Modern Observations of Interstellar Dust in Galaxies

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Modern Observations of Interstellar Dust in Galaxies

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Some things I will *not* talk about: dust, gravel, pebbles, rocks in

- **protoplanetary disks**
- **debris disks**
- **interplanetary space**
- **planetary rings**
- **comets**

Extinction Curves

- Measured attenuation of starlight by interstellar dust $F_\lambda = F_\lambda^0 e^{-\tau_\lambda}$

$$\tau_\lambda = \int n_d C_{\rm ext}(\lambda) ds$$

  $C_{\rm ext}(\lambda) =$ extinction cross section (absorption + scattering)
  $n_d =$ number density of dust grains
  $s =$ path length
  Astronomers measure attenuation in *magnitudes*:

$$\frac{A_\lambda}{\rm mag} \equiv 2.5 \log_{10} \left[F_\lambda^0 / F_\lambda\right]$$
$$= 2.5 \log_{10} \left[e^{\tau_\lambda}\right] = 1.086\, \tau_\lambda$$

- Dust and gas are well-mixed: it is observed that $\tau_\lambda \propto N_{\rm H}$, where $N_{\rm H} \equiv \int n_{\rm H} ds$ is the column density of H nucleons.

$$A_\lambda / N_{\rm H} = 1.086 \times (n_d / n_{\rm H}) C_{\rm ext}(\lambda)$$

- Function A_λ = "the extinction curve".
  Because A_λ tends to be larger for shorter wavelengths, stars are "reddened" – hence we speak of "interstellar reddening".

Measuring Extinction

How do we measure extinction A_λ? If we had a "standard candle" at a known distance, it would be easy:

$$F_\lambda = \frac{L_\lambda}{4\pi D^2} e^{-\tau(\lambda)}$$

$$A_\lambda = 1.086\,\tau(\lambda) = 1.086 \ln\left(\frac{L_\lambda/4\pi D^2}{F_\lambda}\right)$$

Problem: we generally don't know L_λ *or* D!

Solution: the "pair method" to measure *reddening*

$$\frac{(F_{\lambda_1}/F_{\lambda_2})_A}{(F_{\lambda_1}/F_{\lambda_2})_B} = \left[\frac{(L_{\lambda_1}/L_{\lambda_2})_A}{(L_{\lambda_1}/L_{\lambda_2})_B}\right] \times \frac{\exp(-(\tau_A(\lambda_1) - \tau_A(\lambda_2)))}{\exp(-(\tau_B(\lambda_1) - \tau_B(\lambda_2)))}$$

Measuring Extinction, contd.

$$\frac{(F_{\lambda_1}/F_{\lambda_2})_A}{(F_{\lambda_1}/F_{\lambda_2})_B} = \left[\frac{(L_{\lambda_1}/L_{\lambda_2})_A}{(L_{\lambda_1}/L_{\lambda_2})_B}\right] \times \frac{\exp(-(\tau_A(\nu_1) - \tau_A(\nu_2)))}{\exp(-(\tau_B(\nu_1) - \tau_B(\nu_2)))}$$

1. Select a "pair" star *spectroscopically*, so that A and B can be assumed to have the same intrinsic *color*:
$$\frac{(L_{\lambda_1}/L_{\lambda_2})_A}{(L_{\lambda_1}/L_{\lambda_2})_B} = 1 \tag{1}$$
2. Use a pair star "B" that is believed to be *unreddened*:
$$\exp(-\left[\tau_B(\nu_1) - \tau_B(\nu_2)\right]) = 1 \tag{2}$$
Thereby measure
$$\tau_A(\lambda_1) - \tau_B(\lambda_2) = \ln\left[\frac{(L_{\lambda_1}/L_{\lambda_2})_A}{(L_{\lambda_1}/L_{\lambda_2})_B}\right] \tag{3}$$
3. Make measurement at long wavelength λ_2 where we expect $\tau(\lambda_2) \approx 0$: thereby measure $\tau_A(\lambda_1)$.
4. This measures **extinction** = *removal* of light of light by *absorption* or *scattering*

This can be done with

- pairs of stars within our Galaxy
- pairs of (bright) stars in Local Group galaxies (SMC, LMC, M31) (more difficult: need to resolve single stars)

"Pair method" can also be used to study reddening in more distant galaxies:

- gravitationally-lensed images of a single QSO
  both images assumed to have same intrinsic *color* (e.g., Elíasdóttir et al. 2006)
- galaxy reddened by a foreground galaxy (e.g., Holwerda et al. 2009)

foreground galaxy at $z < 0.06$

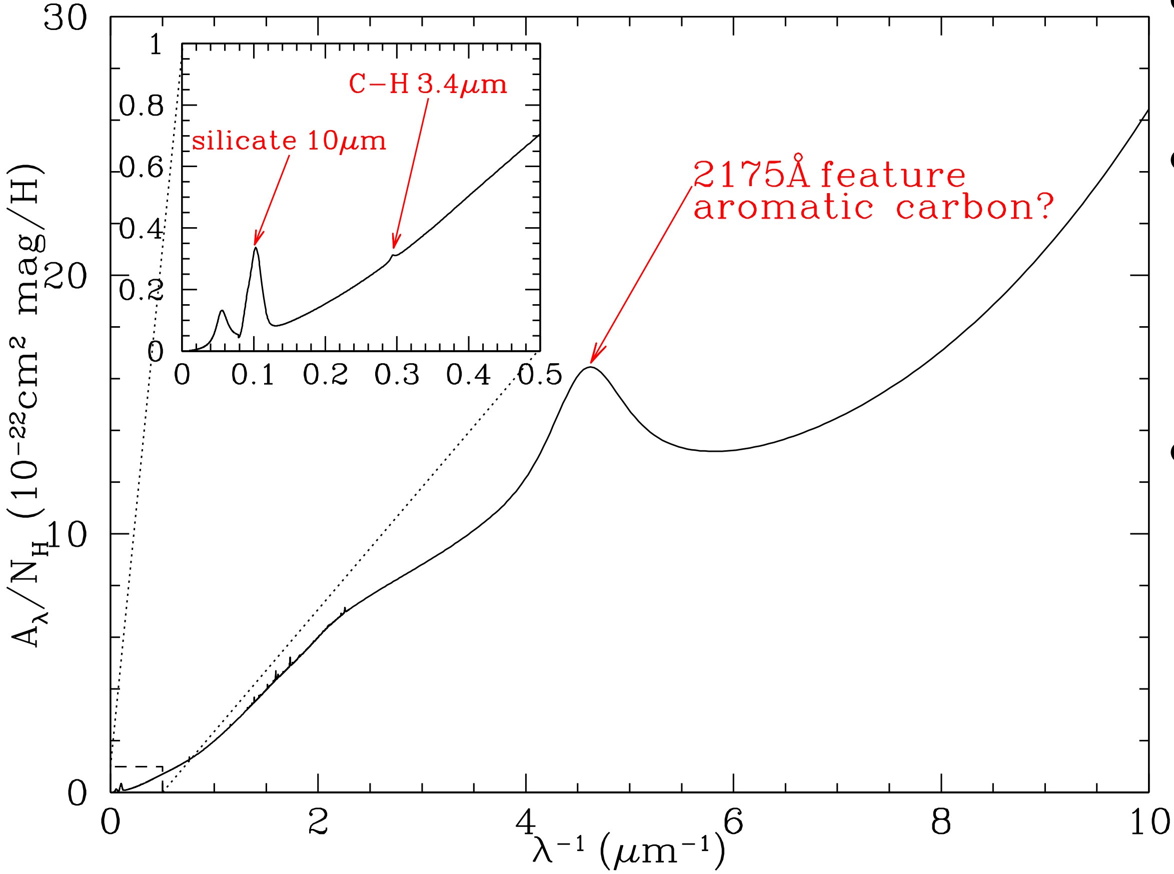
background galaxy at $z = 0.06$

- background galaxy number counts behind foreground galaxy (e.g., Holwerda et al. 2012)
- statistical studies of QSOs reddened by foreground galaxies
  compare QSOs as function of foreground galaxy impact parameter.
  Ménard et al. (2009) used 85000 $z > 1$ QSOs from SDSS.

Can also use Gamma Ray Burst (GRB) afterglows to measure reddening – GRB afterglow spectrum is assumed to be intrinsically a power-law (e.g., Elíasdóttir et al. 2009)

Interstellar Extinction in the Solar Neighborhood

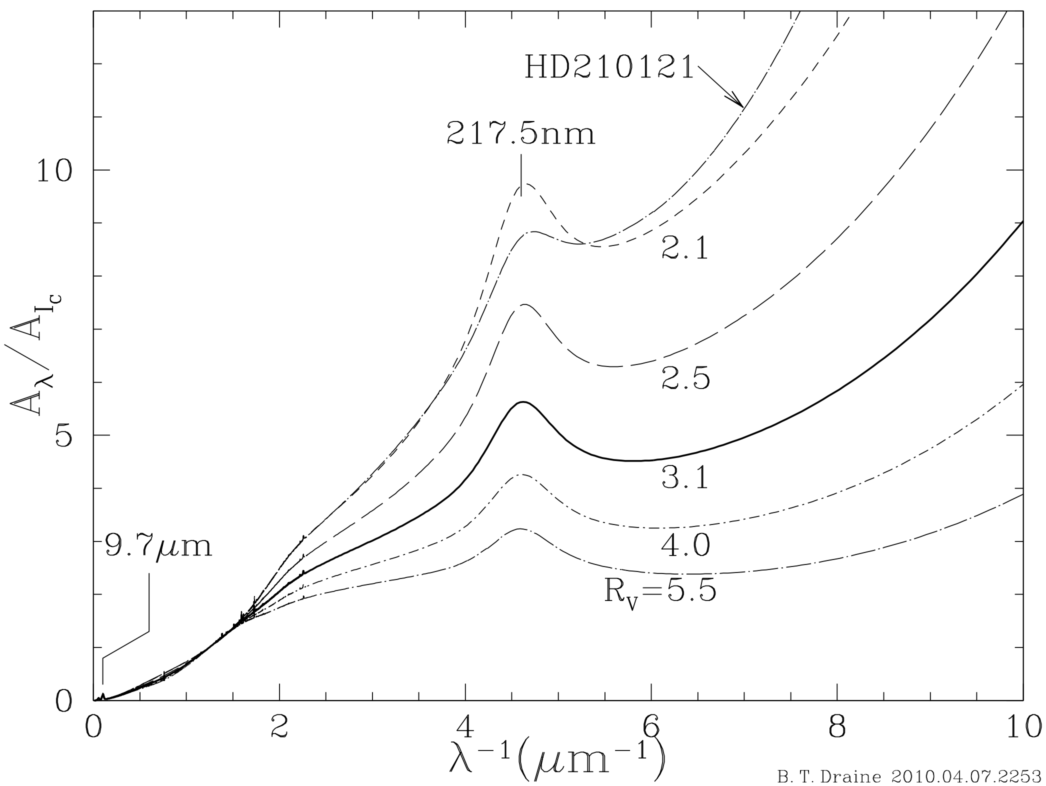
- Because dust and gas appear to be well-mixed, and because H dominates the mass, it is natural to normalize to H: we discuss $A_\lambda/N_{\rm H}$.
- Measure $N_{\rm H}$ (e.g., using Lyα absorption line).
- Result: $A_\lambda/N_{\rm H} = 1.086\tau_\lambda/N_{\rm H}$ for "average" sightline through diffuse ISM:



Principal features

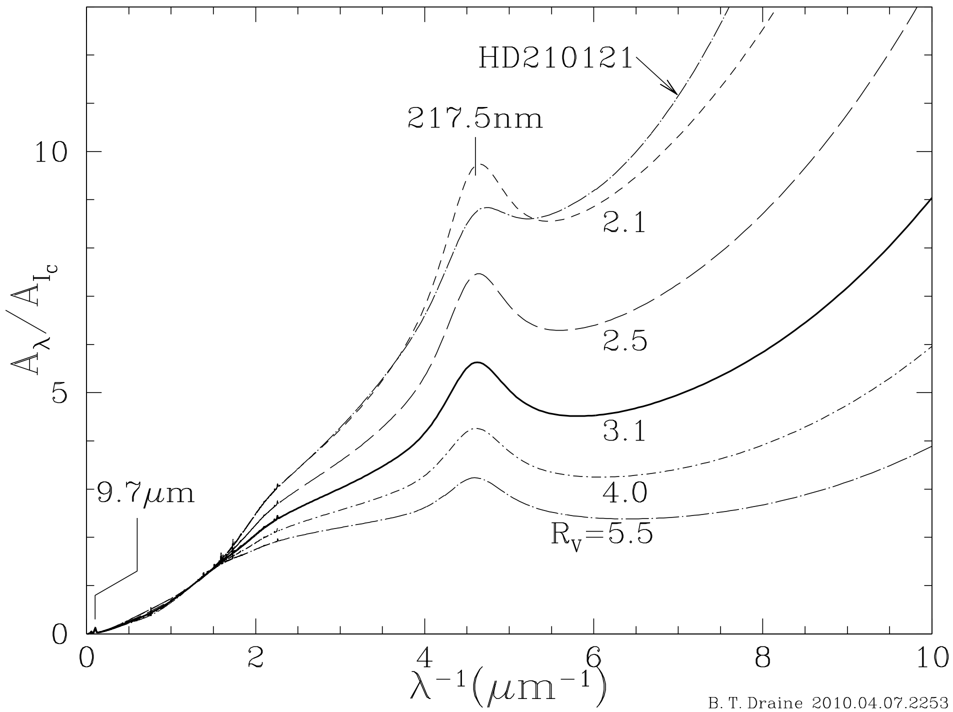
- General rise from IR to vacuum UV ($\sim 0.1\,\mu$m)
- $18\,\mu$m and $10\,\mu$m: O-Si-O bend and Si-0 stretch in amorphous silicates
- $3.4\,\mu$m: C-H stretch in hydrocarbons
- $0.2175\,\mu$m: "2200Å bump". Probably $\pi \rightarrow \pi^*$ electronic transition in sp^2-bonded carbon (e.g., graphite or PAH)
- $\gtrsim 400$ weak features – the *Diffuse Interstellar Bands* – still unidentified.

