The Effects of Earth's Atmosphere (and the ISM) on Astronomical Observations

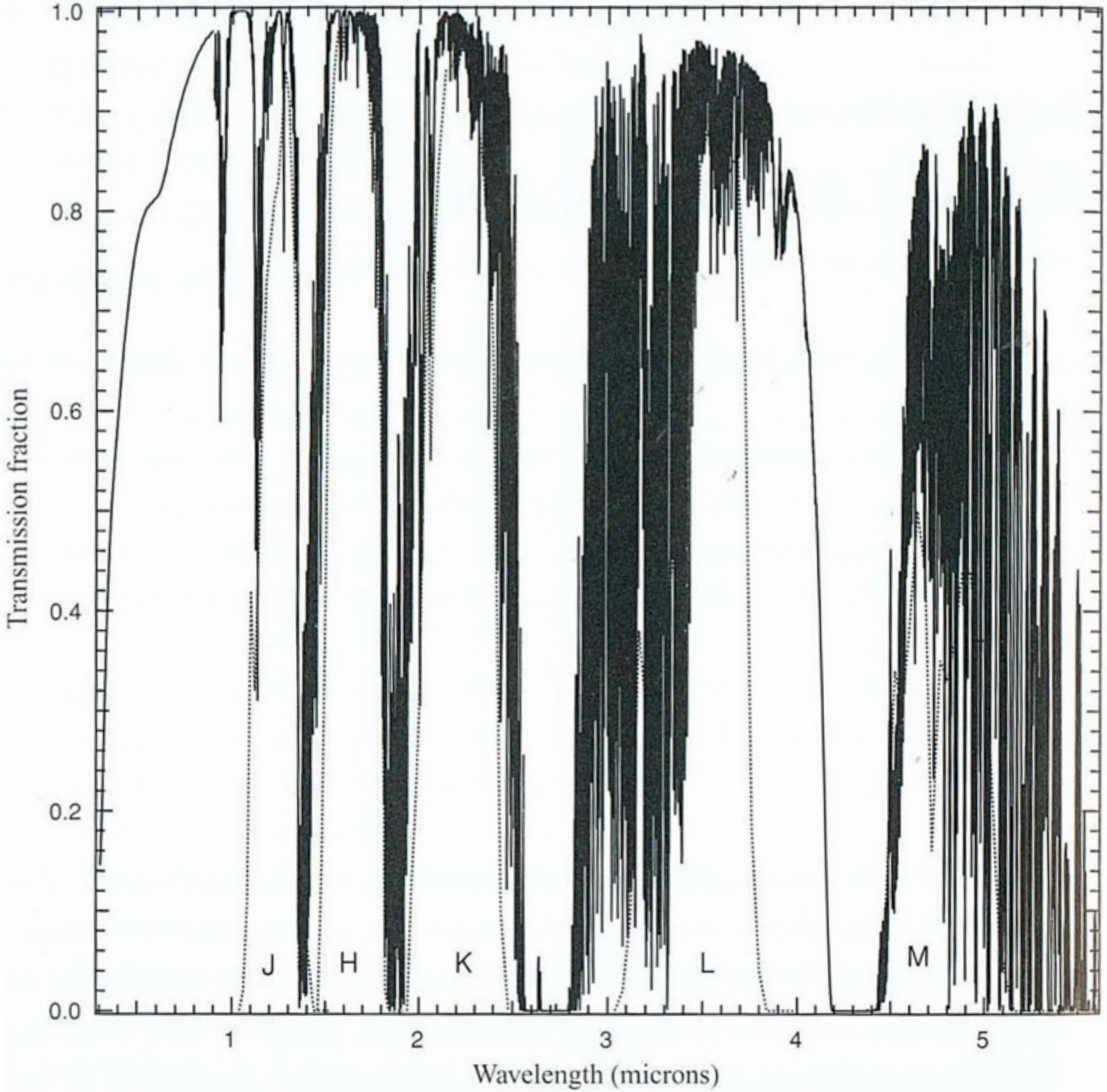
Ast 401/Phy 580
Fall 2015

What does the atmosphere do?

