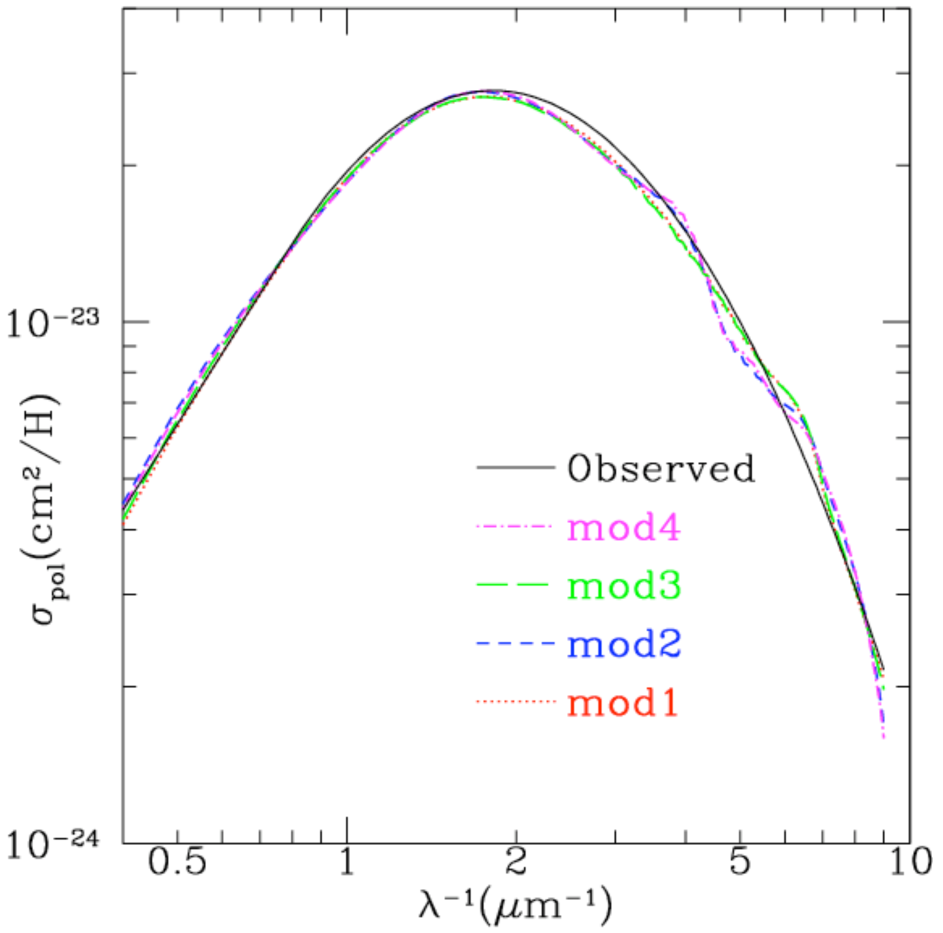
(Draine & Fraisse 2009)

