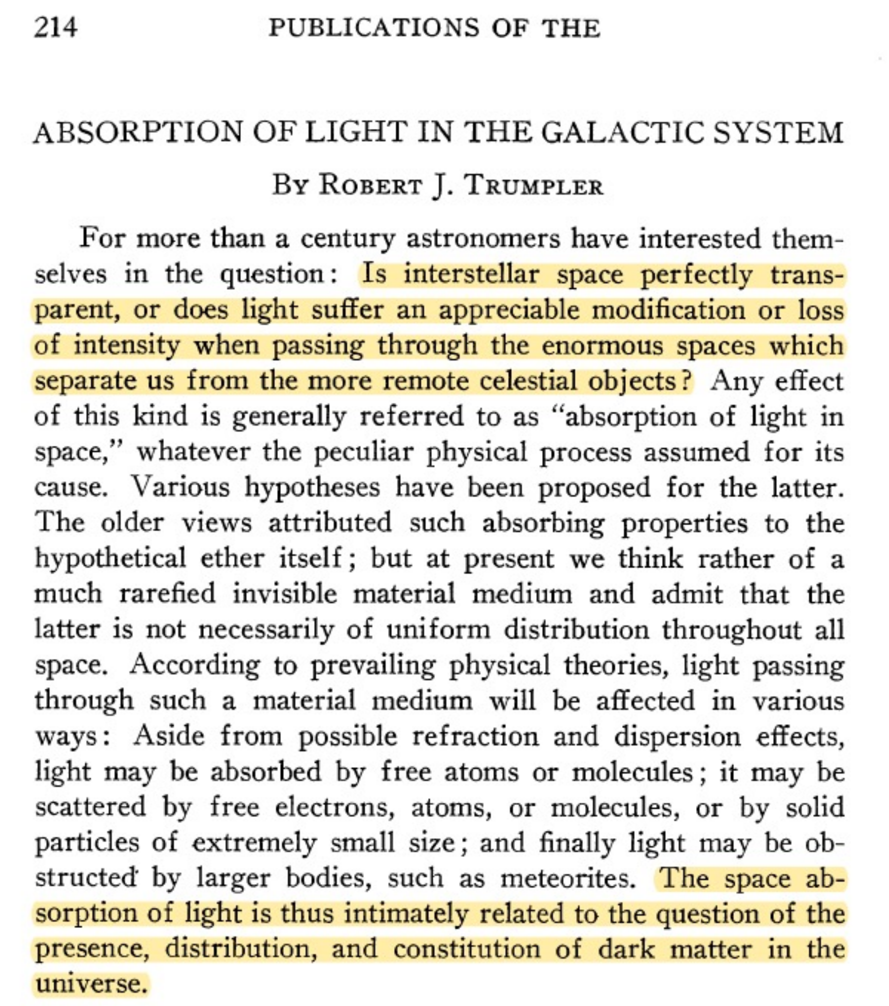
Samir Salim & Desika Narayanan
2020, ARA&A, 58, 529

The dust attenuation law in galaxies

Related reviews/resources

- Draine (2003) – older ARA&A article on dust (focus on grain properties)
- Cardelli, Clayton & Mathis (1989) – classic Milky Way extinction curve
- Pei (1992) – classic SMC and LMC extinction curves

Interstellar dust



ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

By Robert J. Trumpler

For more than a century astronomers have interested themselves in the question: Is interstellar space perfectly transparent, or does light suffer an appreciable modification or loss of intensity when passing through the enormous spaces which separate us from the more remote celestial objects? Any effect of this kind is generally referred to as "absorption of light in space," whatever the peculiar physical process assumed for its cause. Various hypotheses have been proposed for the latter. The older views attributed such absorbing properties to the hypothetical ether itself; but at present we think rather of a much rarefied invisible material medium and admit that the latter is not necessarily of uniform distribution throughout all space. According to prevailing physical theories, light passing through such a material medium will be affected in various ways: Aside from possible refraction and dispersion effects, light may be absorbed by free atoms or molecules; it may be scattered by free electrons, atoms, or molecules, or by solid particles of extremely small size; and finally light may be obstructed by larger bodies, such as meteorites. The space absorption of light is thus intimately related to the question of the presence, distribution, and constitution of dark matter in the universe.

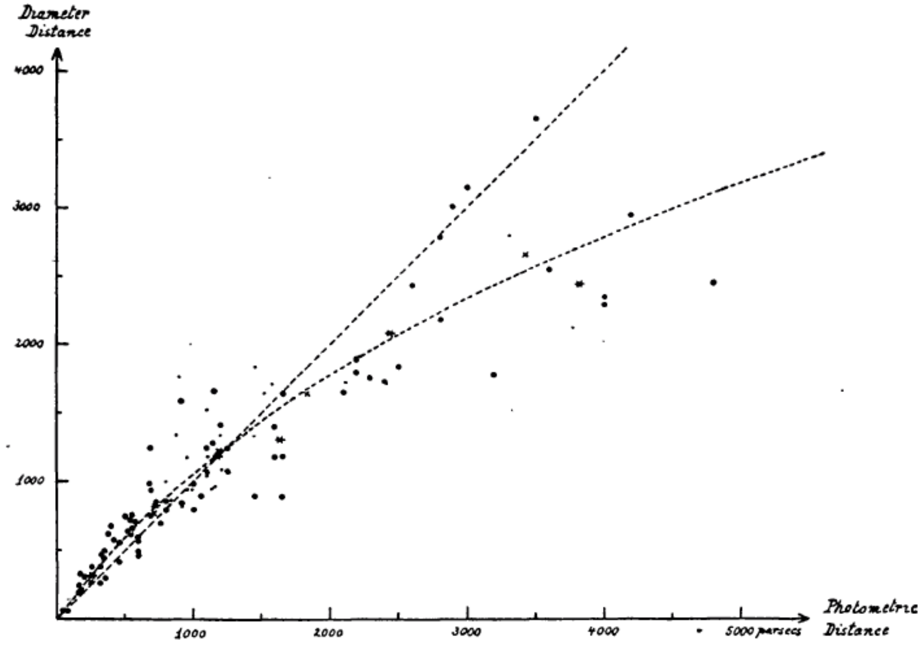


Fig. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Trumpler (1930)

Interstellar dust

- Dust:gas ratio in the Galactic ISM ~1:100. Since gas is ~10% of the baryonic mass in the Milky Way, dust is about 0.1% of the Galactic mass.

