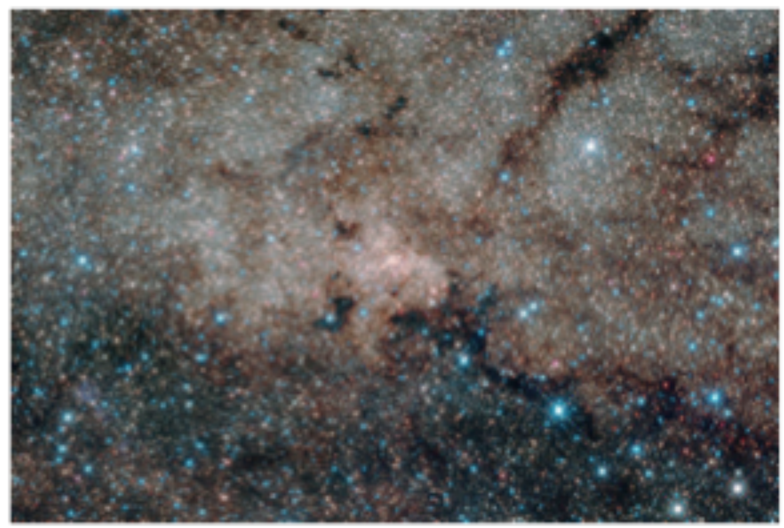
Dust: Messing with your measurements

Dust: Prominent in star-forming regions

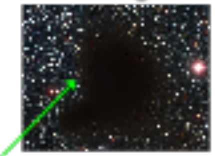
Associated w/ molecular gas

Dust-SF association can be seen globally

Milky Way dust also obscures distant measurements



Dust plays many important roles in galaxies



- Extinction/Attenuation
- Reddening
- Reprocessing UV/optical light into the infrared
- Scatters light.
- Locks up metals
- Catalyzes formation of H_2

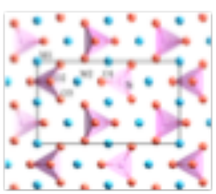
Dust

- Extinction, Reddening & Reddening Laws
- Correcting for the Effects of Dust
  - Foreground and Internal Extinction
- Estimating the Amount of Extinction
  - Inclination corrections
  - Balmer Decrements
  - UV slopes
  - Difficulties in deriving A_x.
- Global trends in extinction
- Dust extinction as a tracer of dense gas

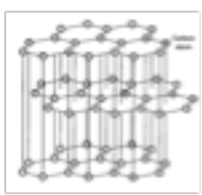
What is dust?

A complex and variable mixture of:

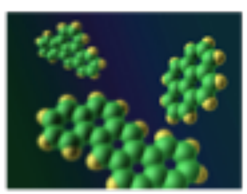
- Large grains (~0.1μm), made of silicates (SiO complexes bonded with Fe or Mg) and graphite.
- "Coal" (200-2000Å in size)
- "PAH"s: Poly Aromatic Hydrocarbons (like benzene rings)
- "Very small grains" (VSG)



Silicates

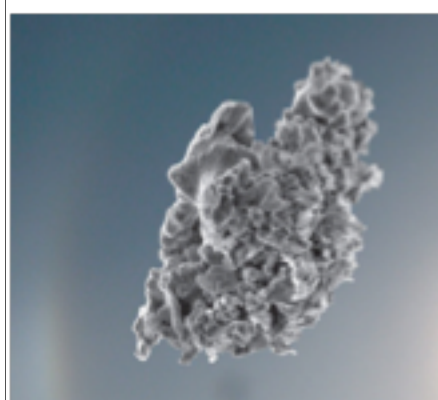


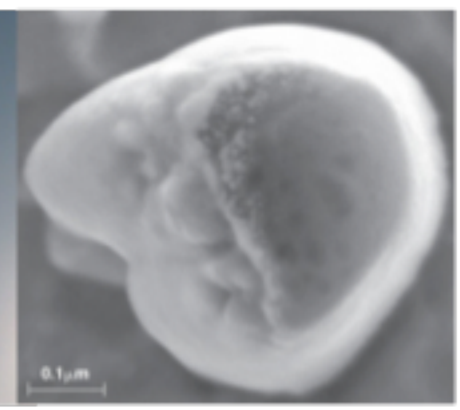
Graphite
Amorphous Carbon



PAHs

Cosmic Dust





J. Freitag and S. Messenger

The dust population evolves

Dust grains are probably created in:

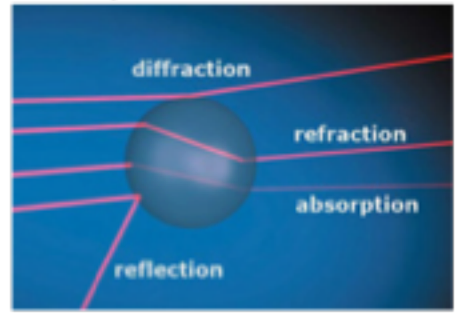
- SN explosions
- Stellar winds (AGB stars in particular)

Dust grains are probably destroyed by:

- Shocks (SN explosions & fast stellar winds)
- Intense radiation

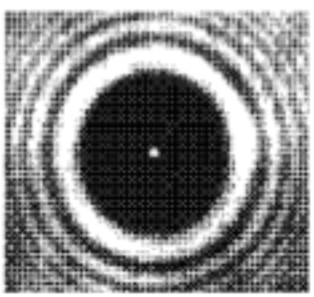
"Dust" refers to a complex population of different grains, with different sizes, that will likely change with enviornment

Dust has complex interactions with light

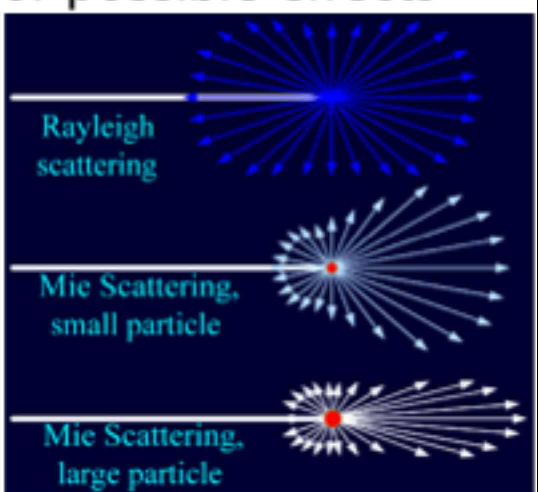


- Interaction depends on size, shape of dust grain
- Affected by composition: affects dielectric constant which then sets complex index of refraction
- Effects calculated as "Mie Scattering": interaction of EM plane wave with $m=n+ik$ index of refraction

Examples of possible effects



Diffraction



Depends on wavelength vs grain size a

$x=2\pi a/\lambda$

Note: Extinction ≠ Absorption

Extinction coefficient defined as ratio of cross section for absorption divided by area of spherical grain

$$\boxed{Q_{\rm ext} = Q_{\rm abs} + Q_{\rm scat}}$$

This can be greater than 1, because of scattering

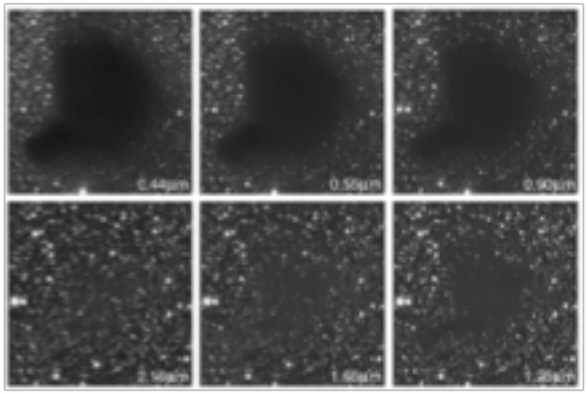
Quantifying dust extinction:

Excellent discussion in Binney & Merrifield 3.7

The attenuation in a bandpass X is defined:

$$A_X = (m_{observed} - m_{true})_X$$

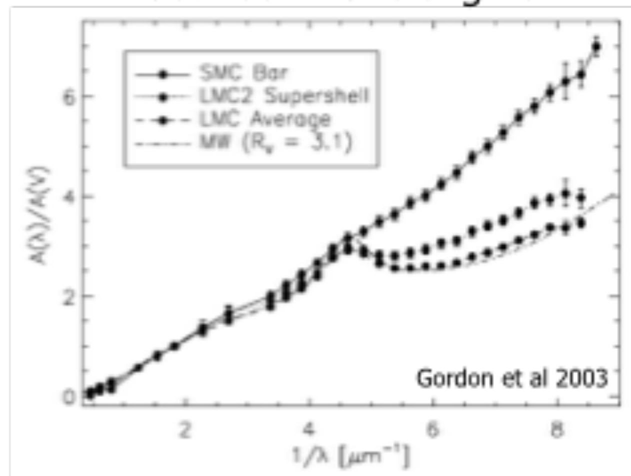
A_V is usually quoted, for historical reasons



Depends strongly on wavelength.