Different models: different axial ratios for oblate spheroids

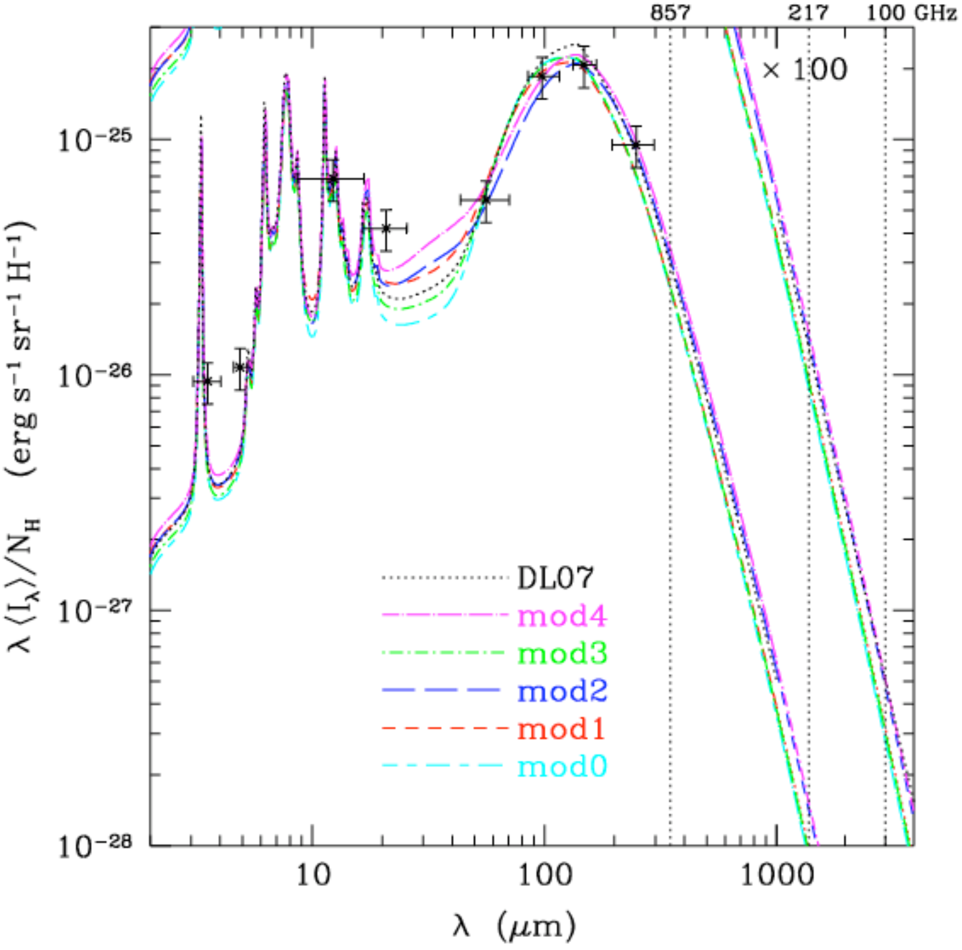
Adopted alignment f(a)



Resulting polarization cross section

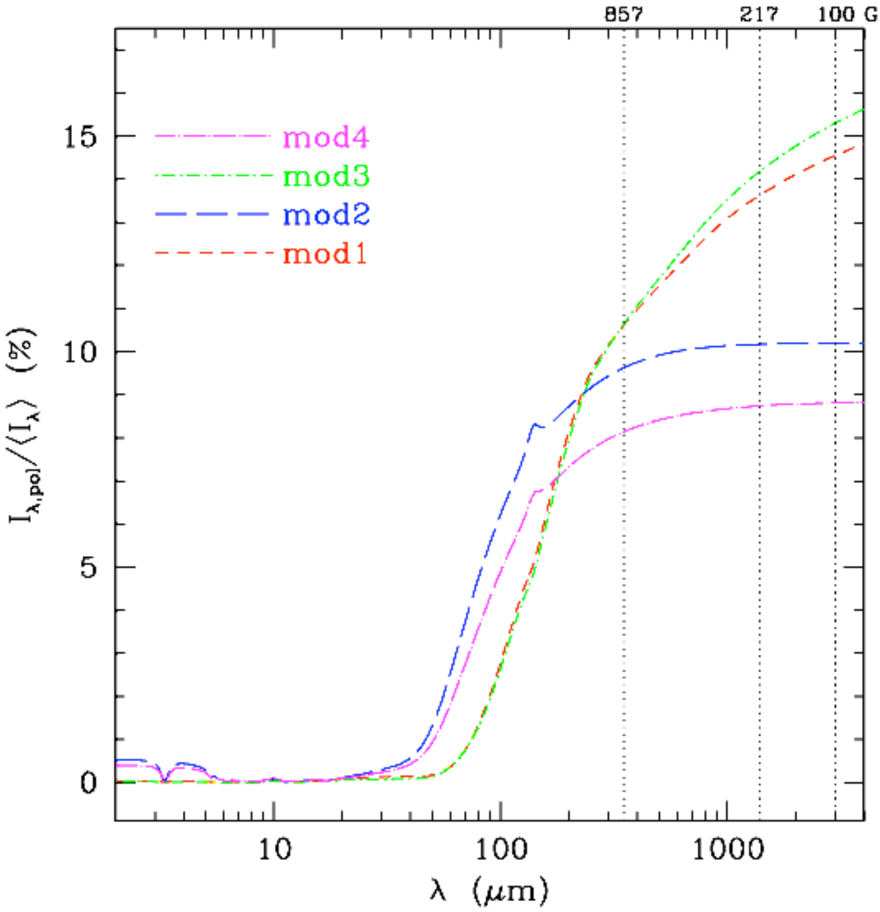


Total Emission



% Polarization

(sightline ⊥ B_0)