1. Extinction
2. Refraction
3. Seeing
4. Scintillation
5. Dispersion (refraction as a function of λ)

Atmospheric Extinction

The atmosphere is mostly transparent at optical and radio wavelengths; there are a few bands in the near-IR (J, H, and K) and mid-IR (L and M) that are also transparent.


1.0
0.8
0.6
0.4
0.2
0.0
Transmission fraction
J
H
K
L
M
1
2
3
4
5
Wavelength (microns)

Atmospheric Extinction

But even in the optical, the air is not completely transparent!

Two components (optical)

- Absorption by atoms, molecules, and aerosols (small dust particles)
- Rayleigh scattering off of molecules ($1/\lambda^4$).

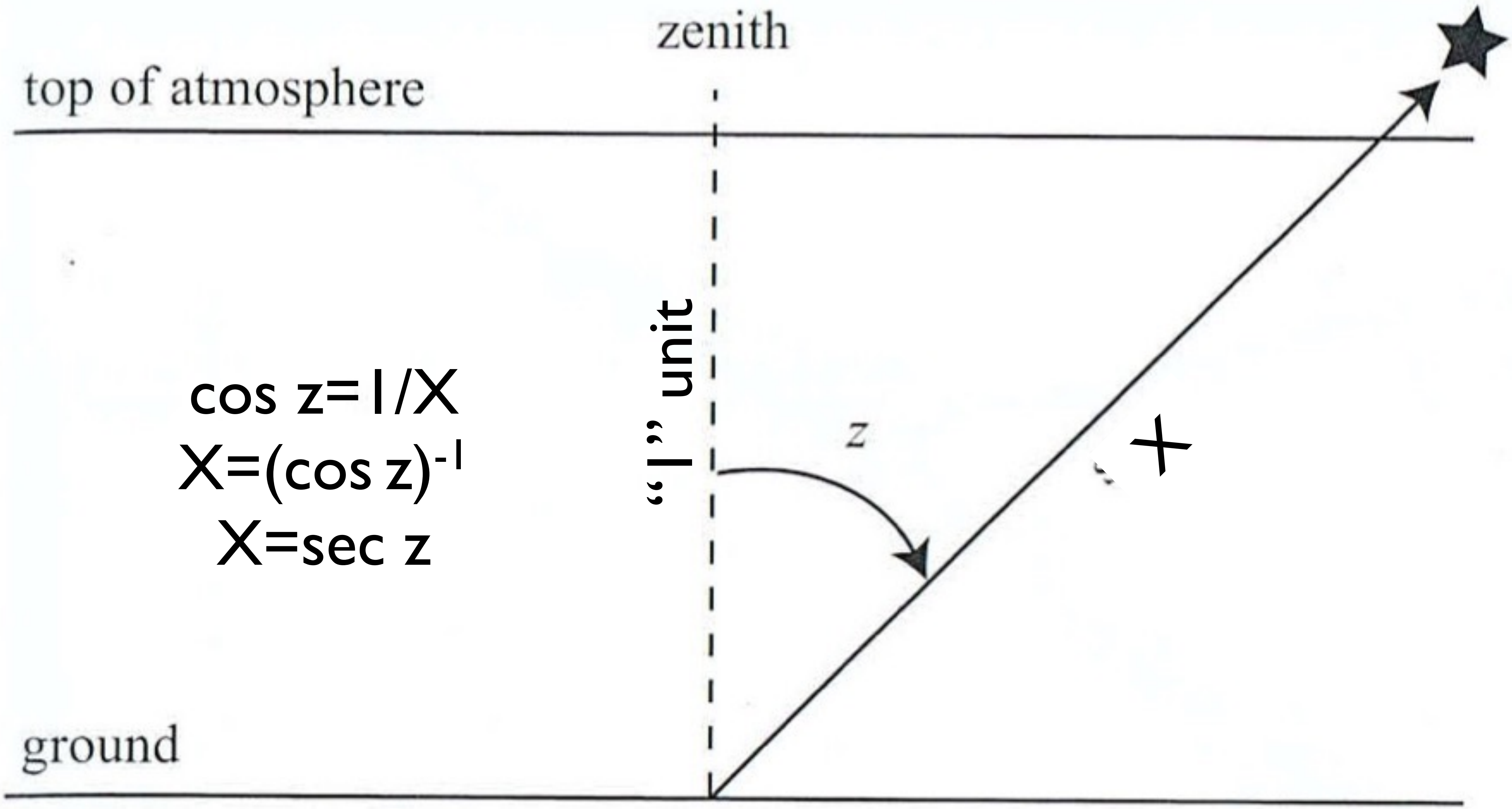
(In the infrared, it's all about water vapor!)

