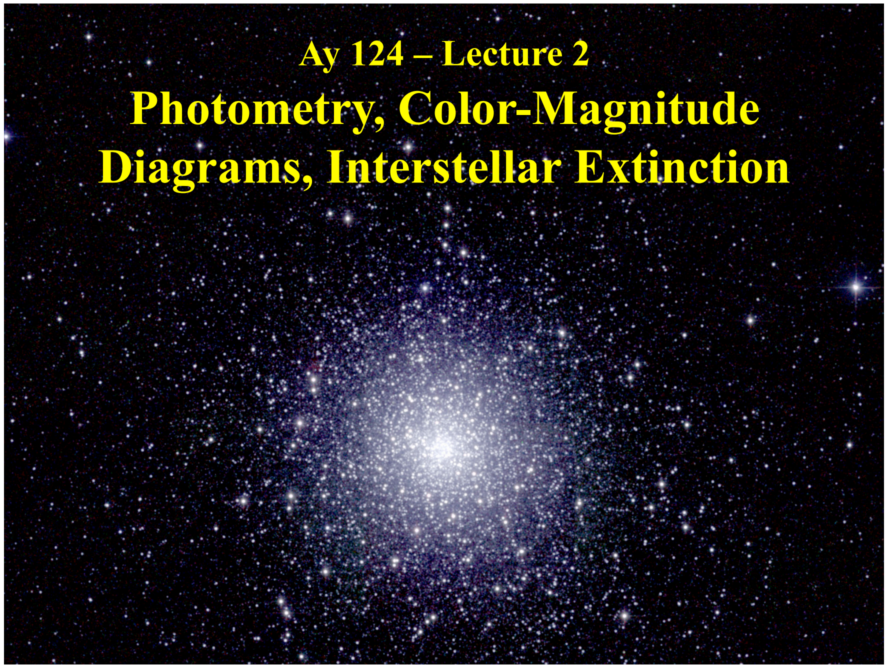


Measuring Flux = Energy/(unit time)/(unit area)

Real detectors are sensitive over a finite range of λ (or ν). Fluxes are always measured over some finite bandpass.

Total energy flux:

$$F = \int F_\nu(\nu) d\nu$$

Integral of f_ν over all frequencies

Units: erg s^{-1} cm^{-2} Hz^{-1}

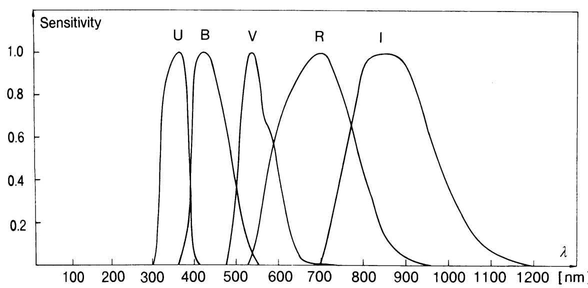
A standard unit for specific flux (initially in radio, but now more common):

$$1 \text{ Jansky (Jy)} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$$

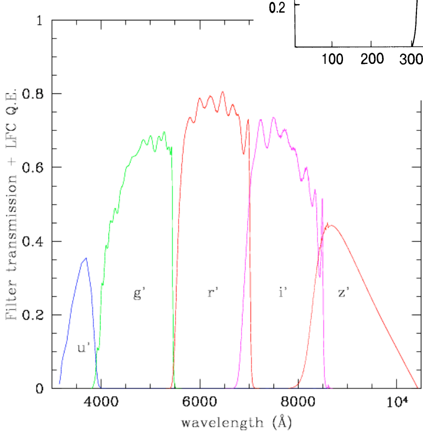
f_ν is often called the ***flux density*** - to get the ***power,*** one integrates it over the bandwith, and multiplies by the area

(From P. Armitage)

Johnson →

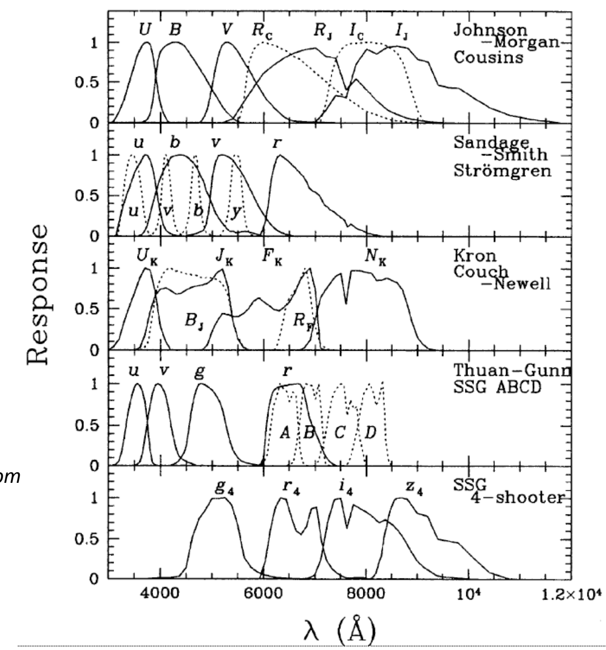


Gunn/SDSS ↓



Some Common Photometric Systems (in the visible)

There are way, way too many photometric systems out there …

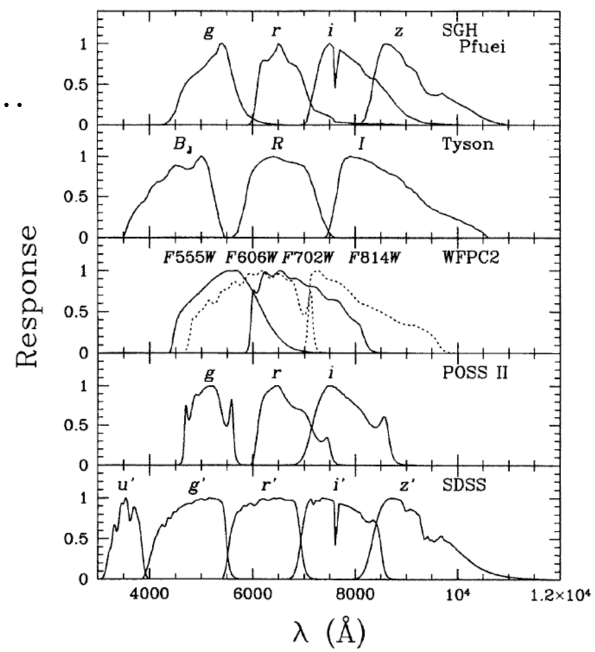


(Bandpass curves from Fukugita et al. 1995, PASP, 107, 945)