IR-submm polarization:

1. ***Model-dependent***
2. ***Frequency-dependent***

TEST of models

Summary of modeling results

- Models require ***nearly all*** Mg, Si, Fe in dust to reproduce extinction (sometimes > 100% -- but actual abundances remain uncertain)
- Broad size distribution: 0.0004 -- 1μm

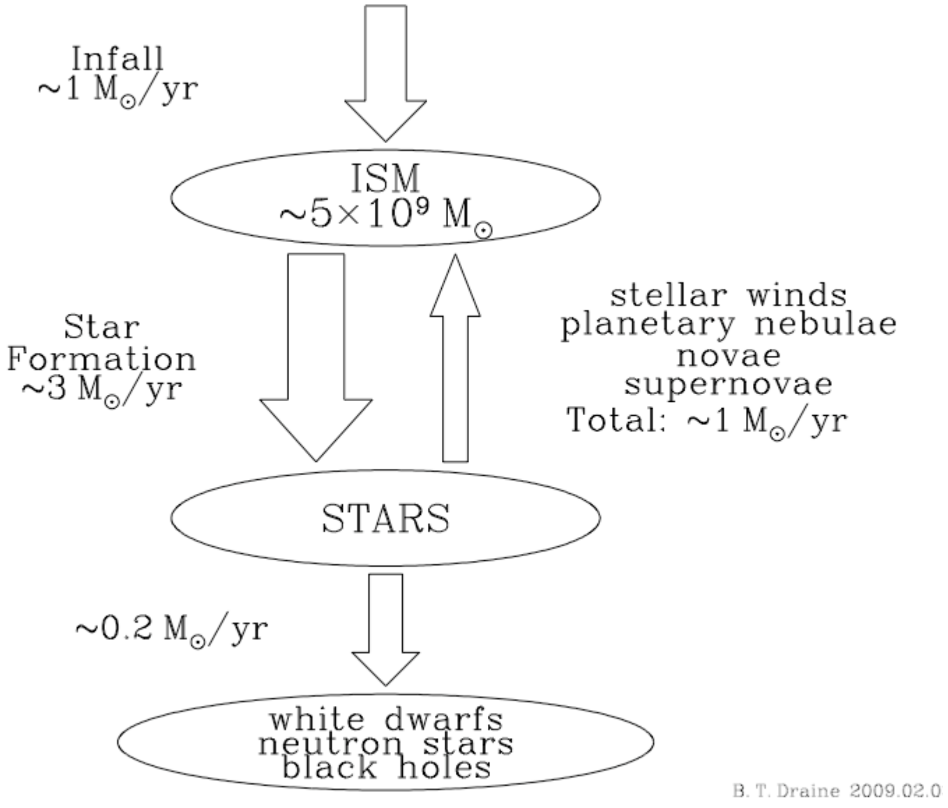
  ~50% of dust mass above/below a = 0.1μm
- Models successfully reproduce extinction in MW, LMC, SMC, and observed IR emission from MW and other galaxies
- Models succesfully reproduce starlight polarization
- PLANCK submm polarization will test models

ISM Mass Budget

- MW: star formation more-or-less steady for past $\sim$ 8Gyr
  $M > 1 M_\odot$ stars dying at $\sim$same rate as being formed
- $M_{\rm ISM} \approx 5 \times 10^9 M_\odot$ in MW
- Sources and Sinks:

$$\begin{aligned} \dot{M}_{\rm ISM} \approx \quad & +1\ M_\odot/\ {\rm yr} && \text{(Infall)} \\ & -3\ M_\odot/\ {\rm yr} && \text{(Star Form.)} \\ & +1\ M_\odot/\ {\rm yr} && \text{(from Stars)} \\ \text{Net}: \quad & -1 M_\odot/\ {\rm yr} && \end{aligned}$$

- ISM declining on timescale $M_{\rm ISM}/|\dot{M}_{\rm ISM}| \approx$ 5–10 Gyr
- Atom in ISM incorporated in a star on timescale $M_{\rm ISM}/{\rm SFR} \approx 5 \times 10^9 M_\odot/(3 M_\odot/{\rm yr}) \approx$ **1.5 Gyr**