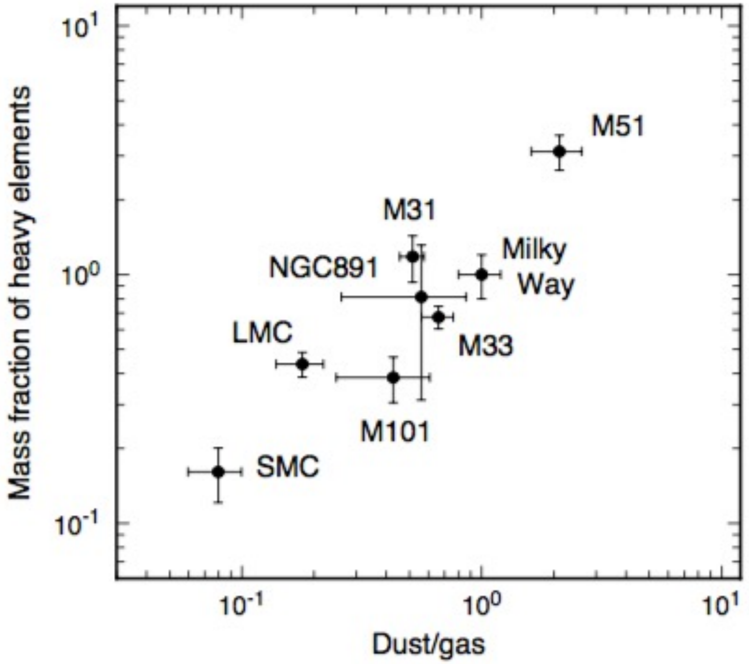
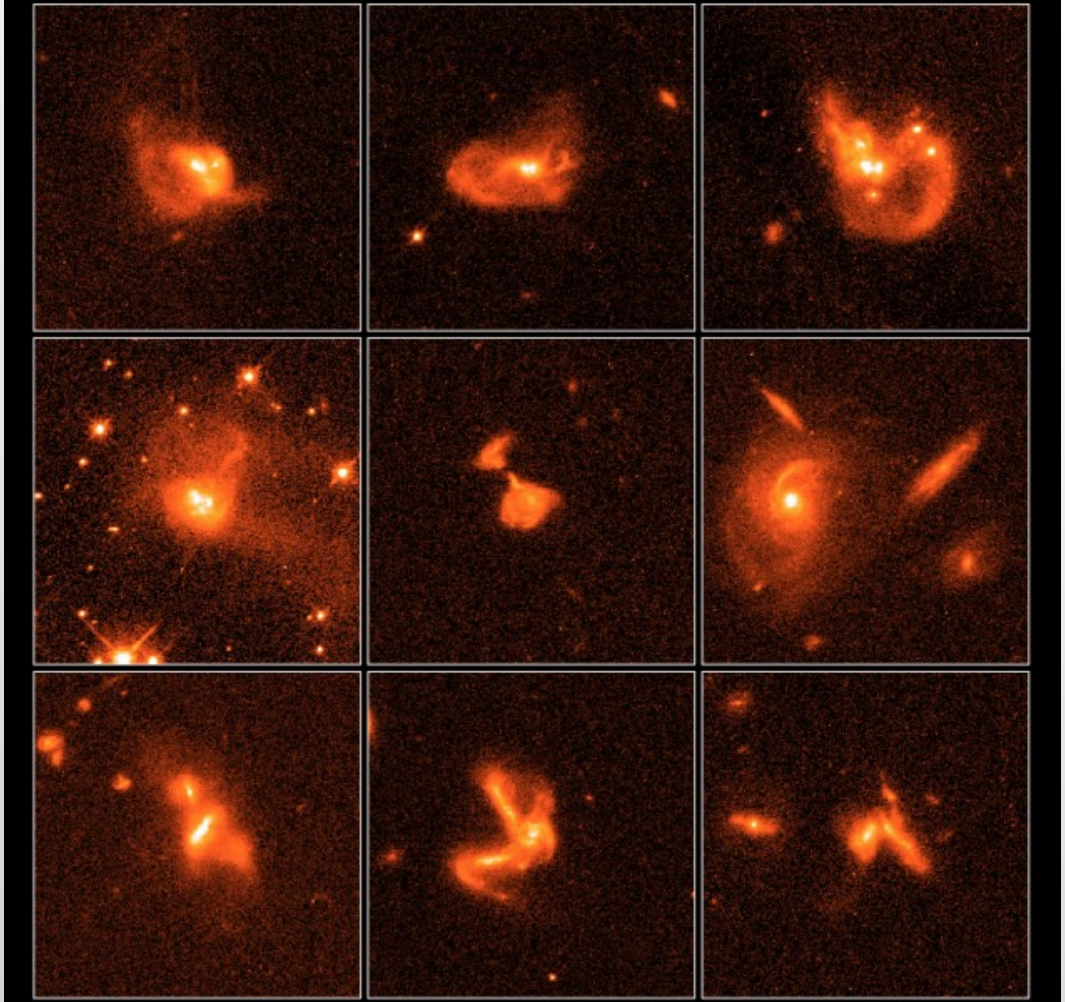


Figure 4: As the metallicity of a galaxy increases, so does its dust fraction (data from Issa et al 1990 and Alton et al 2000).

Interstellar dust

- Dust:gas ratio in the Galactic ISM ~1:100. Since gas is ~10% of the baryonic mass in the Milky Way, dust is about 0.1% of the Galactic mass.
- Formed (mostly) on the surface of dust grains in cool circumstellar environments, e.g winds from AGB stars, massive stars under-going mass loss, nova envelopes, SN ejecta.
- Grains have sizes from ~5 – 300 nm.
- Grain size and composition (e.g. graphites vs. silicates) dictates extinction properties.
- In addition to extinction (the focus of this review) dust is also used as a tracer of star formation (because photons from stars heat dust which re-emit in the IR) and as a tracer of the molecular gas content. Both of these topics are covered in later lectures.
- Despite its small fraction by mass, the re-processing of starlight means that 30-50% of the Milky Way's bolometric luminosity comes from dust!



Ultraluminous Infrared Galaxies
Hubble Space Telescope • WFPC2

NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center),
H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)
STScI-PRC99-45

High rates of star formation and dust make some galaxies extremely bright in the infra-red.

High rates of star formation often triggered by mergers.

Jargon alert: (U)LIRG = (Ultra) luminous IR galaxy. $L > L_{sun}^{12}$

Grain composition

Primarily carbon and silicon based grains (we see strong emission features from these species), but many elements show refractory tendencies.

Jargon alert: A_λ = extinction at a given wavelength (maths coming later)

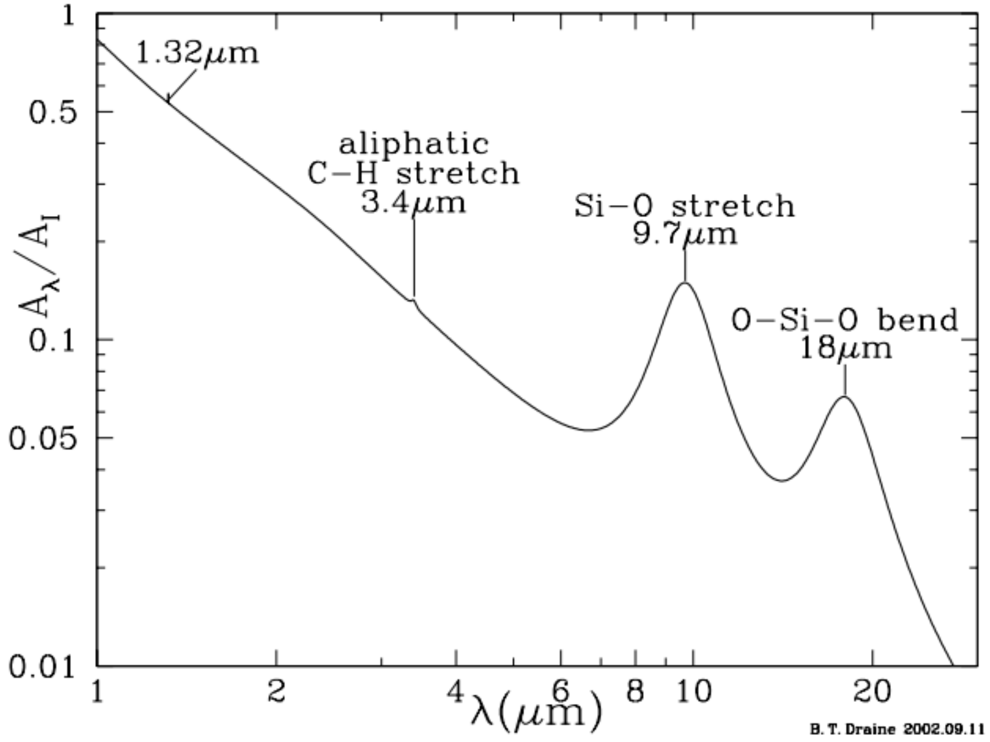


Fig. 3. Infrared extinction, relative to extinction at $I = 900$ nm, showing the strong 9.7 μm and 18 μm silicate features, the 3.4 μm aliphatic C-H stretch, and a weak unidentified DIB at 1.32 μm (Joblin et al. 1990).