… and more …

… and more …

… and more …

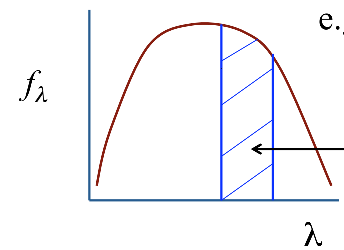


Fluxes and Magnitudes

For historical reasons, fluxes in the optical and IR are measured in magnitudes: $m = -2.5\log_{10} F + \text{constant}$

If F is the total flux, then m is the bolometric magnitude. Usually instead consider a finite bandpass, e.g., V band.

e.g. in the V band ($\lambda \sim$ 550 nm):



$$m_V = -2.5\log_{10} F + \text{constant}$$

flux integrated over the range of wavelengths for this band

(From P. Armitage)

Using Magnitudes

Consider two stars, one of which is a hundred times fainter than the other in some waveband (say V).

$$m_1 = -2.5\log F_1 + \text{constant}$$

$$\begin{aligned} m_2 &= -2.5\log(0.01F_1) + \text{constant} \\ &= -2.5\log(0.01) - 2.5\log F_1 + \text{constant} \\ &= 5 - 2.5\log F_1 + \text{constant} \\ &= 5 + m_1 \end{aligned}$$

Source that is 100 times **fainter** in flux is five magnitudes fainter (**larger** number).

Faintest objects detectable with *HST* have magnitudes of ~ 28 in R/I bands. The sun has m_V = -26.75 mag

(From P. Armitage)

Magnitudes, A Formal Definition

$$m = -2.5\left[\log \int d\lambda R(\lambda) f_\lambda - \log \int d\lambda R(\lambda) f_\lambda(\alpha\ \mathrm{Lyr})\right]$$

e.g.,

$$U = -2.5\ \log \int d\lambda R_U(\lambda) f_\lambda - 14.08 + c_U,$$

$$B = -2.5\ \log \int d\lambda R_B(\lambda) f_\lambda - 13.00 + c_B,$$

$$V = -2.5\ \log \int d\lambda R_V(\lambda) f_\lambda - 13.76 + c_V,$$

Because Vega (= α Lyrae) is declared to be the zero-point! (at least for the UBV… system)

where the peak of the response function is normalized to unity, and c represents the magnitude of α Lyr; $c_U = 0.02$, $c_B = c_V = 0.03$ (Johnson and Morgan 1953).

Defining effective wavelengths (and the corresponding bandpass averaged fluxes)

$$\lambda_{\text{eff}} = \frac{\int d\lambda\, \lambda R(\lambda)}{\int d\lambda R(\lambda)},$$

$$f_\lambda^{\text{eff}}(\alpha \text{ Lyr}) = \frac{\int d\lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)}{\int d\lambda R(\lambda)},$$

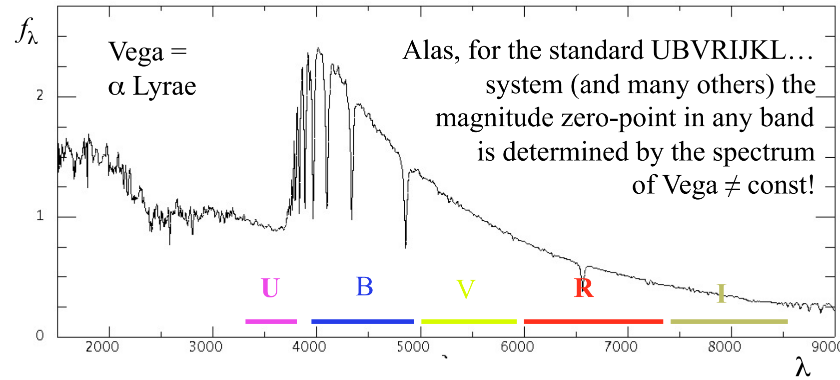
$$\lambda_{\text{eff}}(\alpha \text{ Lyr}) = \frac{\int d\lambda\, \lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)}{\int d\lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)},$$

$$f_\nu^{\text{eff}}(\alpha \text{ Lyr}) = \frac{\int d\nu f_\nu(\alpha \text{ Lyr}) R(\nu)}{\int d\nu R(\nu)},$$

$$\nu_{\text{eff}}(\alpha \text{ Lyr}) = \frac{\int d\nu\, \nu f_\nu(\alpha \text{ Lyr}) R(\nu)}{\int d\nu f_\nu(\alpha \text{Lyr}) R(\nu)}$$

where $f_\nu = \lambda^2 f_\lambda / c$ and $R_\nu = R_\lambda$.

Magnitude Zero Points



Vega calibration ($m = 0$): at $\lambda = 5556$: $f_\lambda = 3.39 \times 10^{-9}$ erg/cm²/s/Å

$f_\nu = 3.50 \times 10^{-20}$ erg/cm²/s/Hz

$N_\lambda = 948$ photons/cm²/s/Å

A more logical system is AB_ν magnitudes: $AB_\nu = -2.5 \log f_\nu \text{ [cgs]} - 48.60$

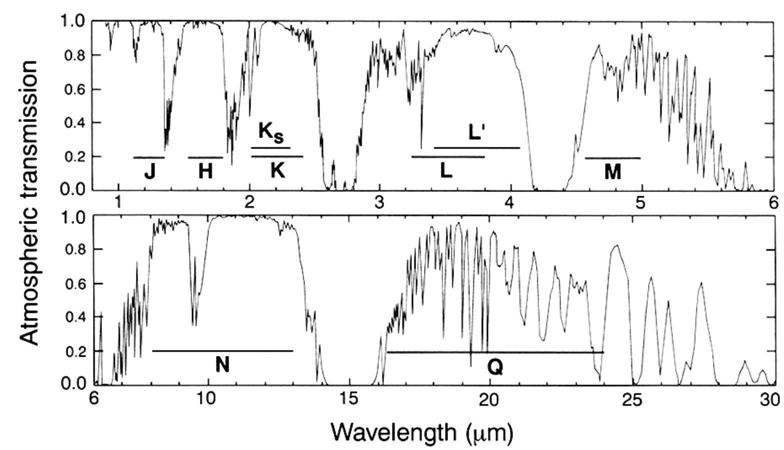
Photometric Zero-Points (Visible)

bandpass system	band	ref[a])	λ_{eff} (Å)	FWHM (Å)	$\lambda_{\text{eff}}^{\text{Vega}}$ (Å)	$f_{\lambda,\text{eff}}^{\text{Vega}}$ ($\times 10^{-9}$cgs/Å)	$c(\nu_{\text{eff}}^{\text{Vega}})^{-1}$ (Å)	$f_{\nu,\text{eff}}^{\text{Vega}}$ ($\times 10^{-20}$cgs/Hz)
Johnson-Morgan	U_3	Buser 78	3652	526	3709	4.28	3617	1.89
	B_2	AS69	4448	1008	4393	6.19	4363	4.02
	V	AS69	5505	827	5439	3.60	5437	3.59
Cousins	R_C	Bessell 90	6588	1568	6410	2.15	6415	3.02
	I_C	Bessell 90	8060	1542	7977	1.11	7980	2.38
Johnson	R_J		6930	2096	6688	1.87	6693	2.89
	I_J		8785	1706	8571	0.912	8545	2.28
SDSS	u'		3585	556	3594	3.67	3530	1.54
	g'		4858	1297	4765	5.11	4748	3.93
	r'		6290	1358	6205	2.40	6210	3.12
	i'		7706	1547	7617	1.28	7623	2.51
	z'		9222	1530	9123	0.783	9098	2.19
Thuan-Gunn	u		3536	412	3542	3.33	3519	1.38
	v		3992	469	4013	6.62	3967	3.50
	g		4927	709	4888	4.84	4885	3.89
	r		6538	893	6496	2.09	6498	2.96