"Attenuation Law"

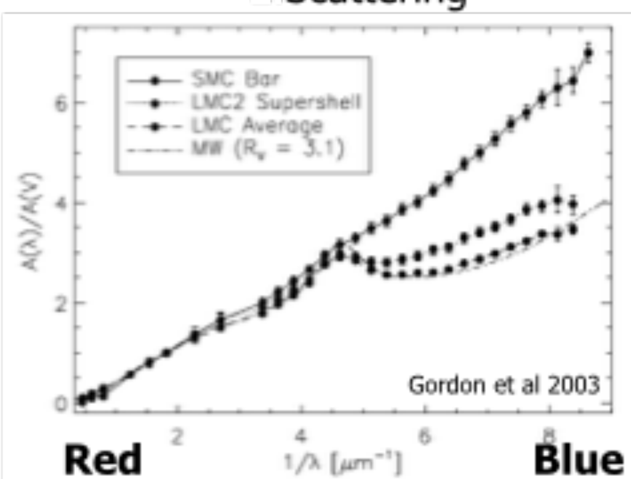
Describes the relative attenuation between wavelengths



 Why inverse wavelength in plots? I have no idea. Someone did it once a long time ago, and now it's the standard…

"Attenuation Law"

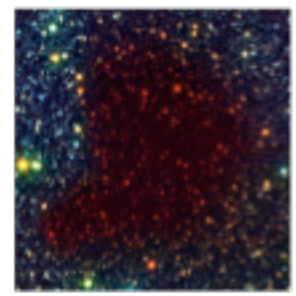
2 Contributions:
1. Extinction (i.e. absorption)
2. Scattering



 Why inverse wavelength in plots? I have no idea. Someone did it once a long time ago, and now it's the standard…

Reddening

Color-dependent attenuation leads to "reddening"

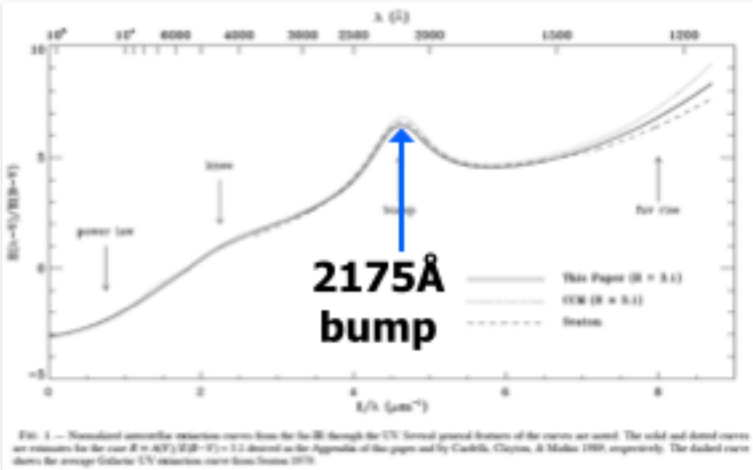


Definition of reddening (or "color excess")

$$E(X\text{-}Y) = (m_X - m_Y)_{observed} - (m_X - m_Y)_{true}$$
$$= (m_{observed} - m_{true})_X - (m_{observed} - m_{true})_Y$$
$$= A_X - A_Y$$

$E(B\text{-}V)$ is usually quoted, for historical reasons

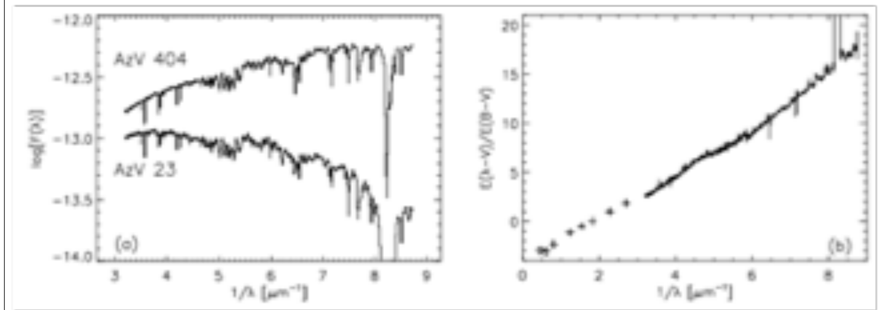
Attenuation curves sometimes plotted in terms of reddening



Fitzpatrick et al 1999

17

Measuring the Attenuation Law



Use pairs of stars with identical spectral types (i.e. absorption features)

Gordon et al 2003

18

Optical attenuation in different bandpasses

RELATIVE EXTINCTION FOR SELECTED BANDPASSES

Filter	λ_{eff} (Å)	$A/A(V)$	$A/E(B-V)$	Filter	λ_{eff} Å	$A/A(V)$	$A/E(B-V)$
Landolt U	3372	1.664	5.434	Strömgren u	3502	1.602	5.231
Landolt B	4404	1.321	4.315	Strömgren b	4676	1.240	4.049
Landolt V	5428	1.015	3.315	Strömgren v	4127	1.394	4.552
Landolt R	6509	0.819	2.673	Strömgren β	4861	1.182	3.858
Landolt I	8090	0.594	1.940	Strömgren y	5479	1.004	3.277
CTIO U	3683	1.521	4.968	Sloan u'	3546	1.579	5.155
CTIO B	4393	1.324	4.325	Sloan g'	4925	1.161	3.793
CTIO V	5519	0.992	3.240	Sloan r'	6335	0.843	2.751
CTIO R	6602	0.807	2.634	Sloan i'	7799	0.639	2.086
CTIO I	8046	0.601	1.962	Sloan z'	9294	0.453	1.479
UKIRT J	12660	0.276	0.902	WFPC2 F300W	3047	1.791	5.849
UKIRT H	16732	0.176	0.576	WFPC2 F450W	4711	1.229	4.015
UKIRT K	22152	0.112	0.367	WFPC2 F555W	5498	0.996	3.252
UKIRT L'	38079	0.047	0.153	WFPC2 F606W	6042	0.885	2.889
Gunn g	5244	1.065	3.476	WFPC2 F702W	7068	0.746	2.435
Gunn r	6707	0.793	2.590	WFPC2 F814W	8066	0.597	1.948
Gunn i	7985	0.610	1.991	DSS-II g	4814	1.197	3.907
Gunn z	9055	0.472	1.540	DSS-II r	6571	0.811	2.649
Spinrad R_s	6993	0.735	2.467	DSS-II i	8183	0.580	1.893
APM b_J	4690	1.236	4.035				

NOTE.—Magnitudes of extinction evaluated in different passbands using the $R_V = 3.1$ extinction laws of Cardelli et al. 1989 and O'Donnell 1994. The final column normalizes the extinction to photoelectric measurements of $E(B-V)$.

Schlegel et al 1998

Note: Corrections given in Schlafly & Finkbeiner 2011

19

Attenuation in the IR

INTERSTELLAR EXTINCTION LAW

λ	$E(\lambda - V)/E(B-V)$	A_λ/A_V	van de Hulst No. 15
U	1.64[a]	1.531	1.555
B	1.00[b]	1.324	1.329
V	0.0[b]	1.000	1.000
R	−0.78[b]	0.748	0.738
I	−1.60[b]	0.482	0.469
J	−2.22 ± 0.02	0.282	0.246
H	−2.55 ± 0.03	0.175	0.155
K	−2.744 ± 0.024	0.112	0.0885
L	−2.91 ± 0.03	0.058	0.045
M	−3.02 ± 0.03	0.023	0.033
N	−2.93	0.052	0.013
8.0 μm	−3.03	0.020 ± 0.003	
8.5	−2.96	0.043 ± 0.006	
9.0	−2.87	0.074 ± 0.011	
9.5	−2.83	0.087 ± 0.013	
10.0	−2.86	0.083 ± 0.012	
10.5	−2.87	0.074 ± 0.011	
11.0	−2.91	0.060 ± 0.009	
11.5	−2.95	0.047 ± 0.007	
12.0	−2.98	0.037 ± 0.006	
12.5	−3.00	0.030 ± 0.005	
13.0	−3.01	0.027 ± 0.004	

[a] From Nandy et al. 1976.
[b] From Schultz and Wiemer 1975.