Atmospheric Extinction

The amount of extinction (at a particular wavelength) depends upon how much atmosphere you're looking through.

Can assume plane-parallel atmosphere....

Airmass "X"



$\cos z = 1/X$

$X = (\cos z)^{-1}$

$X = \sec z$

Atmospheric Extinction

$$X = \sec z$$

At higher z, this breaks down and we need to use

$$X = \sec z[1-0.0012(\sec^2 z-1)]$$

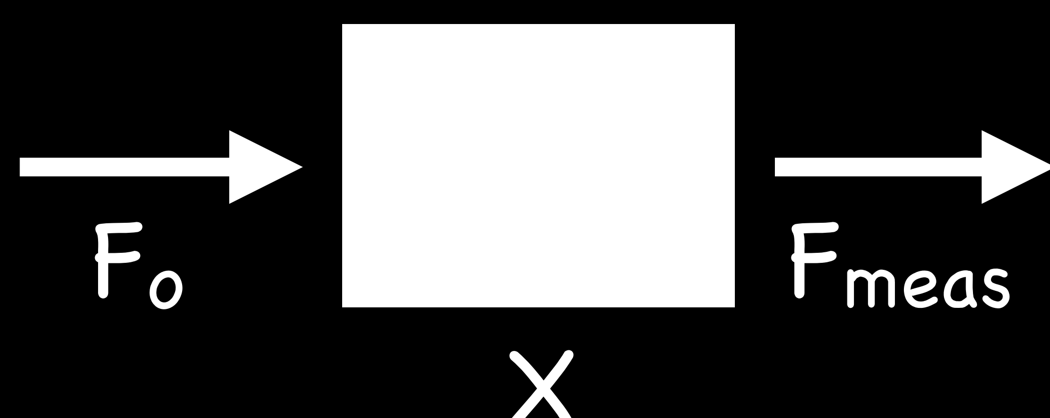
These differ by only 1% at $z=71^\circ$ ($X=3.1$) so the simple one is fine unless you're at VERY high airmass.

Atmospheric Extinction

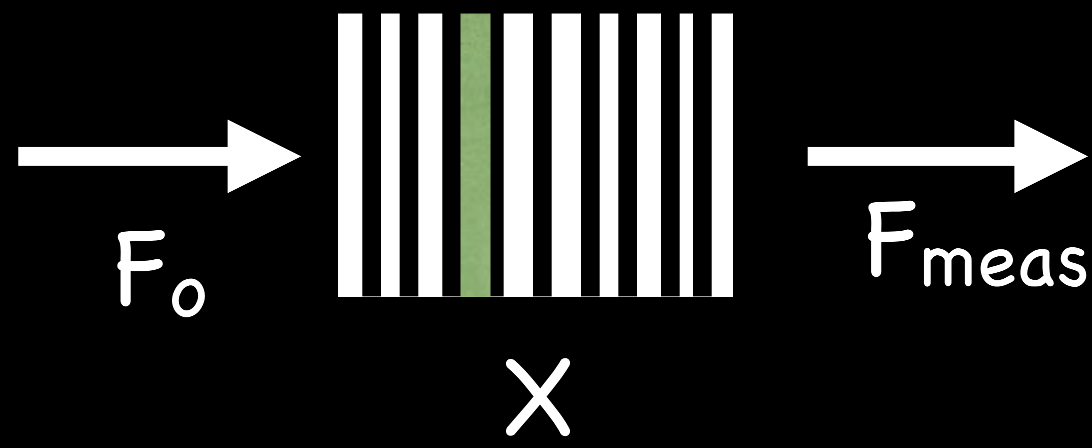
So the flux F_{meas} we MEASURE will be decreased from what it is outside the earth's atmosphere (F_o):