(From Fukugita et al. 1995)

The Infrared Photometric Bands

… where the atmospheric transmission windows are



Infrared Bandpasses

Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

Filter name	λ_{iso}[b] (μm)	$\Delta\lambda$[c] (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (Jy)	N_ϕ (photons s^{-1} m^{-2} μm^{-1})
V	0.5556[d]	...	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^{9}
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^{9}
K	2.179	0.41	4.14×10^{-10}	655	4.53×10^{9}
L	3.547	0.57	6.59×10^{-11}	276	1.17×10^{9}
L'	3.761	0.65	5.26×10^{-11}	248	9.94×10^{8}
M	4.769	0.45	2.11×10^{-11}	160	5.06×10^{8}
8.7	8.756	1.2	1.96×10^{-12}	50.0	8.62×10^{7}
N	10.472	5.19	9.63×10^{-13}	35.2	5.07×10^{7}
11.7	11.653	1.2	6.31×10^{-13}	28.6	3.69×10^{7}
Q	20.130	7.8	7.18×10^{-14}	9.70	7.26×10^{6}

Infrared Bandpasses

Effective Wavelengths[1], Zeropoint Fluxes[2] and Magnitudes [3]

	V	J	H	K	L	L'	M	(M)
λeff	0.545	1.22	1.63	2.19	3.45	3.80	4.75	4.80
ZP	0.000	0.90	1.37	1.88	2.77	2.97	3.42	3.44
F_λ	3590	312	114	39.4	6.99	4.83	2.04	1.97
F_ν	3600	1570	1020	636	281	235	154	152

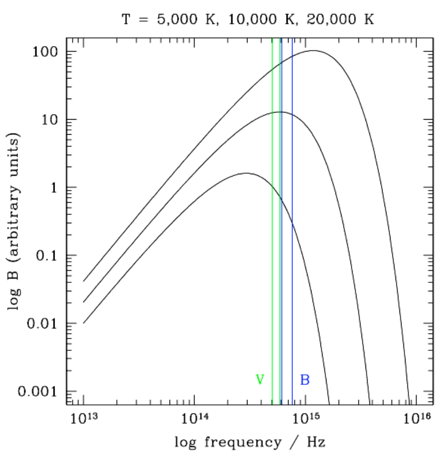
1 In μm

2 F_λ(10^{-15} W cm^{-2} μm^{-1}), F_ν(10^{-30} W cm^{-2} hz^{-1}) for a 0.03 magnitude star from Dreiling and Bell, and Bell Vega models for adopted passbands.

3 Mag = - 2.5 log<F_ν> - 66.08 - ZP

Colors From Magnitudes

The color of an object is defined as the difference in the magnitude in each of two bandpasses: e.g. the *(B-V)* color is: $B\text{-}V = m_B\text{-}m_V$



Stars radiate roughly as blackbodies, so the color reflects surface temperature.

Vega has T = 9500 K, by definition color is zero.

(From P. Armitage)

Apparent vs. Absolute Magnitudes

The absolute magnitude is defined as the apparent mag. a source would have if it were at a distance of 10 pc:

$$M = m + 5 - 5 \log d/\text{pc}$$

It is a measure of the **luminosity** in some waveband.
For Sun: $M_{\odot B} = 5.47$, $M_{\odot V} = 4.82$, $M_{\odot bol} = 4.74$

Difference between the apparent magnitude m and the absolute magnitude M (any band) is a ***measure of the distance*** to the source

$$\underbrace{m - M}_{\text{Distance modulus}} = 5\log_{10}\left(\frac{d}{10\ \text{pc}}\right)$$

Distance modulus

(From P. Armitage)

Photometric Calibration: Standard Stars

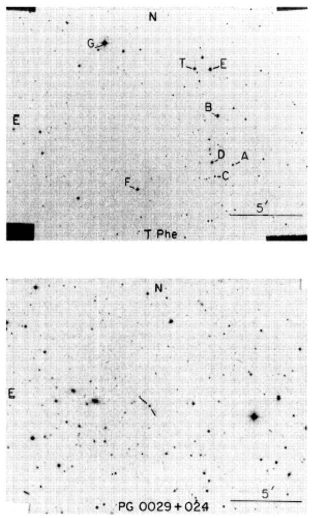
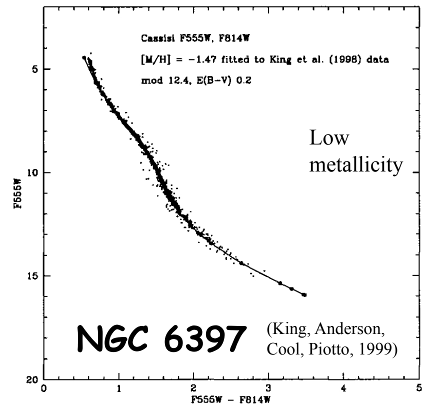


PLATE 21. (a) The field for the T Phe sequence. Star B is the eclipsing binary RW Phe. (b) The field of the star PG0029+024.

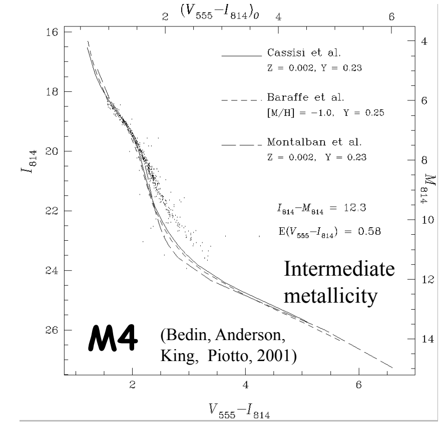
Magnitudes of Vega (or other systems primary flux standards) are transferred to many other, secondary standards. They are observed along with your main science targets, and processed in the same way.