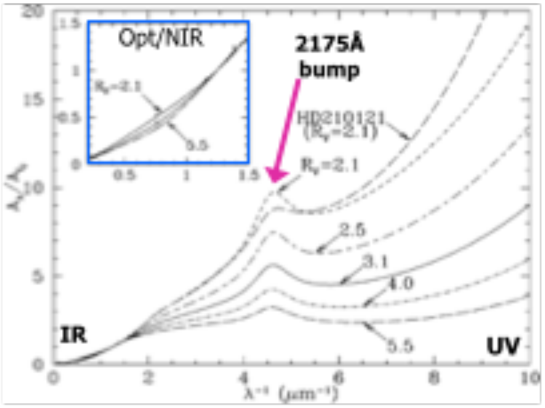
Rieke & Lebofsky 1985

20

Attenuation laws characterized by R_V

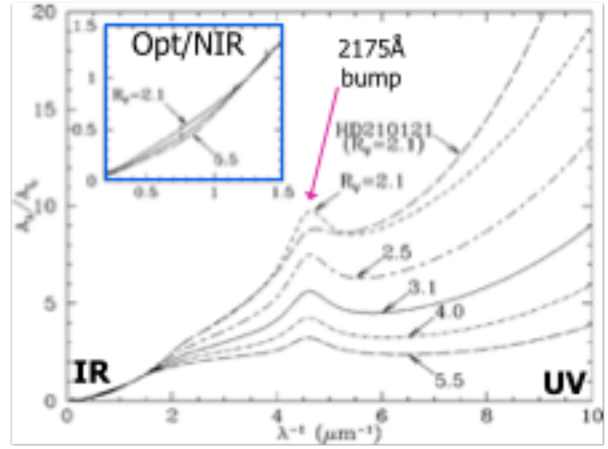
$$R_V = A_V/(A_B - A_V) = A_V/E(B-V)$$

Related to the slope of the extinction curve near the V band



Smaller R_V = More wavelength dependence, more reddening for a given extinction A_V

Attenuation Law Functional Forms



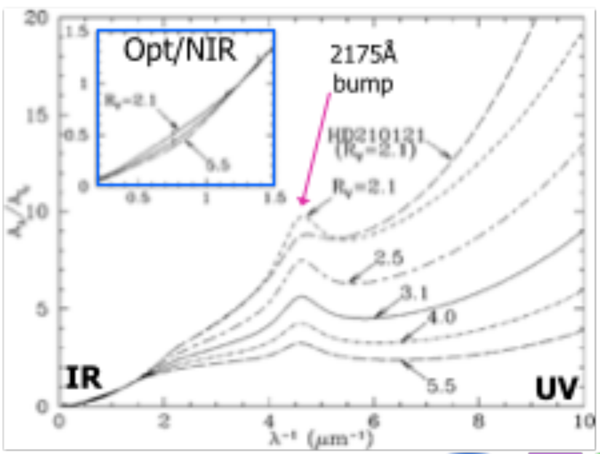
Draine 2003 ARA&A

Family of curves defined by different values of R_V

$$A_\lambda / A_I \approx f(\lambda; R_V, C_1, C_2, C_3, C_4, \lambda_0, \gamma)$$

Cardelli, Clayton, & Mathis (CCM) 1989
Fitzpatrick 1999

Attenuation Law Functional Forms



FUV curvature (fixed)

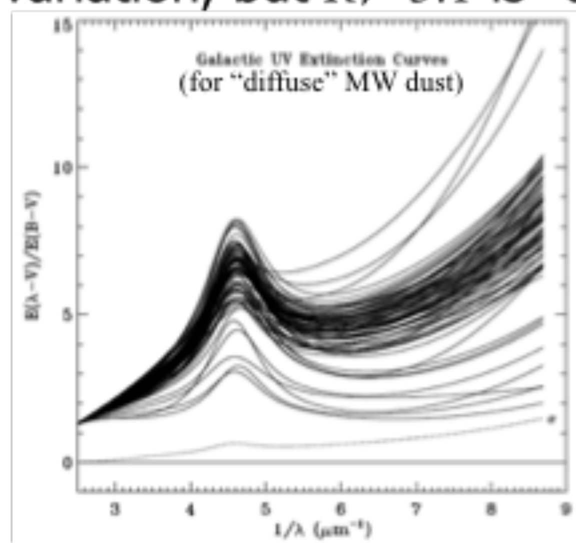
Family of curves defined by different values of R_V

$$A_\lambda / A_I \approx f(\lambda; R_V, C_1, C_2, C_3, C_4, \lambda_0, \gamma)$$

Depends largely on R_V

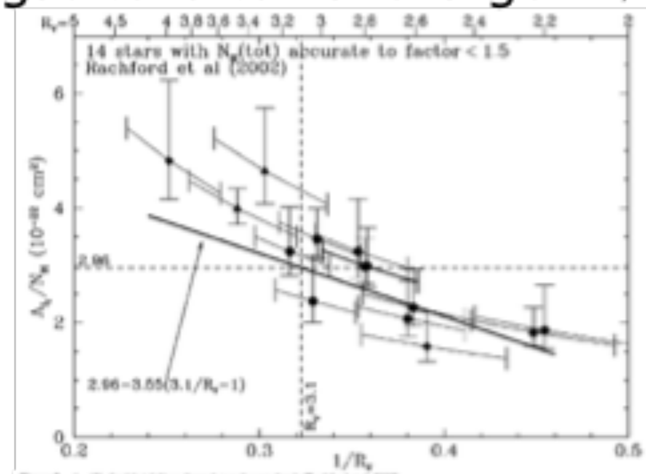
2175Å bump (fixed)

Wide variation, but R_V=3.1 is "typical"



Fitzpatrick et al 1999

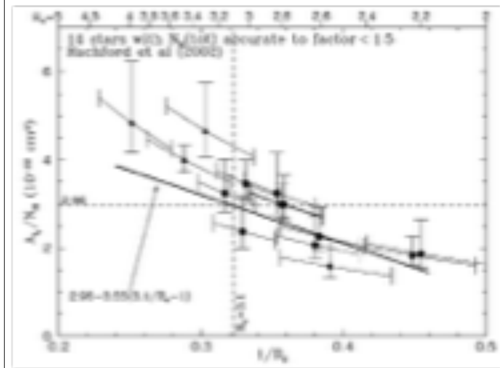
Lines of sight with more dust-per-gas tend to have larger R_V



Draine 2003

25

Expectations for R_V:



Large Grains ("grey extinction") $R_V = \infty$

Raleigh Scattering: $R_V \approx 1.2$

Dustier clouds have proportionally more large grains

26

Different types & sizes of grains produce different features

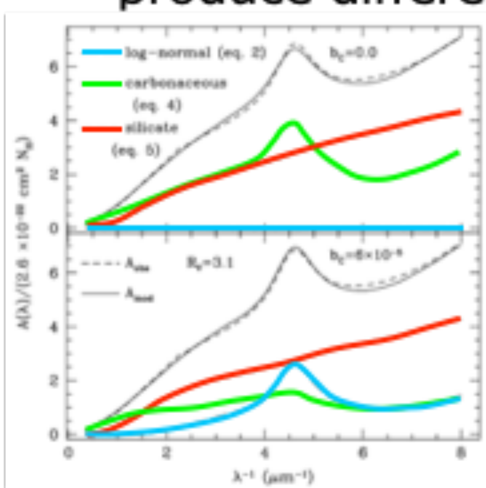


FIG. 8.—Extinction curve A_{mod} resulting from the grain distribution of eqs. (4) and (5), with parameters optimized to fit A_{obs} (see text) for $R_V = 3.1$ (also shown), for $b_C = 0.0$ and 6.0×10^{-5}. The contributions from the three grain distribution components are also shown.