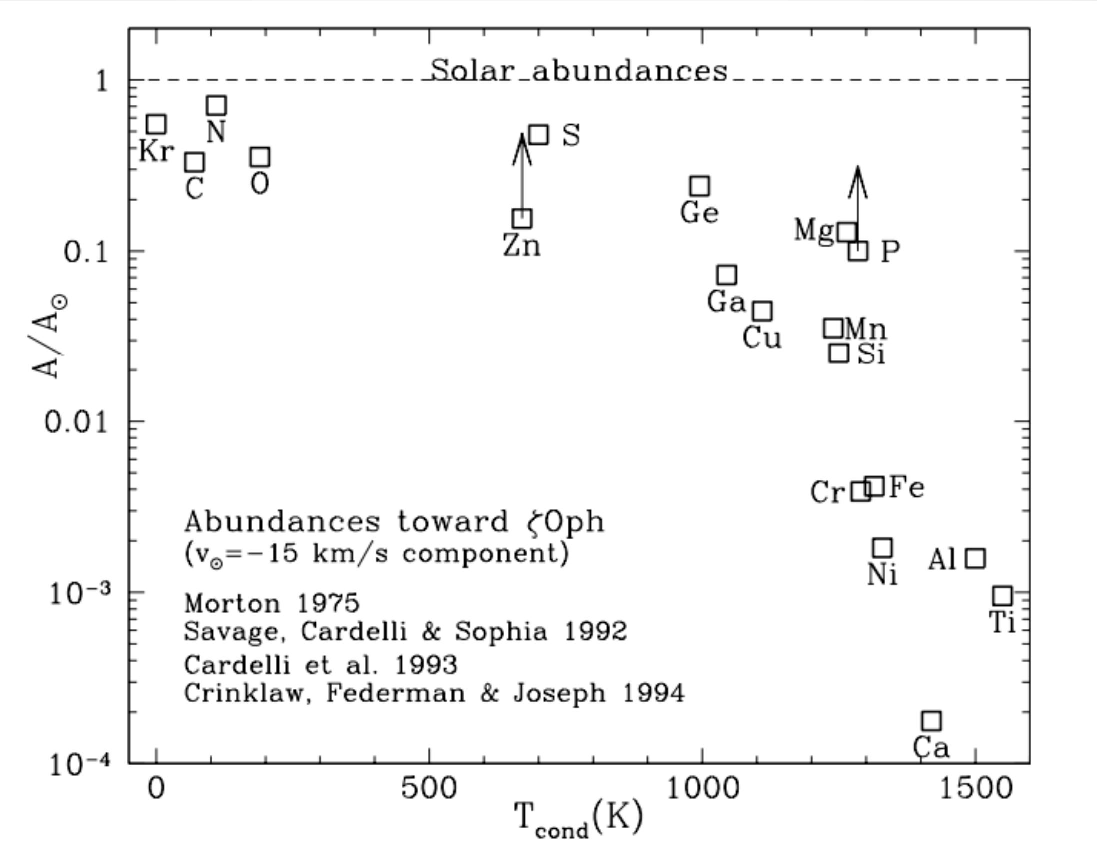
Draine (2003)

Grain composition and depletion from the gas phase

Primarily carbon and silicon based grains (we see strong emission features from these species), but many elements show refractory tendencies.

Jargon alert: refractory = tendency to be depleted from gas phase onto dust.

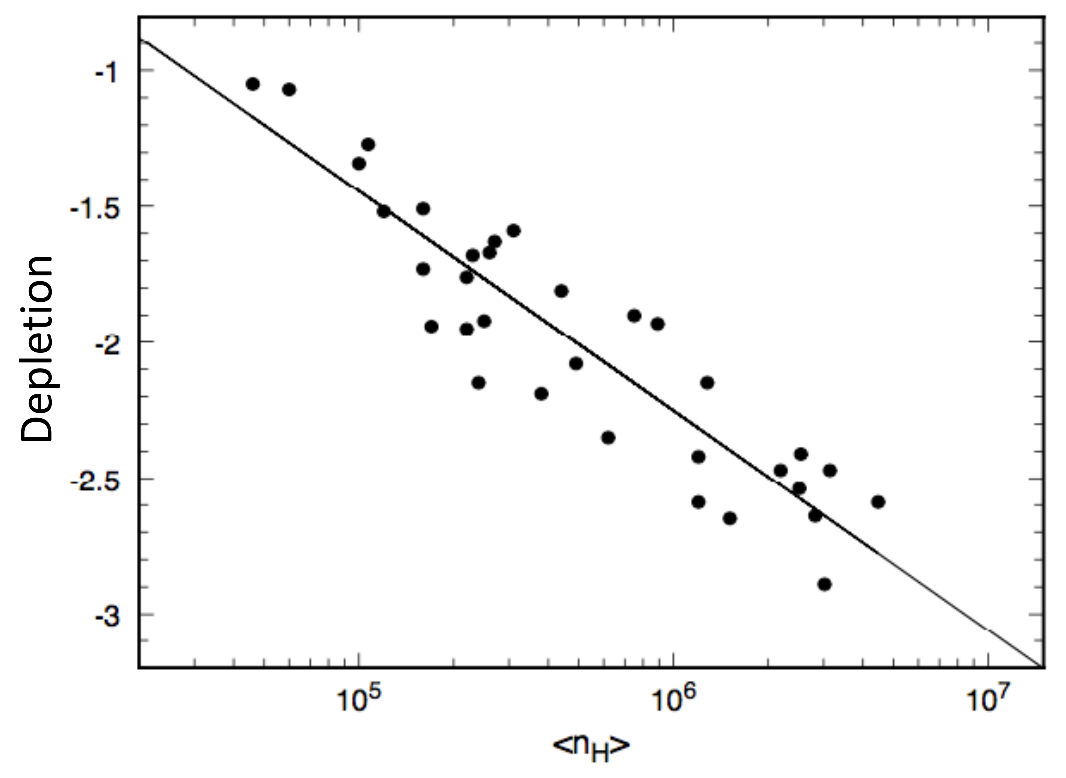
On this plot, A is “abundance” not extinction.



Draine (2003)

Grain composition and depletion from the gas phase

Depletion depends on density. Grains can be destroyed by shocks as seen in the Routly-Spitzer effect.



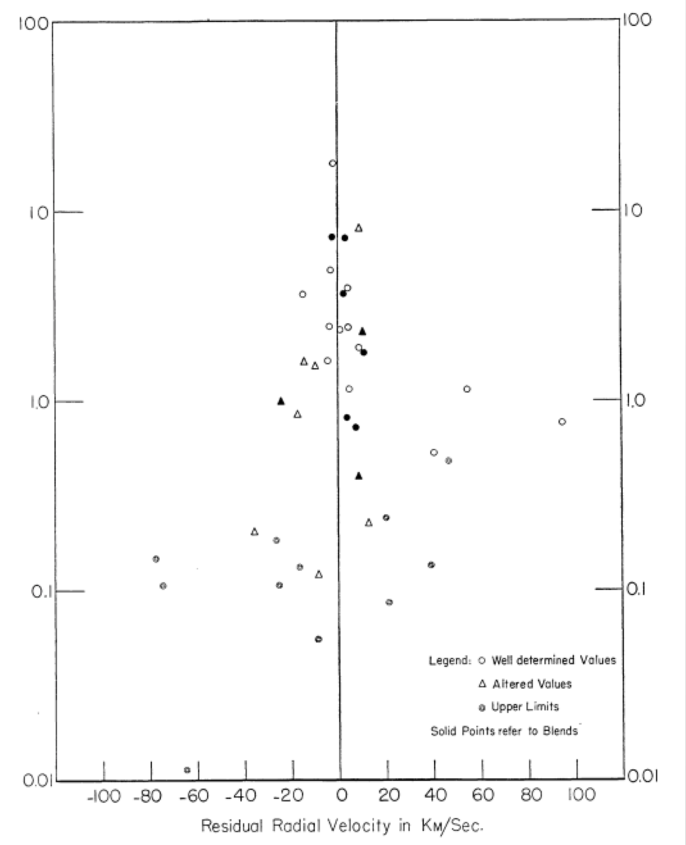


FIG. 1.—Plot of log $N(Na\,\text{I})/N(Ca\,\text{II})$ versus residual radial velocity

Routly & Spitzer (1952)

Extinction and attenuation

Figure 1

Schematic summarizing the difference between extinction and attenuation. The former encapsulates absorption and scattering out of the line of sight, while the latter folds in the complexities of star-dust geometry in galaxies, and may include scattering back into the line of sight, varying column densities/optical depths, and the contribution by unobscured stars.

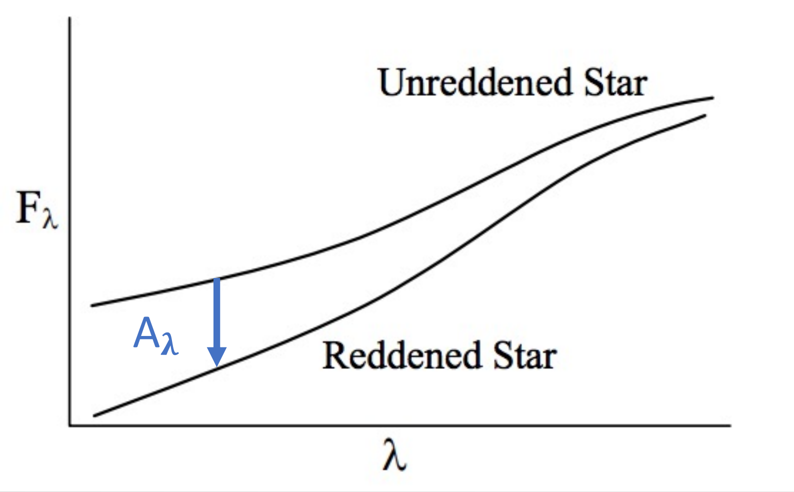
Salim & Narayanan (2022)