Star	α(2000)	δ(2000)	V	B-V	U-B	V-R	R-I	V-I	n	m	V
TPHE A	00:30:09	-46 31 22	14.651	0.793	0.380	0.435	0.405	0.841	29	12	0.0028
TPHE B	00:30:16	-46 27 55	12.334	0.405	0.156	0.262	0.271	0.535	29	17	0.0115
TPHE C	00:30:17	-46 32 34	14.376	-0.298	-1.217	-0.148	-0.211	-0.360	39	23	0.0022
TPHE D	00:30:18	-46 31 11	13.118	1.551	1.871	0.849	0.810	1.663	37	23	0.0033
TPHE E	00:30:19	-46 24 36	11.630	0.443	-0.103	0.276	0.283	0.564	34	8	0.0017
TPHE F	00:30:50	-46 33 33	12.474	0.855	0.532	0.492	0.435	0.926	5	3	0.0004
TPHE G	00:31:05	-46 22 43	10.442	1.546	1.915	0.934	1.085	2.025	5	3	0.0004
PG0029+024	00:31:50	+02 38 26	15.268	0.362	-0.184	0.251	0.337	0.593	5	2	0.0094
PG0039+049	00:42:05	+05 09 44	12.877	-0.019	-0.871	0.067	0.097	0.164	4	3	0.0020
92 309	00:53:14	+00 46 02	13.842	0.513	-0.024	0.326	0.325	0.652	2	1	0.0035
92 235	00:53:16	+00 36 18	10.595	1.638	1.984	0.894	0.911	1.806	5	2	0.0058
92 322	00:53:47	+00 47 33	12.676	0.528	-0.002	0.302	0.305	0.608	2	1	0.0007
92 245	00:54:16	+00 39 51	13.818	1.418	1.189	0.929	0.907	1.836	21	8	0.0028
92 248	00:54:31	+00 40 15	15.346	1.128	1.289	0.690	0.553	1.245	4	2	0.0255

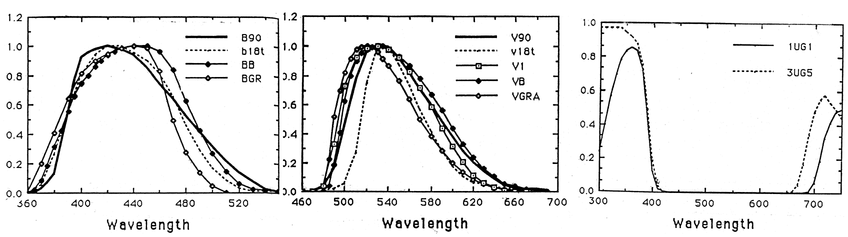


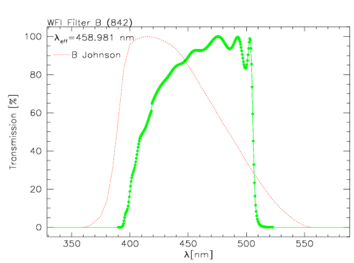
We often need to compare observations with models, on the ***same photometric system***

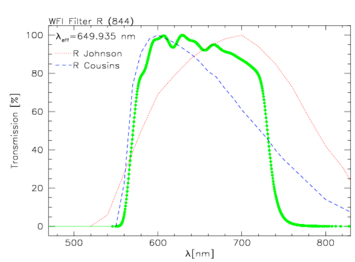
Always, always transform models to observational system, e.g., by integrating model spectra through your bandpasses



Alas, Even The "Same" Photometric Systems Are Seldom Really The Same …

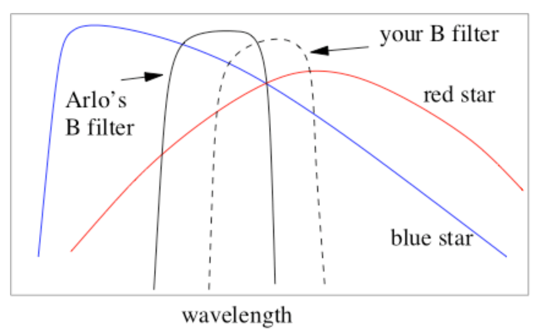






This Generates Color Terms …

… From mismatches between the effective bandpasses of your filter system and those of the standard system. Objects with different spectral shapes have different offsets:



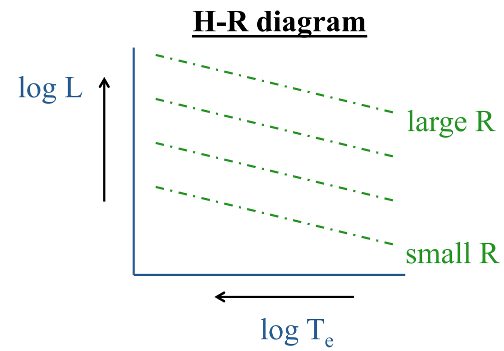
A photometric system is thus effectively (operationally) ***defined by a set of standard stars*** - since the actual bandpasses may not be well known.

Hertzsprung-Russell Diagram (HRD)

- The fundamental tool/framework for understanding stars and their evolution
- Also used as a distance indicator, enabling the mapping of our Galaxy
- The HRD classifies stars by their luminosity and temperature
  - Most stars fall on the Main Sequence of the H-R diagram, a sequence running from hot, luminous stars to cool, dim stars
  - Other stars, such as supergiants, giants, and white dwarfs, fall in different regions of the H-R diagram
- ***Mass is the dominant parameter*** which determines where a star will fall on the HRD
- Metallicity is a secondary parameter, an it shifts the stellar sequences at a given age

The Hertzsprung-Russell Diagram

Plot T_e against L (theorists) or color (e.g., B-V) against absolute magnitude (observers):



HOT, BLUE stars COOL, RED stars

Plot lines of constant stellar radius on the H-R diagram using:

$$L = 4\pi R^2 \sigma T_e^4$$

Individual star is a single point in this plane.

It is a 2-D parameter space in which stars form 1-D sequences, which evolve in time. Metallicity is a "hidden" (2nd) parameter

Hipparcos HRD

The giant branch

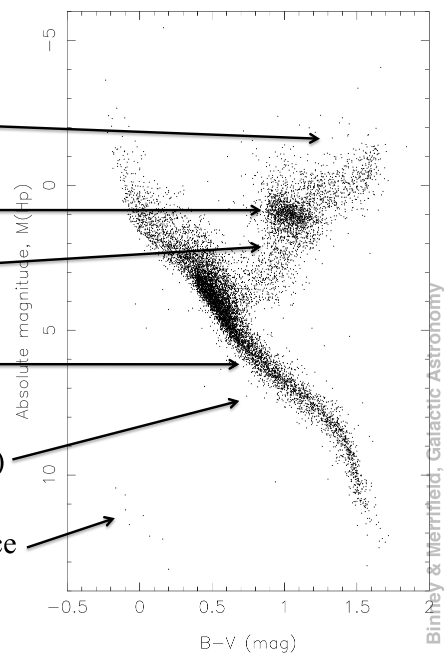
The red clump

The subgiant branch

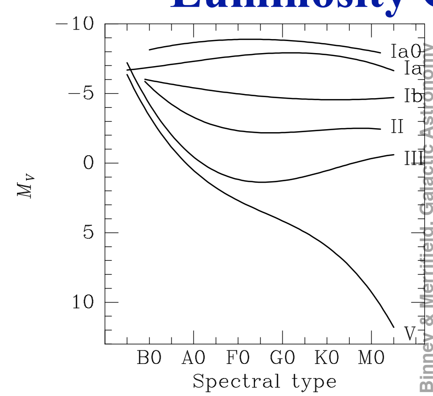
The (Pop I) main sequence

The subdwarfs (Pop II main seq.)