silicates

PAHs + carbonaceous

very small grains

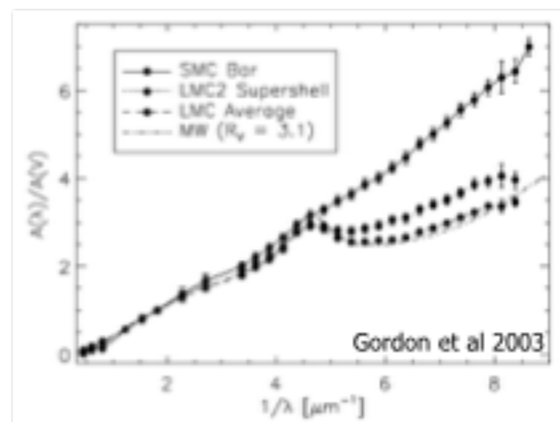
silicates

very small grains

PAHs + carbonaceous

Weingartner & Draine 2001

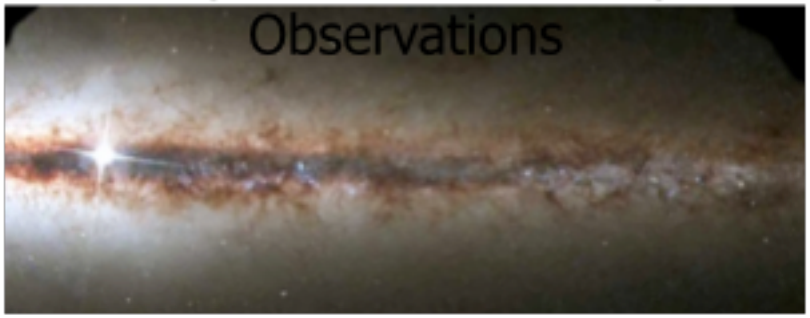
Different galaxies have different mean extinction curves



Different average dust composition

28

Correcting for Dust in Extragalactic Observations

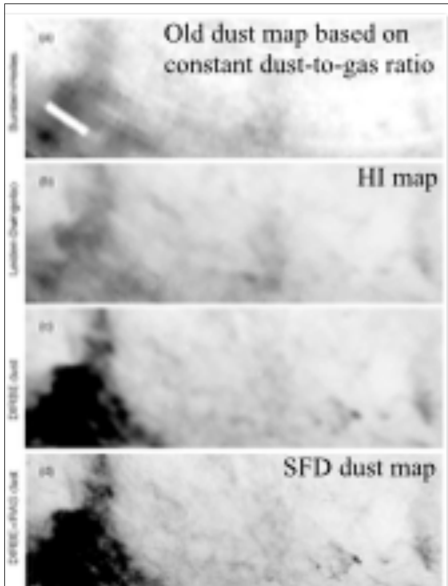


- Foreground Extinction
  - removing effects of the Milky Way
- Internal Extinction
  - removing effects of dust within the observed galaxy

Within the Milky Way, dust extinction can be constrained by combinations of star counts and colors

Important because:

- Light that we observe from extragalactic objects pass through the MW's dust.
- Extinction is a good tracer of molecular gas



Milky Way Dust: Schlegel, Finkbeiner, & Davis 1998 (SFD)

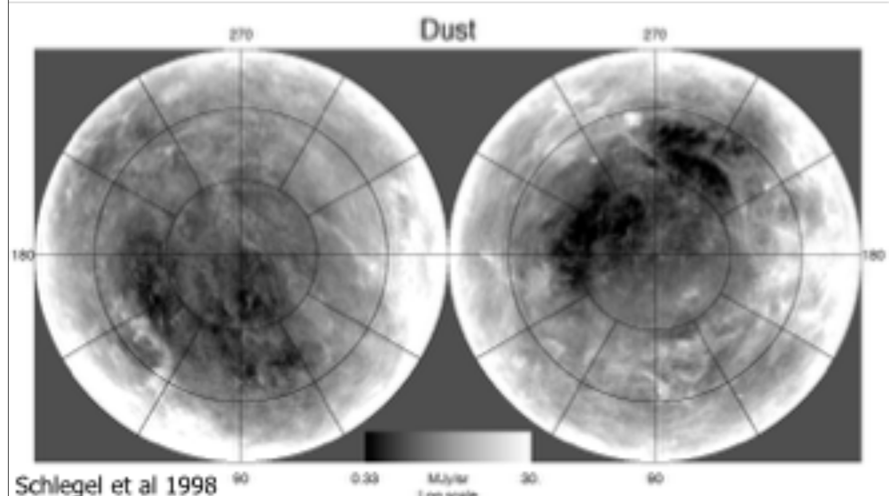
"Foreground Extinction"

- Use black body FIR emission from dust to determine the temperature of dust.
- Combine with maps of FIR emission to measure column density of dust.

Schlegel et al 1998

FIG. 7.—Slice of sky from (a) the BH map, (b) the Leiden-Dwingeloo H I map, (c) our dust map with DIRBE resolution, and (d) our dust map with 18.4' resolution. The slice measures approximately 90° × 30°, centered at $l = 100°$, $b = +35°$.

Not uniform! No "dust free" sitelines

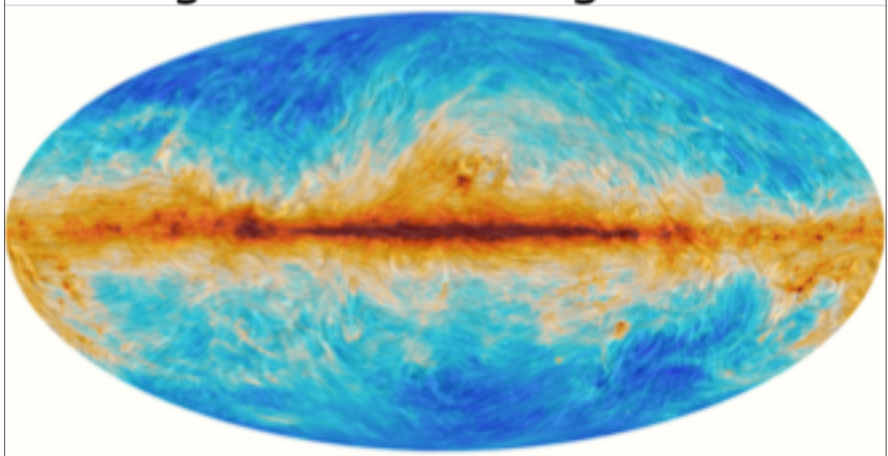


Schlegel et al 1998

All extragalactic observations must correct for this!

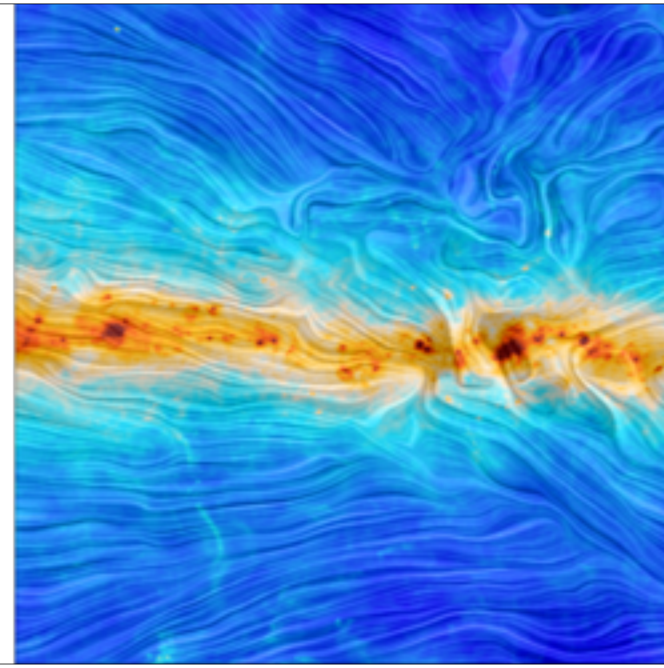
Note: See Schlafly & Finkbeiner 2011 for PS-1 recalibrated maps