Stellar sources

$M > 1 M_\odot$ stars die at rate $\sim 1/\,\mathrm{yr}$

Breakdown of $\sim 1 M_\odot/\,\mathrm{yr}$ mass return to ISM:

gas $(M_\odot/\,\mathrm{yr})$	**dust** $(M_\odot/\,\mathrm{yr})$	Stellar Source
0.4	**0.002**	PNe $(1/\,\mathrm{yr})$
0.5	**0.0025**	RG, RSG, C star winds
0.06	$<$ **0.0001**?	OB, WR star winds
0.25	**0.0001**?	SNe $(1/100\,\mathrm{yr}\,, 10^{-2} M_\odot \mathrm{dust/SN?})$
0.01	**0.00001**	novae $(100/\,\mathrm{yr})$

$\dot{M}_{\mathrm{dust}} \approx 0.005\, M_\odot/\mathrm{yr}$ **from all stellar sources**

Journey through the ISM

- All heavy elements enter ISM via stellar outflows/ejecta
- Suppose fraction $f_{\star 0}(\mathrm{Si}) < 1$ of Si leaving stars is condensed into dust grains (silicates, SiC)
- If nothing else happens, stardust grain will reside in ISM for ∼1.5 Gyr before being incorporated into protostar or protoplanetary disk.
- What could happen to stardust grains (and the Si atoms in them) as they journey through the ISM?

Destructive Processes

- **chem. reaction** with reactive species (H, O)
- **UV photolysis** (silicate immune?)
- **CR damage** (amorphization)

  CR flux uncertain
- **sputtering** in hot gas
- **grain-grain collisions:**
  - coagulation at low velocity
  - shattering at intermediate velocity
  - vaporization at high velocity
  - cratering of large grains by small grains

Sputtering in Hot Gas

- Substantial grain destruction in $v_s > 220\,\mathrm{km\,s^{-1}}$ shock
- Supernova explosion: 10^{51} erg of kinetic energy
- SNR blastwave shock-heats ISM
- Early evolution $\sim$ energy-conserving as blastwave expands:

$$M_{\mathrm{SNR}}\; v_s^2 \approx 10^{51}\,\mathrm{erg}$$

$$M_{\mathrm{SNR}} \approx 1000 M_\odot \left(\frac{220\,\mathrm{km\,s^{-1}}}{v_s}\right)^2$$

$v_s = 220\,\mathrm{km\,s^{-1}}$ shock $\rightarrow T_s = 7 \times 10^5\,\mathrm{K}$ gas.

Effects of Supernova Explosions

- Detailed studies: most grain material sputtered if $v_s \gtrsim 220\,\mathrm{km\,s^{-1}}$.
- Every $\sim 10^2$ yr, SN blastwave destroys grains in $\sim 10^3 M_\odot$ of ISM.
- Grain lifetime against destruction in MW:

$$t_{\rm dest} \approx \frac{5 \times 10^9 M_\odot}{10^3 M_\odot / 100\,\mathrm{yr}} \approx 5 \times 10^8\,\mathrm{yr}$$

- $t_{\rm dest}$ **short compared to 1.5 Gyr residence time**
  MOST STARDUST WILL NOT SURVIVE!

Grain Survival in ISM

Complications:

- ISM is inhomogeneous: denser regions are shielded from effects of blastwave: increase $t_{\rm dest}$ for "typical" grain
- Additional partial destruction by sputtering for $v_s < 220\,{\rm km\,s^{-1}}$: decrease $t_{\rm dest}$
- Additional destruction by grain-grain collisions in much lower velocity shocks: decrease $t_{\rm dest}$

timescale for survival time of random Si atom in grain is $t_{\rm dest} \approx (3-5) \times 10^8\,{\rm yr}$ (Barlow 1978; Draine & Salpeter 1979; Dwek & Scalo 1979; Jones et al. 1994, and other studies...)

Stardust Survival in the ISM

Fraction $f_{\star 0}(\mathrm{Si})$ enters ISM in grains.
Stardust converted to gas on timescale t_{dest}, or incorporated into star on timescale t_{SF}.
$f_{\star}(\mathrm{Si})$ = fraction of Si in stardust in ISM will be

$$f_{\star}(\mathrm{Si}) \approx \frac{f_{\star 0}(\mathrm{Si})}{1 + t_{\mathrm{SF}}/t_{\mathrm{dest}}} \approx 0.25 f_{\star 0}(\mathrm{Si}) \approx \mathbf{0.1}$$

(for $f_{\star 0} \approx 0.5$, $t_{\mathrm{dest}} \approx 0.4\,\mathrm{Gyr}$, $t_{\mathrm{SF}} \approx 1.5\,\mathrm{Gyr}$).