Extinction Curves Vary from One Sight-line to Another



- If normalize to I_C band ($\lambda = 0.802\,\mu\mathrm{m}$), extinction extinction is $\sim$ "universal" (?) for $\lambda \gtrsim 0.8\,\mu\mathrm{m}$
- Significant sightline-to-sightline variation seen in visible and especially UV ($\lambda \lesssim 0.5\,\mu\mathrm{m}$)

Extinction Curves



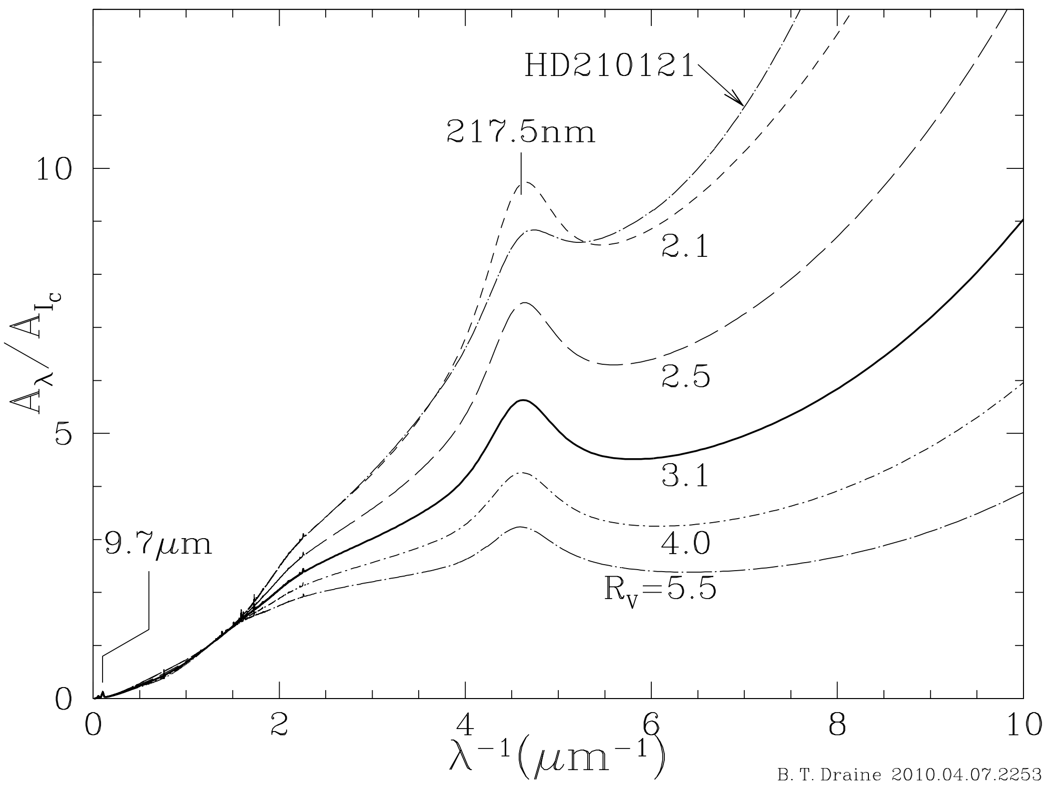
- Curves can be characterized by $R_V \equiv A_V/(A_B - A_V)$ as the parameter. On diffuse sightlines in Milky Way, R_V varies from ~ 2 to $\gtrsim 5$.
- Cardelli et al. (1989) proposed a fitting function with 7 adjustable parameters:

$$\frac{A_\lambda}{A_{\lambda,\mathrm{ref}}} = f_7(\lambda)$$

CCM found that the 7 fit parameters were all strongly-correlated with R_V. Thus the 7-parameter fit can be treated as a one-parameter family of curves, with R_V as the parameter:

$$\frac{A_\lambda}{A_{\lambda,\mathrm{ref}}} \approx f_1(\lambda; R_V)$$

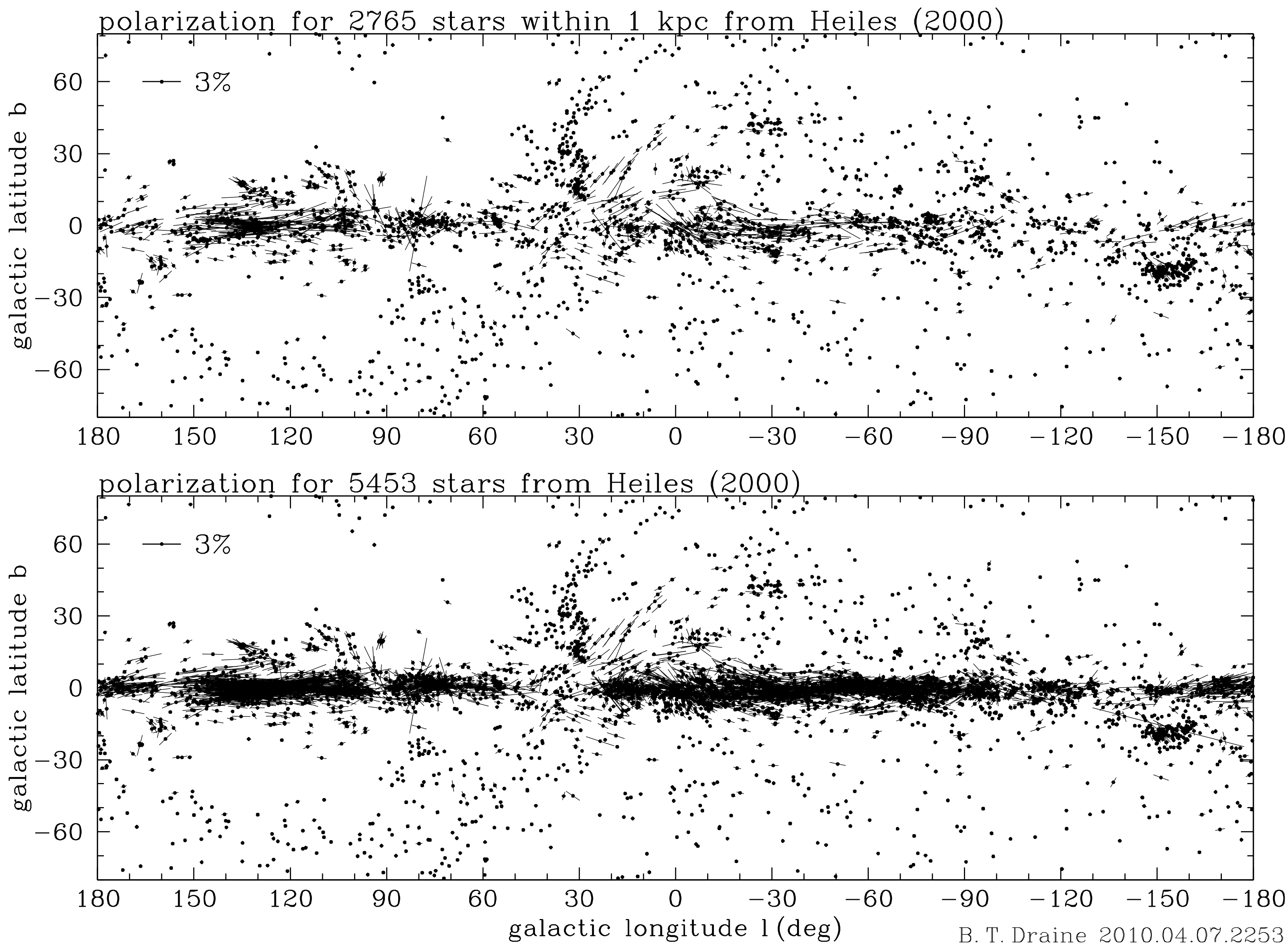
Extinction Curves



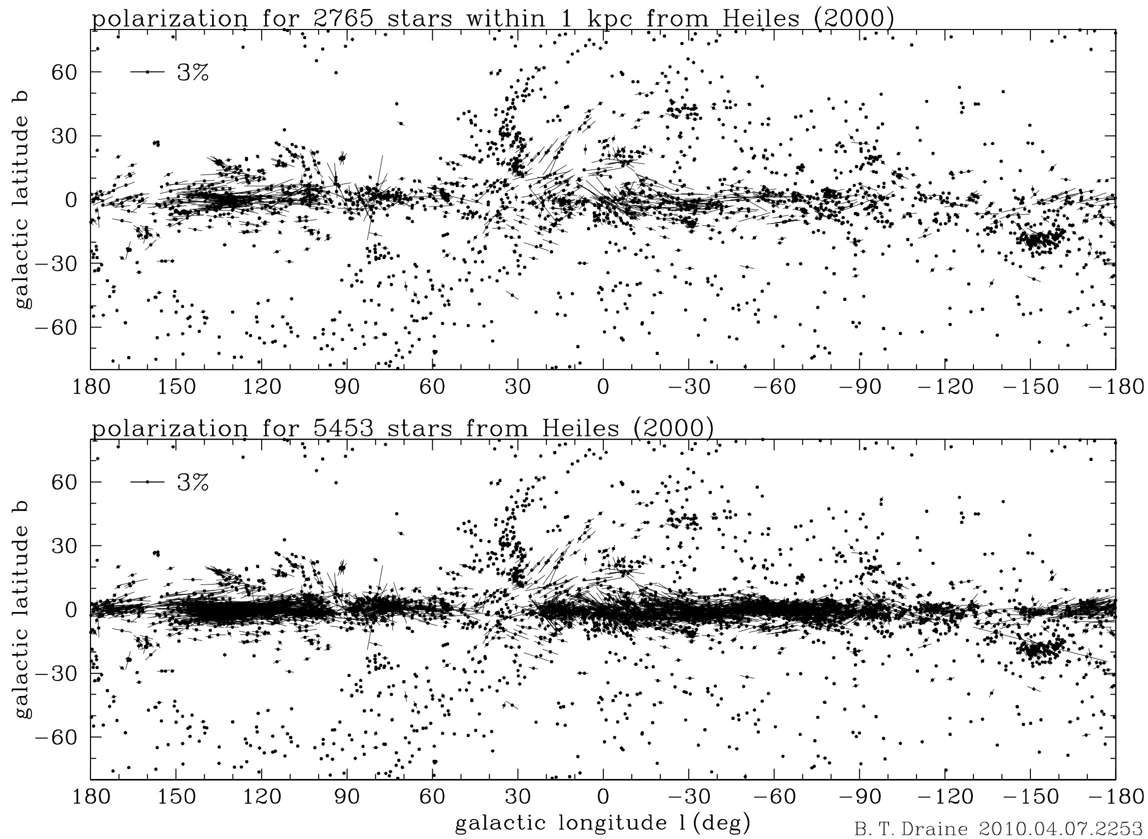
- General rise in extinction for $1 \lesssim \lambda^{-1} \lesssim 10\,\mu\mathrm{m}^{-1}$ requires that $a \lesssim 0.1\,\mu\mathrm{m}$ [otherwise dust would have $2\pi a/\lambda \gtrsim 1$, with extinction ~independent of λ].
- Strong rise down to $\lambda \approx 0.1\,\mu\mathrm{m}$ requires large abundance of grains with $2\pi a/\lambda = 2\pi a/(0.1\,\mu\mathrm{m}) \lesssim 1$, or $a \lesssim 0.1\,\mu\mathrm{m}/2\pi \approx 0.015\,\mu\mathrm{m}$.
- **Conclusion:** must have a very broad size distribution, extending over at least a factor $\gtrsim 10$ in radius, or $\gtrsim 10^3$ in mass.

Polarization of Starlight

- Polarization of starlight discovered serendipitously (Hall 1949; Hiltner 1949)



Polarization of Starlight



- Polarization vs. λ is *continuous* and Polarization is *spatially coherent*:
  - Must be produced by *interstellar dust*
  - Some of the dust grains must be *nonspherical* and *aligned*
  - Coherence: Alignment direction must be determined by interstellar $\vec{\mathrm{B}}_0$

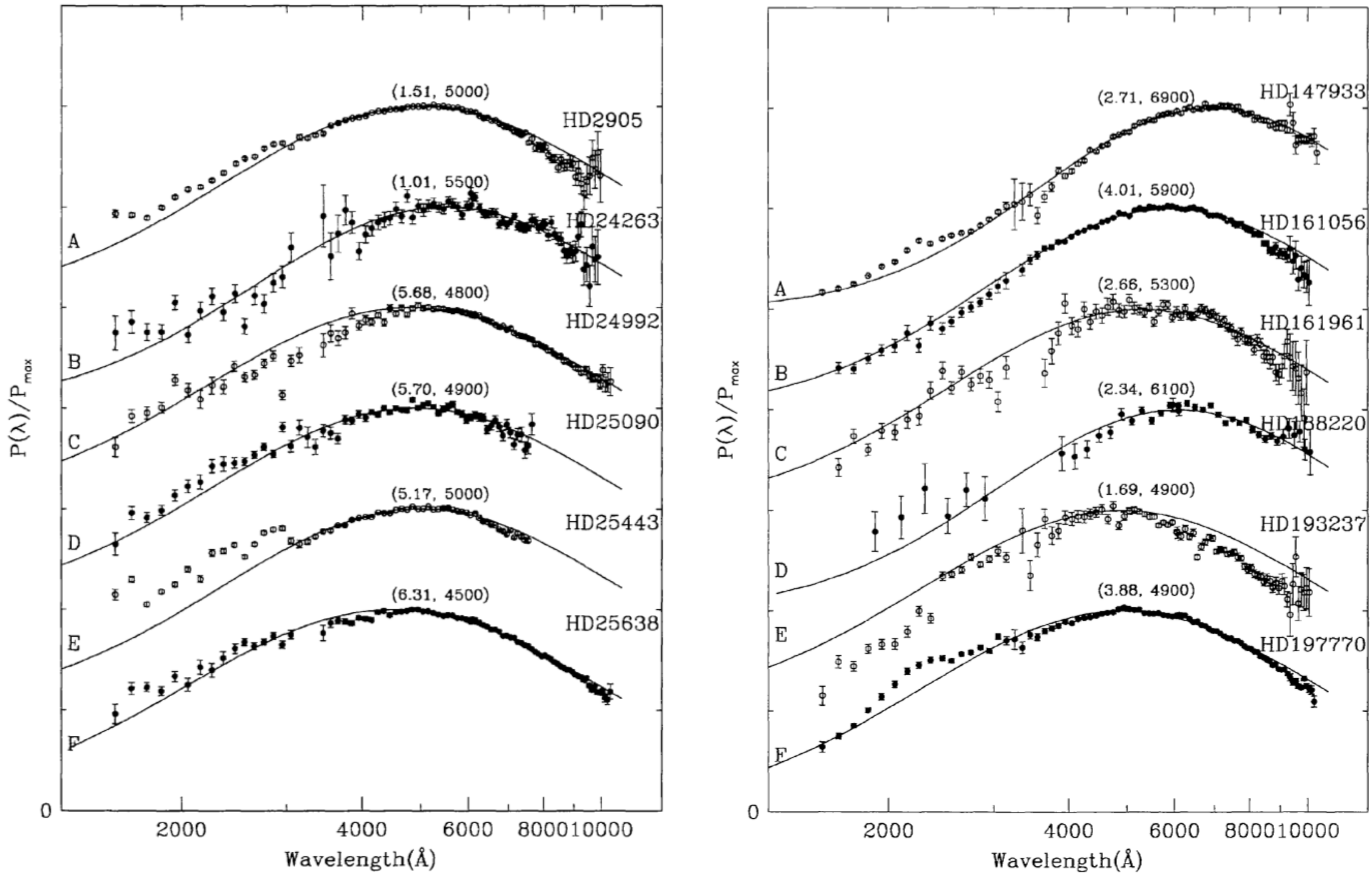
- Polarization is *approximately* described by the "Serkowski law" (Serkowski 1973):

$$p(\lambda) = p_{\rm max} \exp\left[-K\left(\ln(\lambda/\lambda_{\rm max})\right)^2\right]$$

with $\lambda_{\rm max} \approx 0.55\,\mu{\rm m}$ and $K \approx 1.15$

$$0 \leq p_{\rm max} \lesssim 0.09 \times E(B-V) \qquad\qquad p_{\rm max} \lesssim 0.03 A_V$$

Polarization of Starlight



Observed $P(\lambda)/P_{\rm max}$ with empirical Serkowski law fit (Anderson et al. 1996) .

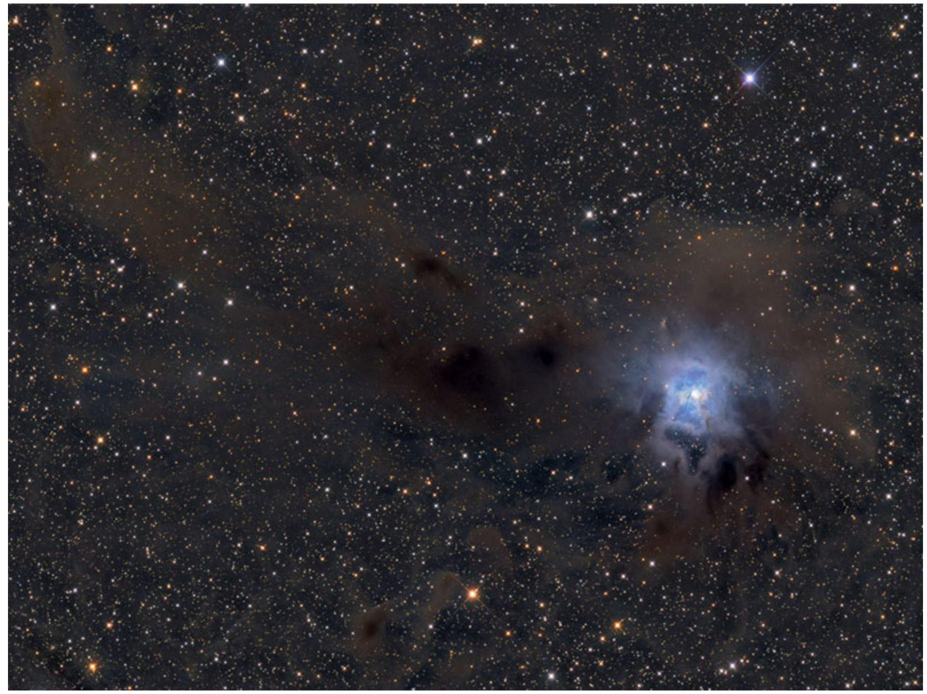
Extinction **rises** into the UV (with 2200Å bump) but polarization **falls** (with no "bump")

Smallest grains are either spherical or not aligned.