MW dust emission is polarized, due to alignment with magnetic field



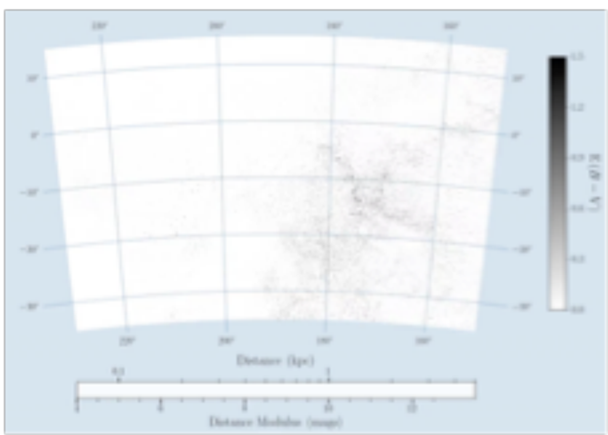
Results from Planck Collaboration 2015

 Nice visualizations: http://astrog80.astro.cf.ac.uk/Planck/Chromoscope/



New 3-D Milky Way dust maps out to ~5 kpc from Pan-STARRS available

Green et al 2014,2015



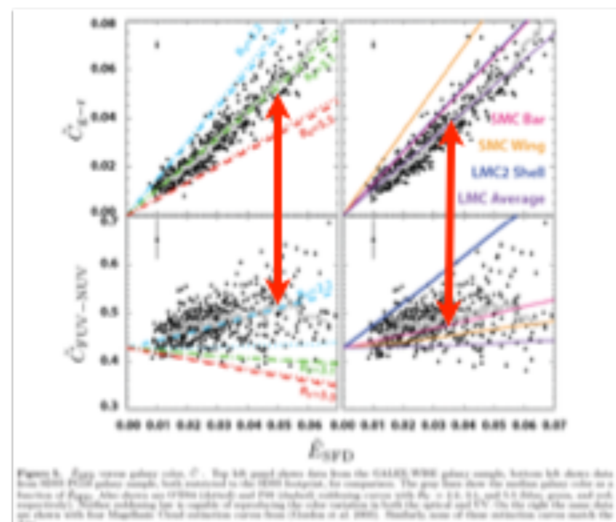
Galactic Anti-center

http://argonaut.skymaps.info

Warning: Extinction law of high-latitude dust is unusual

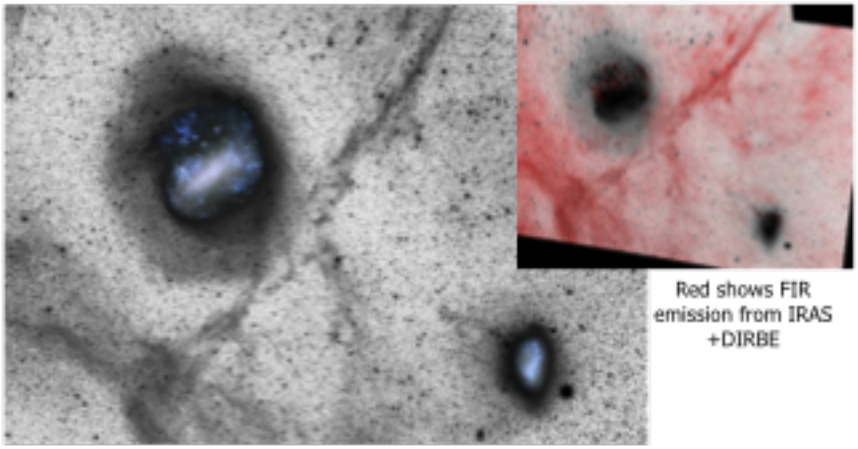
Optical galaxy color vs SFD extinction: R_v=3.1

UV galaxy color vs SFD extinction: R_v=2.2



Peek & Schiminovich 2013

Warning: the dusty high-latitude "cirrus" emits at red optical wavelengths

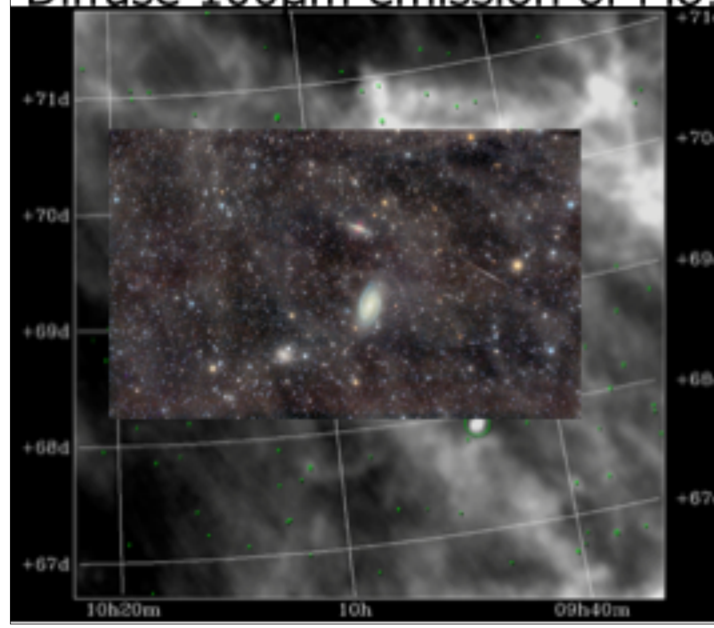


Red shows FIR emission from IRAS +DIRBE

- Probably due to photoluminescence of dust.
- Sometiems referred to as ERE "extended red emission"

see early work by Guhathakurta & Tyson 1990, Szomoru & Guhathakurta 1998

Diffuse 100μm emission of M81 group



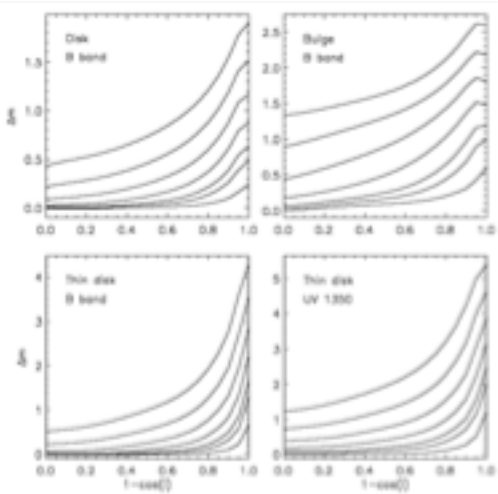
Dominant limitation on faint surface photometry

http://apod.nasa.gov/apod/ap120313.html

"Internal Extinction Corrections": account for galaxies' own dust

- Brings all galaxy magnitudes to those expected if the galaxy were seen face-on.
- Depends on inclination, wavelength, and galaxy luminosity/type

Internal extinction vs inclination



Tuffe et al 2004

Model of normal spirals with different total face-on optical depths

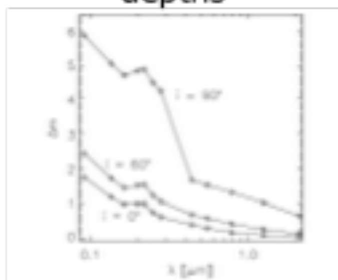
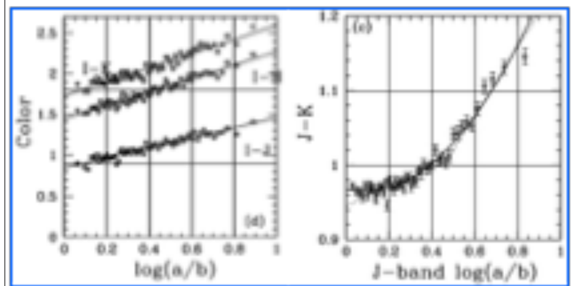


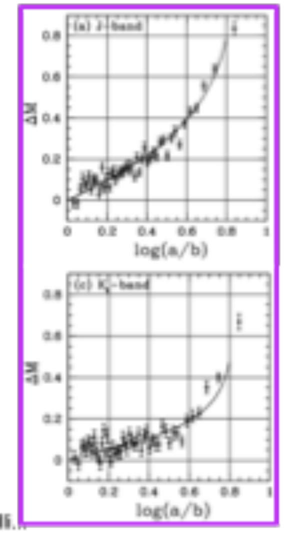
Fig. 7. Composite attenuation curves for the galaxy NGC 891, as would be obtained if the galaxy were viewed at inclinations of 0, 60 and 90 degrees. $\tau_B^f = 4.2$ and $F = 0.22$.

Fig. 2. Examples of the dependence of attenuation (Δm) on inclination (i) for the main geometrical components of our model: disk (*top left*), bulge (*top right*), and thin disk (*bottom left and right*). The examples are plotted for the *B* band for the disk and bulge, and both for the *B* band and UV 1350 Å for the thin disk. In each panel we plotted (*from top to bottom*) 7 attenuation curves, corresponding to τ_B^f: 8, 4, 2, 1, 0.5, 0.3, and 0.1. The face-on orientation corresponds to $1 - \cos i = 0.0$ and the edge-on orientation corresponds to $1 - \cos i = 1.0$.

Internal Extinction: Estimate from inclination, using empirical color dependence



Masters et al 2003



Use the observed color/ magnitude offset as a function of inclination to derive the necessary inclination correction

 See also Tully et al 1998, Matthews et al 1998, Piemi 1999, Bosselli...