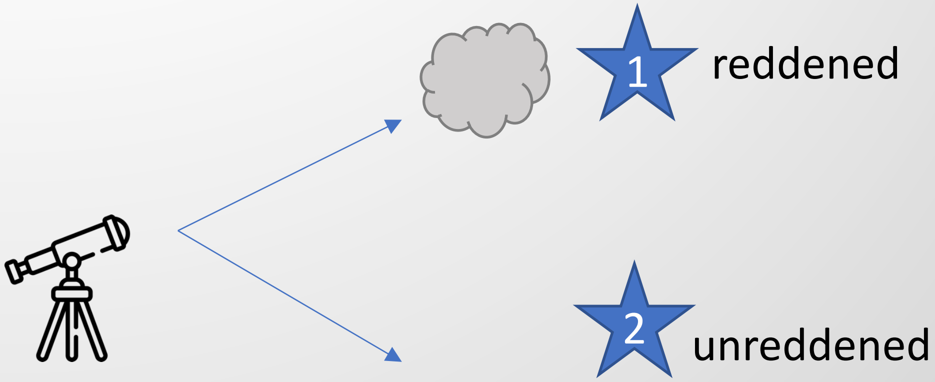
Extinction is the difference in magnitudes between the intrinsic and observed emission:

$$A_\lambda = m_{\lambda,obs} - m_{\lambda,int}$$

How is extinction determined?

Most common method uses pairs of stars of the same spectral type (same absolute magnitude).





Recall: $m-M=-5 + 5\log d(pc)$

If stars are at same distance, any difference in brightness is due to dust:

$$A_\lambda = m_1 - m_2$$

At different distances the same spectral type star has observed (apparent) magnitude difference:

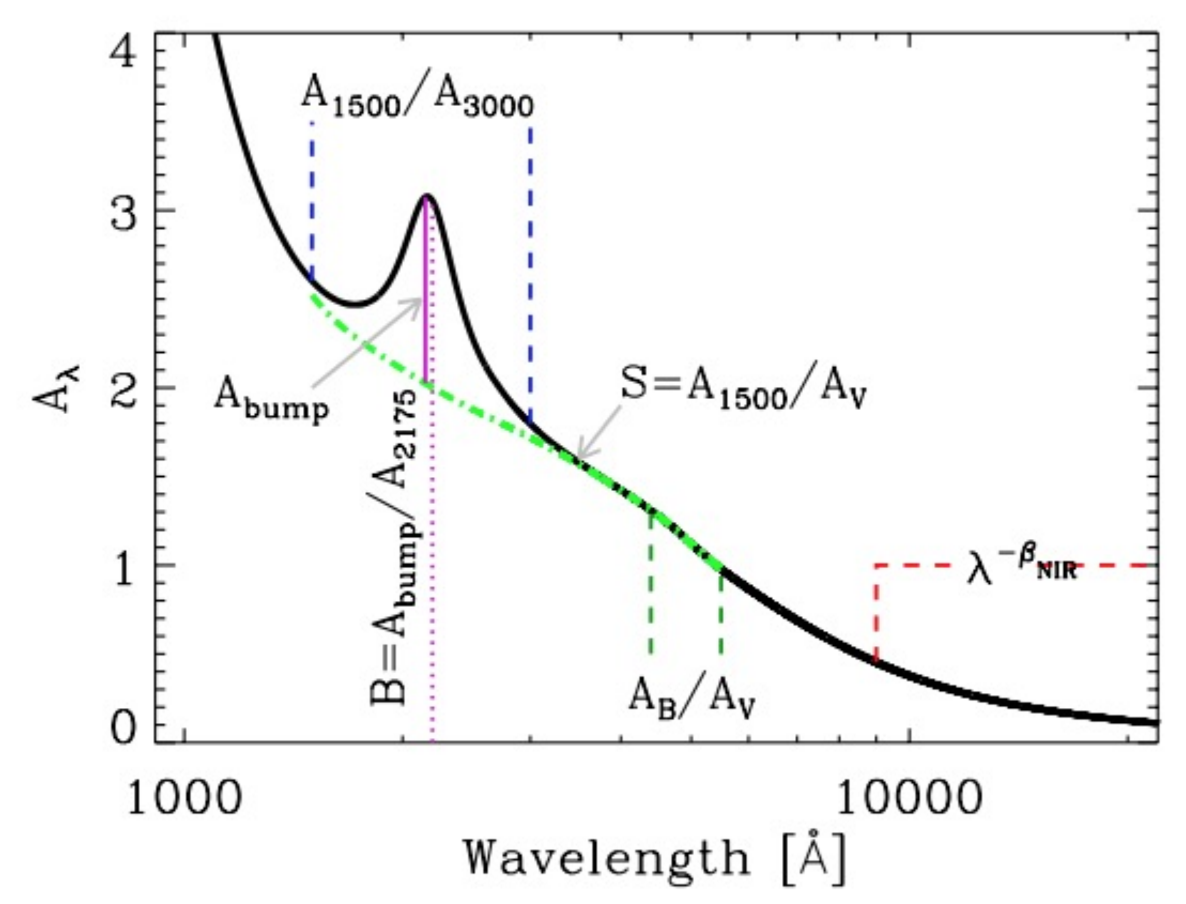
$$m_1 - m_2 = 5 \log (d_1/d_2) + A_\lambda$$

Jargon alert!

A_λ = extinction in magnitudes at given wavelength/band e.g A_{5500} or A_V.

Extinction curves

The extinction curve describes how much extinction there is as a function of wavelength



Broadly speaking (in optical and near-IR):

$A_\lambda \propto 1/\lambda$

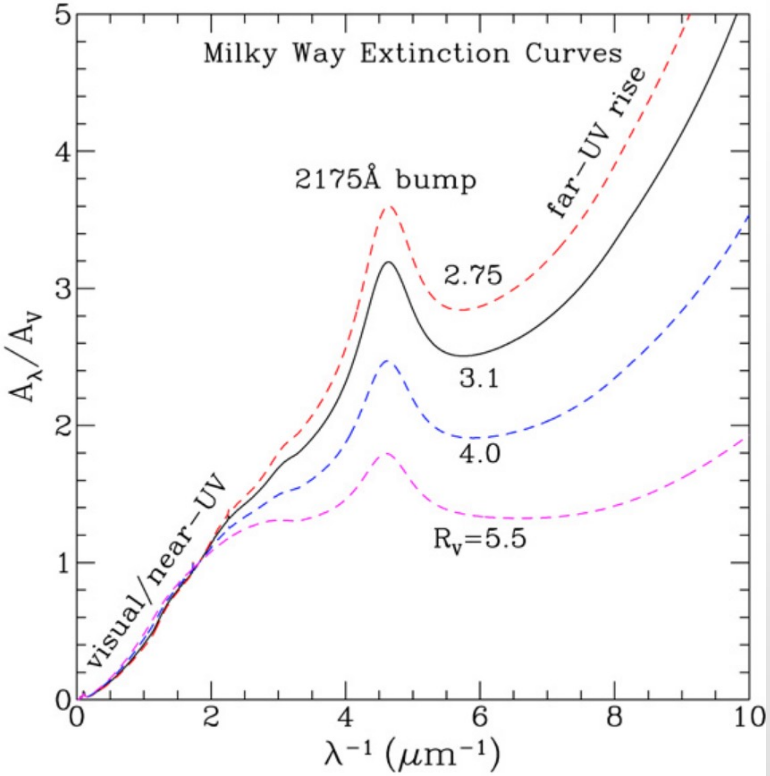
Jargon alert!

S = UV/optical slope

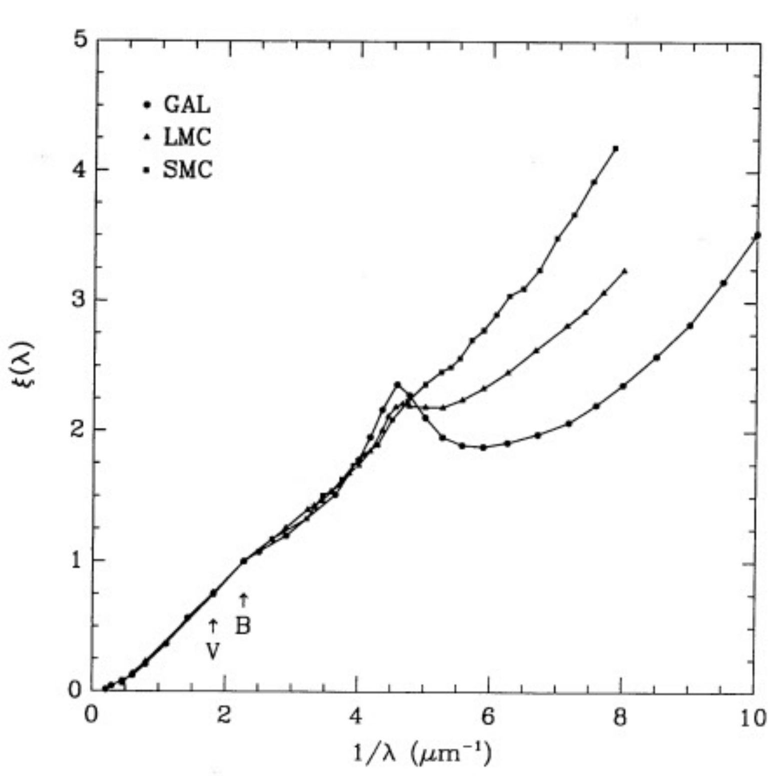
Bump – refers to feature at 2175 A. Likely due to graphites (but exact origin is still debated).