Implications of Wavelength-Dependence of Starlight Polarization

- Grain optics: grains producing polarization near $\lambda_{\rm max} \approx 0.55\,\mu{\rm m}$ have $2\pi a/\lambda \approx 1 \rightarrow a \approx \lambda_{\rm max}/2\pi \approx 0.1\,\mu{\rm m}$.
  - grains with $2\pi a/\lambda \gtrsim 3$ don't care about polarization of light
  - in principle, grains with $a/\lambda \ll 1$ could polarize, but such grains produce little extinction in the optical
- $p(\lambda)/\tau_\lambda$ is very small in the UV: small grains responsible for rise in UV extinction are either *spherical* (unlikely) or *randomly-oriented.*
- Mechanism producing alignment of interstellar grains in the diffuse ISM is size-sensitive:
  - manages to align grains with $a \gtrsim 0.1\,\mu{\rm m}$,
  - does *not* align grains with $a \lesssim 0.05\,\mu{\rm m}$.
  - ***Opposite* to what would be expected for alignment by paramagnetic dissipation (Davis & Greenstein 1951)**

Scattering of Starlight



Two Reflection Nebulae: Pleiades (M45) NGC 7023

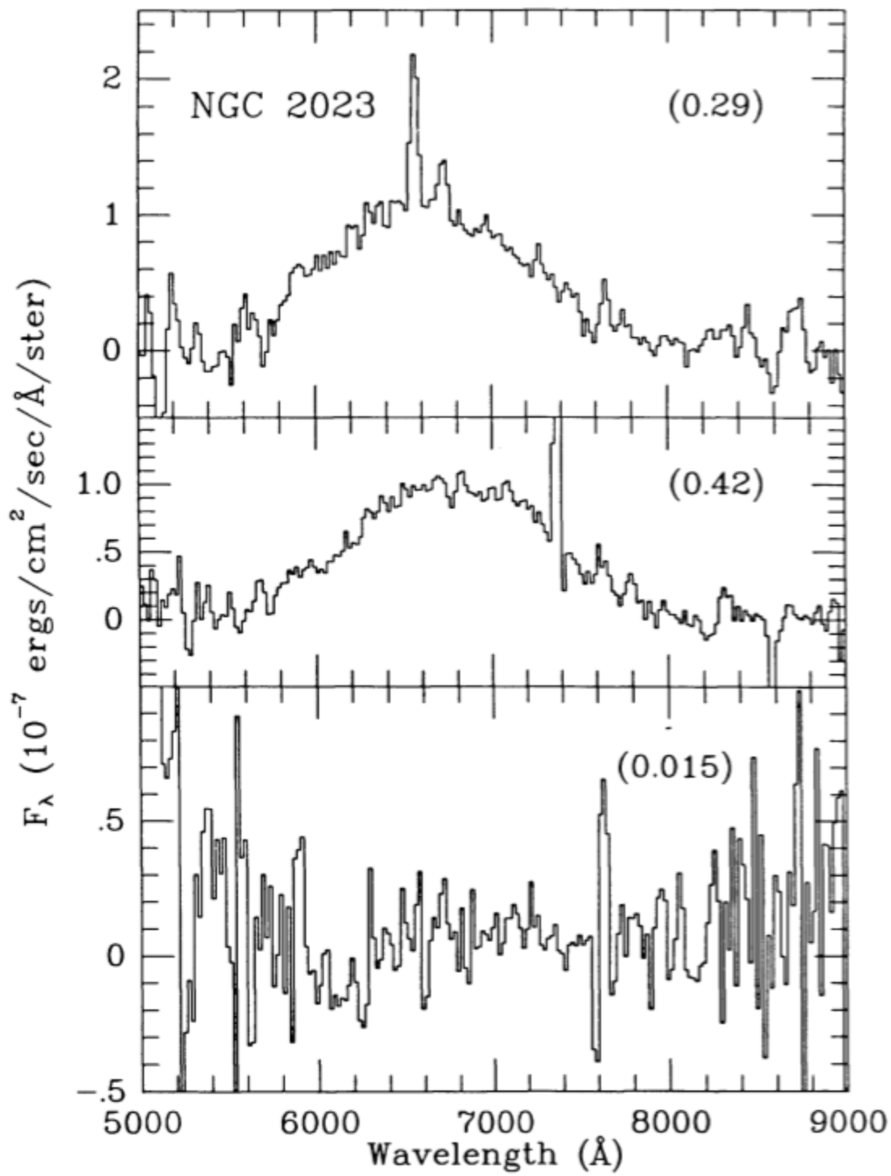
- Dust grains produce substantial scattering at visual wavelenghts:
  - must have $2\pi a/\lambda = (2\pi a/0.55\,\mu\mathrm{m}) \gtrsim 1$, or $a \gtrsim 0.1\,\mu\mathrm{m}$.
- Can determine scattering properties of dust by studying individual reflection nebulae (but this is not easy – requires assumptions about nebular geometry)
- Usually limited to trying to estimate *albedo* $\equiv$ scattering/(scattering+absorption) and *asymmetry factor* $\langle\cos\theta\rangle$, where θ = scattering angle
  Isotropic scattering or Rayleigh scattering each have $\langle\cos\theta\rangle = 0$
  Interstellar grains appear to be forward-throwing, with $\langle\cos\theta\rangle \approx 0.6$ in the optical.

Reflection + Luminescence

Luminescence

- In some reflection nebulae the observed diffuse intensity *exceeds* what is expected from scattering of the stellar light: it appears that dust *luminescences*: absorption of a short wavelength (UV?) photon is followed by emission of a longer-wavelength optical photon.
- Seen in reflection nebulae, planetary nebulae, and the Red Rectangle.
- Termed "Extended Red Emission": broad emission band peaking near ∼7000Å.
- Some proposed candidate materials:
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
  - Silicon Nanoparticles
- Weak in the general ISM

intensity after subtracting scattered light



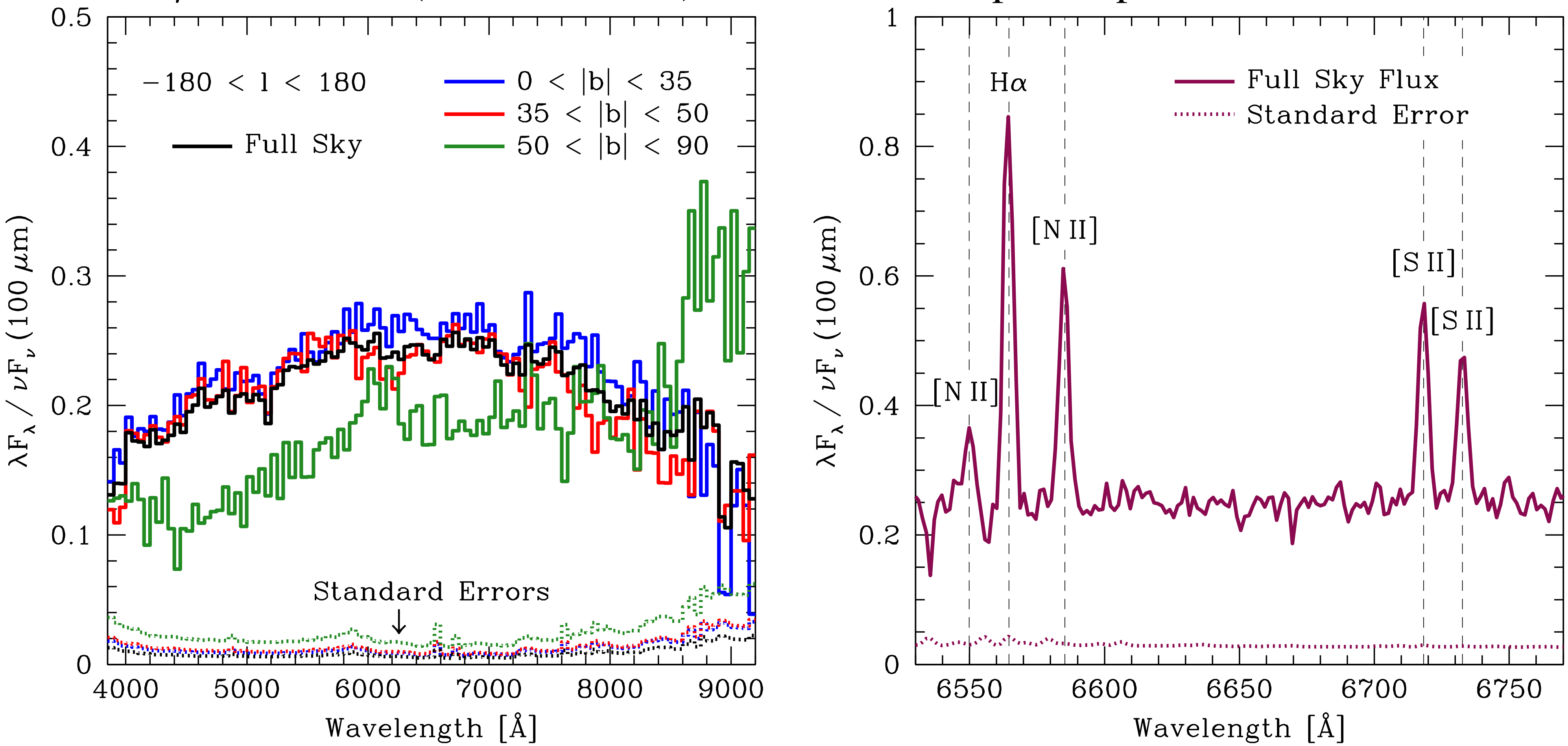
Witt & Boroson (1990)

The Diffuse Galactic Light

Classical "Reflection nebulae" are *bright* because (1) substantial amount of dust present (2) strong illumination by a nearby star.

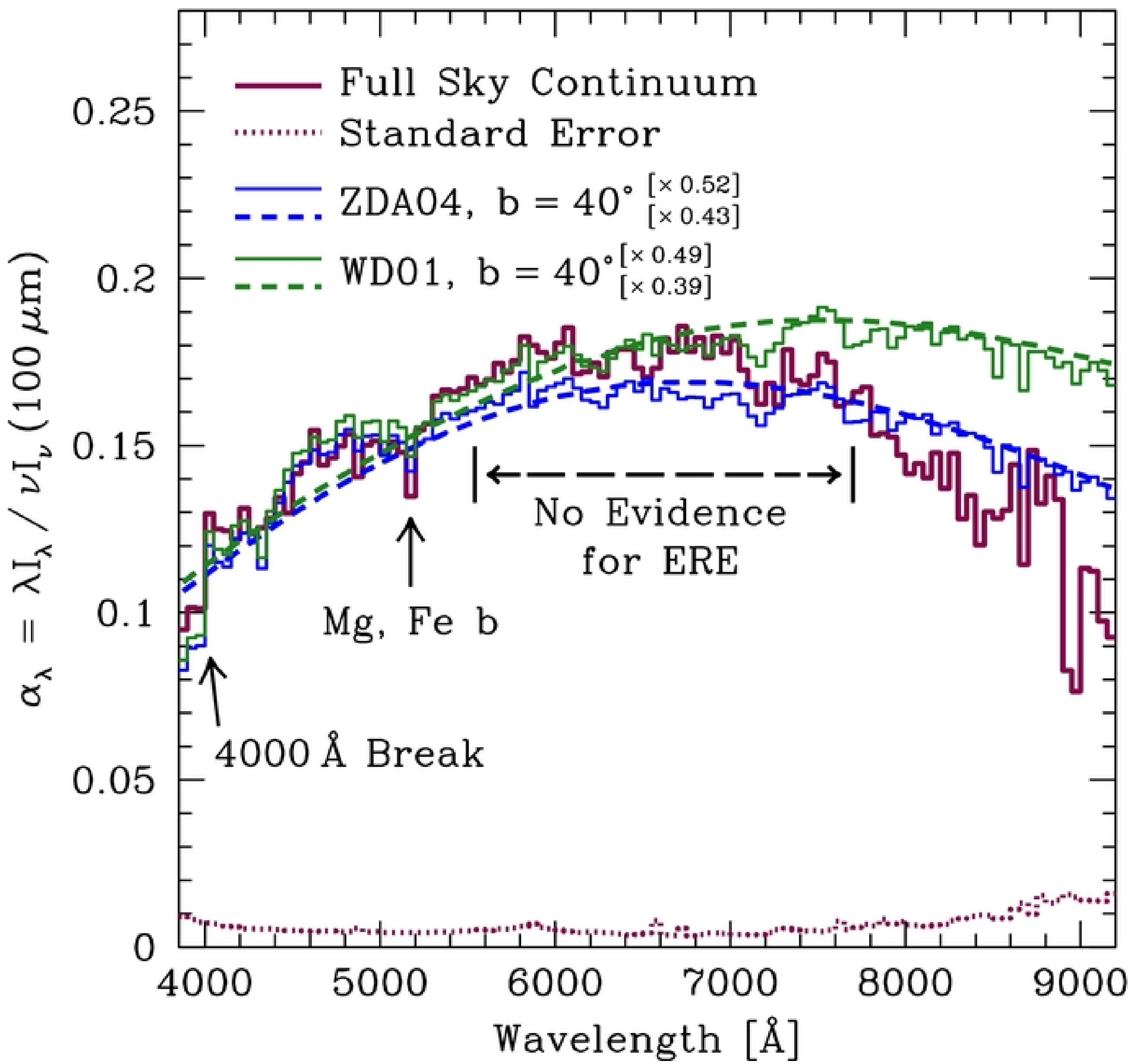
However, the entire Galaxy is dusty, and therefore also has reflected light – the Diffuse Galactic Light (DGL). Faint but measurable

Brandt & Draine (2012) used 92000 "blank sky" spectra from SDSS, cross-correlated with IRAS 100 μm emission ($\propto$ dust column) to measure the optical spectrum of the DGL:



This can be used to test grain models.

Diffuse Galactic Light

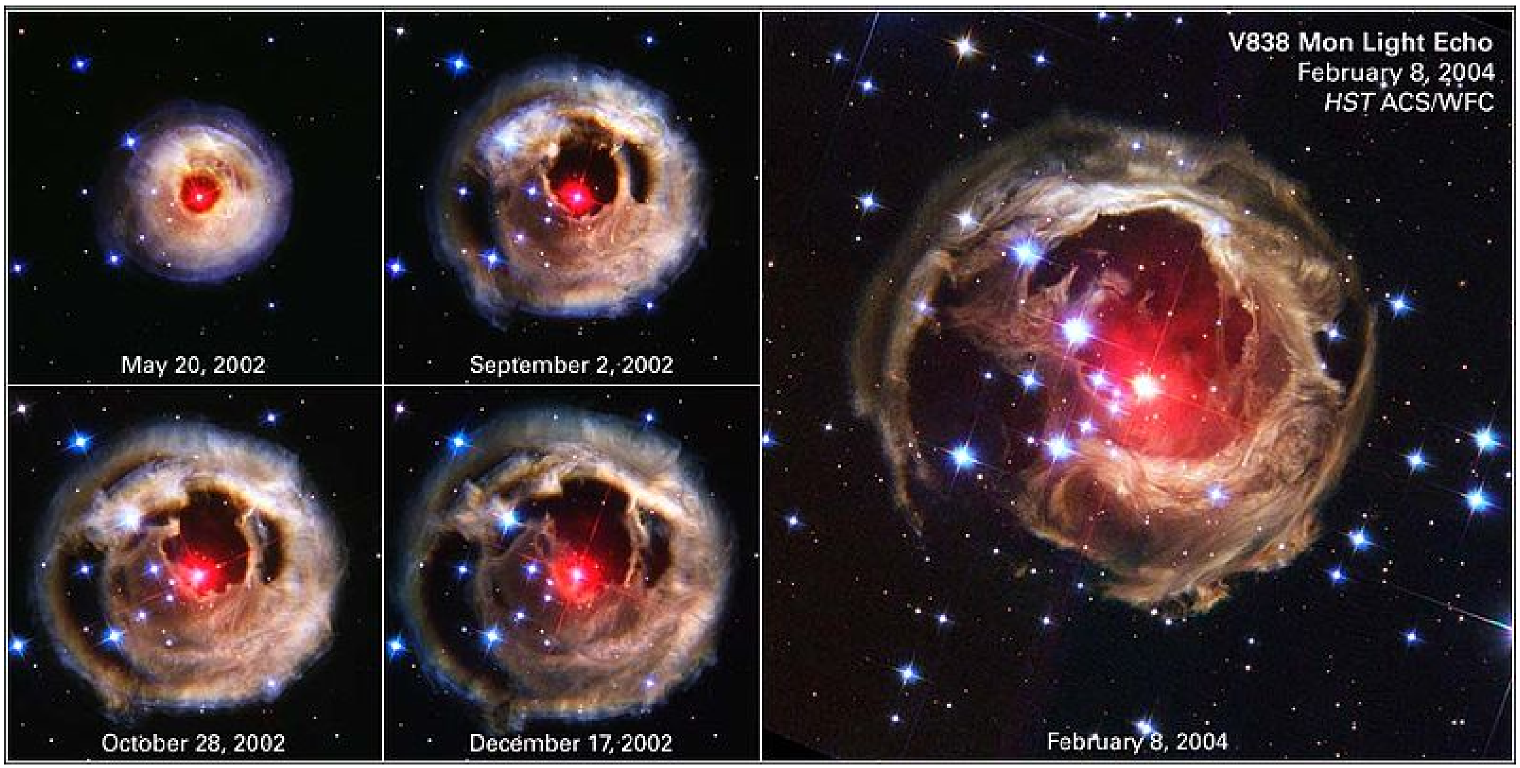


Brandt & Draine (2012)

- Radiative transfer models using illumination from distributed stars, and scattering by distributed dust
- Two dust models:
  WD01: Weingartner & Draine (2001)
  ZDA04: Zubko et al. (2004)
- **Observed DGL can be explained by scattering alone: no evidence for ERE**
- ZDA04 model fits observations better than WD01

Light Echoes: Outburst of V838 Mon

Outburst in Jan. 2002.