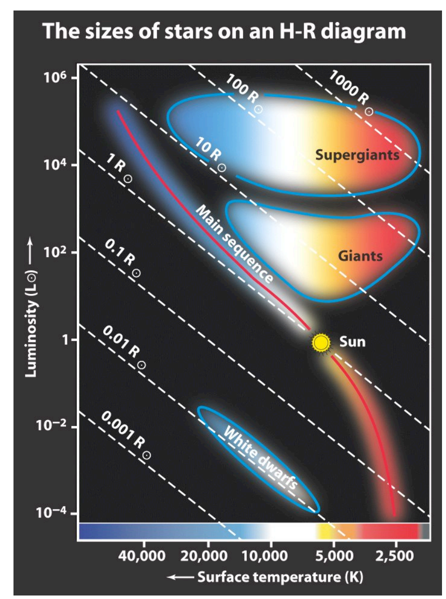
The white dwarf cooling sequence



Luminosity Classification



Ia Bright supergiant
Ib Supergiant
II Bright giant
III Giant
IV Subgiant
V Main sequence star



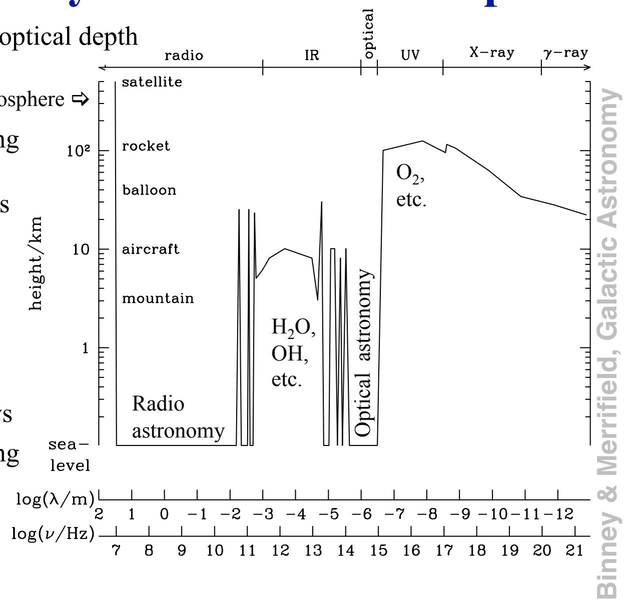
Absorption by the Earth's Atmosphere

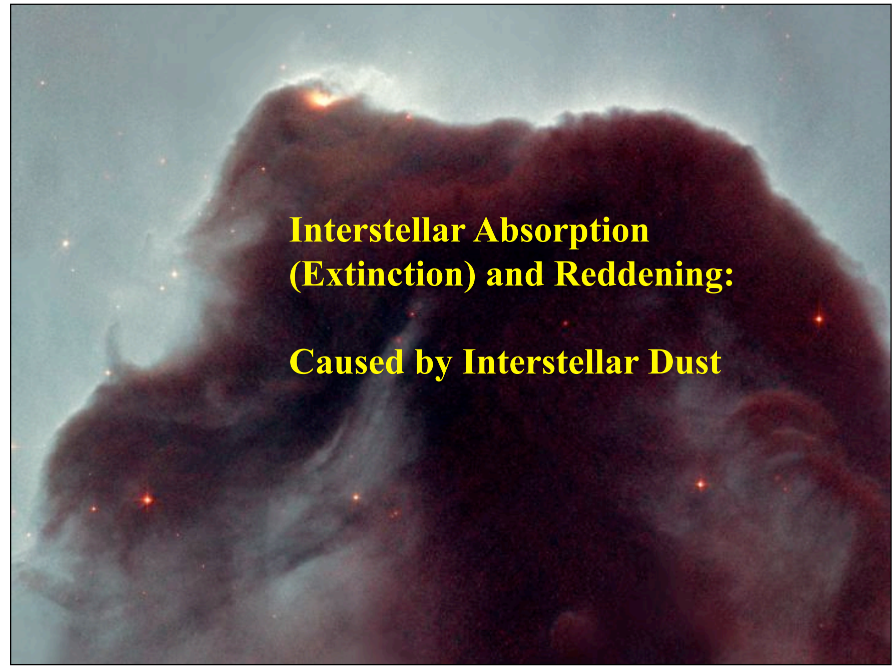
The line shows the optical depth

However, even going into space does not always help: there is the absorption by the Galaxy's ISM:

- Dust absorbs from soft X-rays to IR
- H I absorbs from 912Å to soft X-rays
- Plasma absorbs long wavelength radio

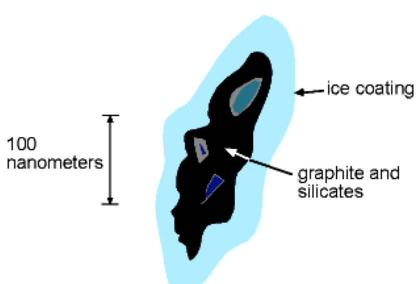
etc., etc.



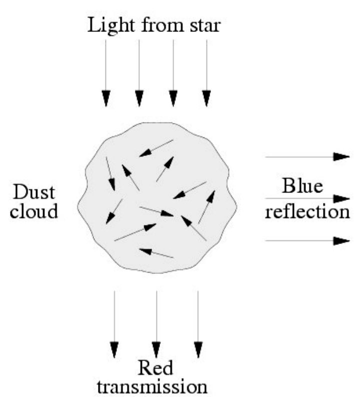


Interstellar Dust Grains

Probability of interaction with a photon increases for photons whose wavelength is comparable to or smaller than the grain size; longer wavelength photons pass through. Thus interstellar extinction = *f(λ)*. (Note: this breaks down for high-energy photons)

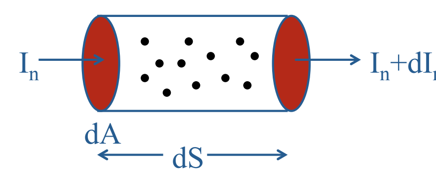


A typical dust grain (note the tiny scale!).