Salim & Narayanan (2022)

Extinction curves



Li et al. (2007)



Pei (1992)

The most common way of plotting extinction curves is to normalize relative to some fixed waveband (often V), i.e. A_λ/A_V. In some older papers this ratio is expressed as $\xi(\lambda) = A_\lambda/A_V$ (although sometimes people define $\xi(\lambda) = A_\lambda/A_B$ in which case $\xi_B = 1.33\,\xi_V$ so care is required!!).

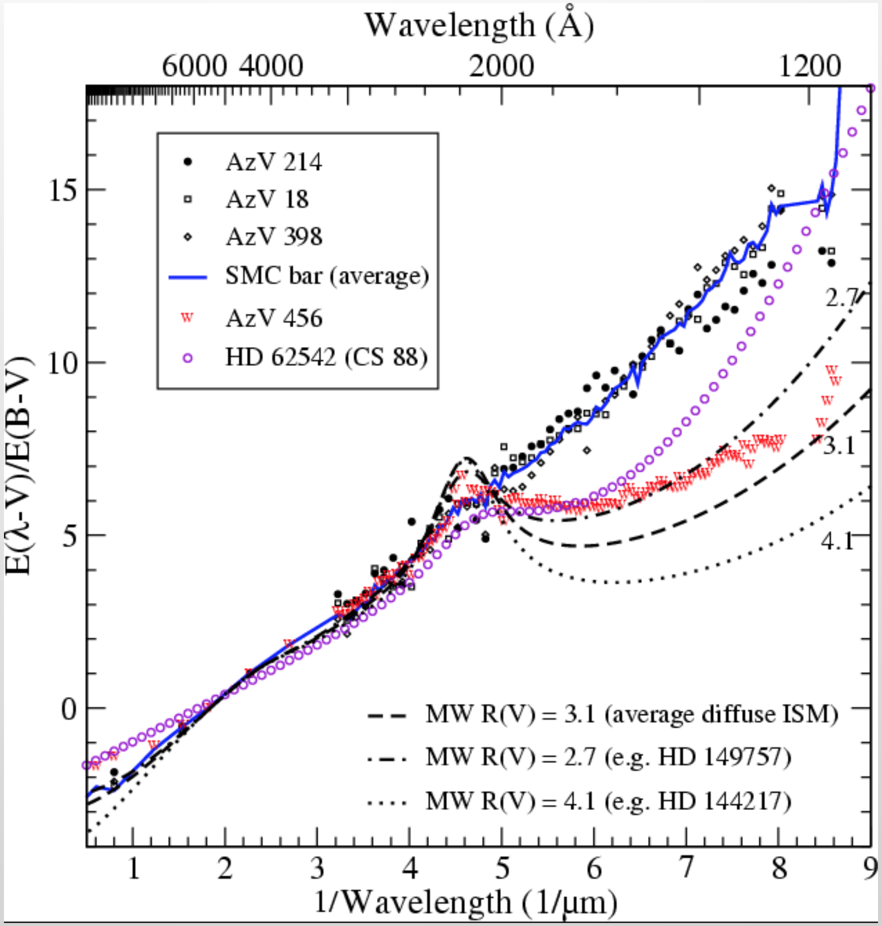
Also note the common convention of plotting 1/ λ.

Extinction curves

Alternatively, can normalize/parametrize extinction curves with the colour excess:

$E(B-V) = A_B - A_V$.
$E(\lambda-V) = A_\lambda - A_V$.

Jargon alert: E(B-V) = colour excess or selective extinction, AKA reddening.



Cox et al. (2007)

Extinction curves

Cardelli et al. (1989) showed that, whilst differing from one line-of-sight to another, Galactic extinction can broadly be parametrized with different values of R_V :

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

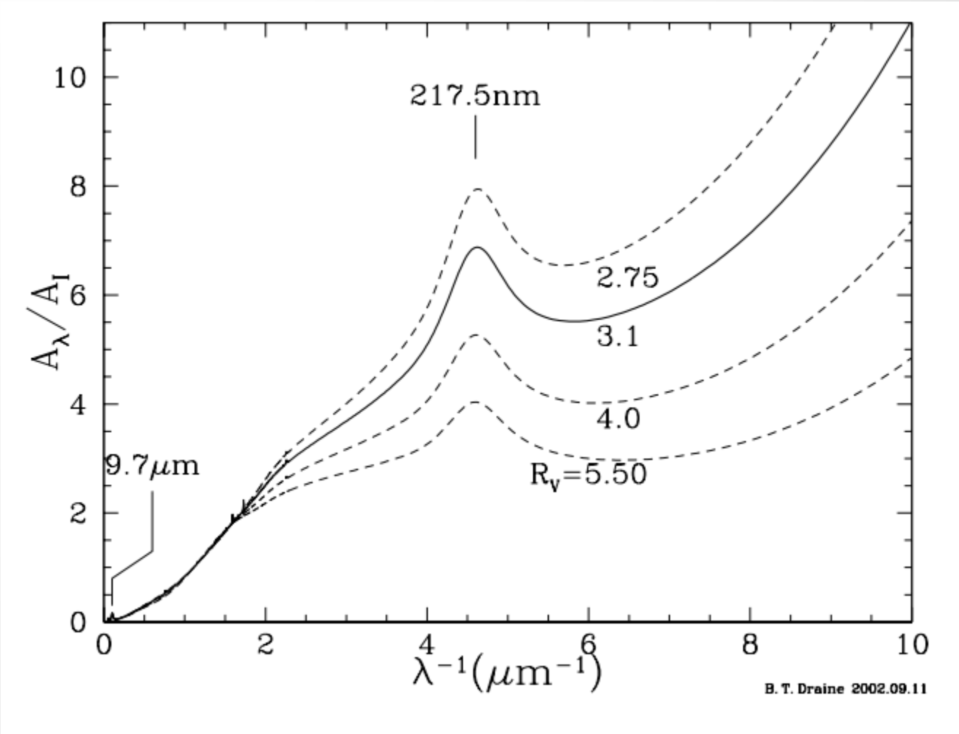
Jargon alert: R_V = total-to-selective extinction.

Equivalently:
$A_B/A_V = 1/R_V + 1$

Some older papers also define:
$k(\lambda) = \xi(\lambda) R_V$

Or equivalently:
$E(B-V) = A_\lambda / k(\lambda)$

Draine (2003)