Light flash from star illuminates dust around the star.

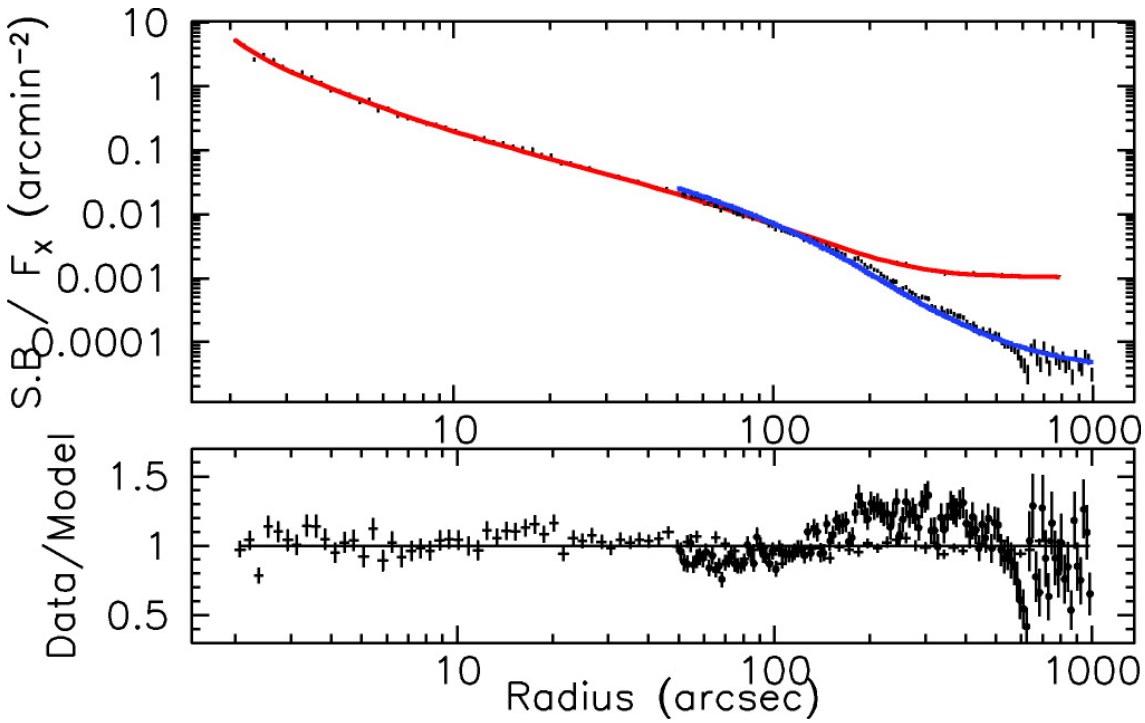
Light Echoes: SN 1987a in the LMC

X-Ray Scattering Halos

X-Ray point sources (e.g., AGNs, LMXRBs) seen through foreground dust have X-ray halos due to small-angle scattering of X-rays by dust. Typical scattering angle

$$\begin{aligned} \theta &\approx \lambda/2a \\ &\approx 6\,\text{Å}/2000\,\text{Å} \\ &\approx 60'' \end{aligned}$$

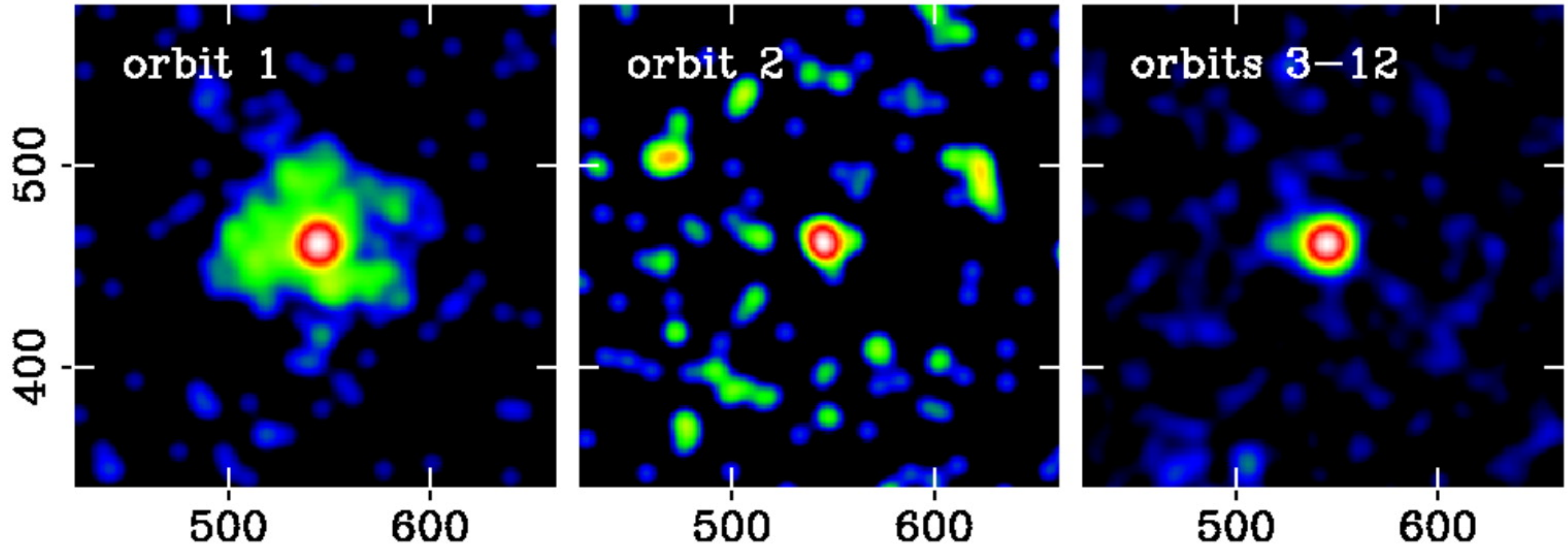
for $h\nu = 2\,\mathrm{keV}$ and $a = 0.1\,\mu\mathrm{m}$ grain.



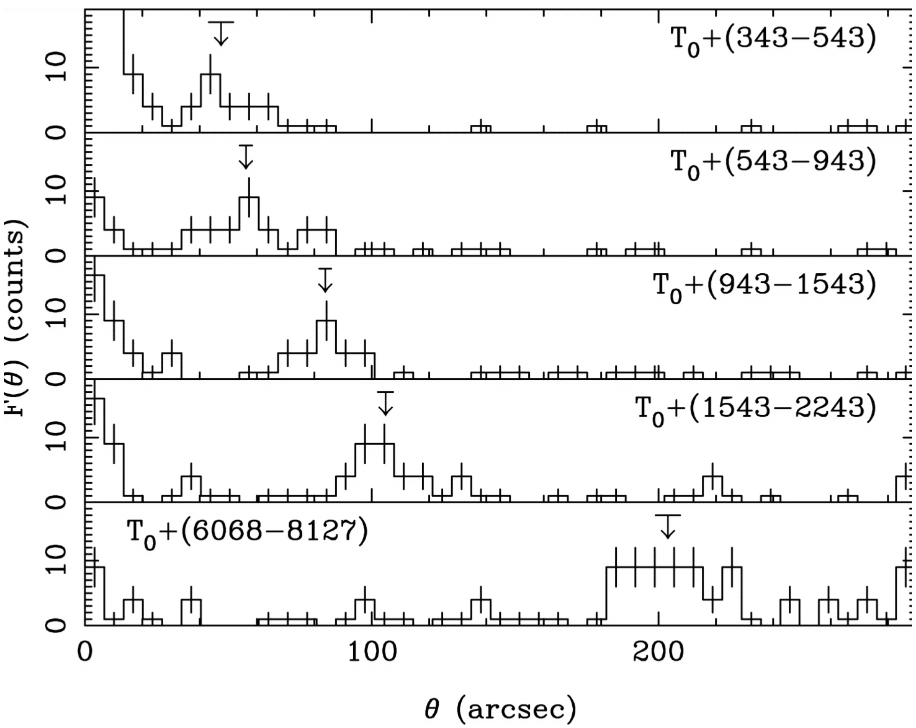
Scattering halo for GX13+1 measured by Chandra and compared to a model (Smith 2008).

Test of dust model: Angular structure of the X-ray scattering halo is sensitive to the grain size distribution. Total intensity is proportional to the amount of dust.

X-Ray Halo Around GRB 050724



0.2–5keV X-ray images of GRB 050724: 1300 ± 950s, 7000 ± 1000s, and later. From Vaughan et al. (2006).



$$\Delta t = \frac{1}{2}\frac{D\theta^2}{c}$$

Dust in a sheet at distance $D \approx 139 \pm 9\,\mathrm{pc}$, $\Delta D < 22\,\mathrm{pc}$

N.B. This method could in principle be used to determine distance to M31 to absolute accuracy **$\pm 1\%$** using background AGN (Draine & Bond 2004) (all we need is $\sim$5 Ms of time on Chandra...)

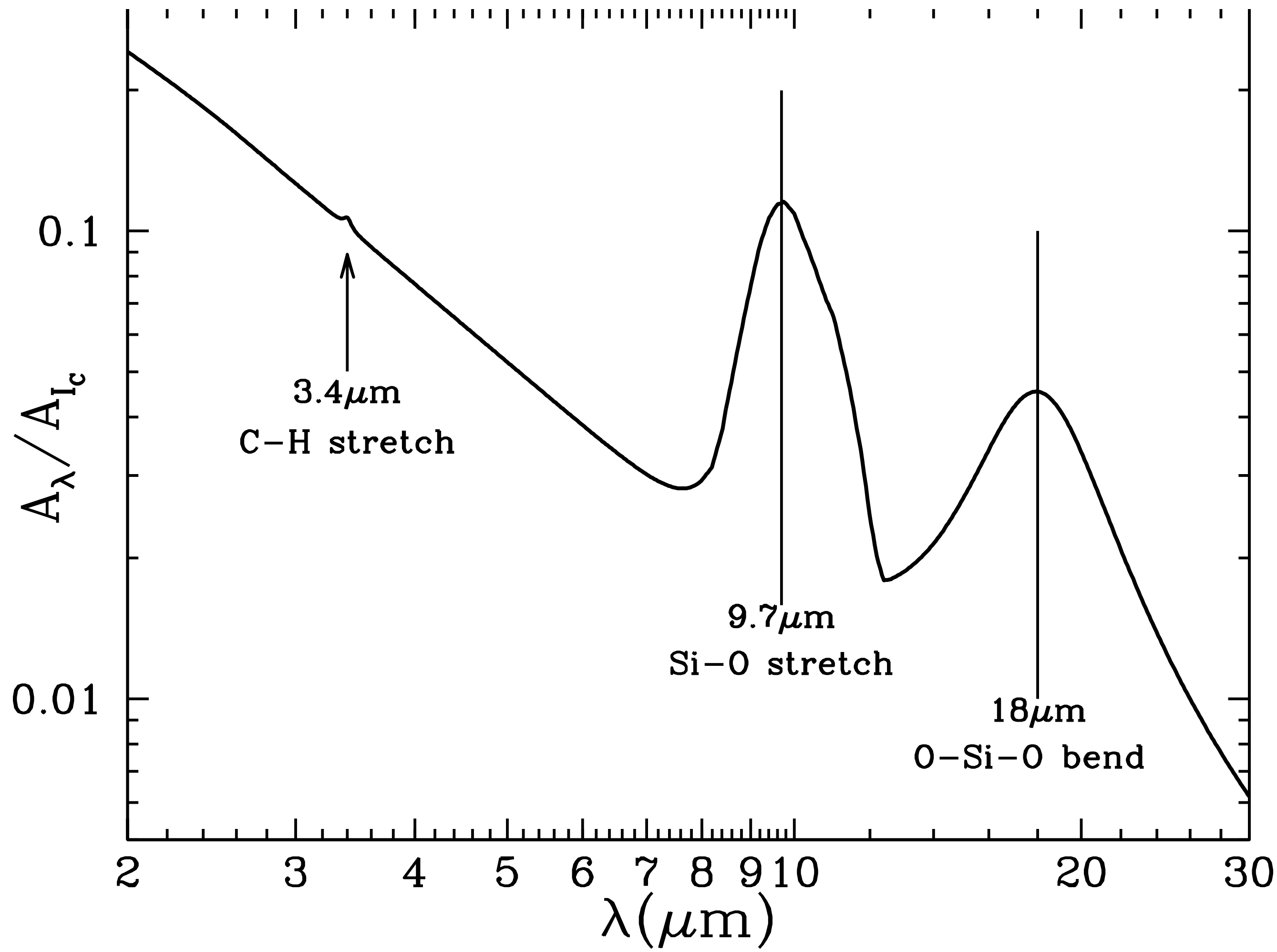
Infrared Spectroscopy (in Absorption)
Dust in the Diffuse ISM

9.7μm feature (and 18μm feature)

- *amorphous silicate.*
- consistent with olivine composition $Mg_{2x}Fe_{2-2x}SiO_4$ $(0 \leq x \leq 1)$
- Strong: requires substantial fraction of interstellar Si in silicates
- Lack of "fine structure": $< 2\%$ of interstellar silicates can be crystalline (Kemper et al. 2005)

3.4μm feature:

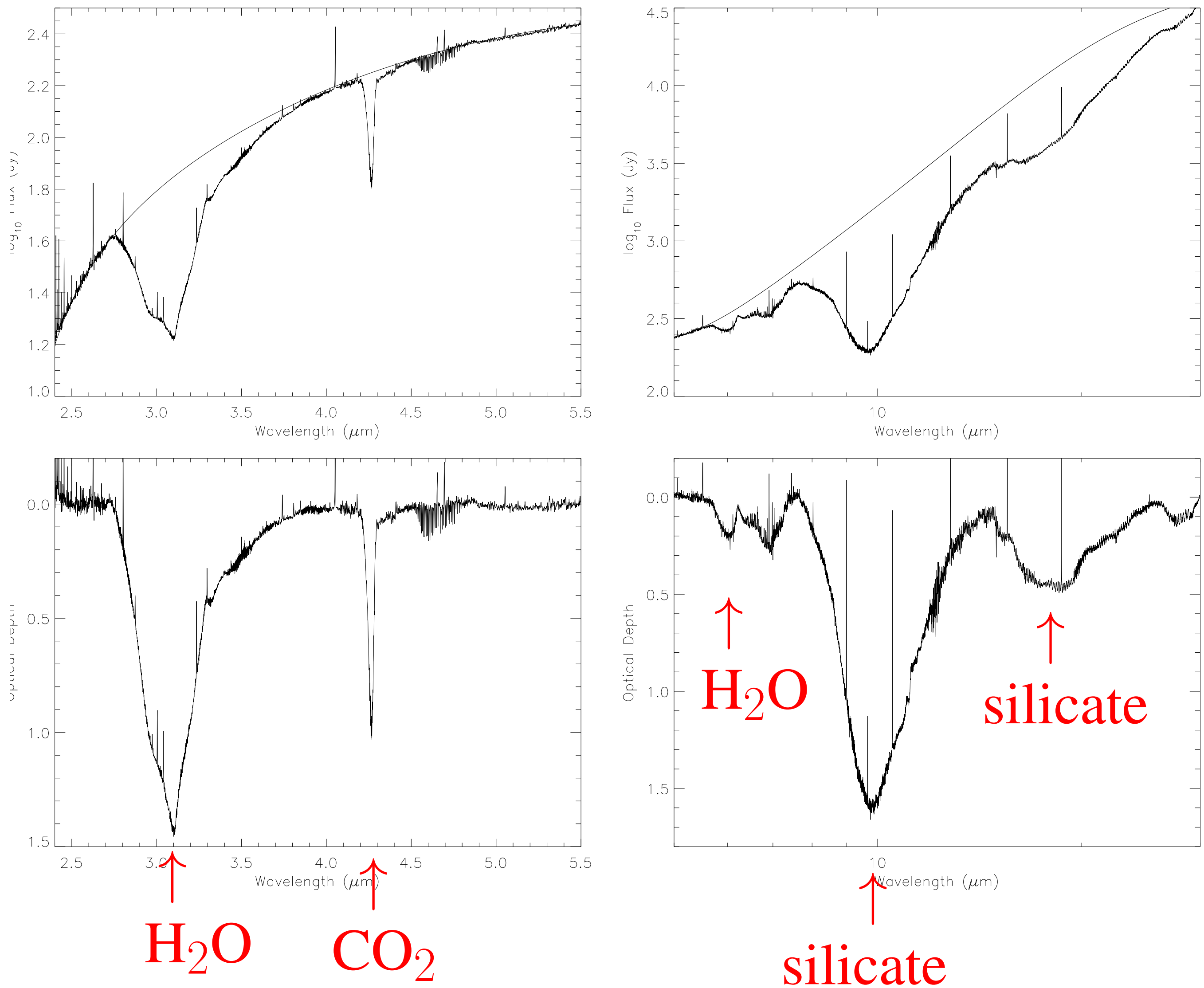
- C-H stretch in *aliphatic (chain-like) hydrocarbons*



Infrared Spectroscopy (in Absorption
Ices in Dark Clouds

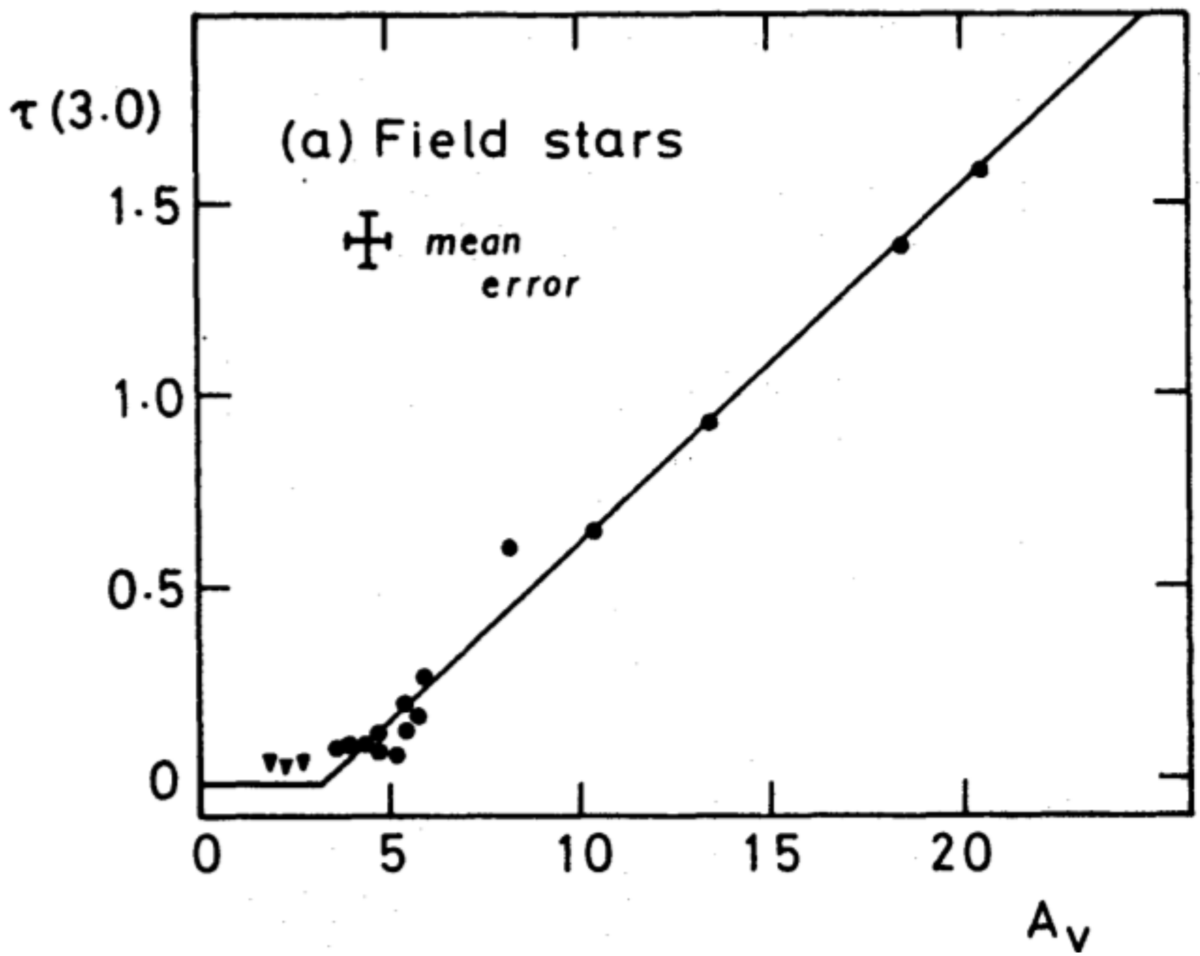
- Ice features seen *only* in dark clouds with $A_V \gtrsim 3.3\mathrm{mag}$
- H_2O dominates
- Also
  - CO
  - CO_2
  - CH_3OH
  - NH_3

Toward BN Object in OMC-1: Gibb et al. (2004)



Infrared Spectroscopy in Absorption

H_2O Ice



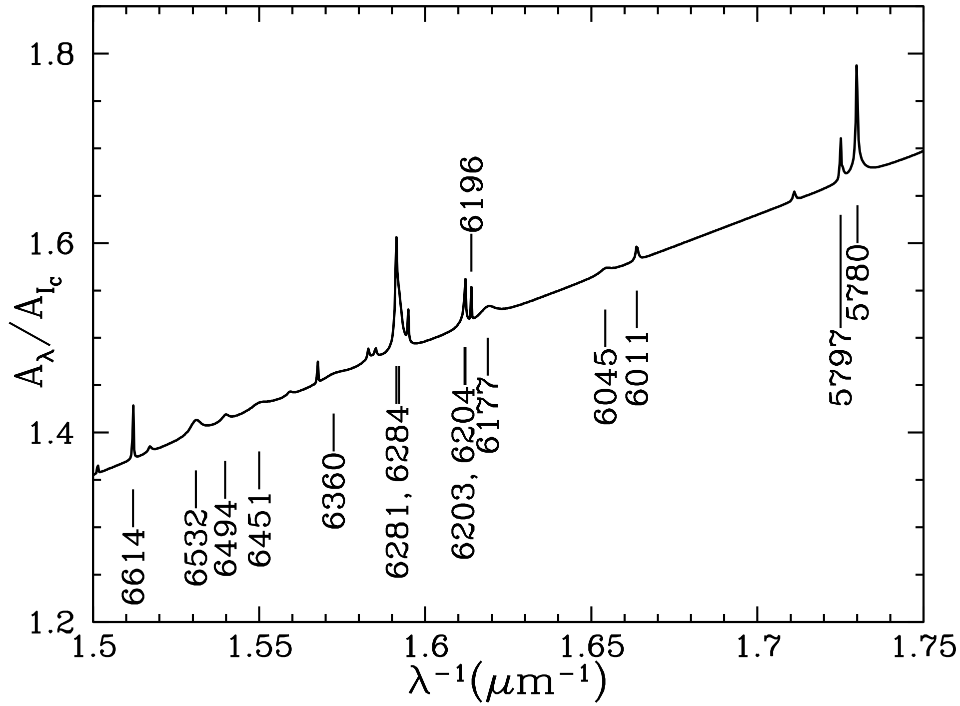
$\Delta\tau(3.0\,\mu\mathrm{m})$ **vs** A_V **in Taurus Molecular Cloud (Whittet et al. 1988)**

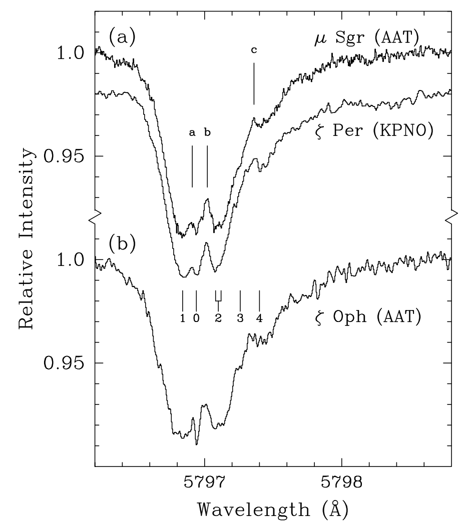
Threshold of $A_V \approx 3.3\,$mag for H_2O ice to be seen.

Apparently need shielding of $A_V \approx 3.3/2 = 1.65\,$mag for H_2O ice to be able to survive against UV photodesorption.

Optical Spectroscopy of Dust: The Diffuse Interstellar Bands

- $\gtrsim$ 400 spectroscopic features
  typical width ∼1Å.
- 90 years since first discovery (Heger 1922)
- But not a single confirmed ID!
  This is embarassing...
- Possibly electronic transitions in large molecules (PAHs?), broadened by rotational structure.
- No matches to lab spectra (yet), but lab work is very difficult
- To date: have not found 2 DIBs that correlate perfectly (McCall et al. 2010)
- Puzzle: why no vibronic sequences seen?
  $X(v=0) \rightarrow A(v=0,1,2,...)$



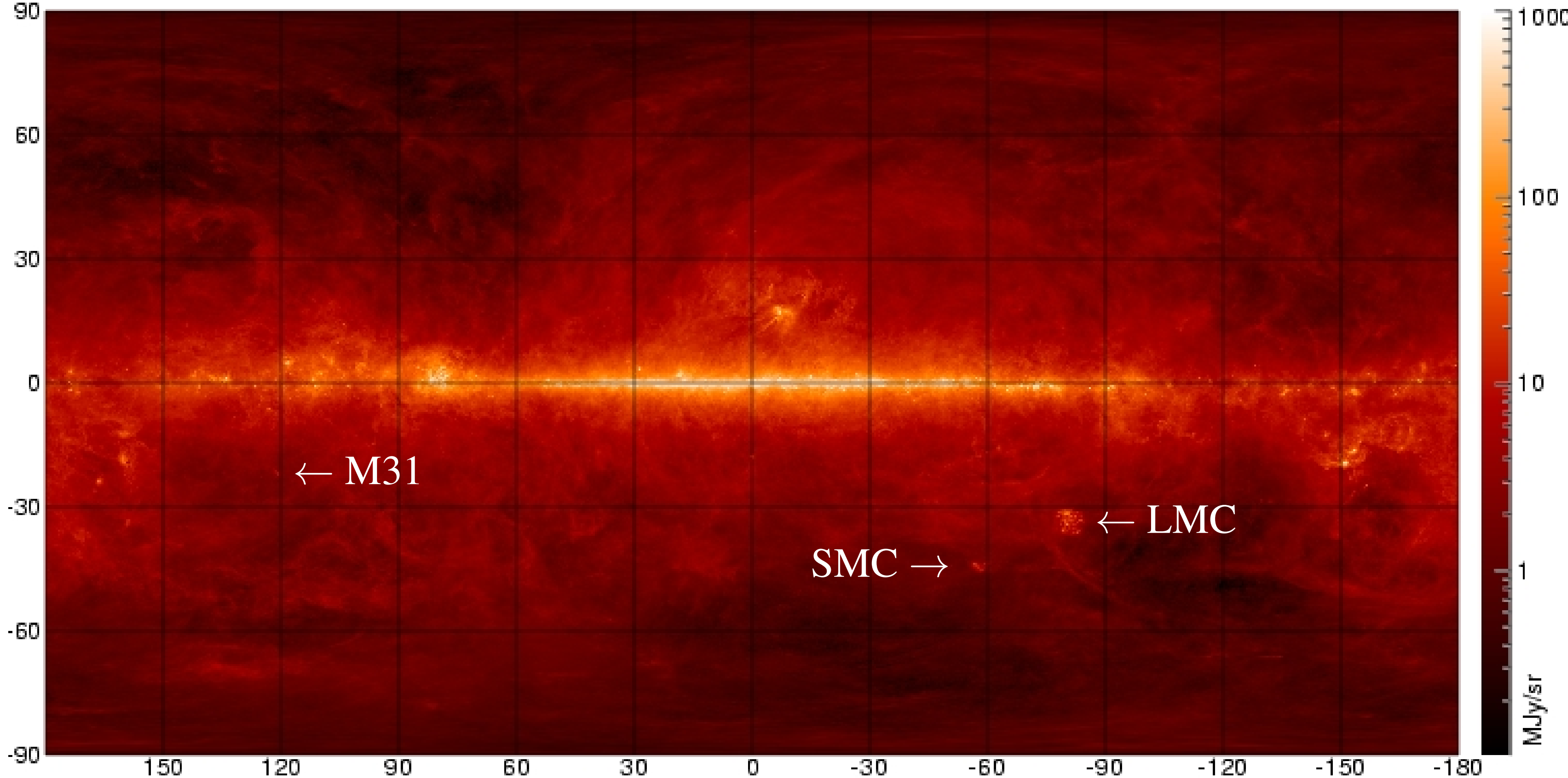


from Kerr et al. (1998)

Infrared Emission

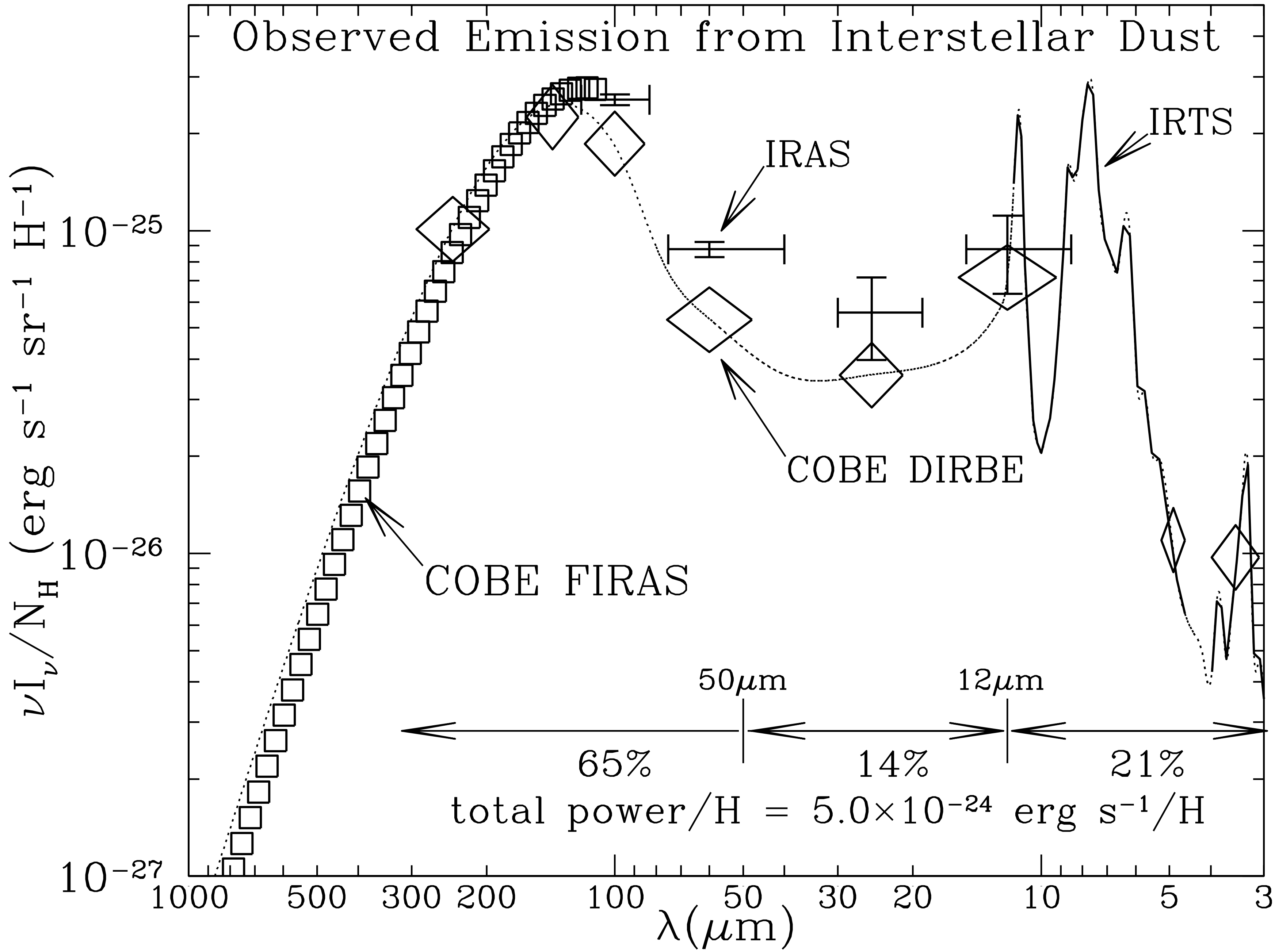
100 μm IRAS/COBE Map of Sky (after zodi subtraction)