Absorption of Light (In General)

If the radiation travels through a medium which absorbs (or scatters) radiation, the energy in the beam will be reduced:



Number density of absorbers (particles per unit volume) = n
Each absorber has cross-sectional area = s_n (units cm^2)

If beam travels through ds, total area of absorbers is:

$$\text{number of absorbers} \times \text{cross-section} = n\,dA\,ds \times \sigma_\nu$$

(From P. Armitage)

Fraction of radiation absorbed = fraction of area blocked:

$$\frac{dI_\nu}{I_\nu} = -\frac{n dA ds \sigma_\nu}{dA} = -n\sigma_\nu ds$$

$$dI_\nu = -n\sigma_\nu I_\nu ds \equiv -\alpha_\nu I_\nu ds$$

absorption coefficient (units cm^{-1})

Can also write this in terms of mass:

$$\alpha_\nu \equiv \rho\kappa_\nu$$

κ_ν is called the mass absorption coefficient or the **opacity**

Opacity has units of $cm^2\ g^{-1}$ (i.e. the cross section of a gram of gas).

(From P. Armitage)

Equation of radiative transfer for pure absorption:
Rearrange previous equation:

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu$$

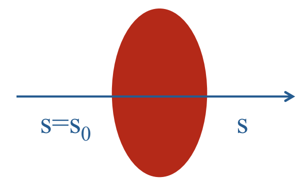
Different from emission because depends on how much radiation we already have

Integrate to find how radiation changes along path:

$$\int_{s_0}^{s} \frac{dI_\nu}{I_\nu} = -\int_{s_0}^{s} \alpha_\nu(s')ds'$$

$$\left[\ln I_\nu\right]_{s_0}^{s} = -\int_{s_0}^{s} \alpha_\nu(s')ds'$$

$$I_\nu(s) = I_\nu(s_0)e^{-\int_{s_0}^{s}\alpha_\nu(s')ds'}$$



(From P. Armitage)

e.g., if the absorption coefficient is a constant (example, a uniform density gas of ionized hydrogen):

$$I_\nu(\Delta s) = I_0 e^{-\alpha_\nu \Delta s}$$

Specific intensity after distance Ds

Initial intensity

Radiation exponentially absorbed with distance

Radiative transfer equation with both absorption and emission:

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

absorption

emission

(From P. Armitage)

Optical Depth

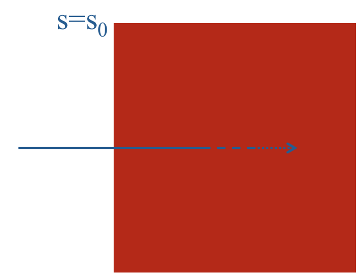
Look again at general solution for pure absorption:

$$I_\nu(s) = I_\nu(s_0)e^{-\int_{s_0}^{s}\alpha_\nu(s')ds'}$$

Imagine radiation traveling into a cloud of absorbing gas, exponential defines a scale over which radiation is attenuated.

When: $\int_{s_0}^{s}\alpha_\nu(s')ds' = 1$

…intensity will be reduced to 1/e of its original value.

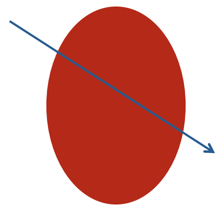


(From P. Armitage)

Define **optical depth** τ as:

$$\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s')ds'$$

or equivalently $\quad d\tau_\nu = \alpha_\nu ds$



A medium is **optically thick** at a frequency ν if the optical depth for a typical path through the medium satisfies:

$$\tau_\nu \geq 1$$

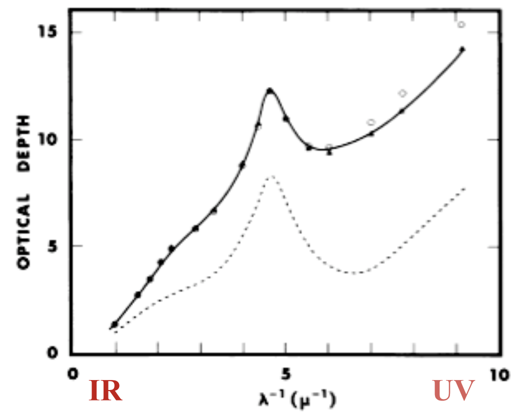
Medium is said to be **optically thin** if instead:

$$\tau_\nu < 1$$

Interpretation: an optically thin medium is one which a typical photon of frequency ν can pass through without being absorbed.

Interstellar Extinction Curve

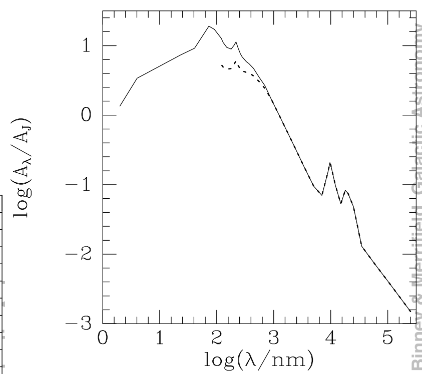
Note: this is a log of the decrement! (i.e., just like magnitudes)

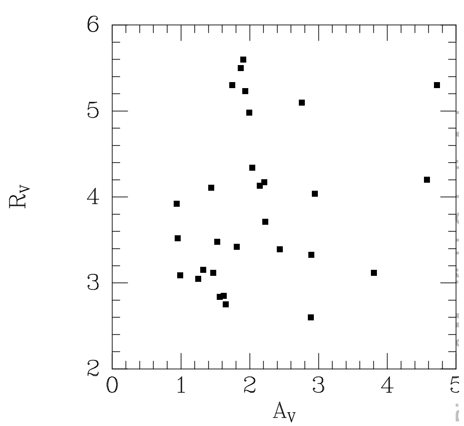


The bump at λ ~ 2200 Å is due to silicates in dust grains. This is true for most Milky Way lines of sight, but not so in some other galaxies, e.g., the SMC

Extinction Curves are Not Universal

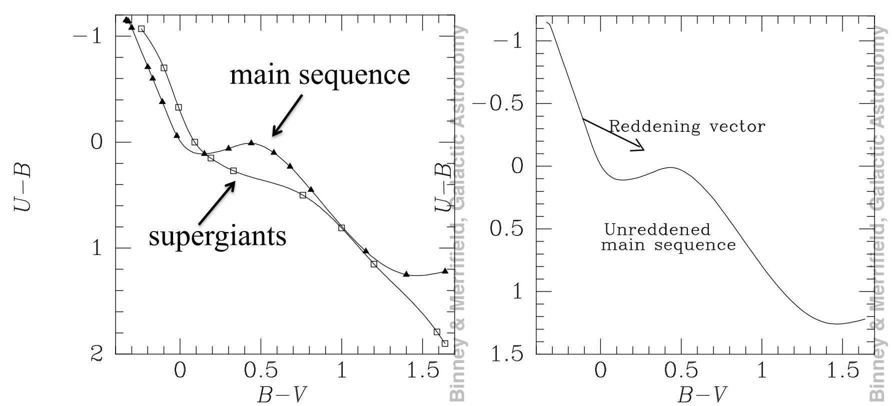
It depends on the chemical composition and size distribution of the dust grains