$$F_{meas} = F_o\, 10^{-(kX)}$$

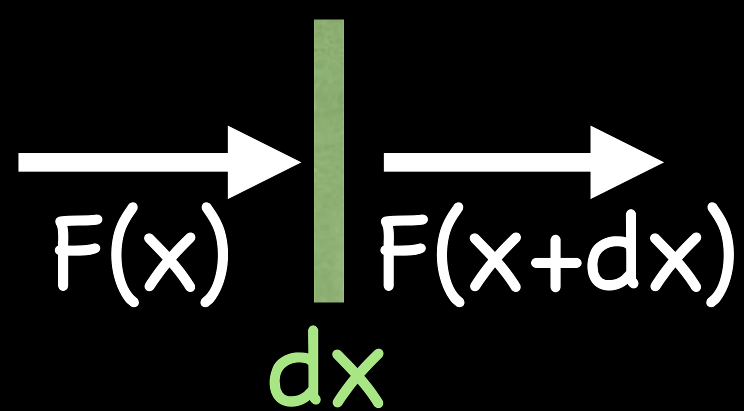
This is standard "attenuation" or extinction.



Atmospheric Extinction



$$F_{meas} = F_o\ 10^{-(kX)}$$



$$dF(x) = -F(x)\ k'\ dx$$

$$dF(x)/F(x) = -k'\ dx$$

$$\ln F(x) = -k'x + C$$

$$F(x) = C\ e^{-k'x}$$

But $F(x) = F_o$ at $x = 0$

$$F(x) = F_o e^{-k'x}$$

$$F(X) = F_o\ 10^{-(kX)}$$

Atmospheric Extinction

So the flux F_{meas} we MEASURE will be decreased from what it is outside the earth's atmosphere (F_o):

$$F_{meas} = F_o \, 10^{-(kX)}$$

This is standard "attenuation" or extinction.