Image credit: D. Finkbeiner

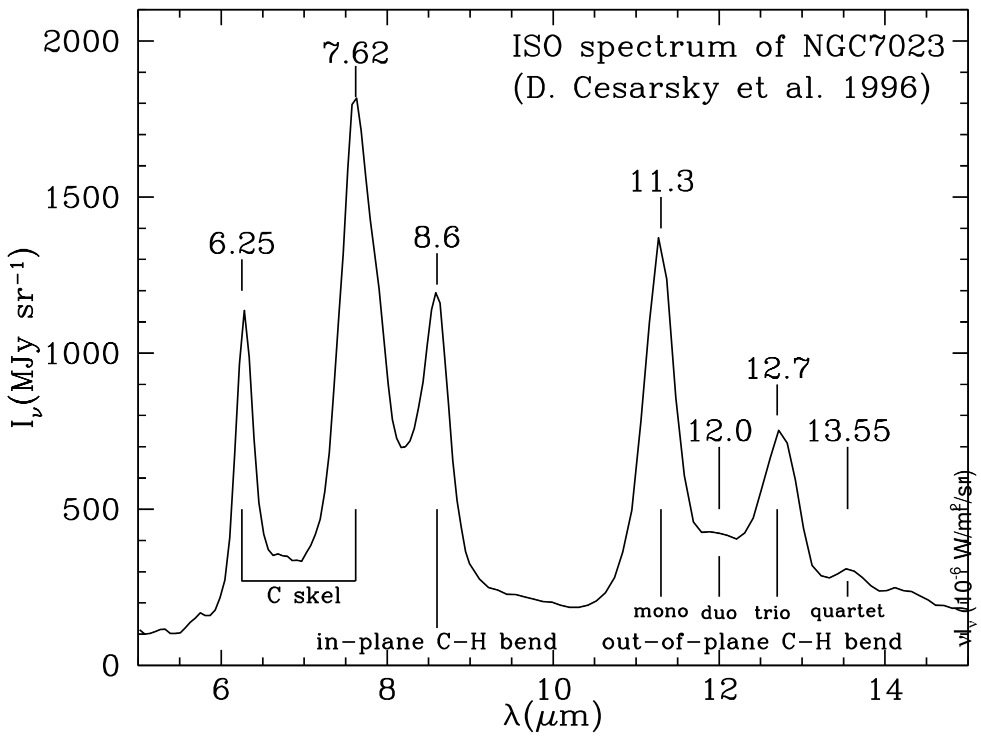


galactic longitude (deg.)

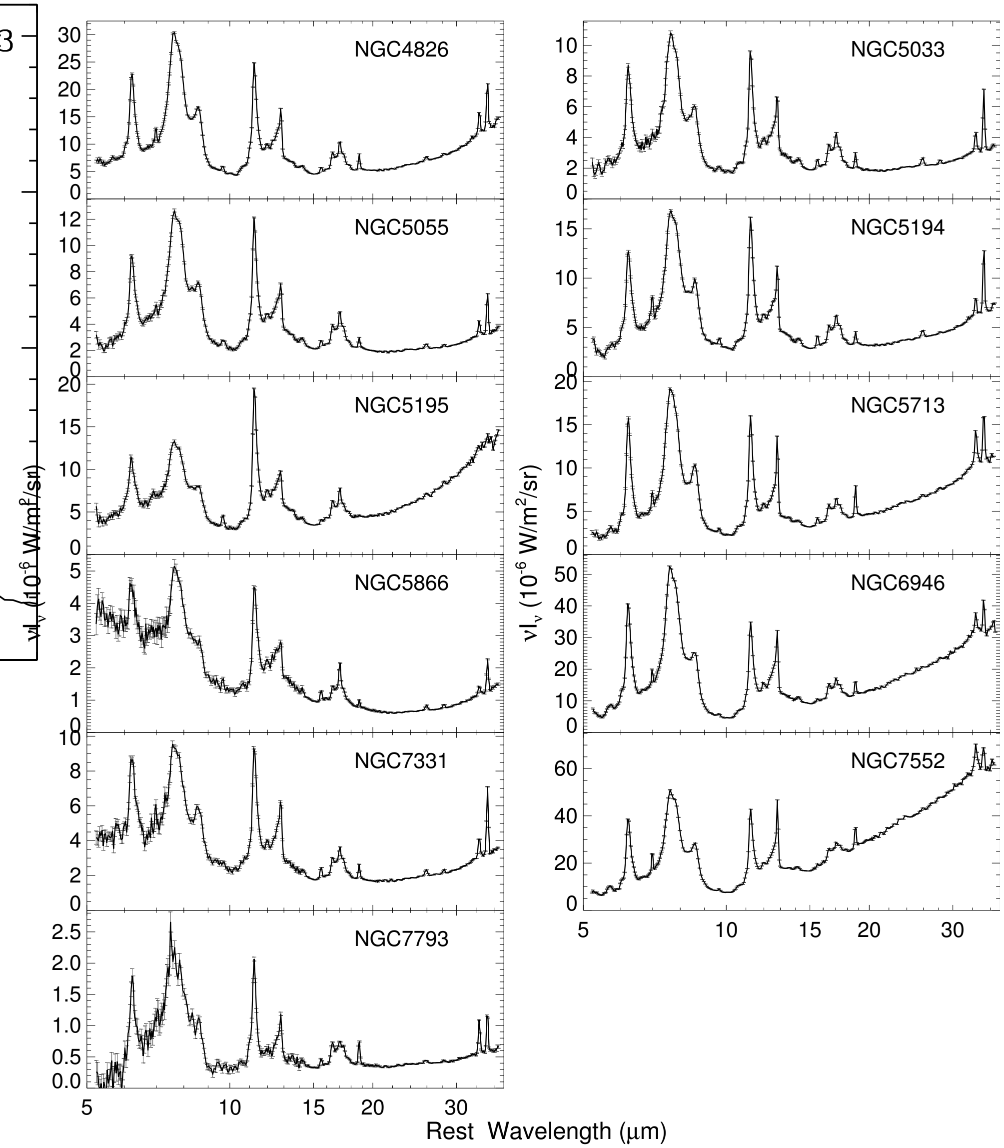
Emission Spectrum of the Diffuse ISM



PAH Emission Features

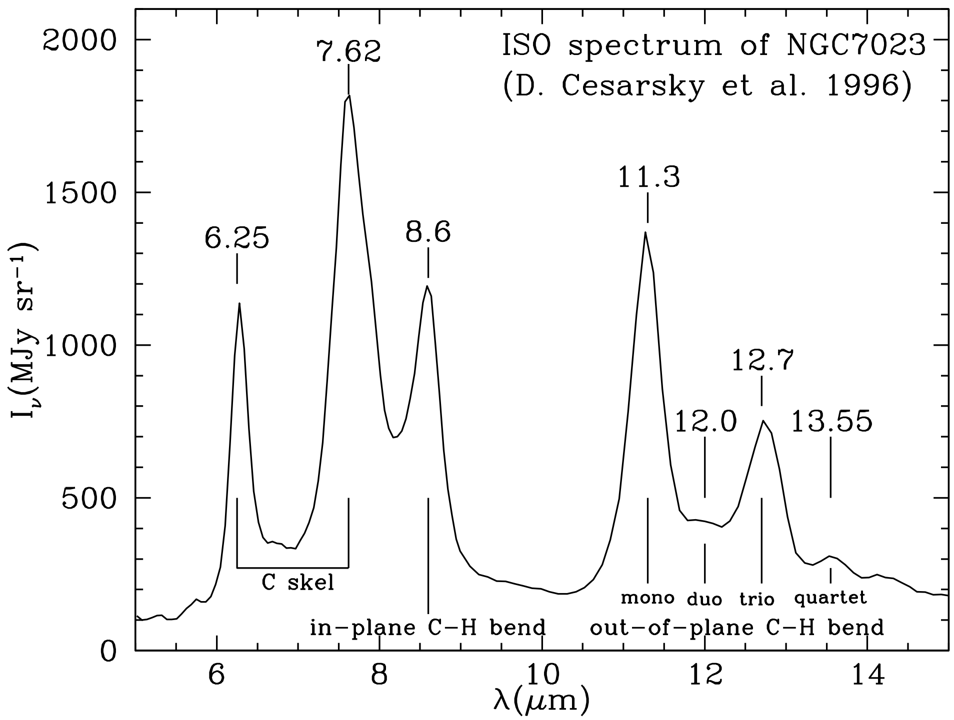


ISO 5–15μm spectrum of the reflection nebula NGC 7023 (Cesarsky et al. 1996)



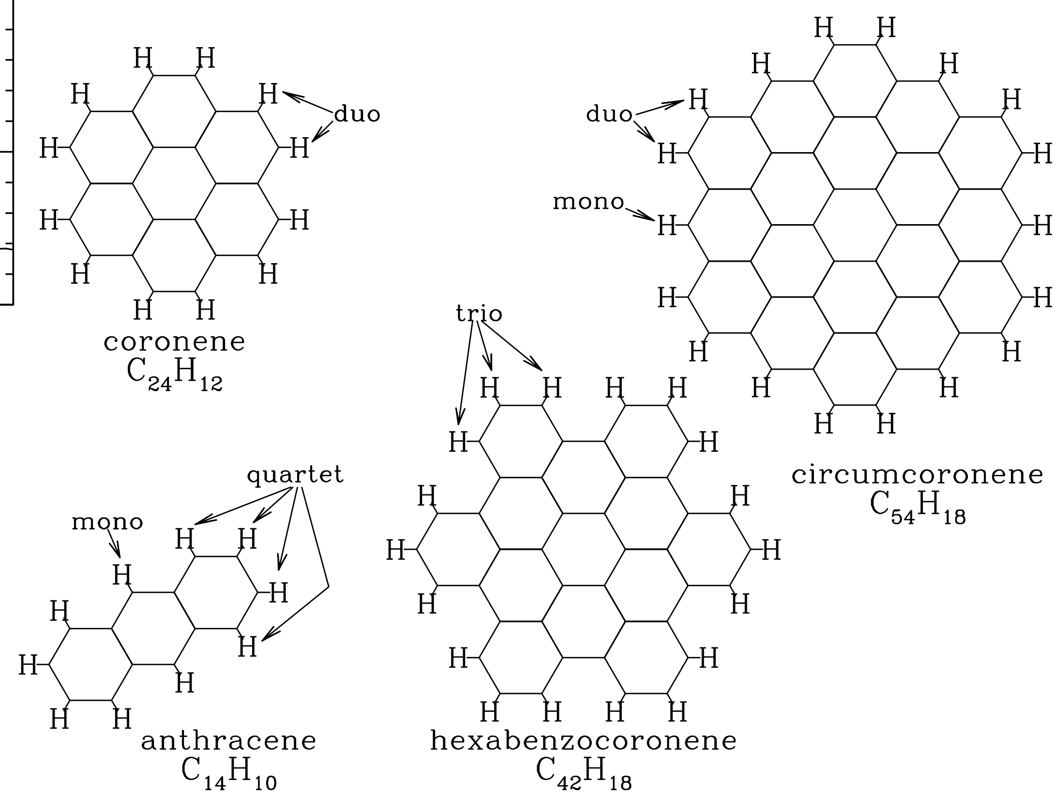
From SINGS survey (Smith et al. 2007)

Polycyclic Aromatic Hydrocarbon Molecules (PAHs)



ISO 5–15μm spectrum of the reflection nebula NGC 7023 (Cesarsky et al. 1996)

- Need $\gtrsim$ 15% of C in PAHs to explain observed emission. (Li & Draine 2001; Draine & Li 2007)
- Particles must be primarily PAH material (not "aliphatic" = chainlike) (Li & Draine 2012)



Some examples of PAHs

Need $\gtrsim 25$ C atoms to survive in ISM

Infrared Emission from Other Galaxies

Spitzer Space Telescope (D=90cm)

- 7 bands: 3.6, 4.5, 6, 8, 24, 70, 160μm
- 8μm band well-matched to PAH emission peak
- 24μm band captures hot ($\sim$100K) dust
- 70, 160μm bands capture dominant dust emission
  70/160 flux ratio sensitive to $T_{\rm dust}$

Herschel Space Observatory (D=3.5m)

- 6 bands: 70, 100, 160, 250, 350, 500μm
- better determination of TIR emission
- sensitive to colder dust than Spitzer (500μm vs. 160μm)
- superior angular resolution near peak of dust emission

NGC 6946 (Aniano et al. 2012)