Often parametrized by
$R_V = A_V / E_{B-V}$

Color Sequence(s)



Since the extinction affects different colors differently, the shift of the color seq. can be used to estimate the reddening/extinction

Interstellar Extinction in Standard Photometric Bandpasses

λ	$E(\lambda - V)/E(B-V)$	A_λ/A_V
U	1.64^a	1.531
B	1.00^b	1.324
V	0.0^b	1.000
R	-0.78^b	0.748
I	-1.60^b	0.482
J	-2.22 ± 0.02	0.282
H	-2.55 ± 0.03	0.175
K	-2.744 ± 0.024	0.112
L	-2.91 ± 0.03	0.058
M	-3.02 ± 0.03	0.023

Note:
This is the ratio of extinction in magnitudes!

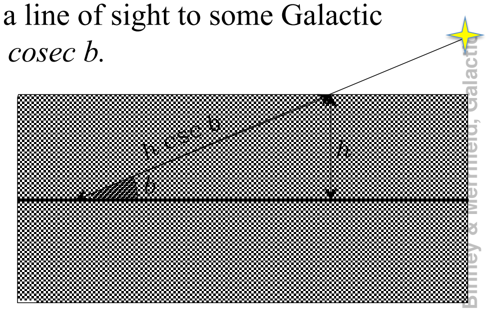
Dramatically lower extinction in IR! Which is why we use IR imaging to see through the dust…

The Cosecant Law

A rough estimate of the extinction along a given line of sight:

Approximate the dust layer as a uniform, finite slab of dust. Then the path length along a line of sight to some Galactic latitude b is proportional to *cosec b.*

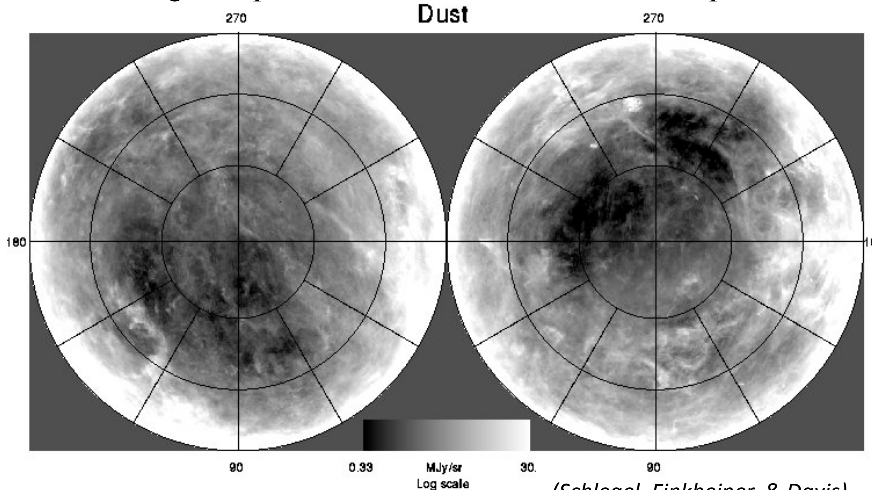
Then just multiply the extinction towards the Galactic poles ($A_V \sim 0.1$ mag) by *cosec b* (all in magnitudes)



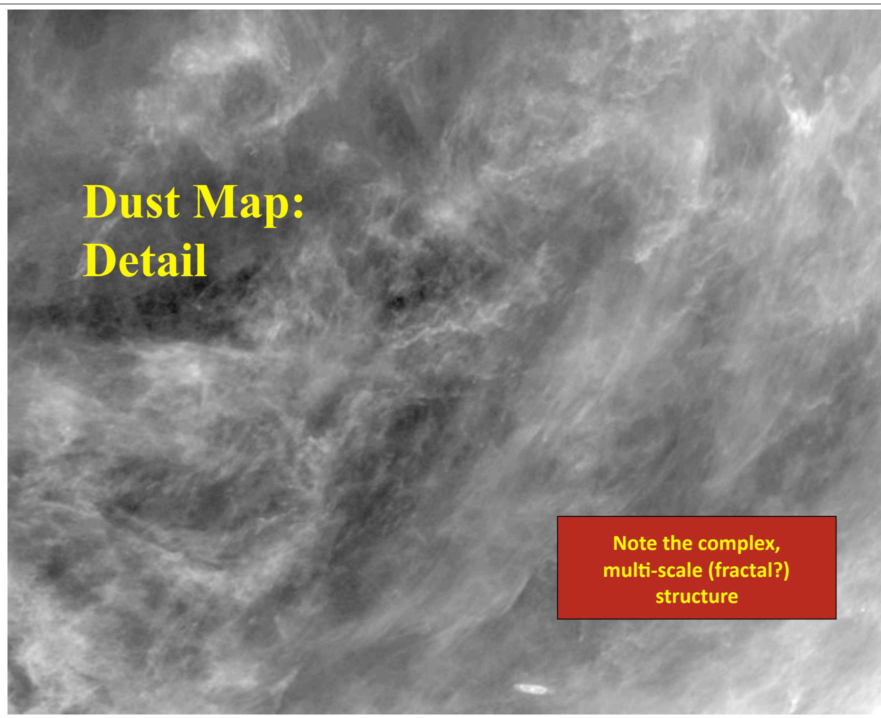
Nowadays we actually use dust maps, derived from the FIR and radio emission maps, e.g., by Schlegel, Finkbeiner, & Davis