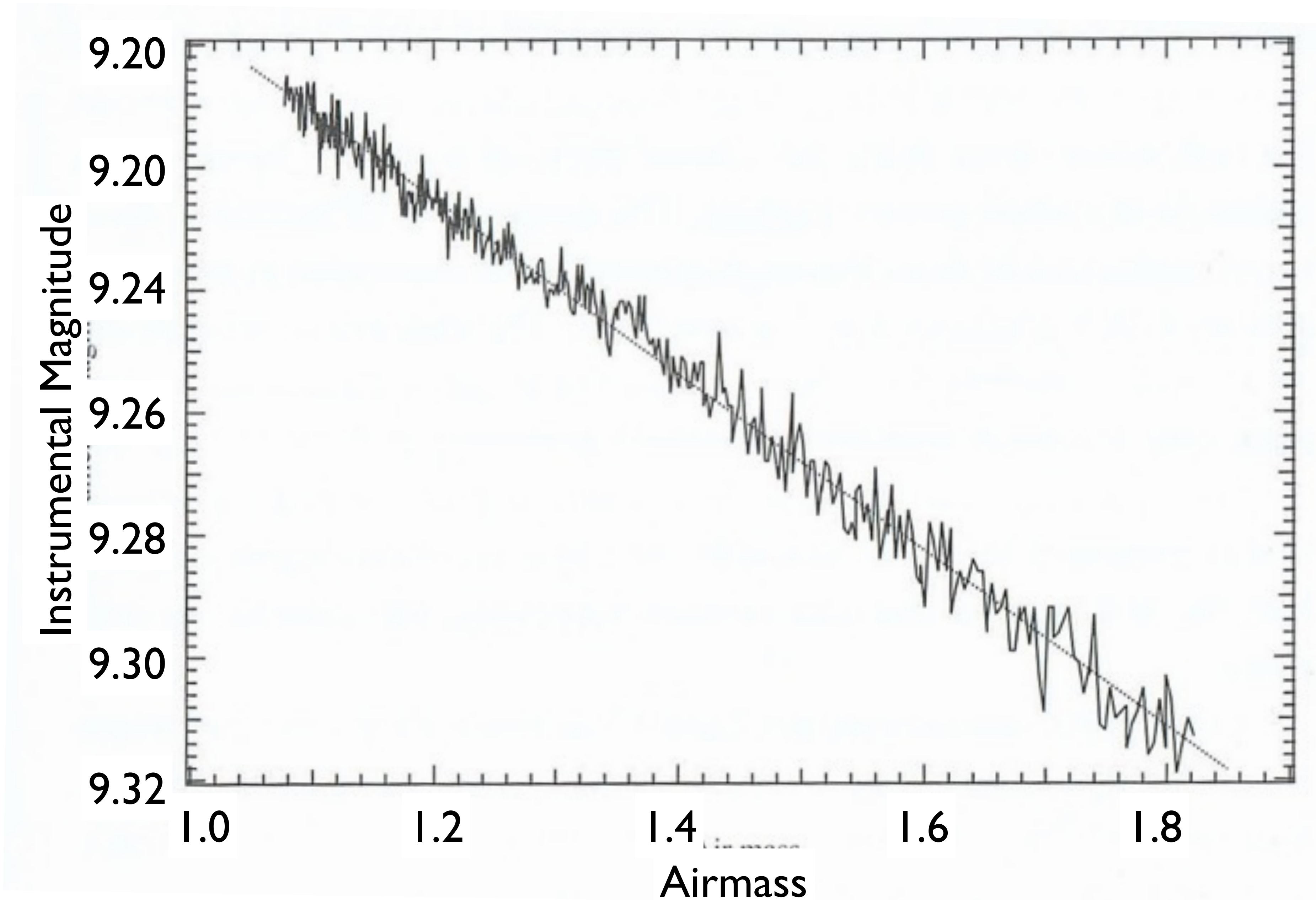
What if we go to magnitudes?