Internal extinction: Estimate correction from "Balmer Decrement"

The value of the Balmer extinction is derived from the observed ratio of Hα and Hβ line intensities using the relation

$$C(\mathrm{H}\beta) = \frac{1}{f(\mathrm{H}\beta) - f(\mathrm{H}\alpha)} \log \frac{I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)}{I^0(\mathrm{H}\alpha)/I^0(\mathrm{H}\beta)} \quad (1)$$

where $I^0(\mathrm{H}\alpha)/I^0(\mathrm{H}\beta)$ is the intrinsic intensity ratio of these two lines and $f(\mathrm{H}\beta) - f(\mathrm{H}\alpha)$ is equal to 0.335. The value

- In "case B" recombination, Hα and Hβ are always emitted in the same ratio.
- Hβ is emitted at a **shorter** wavelength, and will thus suffer more extinction than Hα.
- The observed ratio of Hα/Hβ **increases** with extinction

Internal extinction: Estimate correction from the slope of the UV spectrum

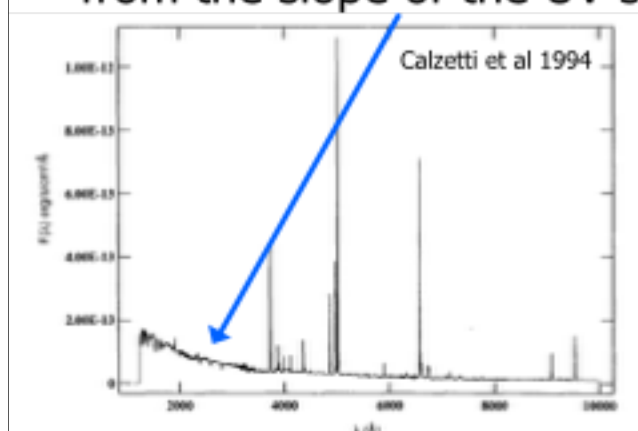
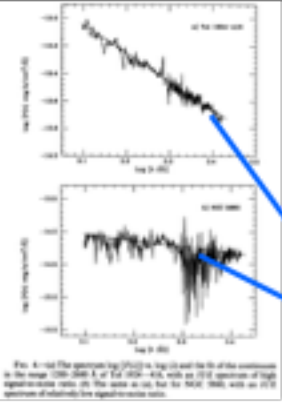


FIG. 2.—An example of UV and optical spectrum with *no normalization between the two wavelength ranges*. The galaxy is NGC 5253. The flux in ergs cm^{-2} s^{-1} Å^{-1} is plotted as a function of the wavelength λ in the range 1220–10000 Å. The joining point between the UV and optical is at 3200 Å.

Most star bursts have a reasonably constant power-law slope at UV wavelengths (tail of O/B star blackbody).

If redder, then probably due to dust

UV slope β correlates with Balmer decrement



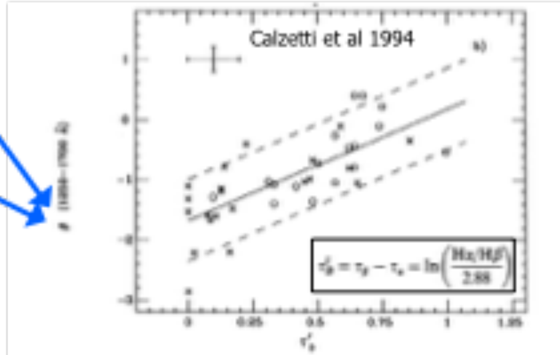


FIG. 5.—The UV power-law index β is shown as a function of the Balmer optical depth τ_B^l (eq. [2]). The bluer galaxies have small values of β (close to β = −2), and the redder galaxies have large values of β (close to β = 0). (a) The fitting routine to obtain β has made use of the 10 windows listed in Table 2, so the wavelength range fitted is 1250–2600 Å. (b) β has been obtained in the range 1250–1700 Å. In both figures the 1 σ error bars are shown in the upper left-hand corner; the best linear fit is shown as a continuous line, and the upper and lower envelopes to the data are drawn as dashed lines. The asterisks indicate galaxies with LMC-like metallicity, and the circles indicate galaxies with MW-like metallicity.

This is a particularly useful way to constrain extinction at high-redshift where only the UV is visible.

Templates that fit the empirical correlation:

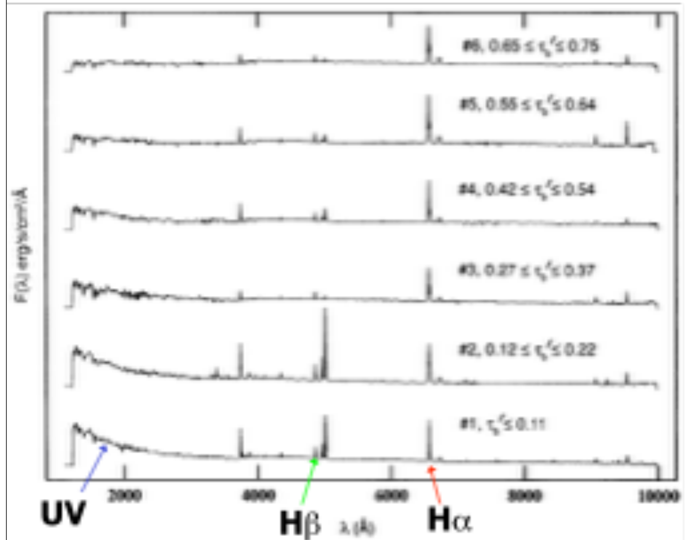


FIG. 17.—The spectra of the six templates are shown for increasing values of the extinction parameter τ_B^l, from the bottom to the top of the figure.

Reddening (observed Balmer decrement &/or UV slope) ≠ **Total extinction**

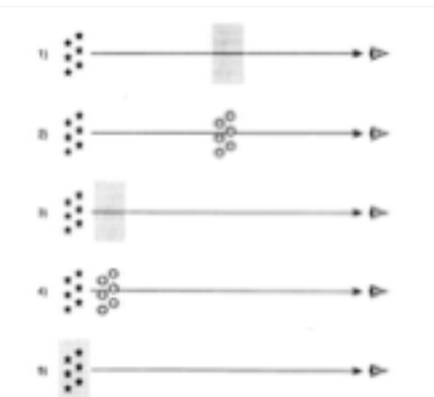
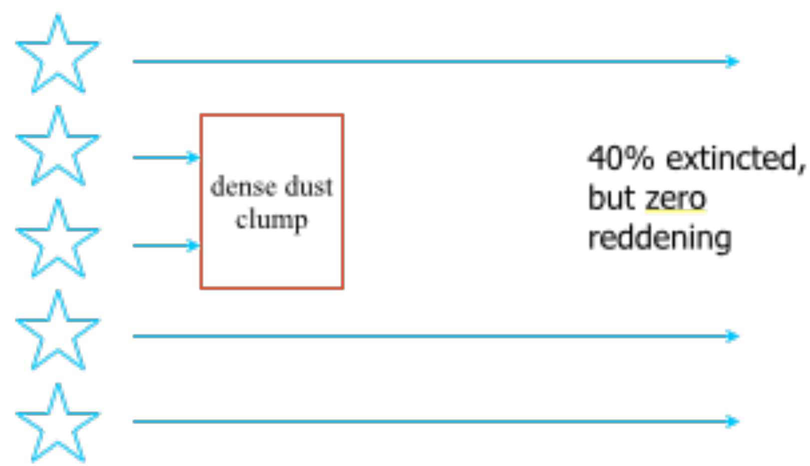


FIG. 8.—A schematic representation of the five configurations of dust/ionized gas discussed in § 4. From top to bottom, they are (1) the uniform dust screen; (2) the clumpy dust screen; (3) the uniform scattering slab; (4) the clumpy scattering slab; (5) the internal dust model.

Problem 1: Can produce arbitrary combinations of reddening and extinction by varying the relative distributions and clumpiness of the dust and the stars

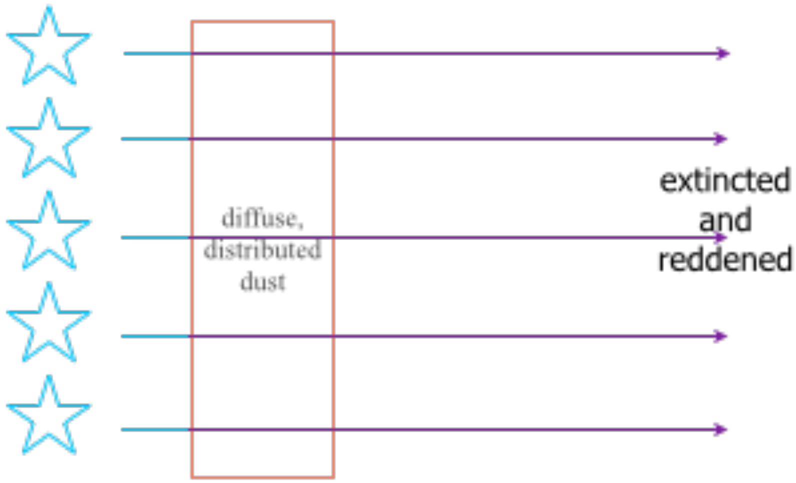
Calzetti et al 1994

Why dust geometry decouples reddening and extinction:

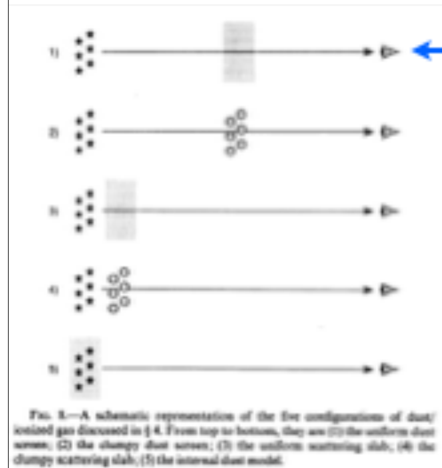


40% extincted, but zero reddening

Why dust geometry decouples reddening and extinction:



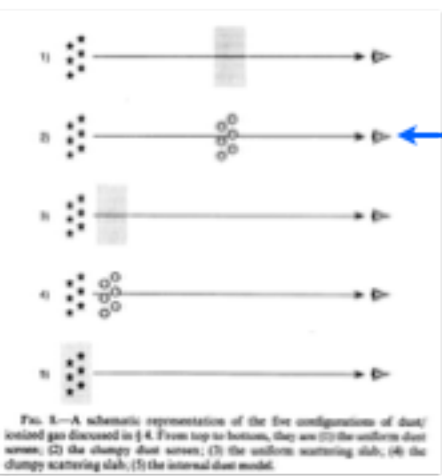
Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**



Everything reddened, everything extincted, little scattering

Calzetti et al 1994

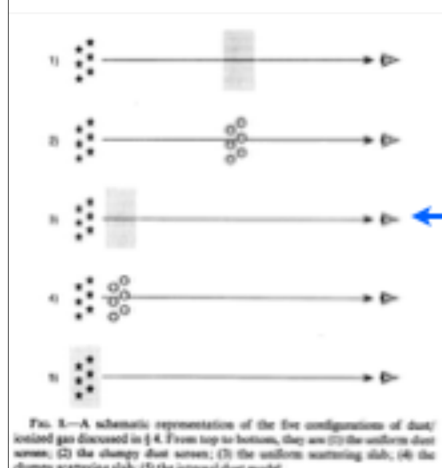
Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**



Some stars reddened and more heavily extincted, other stars unobscured, little scattering

Calzetti et al 1994

Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**



Everything reddened, everything extincted, lots of scattering

Calzetti et al 1994

Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**

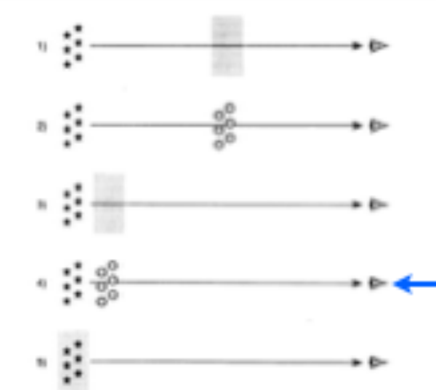


Fig. 1.—A schematic representation of the five configurations of dust/ionized gas discussed in § 4. From top to bottom, they are (1) the uniform dust screen; (2) the clumpy dust screen; (3) the uniform scattering slab; (4) the clumpy scattering slab; (5) the internal dust model.

Some stars reddened and more heavily extincted, other stars unobscured, lots of scattering

Calzetti et al 1994

Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**

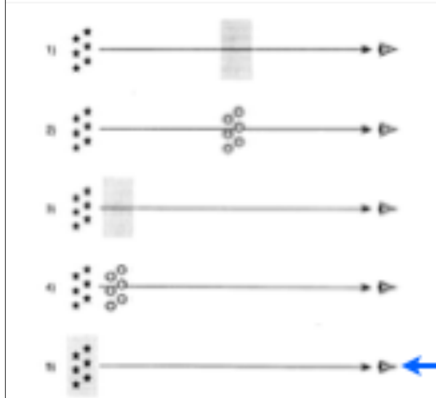
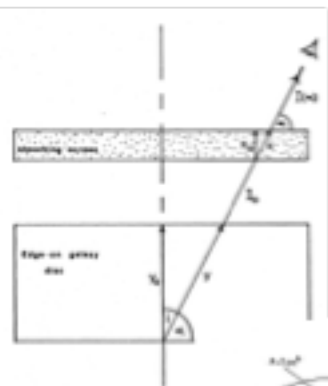


Fig. 1.—A schematic representation of the five configurations of dust/ionized gas discussed in § 4. From top to bottom, they are (1) the uniform dust screen; (2) the clumpy dust screen; (3) the uniform scattering slab; (4) the clumpy scattering slab; (5) the internal dust model.

Range of reddening and extinction for stars, lots of scattering

Calzetti et al 1994

These effects were first calculated by Disney et al 1989



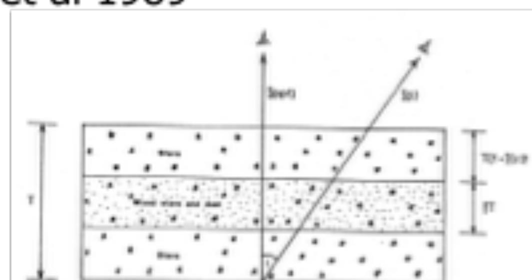
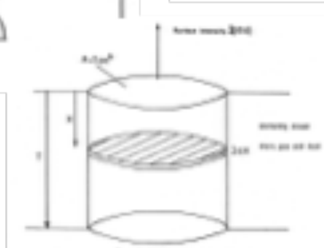


Figure 6. Geometry of the sandwich model



- uniformly mixed
- "screen"
- "sandwich"
- "triplex" (mixed exponentials)

Clumpier dust lets more unextincted UV light through

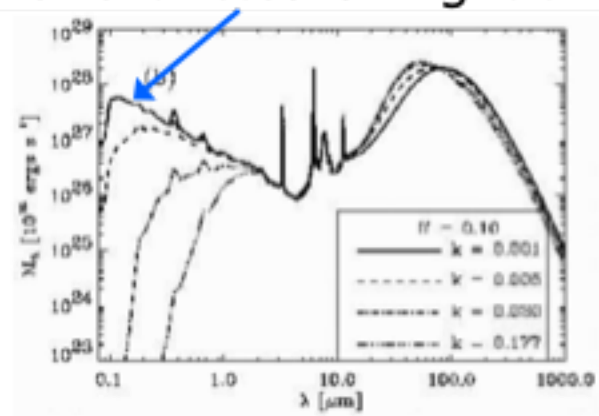
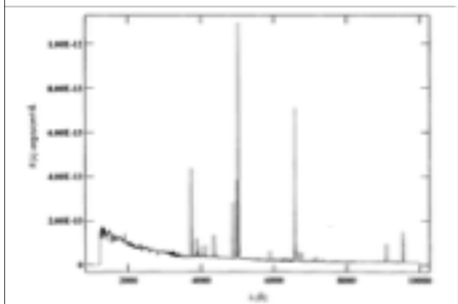


FIGURE 14. The effect of "passive" clumps on the FIR/submm SEDs, taken from Misselt et al. [41]. Model SEDs are for a range of density ratios k between the diffuse and clumpy media and for a filling factor ff = 0.1. All models are calculated assuming a spherical shell geometry. It is obvious that the effect of increasing the degree of clumpiness (decreasing k) is to make the SEDs cooler.