But observe extreme “depletion” of Si:

$f(\mathrm{Si}) \approx \mathbf{0.9}$, mainly in amorph. silicates. Therefore:

- **MOST of the amorph. silicate material in the ISM must have formed in the ISM**

Growth of Grain Material in ISM

Let $\Sigma_{d,21} 10^{-21}\,\mathrm{cm}^2/\mathrm{H}$ = dust geometric cross section/H nucleon. From modeling extinction, we know that $\Sigma_{d,21} \gtrsim 1$

- **Time for gas atom moving with speed v_a (relative to grain) to collide with grain surface:**

$$\tau_{acc} \approx \frac{1}{n_{\rm H}\Sigma_d v_a} = 1.5\times 10^7\,{\rm yr} \left(\frac{20\,{\rm cm}^{-3}}{n_{\rm H}}\right) \frac{1}{\Sigma_{d,21}} \left(\frac{{\rm km\,s}^{-1}}{v_a}\right)$$

- **Evidently atoms *can* deplete from gas and be incorporated into grains on timescale $\ll t_d \approx 4 \times 10^8\,\mathrm{yr}$.**

Grain Growth in ISM...

- **Mix of arriving atoms: H, He, C, O, Mg, Si,...
rate for one surface site to be hit by an O atom:**

$$\begin{aligned} \tau_{\rm O}^{-1} &\approx 10^{-15}\,{\rm cm}^2 \left(4 \times 10^{-4} n_{\rm H}\right) \frac{v_{\rm O}}{4} \\ &= \frac{1}{1.5 \times 10^5\,{\rm yr}} \left(\frac{n_{\rm H}}{20\,{\rm cm}^{-3}}\right) \left(\frac{v_{\rm O}}{{\rm km\,s}^{-1}}\right) \end{aligned}$$

Complication: Arrival rate of ions (e.g., Si^+) modified by charge on grains.

- **Growth occurs in presence of UV: $\tau_{\rm UV\,exc} \approx 3000\,{\rm yr}$.**
- **Resulting material will be determined by substrate, arriving mix and UV.**
  - **Amorphous silicate?**
  - **Hydrocarbon material? (PAHs?)**

Since these are the materials that are present, they must be what forms under these growth conditions.

Grain Growth in ISM

Implications for Dynamics of Multiphase ISM

(Weingartner & Draine 1999)

- MC, CNM – densities high enough to maintain observed depletions
- WNM – densities too low to maintain depletions
- **Require rapid ($\tau \approx 10^7\,\mathrm{yr}$) exchange between (WIM,WNM) and (CNM,MC) to explain observed depletions in WNM.**

Grain Growth in ISM…

- Most ($\sim$90%) interstellar amorphous silicate is **NOT stardust** – it is grown in ISM:
- Explains why interstellar crystalline silicate fraction $<$**2%** whereas **silicate stardust in meteorites** is **20%** crystalline (Keller 2008).
- If true for MW, presumably also in other star-forming galaxies
- **Large amounts of dust seen in high-z systems (e.g., J114816 @ $z = 6.4$) can be grown in ISM: SNe, AGB stars need provide only a fraction of the dust (seed material).**

something that worries me...