0.1° = 12 kpc @ 6.8 Mpc

SPIRE 250μm map, $18''$ FWMH = 590 pc

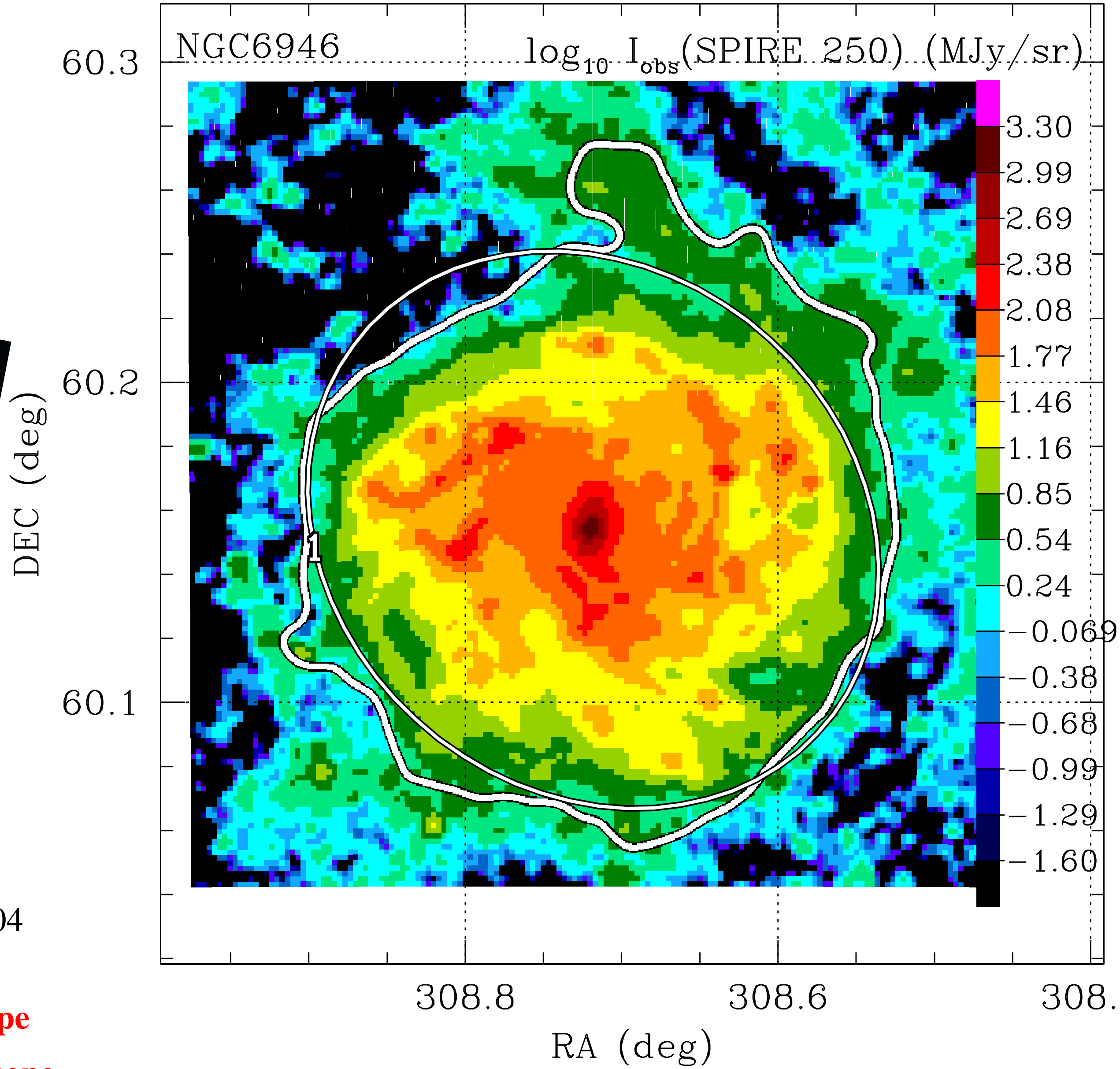


image credit: Kuzio de Naray & McGaugh 2004

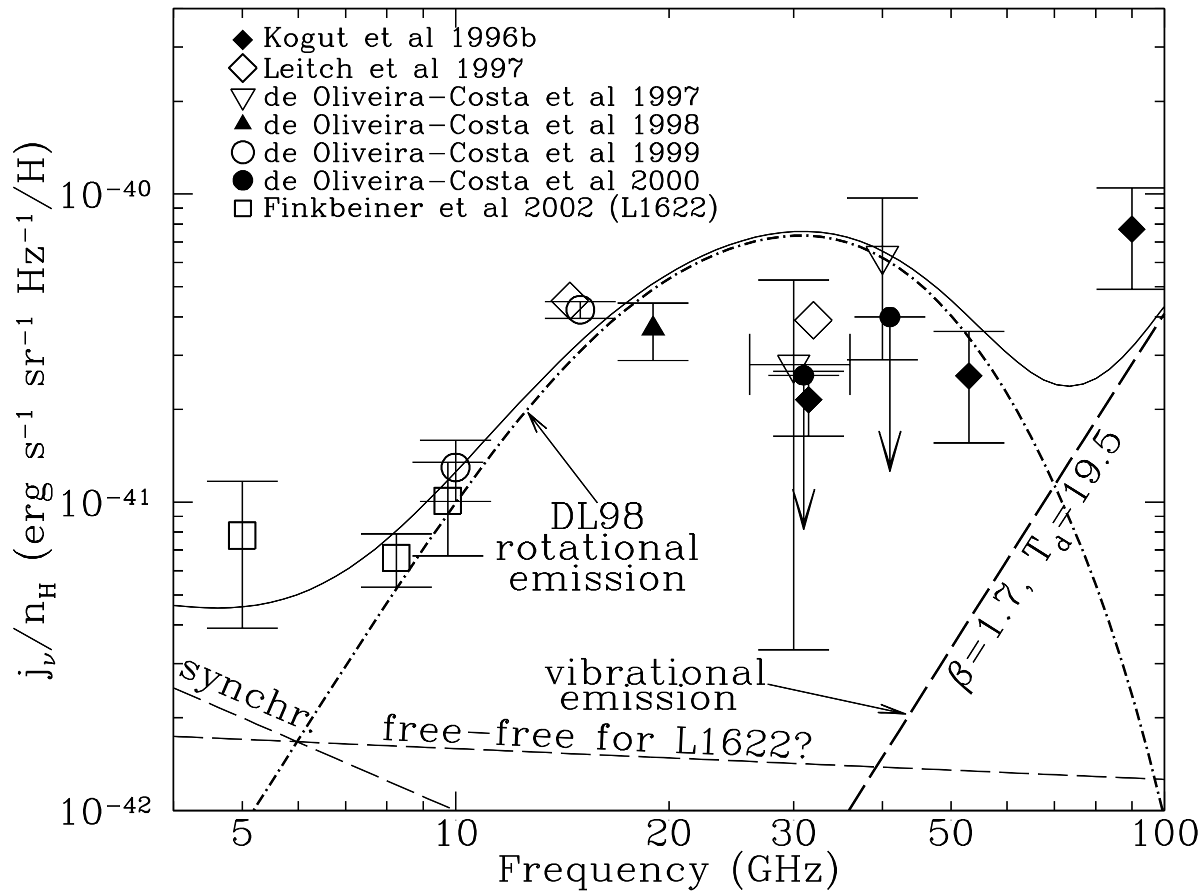
IR Observations:

- **IRAC (3.6–8μm) on Spitzer Space Telescope**
- **MIPS (24–160μm) on Spitzer Space Telescope**
- **PACS (70–160μm) on Herschel Space Observatory**
- **SPIRE (250–500μm) on Herschel Space Observatory**

Microwave Emission

- Full-sky microwave maps to study Cosmic Microwave Background (CMB)
- Foregrounds:
  - synchrotron: use radio-frequency sky as spatial template
  - free-free: use Hα sky as spatial template
  - dust: use IRAS 100 μm sky as template

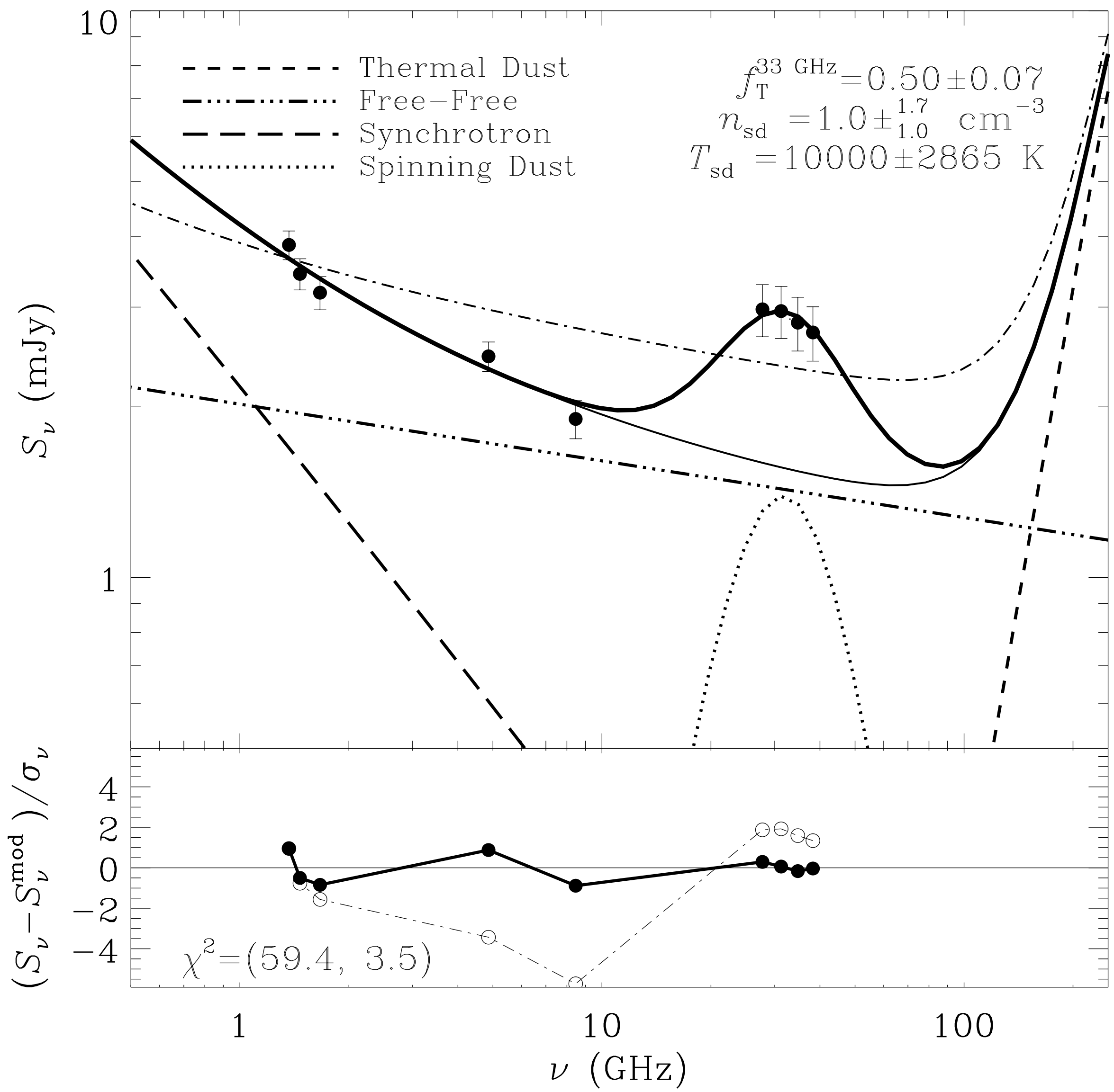
Surprise: **"Anomalous Microwave Emission"** associatedwith dust



What process is responsible for this emission?

"spinning dust": PAH particles spinning at 10–60 GHz

Anomalous Microwave Emission from Other Galaxies



NGC 6946: Murphy et al. (2010)

X-Ray Spectroscopy of Dust

X-ray spectroscopy by

- Chandra
- XMM-Newton

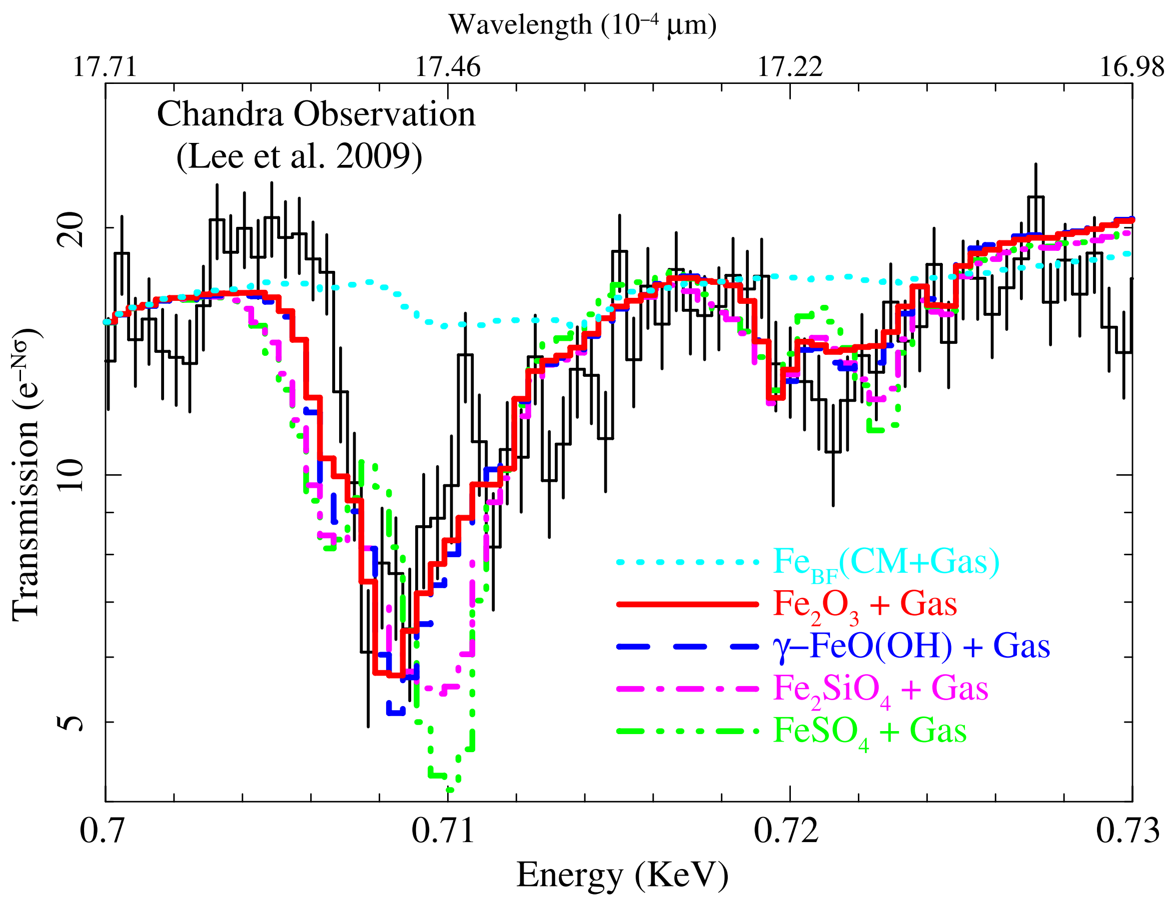
can potentially reveal **quantity** and **composition** of dust

- K-edge absorption by C, O, Mg, Si, Fe
- L-edge absorption by Fe
- absorption spectra sensitive to chemical binding.
- **Need ∼1 eV resolution to discriminate**

Chandra: $\Delta E \sim 1\,\mathrm{eV}$ @ 1 keV

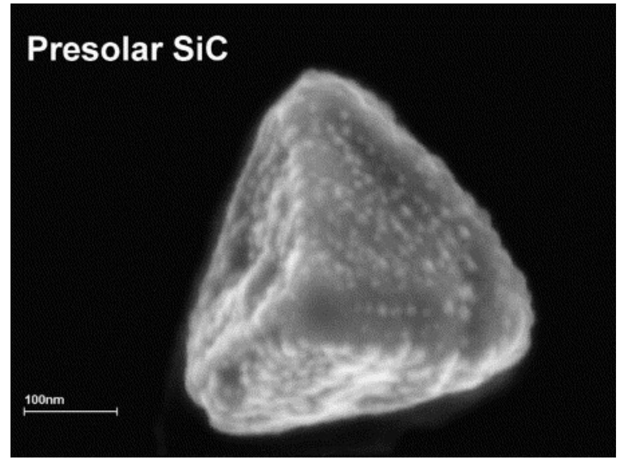
Astro-H: $\Delta E \sim 7\,\mathrm{eV}$

Chandra spectrum of Cyg X-1 (Lee 2010)

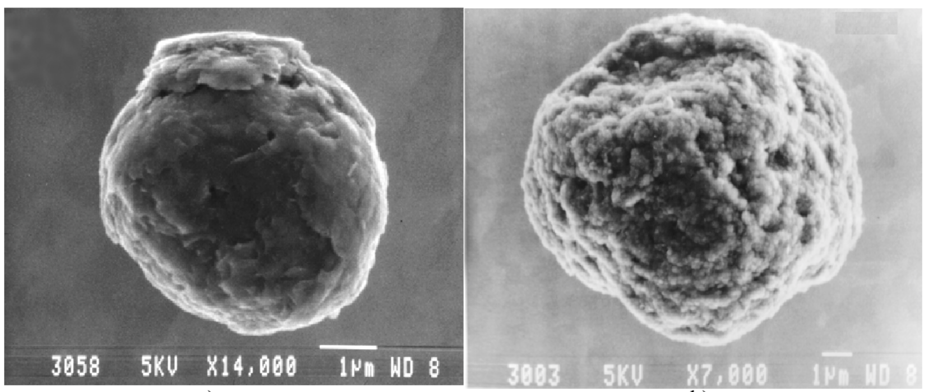


Presolar Grains in Meteorites

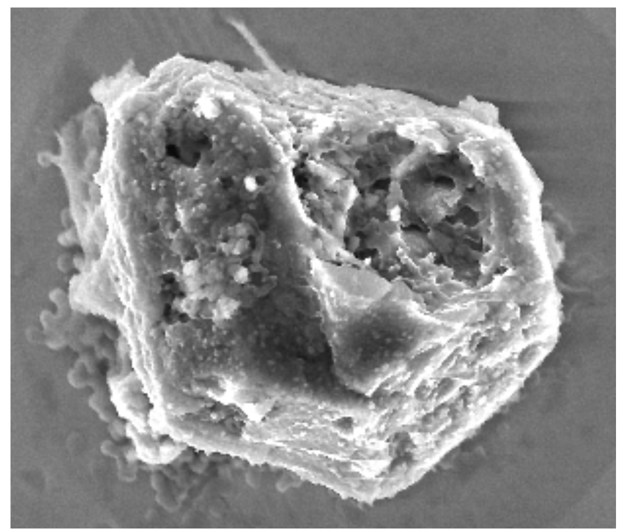
Piece of the Allende meteorite
(carbonaceous chondrite)



presolar SiC grain from Murchison meteorite
from Hoppe (2002)
presumed to come from AGB star



presolar graphite grains (courtesy S. Amari)
left: onion-like; right: cauliflower-like
presumed to come from AGB stars



another presolar SiC grain from
Murchison ($D \approx 2\mu$m)

Presolar Grains in Meteorites

Types and properties of major presolar materials* identified in meteorites and IDPs. See Huss & Draine (2007) and references therein.