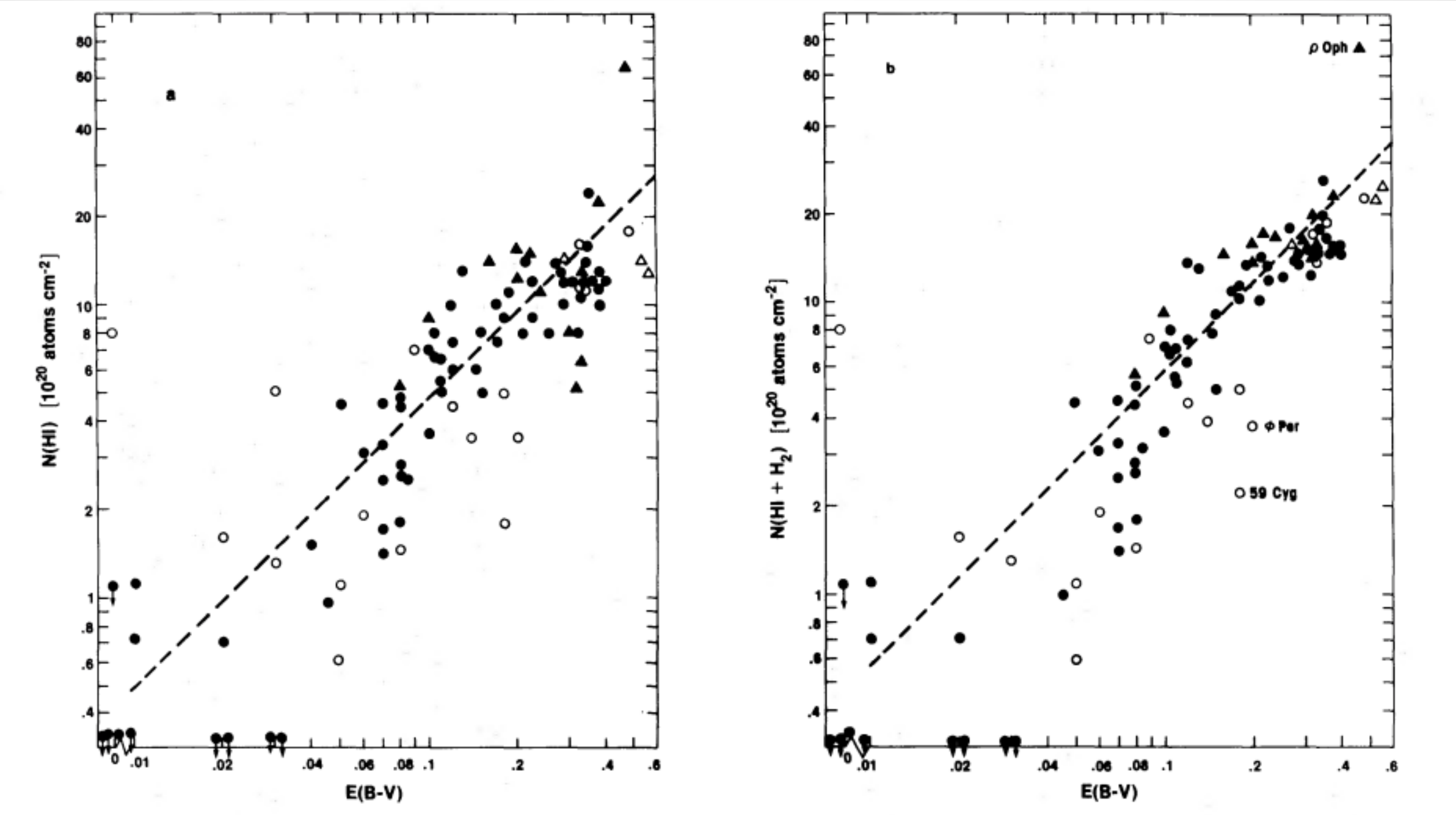


Empirically, R_V correlates with the size of dust grains. Average Milky Way sightline has $R_V \sim 3.1$.

Ultimately, despite the confusing definitions, these are all just ways of being able to parametrize A_λ

The connection between gas and dust

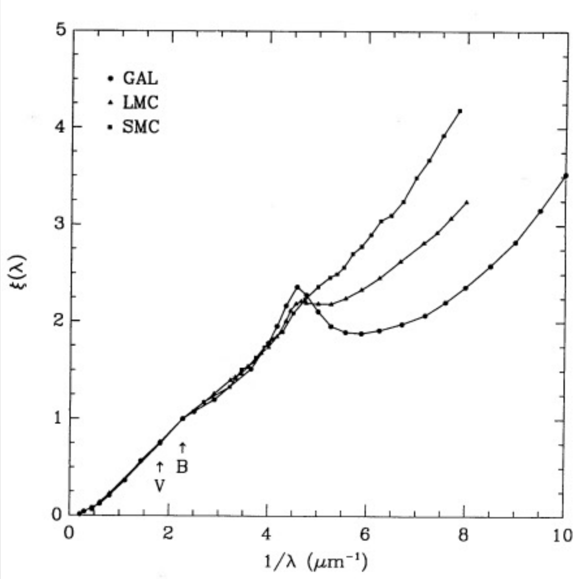
Bohlin et al. (1978)



Typical values in the Milky Way:
$A_V / N_H \sim 5.35 \times 10^{-22}$ mag / cm^2
N(HI) $\sim 5.9 \times 10^{21} \times$ E(B-V)

Extinction curves in other galaxies

Pei (1992)

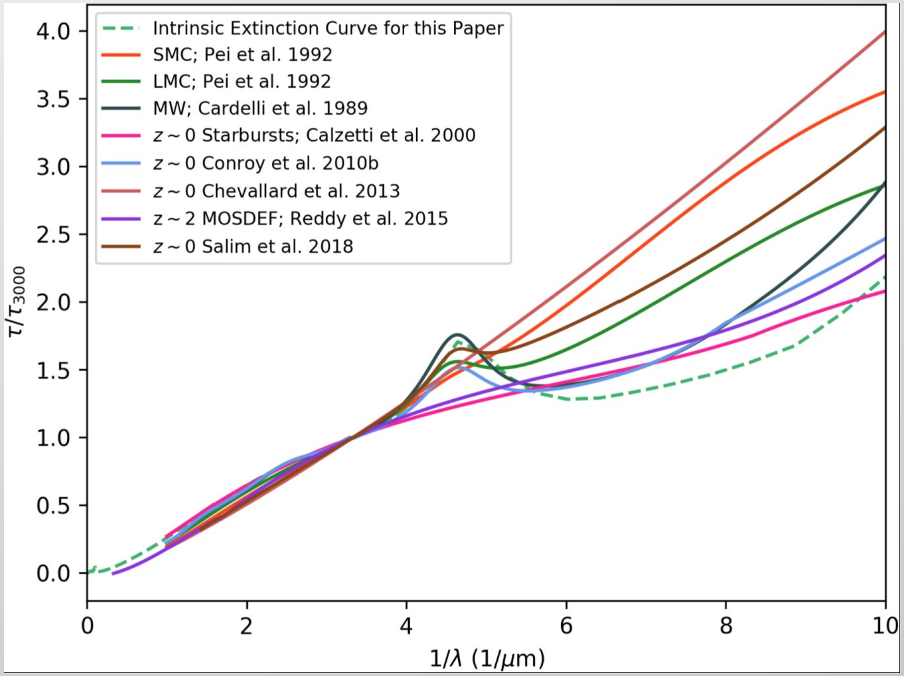


LMC has much weaker 2175 A bump than the Milky Way.

SMC has essentially no bump at all. Possibly due to grain destruction and/or low metallicity?

A more modern compilation taken from Narayanan et al. (2018). Despite decades of progress, Pei et al. and CCM remain standards in the field (along with the Calzetti law for starbursts).

More on this in the guest lecture!