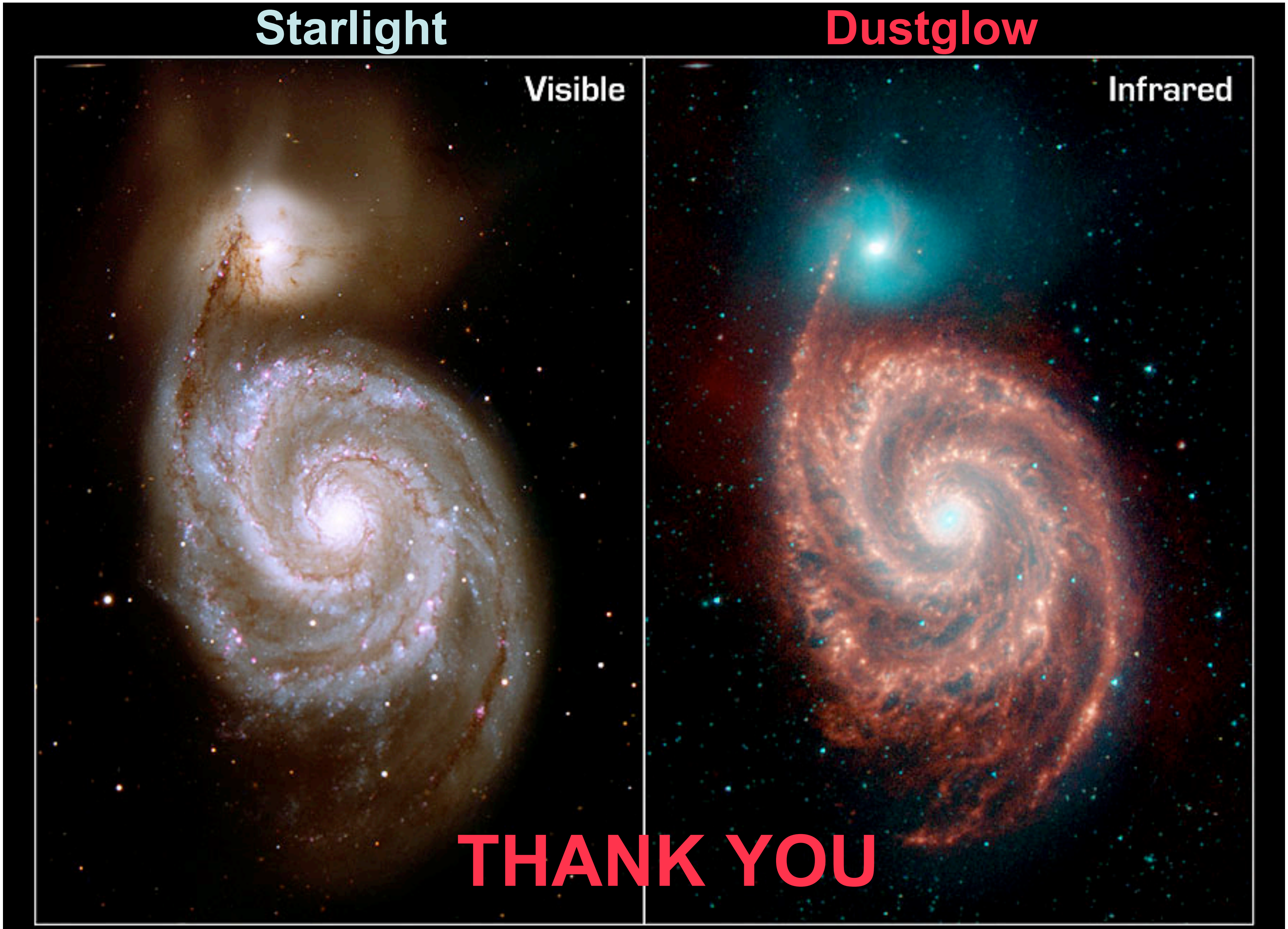
- PAHs are expected to produce strong absorption in vicinity of 2200Å (due to $\pi \rightarrow \pi^*$ electronic transitions), with strength that (in MW) should be comparable to the observed interstellar 2200Å feature on diffuse sightlines in the MW.
- Seems natural to attribute observed 2175Å feature in MW to absorption by PAHs
- PAHs appear to be ubiquitous in “normal” star-forming galaxies and normal-metallicity starburst galaxies.
- Expect 2200Å absorption feature to be ubiquitous in measured extinction curves, but
  - Doesn’t appear on the Calzetti starburst extinction curve
  - Is absent or weak in integrated UV spectra of ”normal” galaxies (Conroy 2009, arXiv:0905.4073)

Why not?

- Radiative transfer effect?
- Could 2175Å feature be due to scattering, rather than absorption? [seems impossible, but...]

Summary

- Model consisting of amorphous silicate, graphitic carbonaceous material, and PAHs can reproduce
  - observed extinction in MW, LMC, SMC
  - observed polarization of starlight in MW
  - observed IR emission from MW and other galaxies
- Violent ISM → short lifetimes for grains
- Observed dust abundance and depletions of Si etc. → **most grain material is grown in the ISM**
- Must somehow grow amorphous silicate in cold UV-irradiated ISM
- MW is not special: most dust in star-forming galaxies must be grown in the ISM.
- **Worry – why isn't the 2200Å feature more common on measured extragalactic extinction curves?**



THANK YOU

Spiral Galaxy M51 (“Whirlpool Galaxy”)

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

Spitzer Space Telescope • IRAC

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