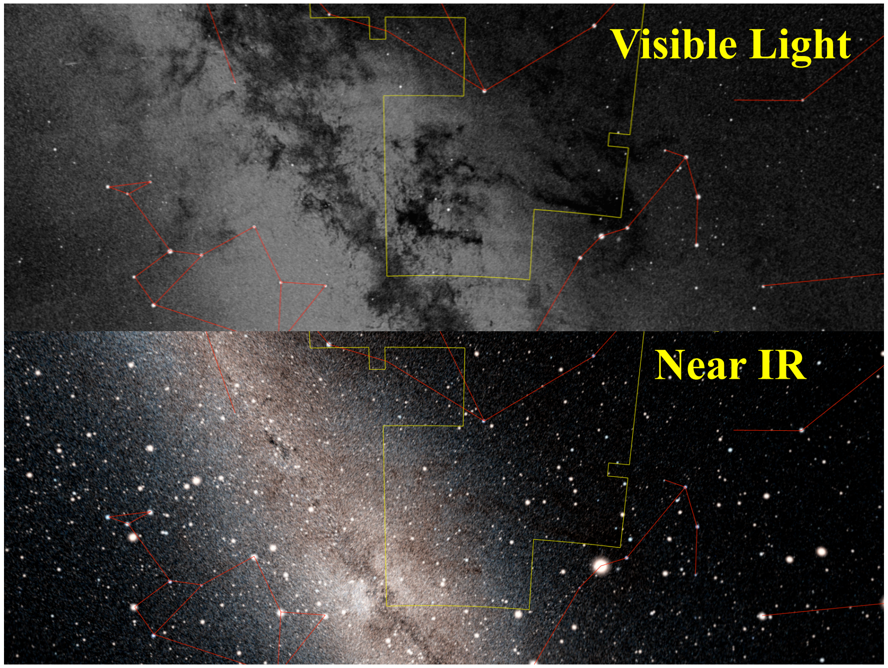
Galactic Extinction Map

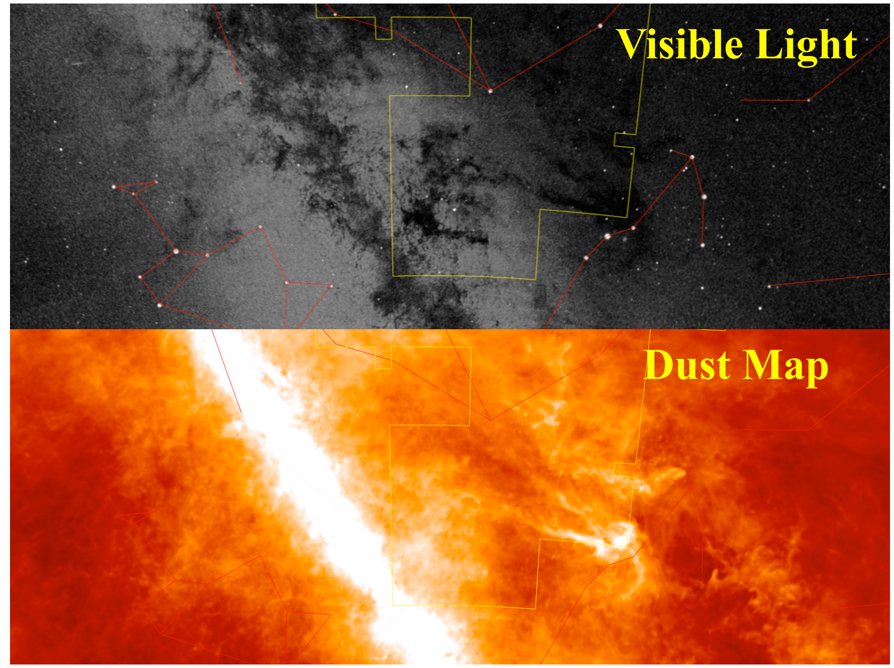
From IRAS FIR fluxes (thermal emission from dust, and H I and molecular gas maps. These are the two Galactic hemispheres:

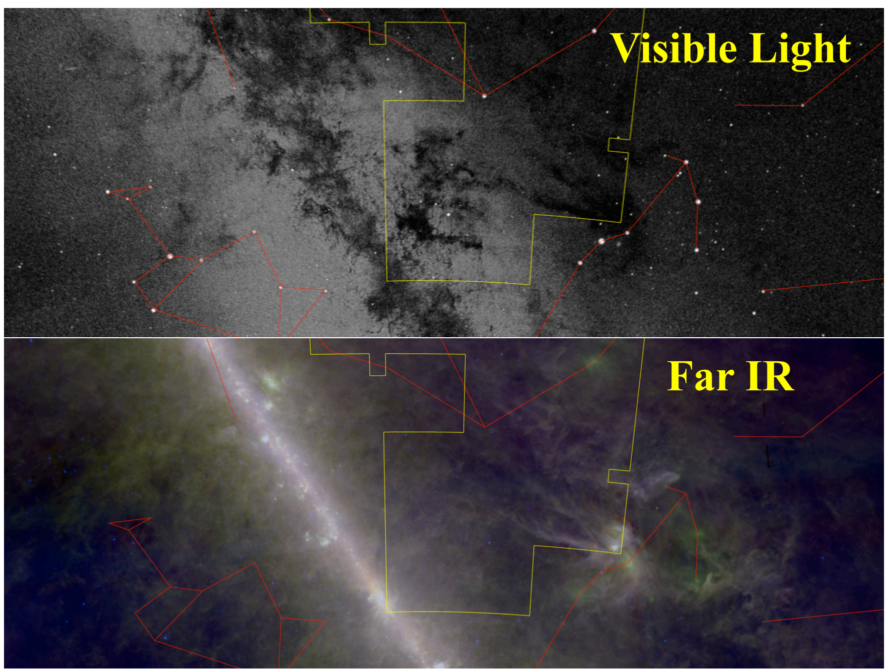


(Schlegel, Finkbeiner, & Davis)



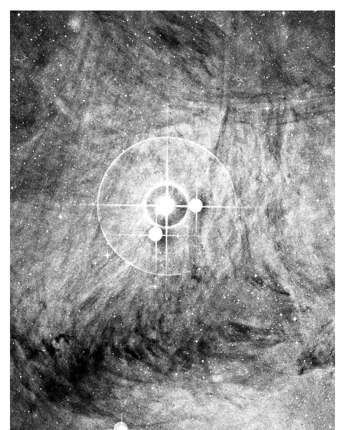


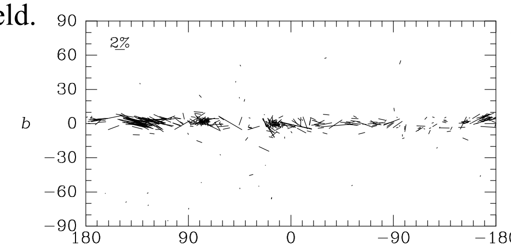


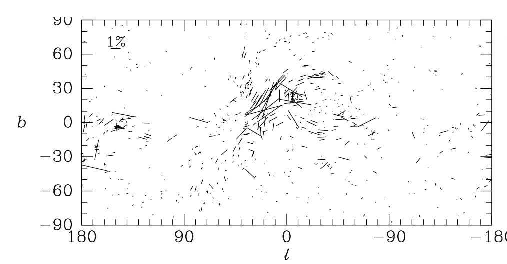


Interstellar Polarization

Interstellar magnetic field orients the dust grains, which then serve as a polarizing screen. Measuring the polarization of starlight can then be used to map the field.







Binney & Merrifield, Galactic Astron

Binney & Merrifield, Ga