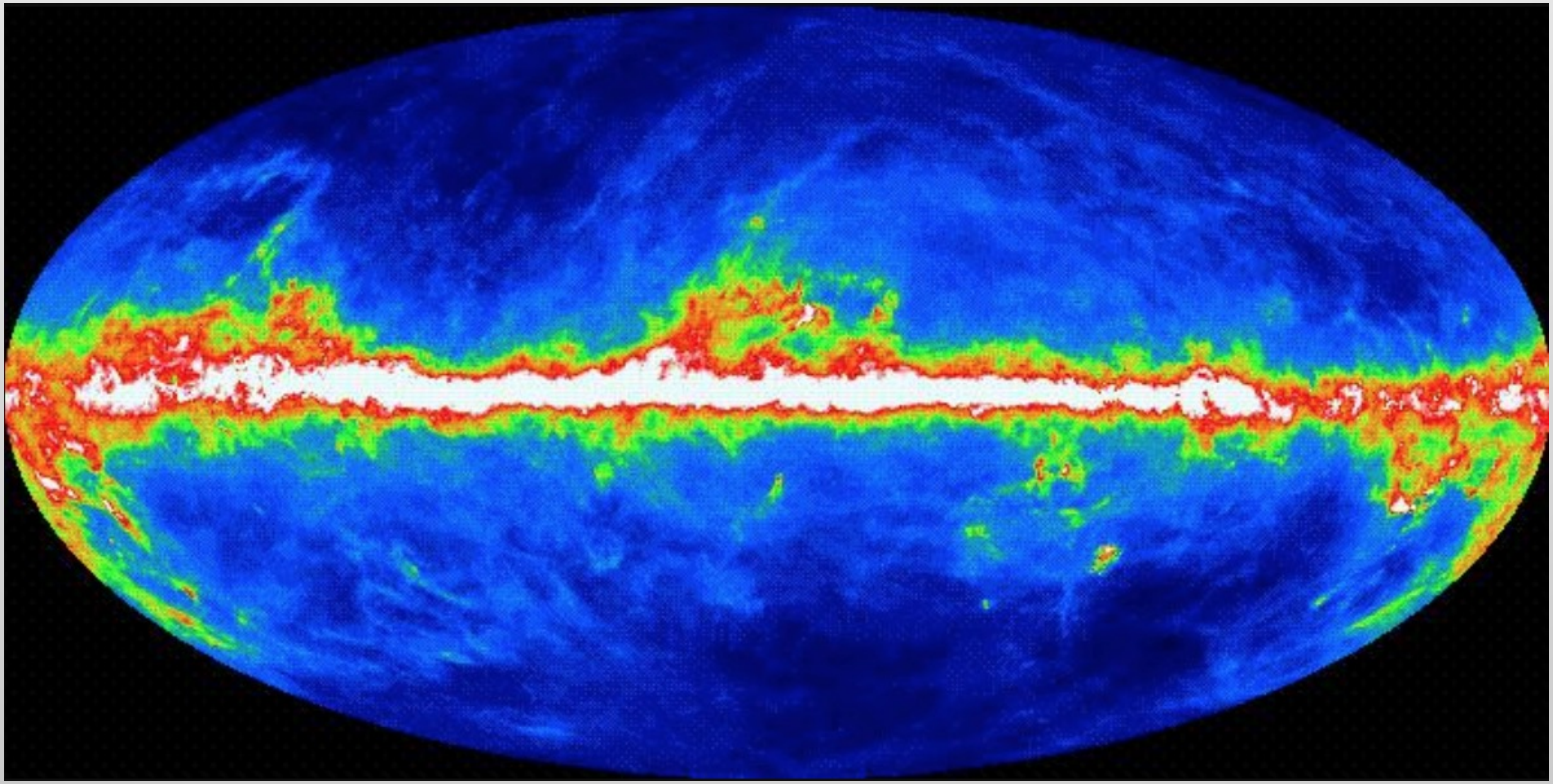


Narayanan et al. (2018)

Correcting for extinction: 1. Foreground extinction

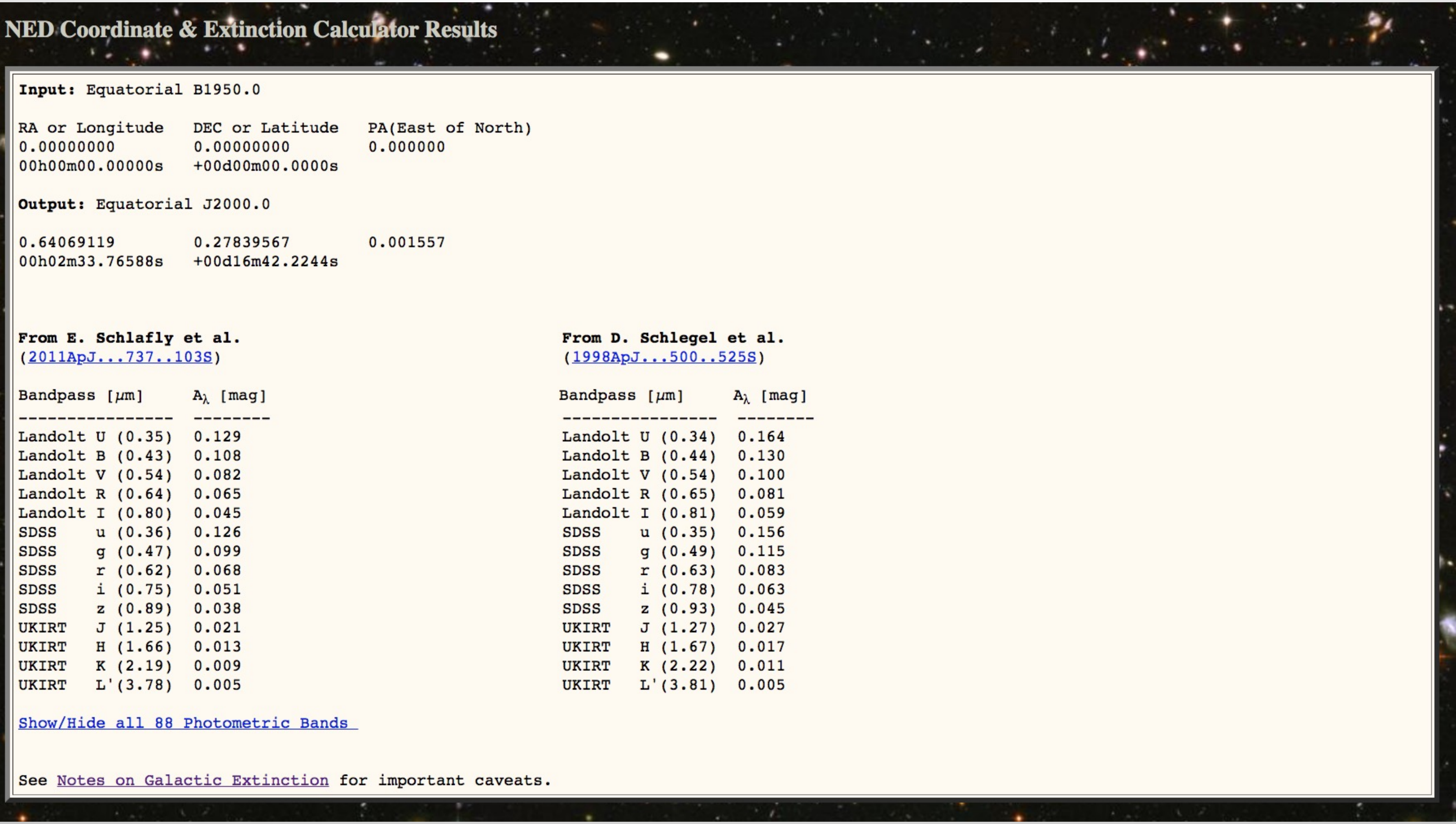
(i.e. in the Milky Way)

Most widely used Galactic extinction map produced by Schlegel, Finkbeiner & Davis (1998) from measurements made combining data from the Diffuse IR background Experiment (DIRBE) on the COBE satellite and IRAS.



All sky 100 micron map

Dial up extinction corrections from NED:
https://ned.ipac.caltech.edu/forms/calculator.html



NED Coordinate & Extinction Calculator Results

Input: Equatorial B1950.0

```
RA or Longitude    DEC or Latitude    PA(East of North)
0.00000000         0.00000000         0.000000
00h00m00.00000s    +00d00m00.0000s
```

Output: Equatorial J2000.0

```
0.64069119         0.27839567         0.001557
00h02m33.76588s    +00d16m42.2244s
```

From E. Schlafly et al.
(2011ApJ...737..103S)

Bandpass [μm]	A_λ [mag]
Landolt U (0.35)	0.129
Landolt B (0.43)	0.108
Landolt V (0.54)	0.082
Landolt R (0.64)	0.065
Landolt I (0.80)	0.045
SDSS u (0.36)	0.126
SDSS g (0.47)	0.099
SDSS r (0.62)	0.068
SDSS i (0.75)	0.051
SDSS z (0.89)	0.038
UKIRT J (1.25)	0.021
UKIRT H (1.66)	0.013
UKIRT K (2.19)	0.009
UKIRT L'(3.78)	0.005

From D. Schlegel et al.
(1998ApJ...500..525S)

Bandpass [μm]	A_λ [mag]
Landolt U (0.34)	0.164
Landolt B (0.44)	0.130
Landolt V (0.54)	0.100
Landolt R (0.65)	0.081
Landolt I (0.81)	0.059
SDSS u (0.35)	0.156
SDSS g (0.49)	0.115
SDSS r (0.63)	0.083
SDSS i (0.78)	0.063
SDSS z (0.93)	0.045
UKIRT J (1.27)	0.027
UKIRT H (1.67)	0.017
UKIRT K (2.22)	0.011
UKIRT L'(3.81)	0.005

Show/Hide all 88 Photometric Bands

See Notes on Galactic Extinction for important caveats.