Material	Source	Grain Size (μm)	Abundance (ppm)†
Amorphous silicates	circumstellar	0.2-0.5	20-3600
Forsterite (Mg_2SiO_4) / Enstatite ($MgSiO_3$)	circumstellar	0.2-0.5	10-1800
Diamond		$\sim$0.002	$\sim$1400
P3 fraction	?		
HL fraction	circumstellar		
Silicon carbide	circumstellar	0.1-20	13-14
Graphite	circumstellar	0.1-10	7-10
Spinel ($MgAl_2O_4$)	circumstellar	0.1-3	1.2
Corundum (Al_2O_3)	circumstellar	0.5-3	0.01
Hibonite ($CaAl_{12}O_{19}$)	circumstellar	1-2	0.02
TOTAL	circumstellar	0.002-20	**1450-6800**

⋆Other presolar materials include TiC, MoC, ZrC, RuC, FeC, Si_3N_4, TiO_2, and Fe-Ni metal.

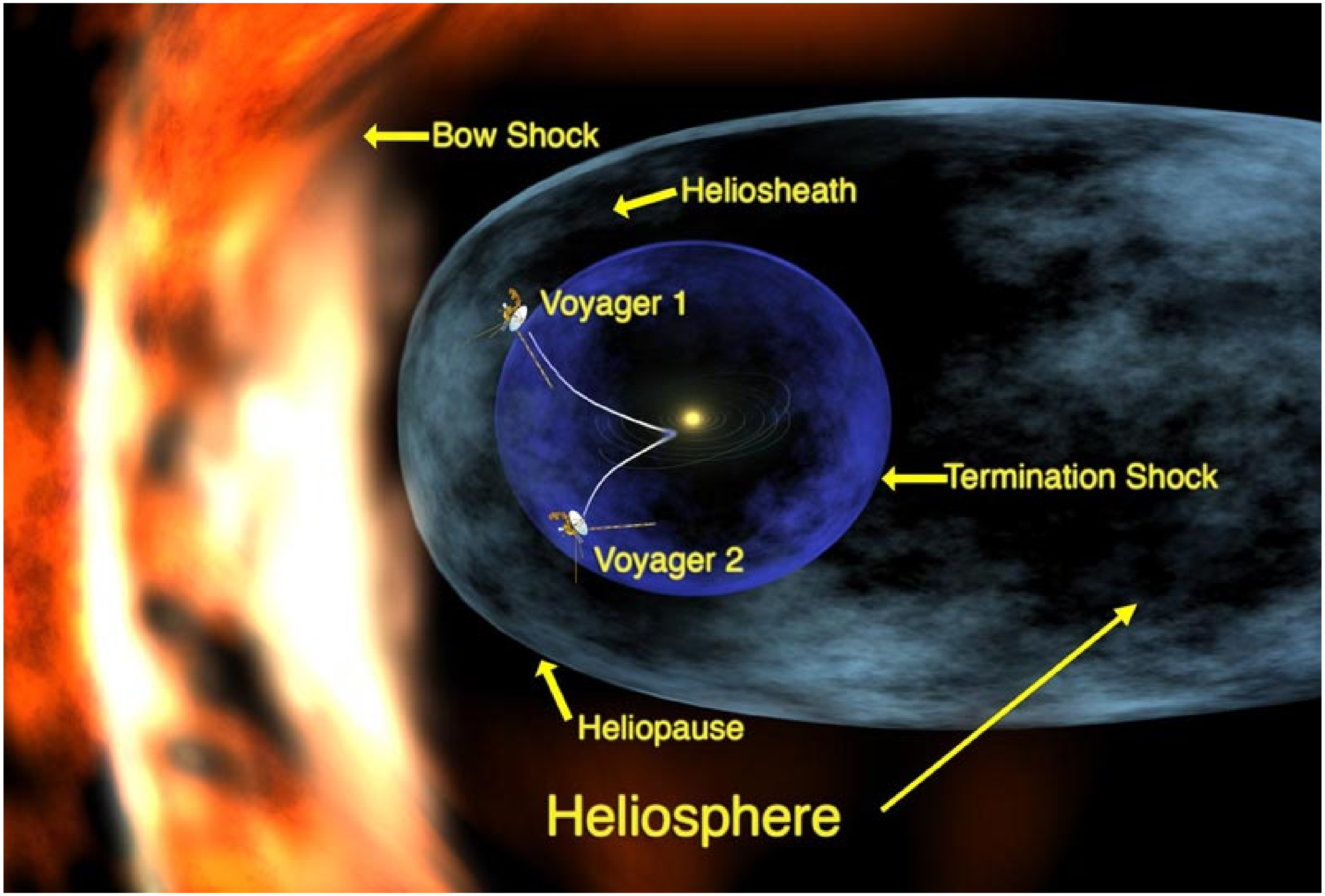
†Abundance in fine-grained fraction (= matrix in primitive chondrites).

- Presolar grains are identified by isotopic anomalies – must differ from *average* isotopic ratios in protosolar nebula.
- Grains with isotopic anomalies will generally be **stardust** – grains formed in outflows from individual stars with their particular isotopic composition.
- **(0.4±0.25)%** of mass in primitive meteorite is **stardust**
- Such grains were part of ISM 4.568 Gyr ago – but they may have been a minority fraction of interstellar dust.

Presolar Grains in Meteorites

- These presolar grains were part of the interstellar grain population 4.6Gyr ago (prior to formation of the solar nebula)
- Similar grains must be present in the ISM today
- These grains are only identified by complex selection, including *unusual isotopic abundances* that prove that they did not condense in the solar nebula: they are "stardust"
- For various reasons, I think that stardust accounts for only a small fraction ($\sim$10%) of the interstellar grain population.
- Therefore:
  We cannot reconstruct the interstellar grain population from the identified presolar grains.

Interstellar Dust Entering the Heliosphere Today



- LIC is moving at $\sim$26.2 $\mathrm{km\ s^{-1}}$ relative to Sun, approaching from $(\ell, b) = (4.7°, +15.3°)$ (5° from ecliptic) (Möbius et al. 2004)
- Spacecraft can sample grains passing through heliosphere

Interstellar Dust Entering the Heliosphere Today

Nature 362, 428 (1993)

Discovery of jovian dust streams and interstellar grains by the Ulysses spacecraft

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ON 8 February 1992, the Ulysses spacecraft flew by Jupiter at a distance of 5.4 AU from the Sun. During the encounter, the spacecraft was deflected into a new orbit, inclined at about 80° to the ecliptic plane, which will ultimately lead Ulysses over the polar regions of the Sun[1]. Within 1 AU from Jupiter, the onboard dust detector[2] recorded periodic bursts of submicrometre dust particles, with durations ranging from several hours to two days, and occurring at approximately monthly intervals (28 ± 3 days). These particles arrived at Ulysses in collimated streams radiating from close to the line-of-sight direction to Jupiter, suggesting a jovian origin for the periodic bursts. Ulysses also detected a flux of micrometre-sized dust particles moving in high-velocity (≥26 km s^{-1}) retrograde orbits (opposite to the motion of the planets); we identify these grains as being of interstellar origin.

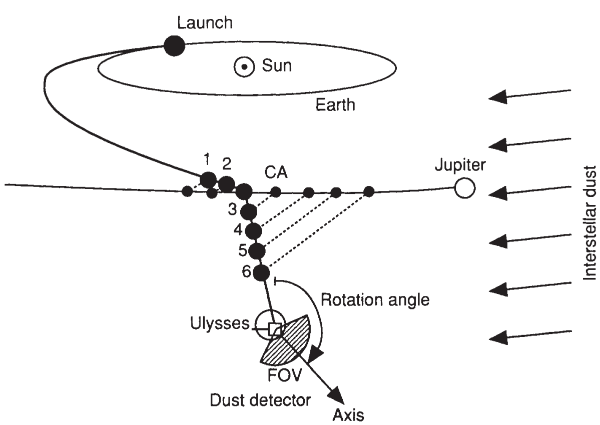

FIG. 1 Ulysses trajectory and geometry of dust detection—oblique view from above the ecliptic plane also showing the Sun and the orbits of Earth and Jupiter (in the foreground). Arrows indicate the flow of interstellar dust. The trajectory of Ulysses[1] after Jupiter closest approach (CA) is deflected into an orbit inclined at 80° to the ecliptic going south. Numbers along the trajectory refer to positions of Ulysses at which dust streams were detected—dotted lines point to Jupiter. Two hundred days after CA, Ulysses had reached a distance of 1.6 AU from Jupiter and an ecliptic latitude of −9°. The spacecraft spins around an axis which, along with the high-gain antenna, points towards Earth. The dust detector onboard has a 140° conical field-of-view (FOV), and is mounted almost at a right angle (85°) to the Ulysses spin axis. Radiant directions from which it can sense impacts therefore include the plane perpendicular to the spacecraft–Earth line. The rotation angle of the sensor axis at the time of a dust impact is measured from the ecliptic north direction. The spin-averaged sensitive area[2] of the dust detector to a mono-directional stream of dust grains is ≤0.02 m^2; the maximum occurs when the centre of the detector FOV passes through the stream during spacecraft rotation.

TABLE 1 Dust burst characteristics

Days from CA	−57.7	−32.1	31.4	59.8	86.9	117.4
Date (yr/d)	91/346	92/7	92/71	92/99	92/126	92/157
Duration (h)	4.7	6.0	25.0	43.4	19.8	16.3
Number of particles	3	4	124	7	4	4
Mass range ($\times 10^{-15}$ g)	3–6	0.1–7	1–90	2–9	5–20	3–4
Mean mass ($\times 10^{-15}$ g)	4	3	9	4	9	4
Speed range (km s^{-1})	28–37	27–56	28–44	28–44	20–37	28–37
Mean speed (km s^{-1})	31	37	42	33	29	30
Mean rotation angle	201°	211°	51°	54°	44°	32°
Distance to Sun (AU)	4.93	5.14	5.40	5.39	5.38	5.36
Distance to Jupiter (R_J)	995	562	553	1025	1480	1980

The time corresponds to the centre of the burst. Closest approach (CA) to Jupiter occurred on 92/39.5. The definition of stream particles and hence the number of members is somewhat arbitrary, but here it refers only to small (mass ≤5×10^{-14} g) and collimated (±70° from mean rotation angle) particles. Jupiter radius R_J=71,400 km.

The Ulysses dust detector is a multi-coincidence impact ionization detector[2] with a sensitivity 10^5 times higher than any dust detector previously flown in the outer Solar System. Masses and impact speeds of dust particles are determined from the measured amplitudes and rise-times of the impact charge signals. We restrict our analysis here to reliably identified[3] impact events (that is for small impact events, triple coincidence is required). The mass sensitivity threshold is 4×10^{-15} g at 20 km s^{-1} and 6×10^{-16} g at 40 km s^{-1} impact speed, as deduced from laboratory impact calibrations with carbon, silicate and iron dust particles[4]. The accuracy of the speed determination is a factor of two and that of the mass determination is a factor of 10 in the calibrated range[5]. From 8 days before closest approach (CA) to Jupiter until 2 days after, the instrument sensitivity was reduced by ground command by about a factor of two. For 17 hours each side of CA this sensitivity was further reduced by a factor of more than 10, for reasons of instrument safety. The trajectory of Ulysses and the geometry of dust detection is explained in Fig. 1.

The impact rate observed by Ulysses (Fig. 2) of big particles was low (~0.3 impacts per day) for most of the time, although a statistically significant peak of big particles did occur at the time of Jupiter encounter[6]. For most of 1991, when Ulysses was <4 AU from the Sun, the impact rate of small particles was also low. Within a few months of Jupiter fly-by, however, six bursts

- Grun et al. (1993): Dust impact detector on Ulysses detected impacts consistent with kinematics of "interstellar wind"
- Able to estimate impactor masses → size distribution
- $a \lesssim 0.1\,\mu$m grains expected to be deflected by $\vec{B}$ in solar wind ($\Delta v \approx 500\,\mathrm{km\,s^{-1}}$):

$$R_{\rm gyro} = 2500 \left(\frac{5\,{\rm V}}{U}\right)\left(\frac{3\,\mu{\rm G}}{B}\right)\left(\frac{a}{0.1\,\mu{\rm m}}\right)^2 {\rm AU}$$

  Suppression of $a \lesssim 0.1\,\mu$m grains is expected

- $a \approx 0.1-0.3\,\mu$m grains: impact rate measured by *Ulysses* is in agreement with expectations for interstellar dust

Interstellar Dust Entering the Heliosphere Today

- size distributions from interstellar dust models:
  - ◇ (total H mass)/(dust mass) ≈ 100
  - ◇ $\sim$50% of dust mass above/below $\sim 0.15\,\mu$m
    $M \approx 4 \times 10^{-14}(a/0.15\,\mu\mathrm{m})^3\,\mathrm{g}$
- $n_{\mathrm{H},LIC} \approx 0.22\,\mathrm{cm}^{-3}$, $v_{LIC,\odot} \approx 26\,\mathrm{km\,s}^{-1}$
- **predicted** dust mass flux
  $\rho_{\rm dust} v_{LIC,\odot} \approx 0.01 n_{\rm H} m_{\rm H} v_{LIC,\odot} \approx 1.0 \times 10^{-20}\,\mathrm{g\,cm}^{-2}\,\mathrm{s}^{-1}$.
- **Success!:** *Ulysses* observed $\sim$expected mass flux of $M < 10^{-12.5}\,\mathrm{g}$ particles.
- **PROBLEM: *Ulysses* found comparable mass flux of $M > 10^{-12}\,\mathrm{g}$ particles:**
  mass flux $\gtrsim 4 \times 10^{-21}\,\mathrm{g\,cm}^{-2}\,\mathrm{s}^{-1}$ **of** $M > 10^{-12}\,\mathrm{g}$ **particles.**

These grains should not be there!!

Is it possible that there is a population of very large grains in the ISM?

Interstellar Dust Entering the Heliosphere Today

- Size distribution "measured" by impacts on Ulysses and Galileo (Landgraf et al. 2000) extends up to $a \approx 1.3\,\mu\mathrm{m}$
  $\rightarrow$ extinction curve with $R_V \approx 5.8$ (Draine 2009)
  vs. observed $R_V = 3.1$.
- Either size distribution at location of the Sun differs from average ISM
  (but how could this be?)
  OR
  the spacecraft experiments are not measuring interstellar grains.

More headaches: Radar observations of "hyperbolic micrometeors":

- Arecibo (Meisel et al. 2002): $0.3\,\mu\mathrm{m} < a < 10\,\mu\mathrm{m}$
- AMOR (Taylor et al. 1996): $a > 25\,\mu\mathrm{m}$.

Particles are claimed to be interstellar based on hyperbolic orbital parameters.
But: total mass density contributed by these particles in interstellar space would be $\sim$50 times greater than allowed by solar abundances!

Someone is wrong...

Observational test for very large interstellar grains: "Brilliant Pebbles"
Optical halos around reddened stars due to forward scattering (Socrates & Draine 2009)

Next Time: Theory

- How do we model the interstellar grain population?
- 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
- Implications for Grain Growth in ISM of Milky Way and Other Galaxies


THANK YOU

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