Popescu & Tuffs 2005

Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**

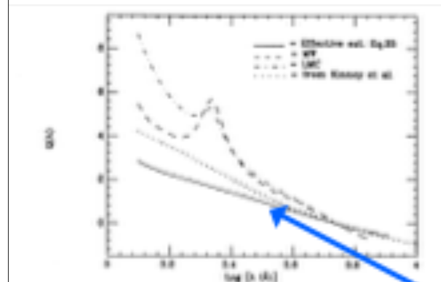


Problem 2: The extinction and/or reddening in different parts of the spectrum may be caused by different dust structures

Dust in HII regions ≠ Dust near exposed O/B stars ≠ Dust in field stars that dominate the red continuum

Calzetti et al 1994

Reddening (observed Balmer decrement & UV slope) ≠ **Total extinction**



Problem 3: The extinction law may vary from galaxy to galaxy, or within different parts of the same spectrum, due to variations in dust content

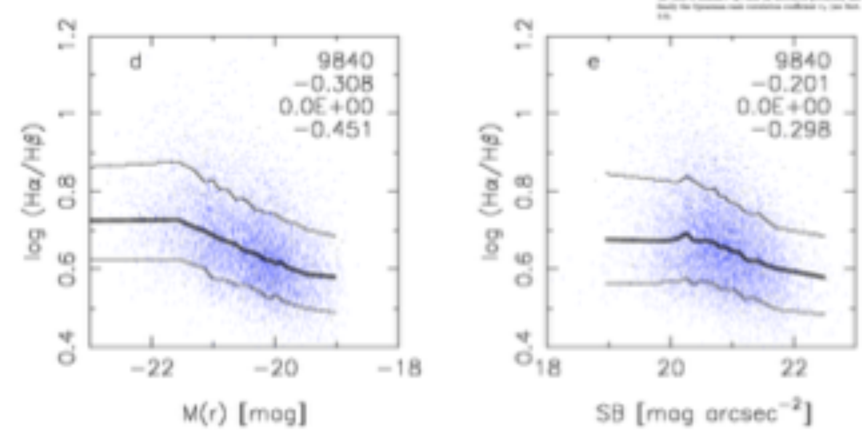
Extinction law for HII regions & UV in starbursts seems "greyer" than typical MW extinction

Calzetti et al 1994

Global Trends in Dust Extinction

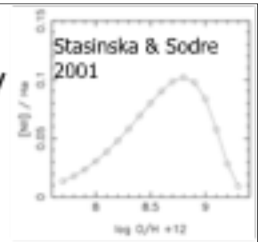
- Galaxy-to-Galaxy
- Within Galaxies

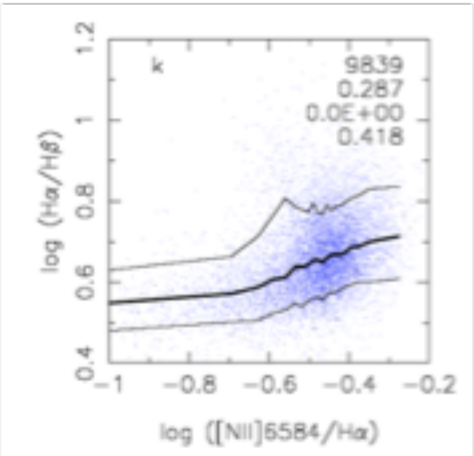
Lower mass, late-type disks have less extinction.

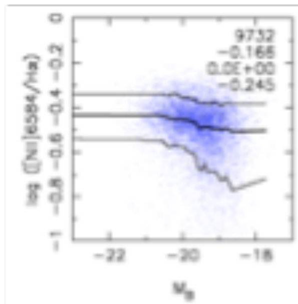


SDSS: Stasinska et al 2004

This trend is probably partially (but not completely) driven by metallicity

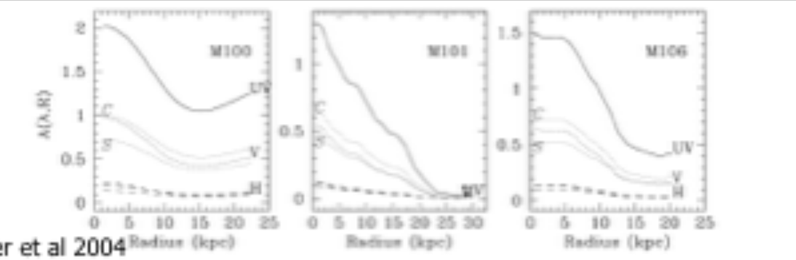






[NII]/Hα is a reasonable metallicity indicator, and low luminosity galaxies have low metallicity, & thus less dust

Within spiral disks, extinction drops with radius



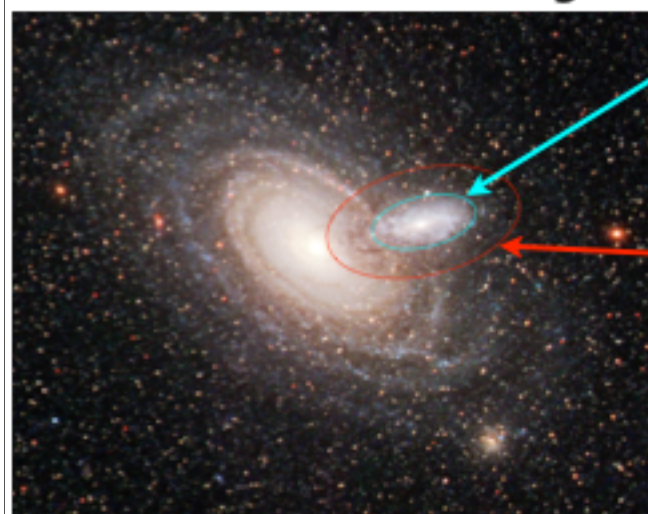
Bossier et al 2004

- Outer regions of disks have similar properties to the inner regions of low mass, low surface density disks.

Empirical constraints come from a few cases where galaxies are seen in projection

Galaxies tend to be opaque in their spiral arms, but optically thin between them.

Dust exists at large radii.



Stars peter out here...

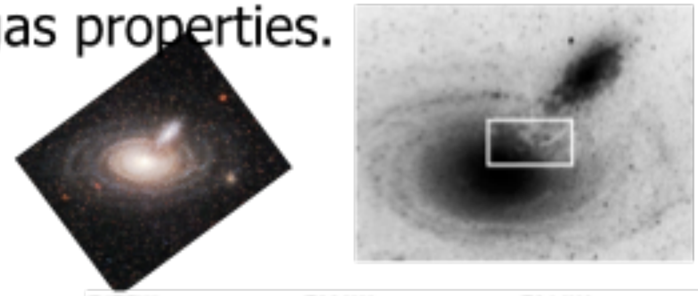
Dust continues out to here.

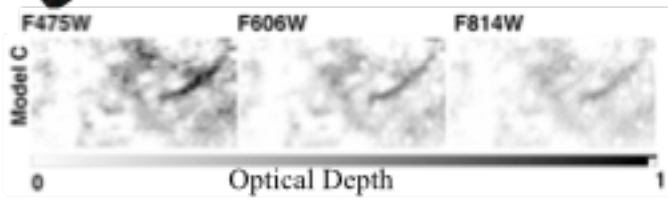
(i.e. there is dense gas at large radii!)

Foreground galaxy silhouette

Holwerda et al 2009

Use attenuation maps to constrain gas properties.

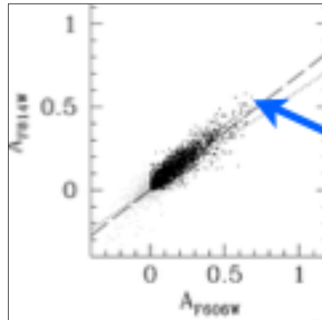


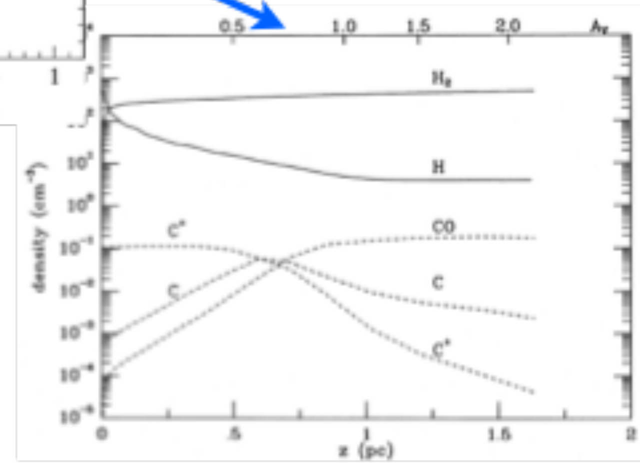


$\boxed{\text{No high optical depths with } A_V>1}$

65

Outer gas is likely to be "translucent", and lacking in CO

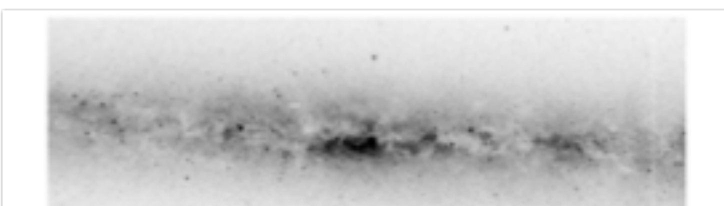




66

Geometry: Dust lanes in massive galaxies

But in low mass galaxies (V_c<120km/s), dust layer is thicker and more diffuse Dalcanton et al 2004



Matthews & Wood 2001

67

Unusual Dust in Unusual Galaxies

68