Correcting for extinction: 2. Internal extinction

(i.e. in a given galaxy)

Want to recover the intrinsic flux from an observed (extincted) flux. Recall the general definition of astronomical magnitudes:

$m_1 - m_2 = -2.5 \log (f_2 / f_1)$

As applied to extinction:

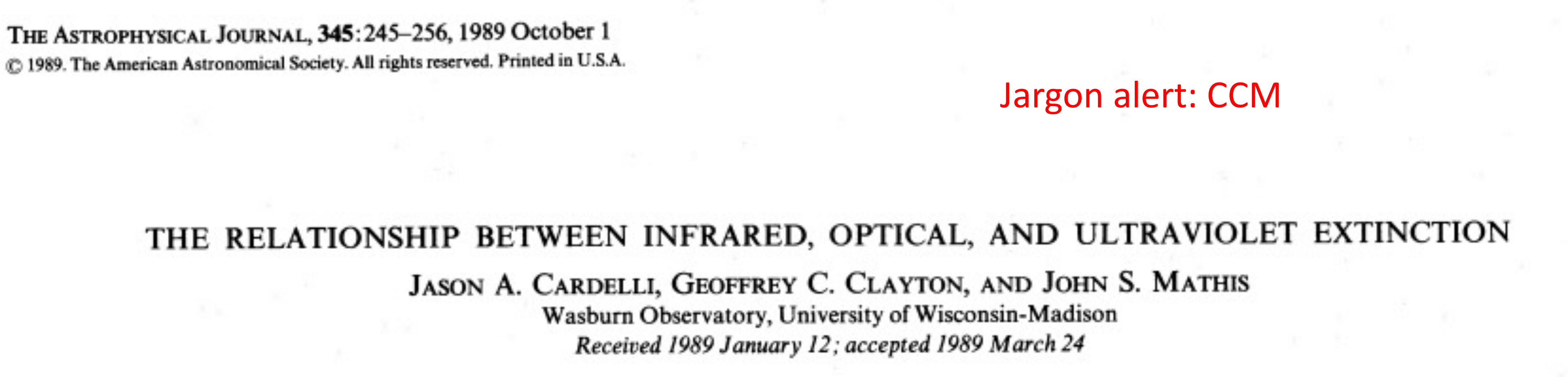
$A_\lambda = m_{\lambda,obs} - m_{\lambda,int} = -2.5 \log (f_{\lambda,int} / f_{\lambda,obs})$

Alternatively, this can be written:

$f_{\lambda,int} / f_{\lambda,obs} = 10^{0.4 * A\lambda}$

In practice, need to determine A_λ to correct the flux as a function of wavelength. This is determined by 1) *assuming* an extinction curve shape and 2) *measuring* a normalization.

Step 1: Common choices are either a Milky Way (with your choice of R_V), SMC or LMC type curve.



THE ASTROPHYSICAL JOURNAL, **345**:245–256, 1989 October 1

Jargon alert: CCM

THE RELATIONSHIP BETWEEN INFRARED, OPTICAL, AND ULTRAVIOLET EXTINCTION

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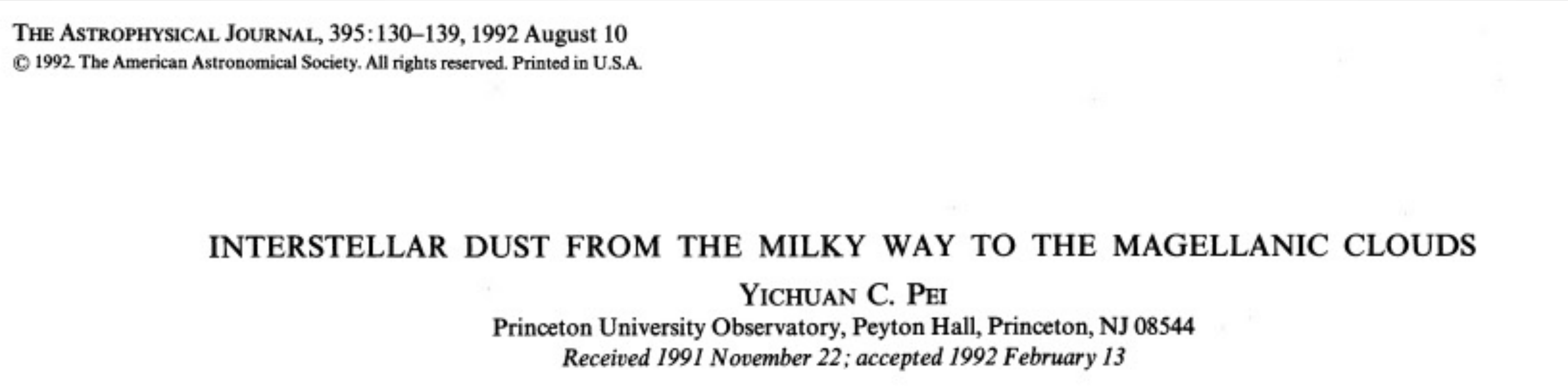
Received 1989 January 12; accepted 1989 March 24



THE ASTROPHYSICAL JOURNAL, 395:130–139, 1992 August 10

INTERSTELLAR DUST FROM THE MILKY WAY TO THE MAGELLANIC CLOUDS

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Received 1991 November 22; accepted 1992 February 13

Correcting for extinction: 2. Internal extinction

(i.e. in a given galaxy)

Step 2: Determine normalization (we'll use E(B-V)) by using the Balmer decrement, which has a known theoretical value.

Jargon alert: Balmer decrement = Hα/Hβ

$f_{H\alpha,int}/f_{H\beta,int} = 2.85$ (although the exact number does depend on ISM conditions)

Recall that

$f_{\lambda,int}/f_{\lambda,obs} = 10^{0.4*A\lambda}$

Alternatively:

$f_{\lambda,int}/f_{\lambda,obs} = 10^{0.4*k(\lambda)\,E(B-V)}$ (1)

So we can write the ratio of the two Balmer lines as:

$$\frac{f_{H\alpha,int}/f_{H\alpha,obs}}{f_{H\beta,int}/f_{H\beta,obs}} = \frac{10^{0.4A(H\alpha)}}{10^{0.4A(H\beta)}}$$

Correcting for extinction: 2. Internal extinction

(i.e. in a given galaxy)

$$\frac{f_{H\alpha,int}/f_{H\alpha,obs}}{f_{H\beta,int}/f_{H\beta,obs}} = \frac{10^{0.4A(H\alpha)}}{10^{0.4A(H\beta)}} \qquad (2)$$

We'll now write this in terms of the normalized extinction curve i.e. $k(\lambda)\,E(B\text{-}V) = A_\lambda$

$$\frac{f_{H\alpha,int}/f_{H\alpha,obs}}{f_{H\beta,int}/f_{H\beta,obs}} = \frac{10^{0.4k(H\alpha)E(B-V)}}{10^{0.4k(H\beta)E(B-V)}} \qquad (3)$$

Which can be re-arranged (and substitute the intrinsic Balmer decrement value) to give:

$$E(B-V) = \frac{log(\frac{2.85}{f_{H\alpha,obs}/f_{H\beta,obs}})}{0.4[k(H\alpha) - k(H\beta)]} \qquad (4)$$

We can now solve for E(B-V) by looking up the values of k(Hα) and k(Hβ) for a given extinction curve.

Correcting for extinction: 2. Internal extinction

(i.e. in a given galaxy)

Example for the CCM MW extinction curve. First they define ξ(**λ**) in terms of their derived curve coefficients:

$$\langle A(\lambda)/A(V)\rangle = a(x) + b(x)/R_V \, . \qquad (1)$$

Then they list how to determine the coefficients, in different wavelength regimes, e.g:

Optical/NIR: $1.1\ \mu\mathrm{m}^{-1} \leq x \leq 3.3\ \mu\mathrm{m}^{-1}$ and $y = (x - 1.82)$;

$$\begin{aligned} a(x) = 1 &+ 0.17699y - 0.50447y^2 - 0.02427y^3 + 0.72085y^4 \\ &+ 0.01979y^5 - 0.77530y^6 + 0.32999y^7 \, ; \qquad (3a) \end{aligned}$$

$$\begin{aligned} b(x) = &\ 1.41338y + 2.28305y^2 + 1.07233y^3 - 5.38434y^4 \\ &- 0.62251y^5 + 5.30260y^6 - 2.09002y^7 \, . \qquad (3b) \end{aligned}$$

Recall definitions:

$\xi(\lambda) = A(\lambda)/A(V)$

$k(\lambda) = \xi(\lambda)\, R_V$

For an $R_V = 3.1$ these coefficients give k(Hα)=2.535 and k(Hβ)=3.60 which can be substituted in equation (4) to yield E(B-V). In turn E(B-V) can be inserted in equation (1) to correct any wavelength.

Summary

- Dust forms an important component of the ISM.

- Correcting for dust is essential if you want to recover intrinsic fluxes/magnitudes.

- Extinction curves can vary considerably, both within the Galaxy and from galaxy-to-galaxy.

- Need to consider both foreground (Galactic) and internal (for a given galaxy) extinction.