$$-2.5 \log F_{meas} = -2.5 \log F_o + kX$$

$$-2.5 \log (F_{meas}/F_o) = kX$$

$$\Delta \, mag = kX$$

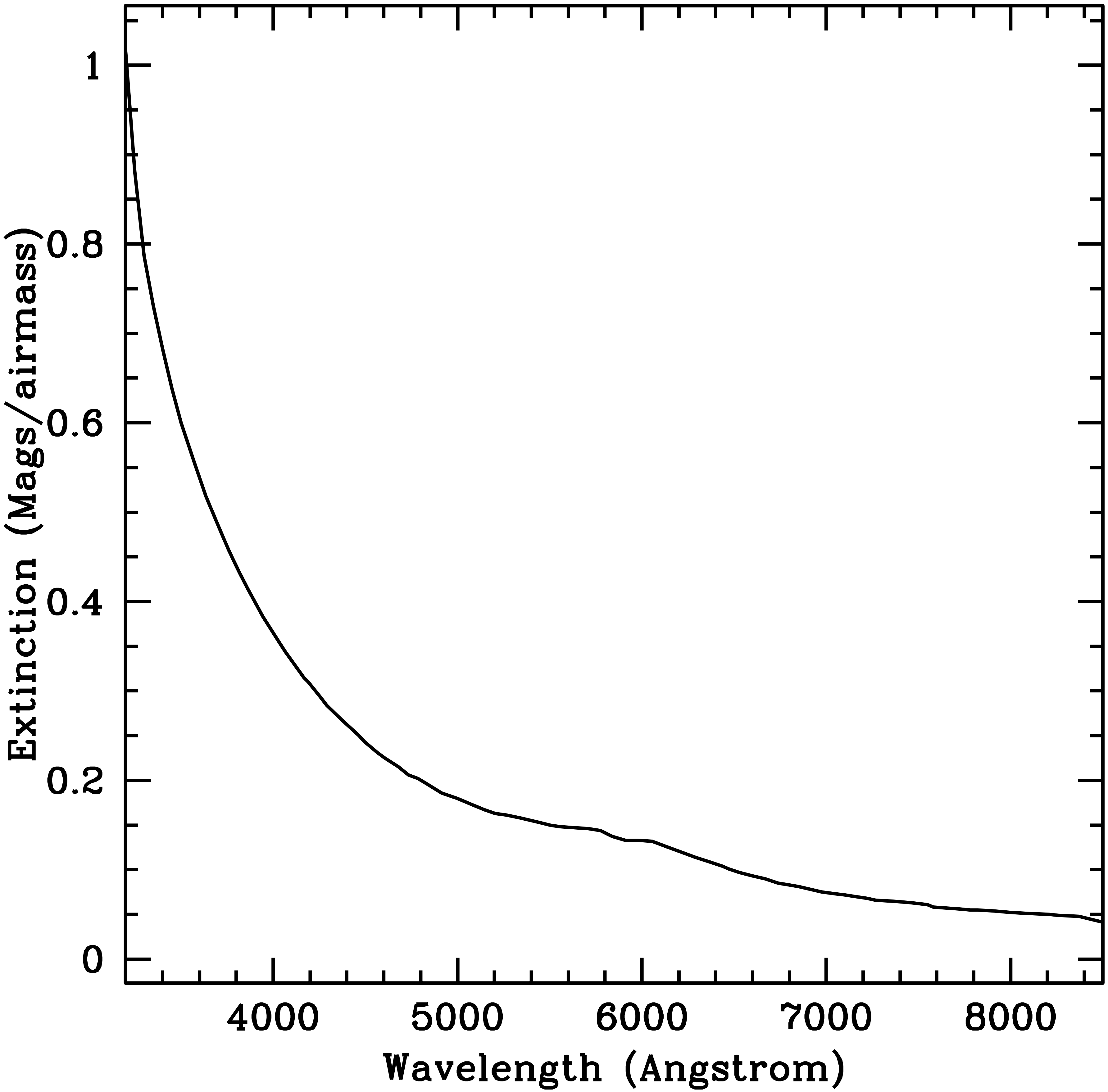
Atmospheric Extinction



Well, sure ‘nuff...

Atmospheric Extinction

If we measure the extinction using spectrophotometry, we get something like this:



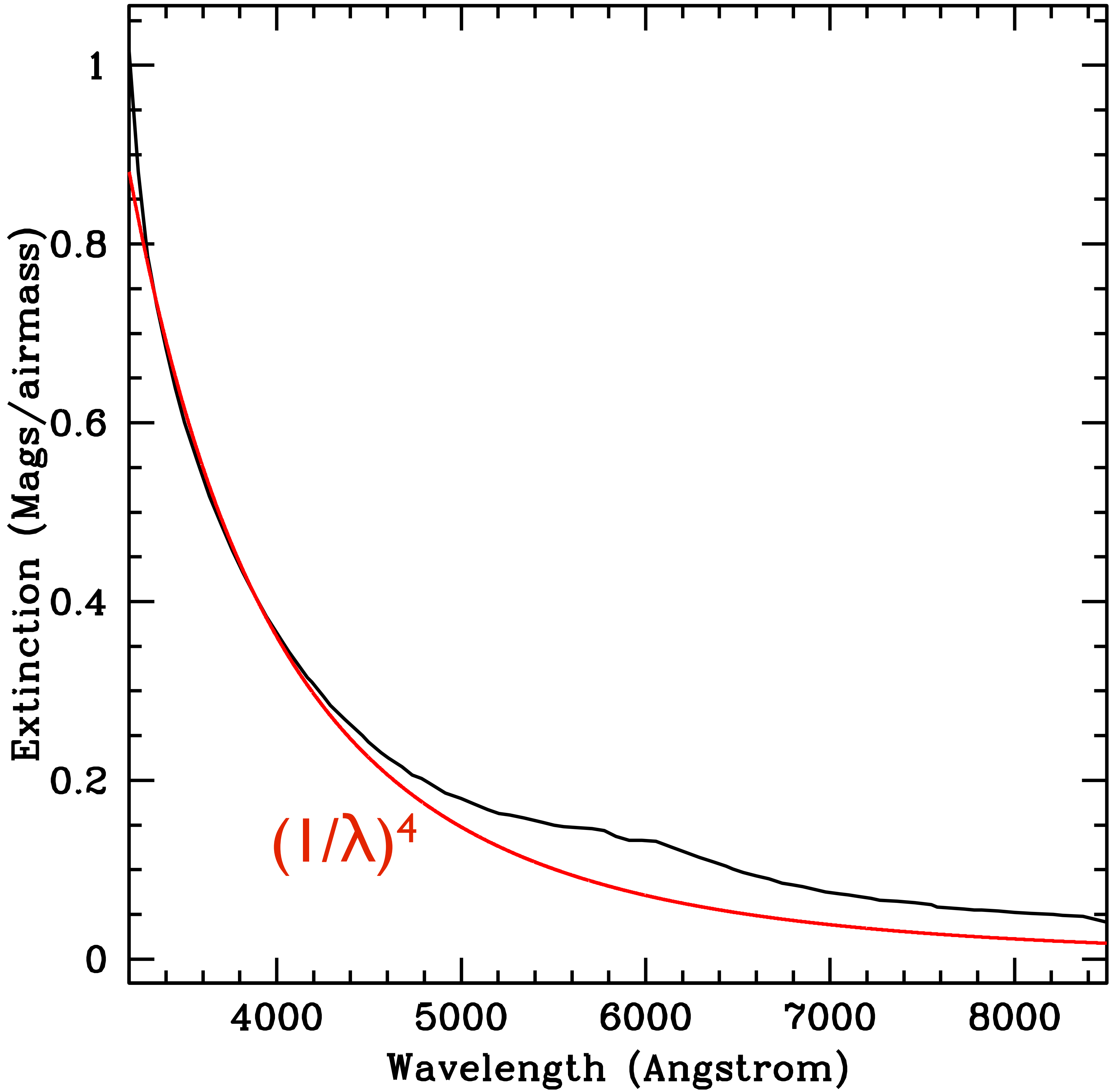
1
0.8
0.6
0.4
0.2
0
Extinction (Mags/airmass)
4000
5000
6000
7000
8000
Wavelength (Angstrom)

Atmospheric Extinction

Recall that a major component of atmospheric extinction is Rayleigh scattering. For that,

$$F=F_o\ 10^{-(kX)}$$

with $k=const/\lambda^4$


Extinction (Mags/airmass)
1
0.8
0.6
0.4
0.2
0
4000
5000
6000
7000
8000
Wavelength (Angstrom)
(1/λ)4

Atmospheric Extinction

"Typical" extinction terms:

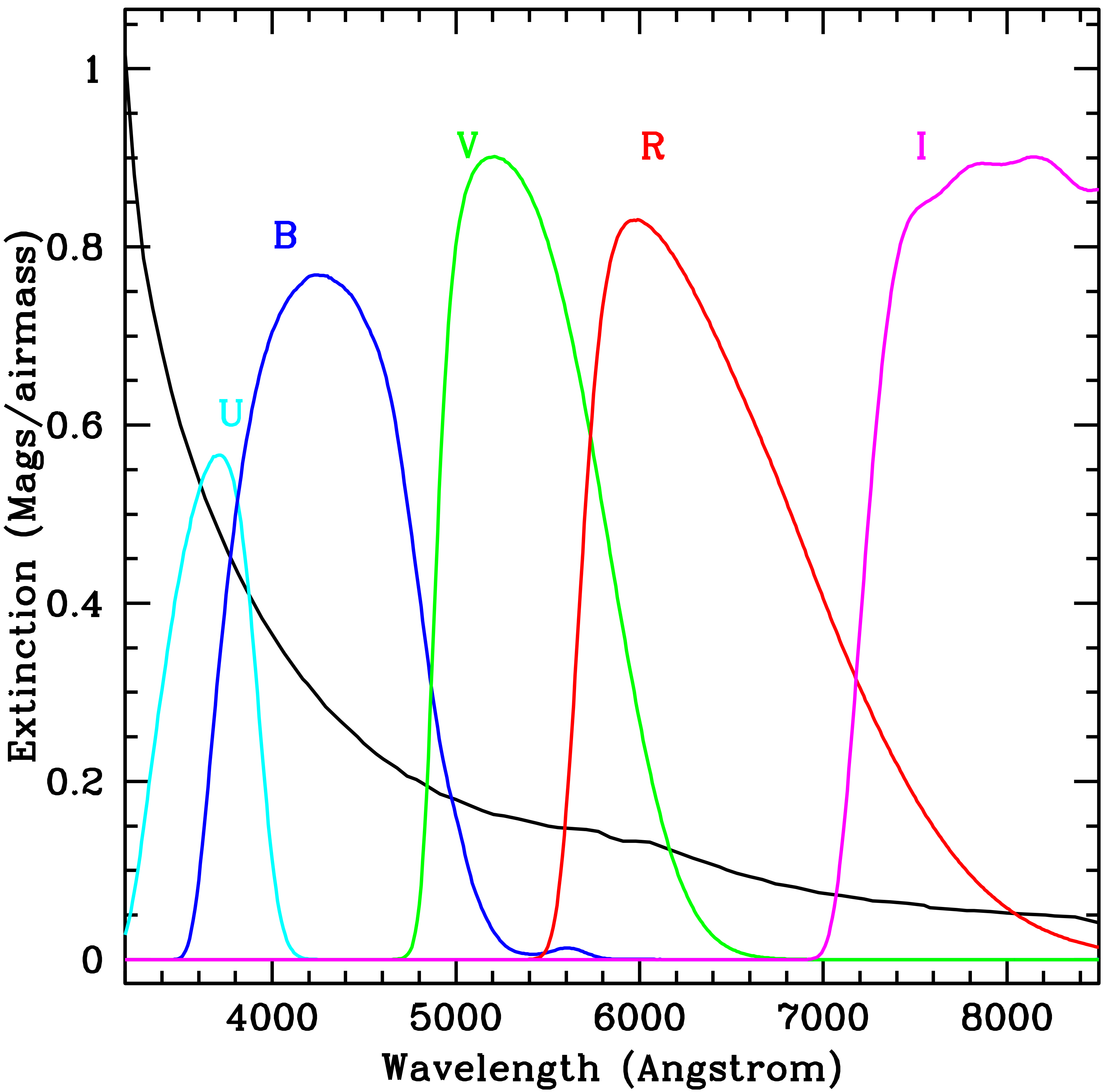
k_U = 0.50 mag/airmass

k_B = 0.25 mag/airmass

k_V = 0.15 mag/airmass

k_R = 0.10 mag/airmass

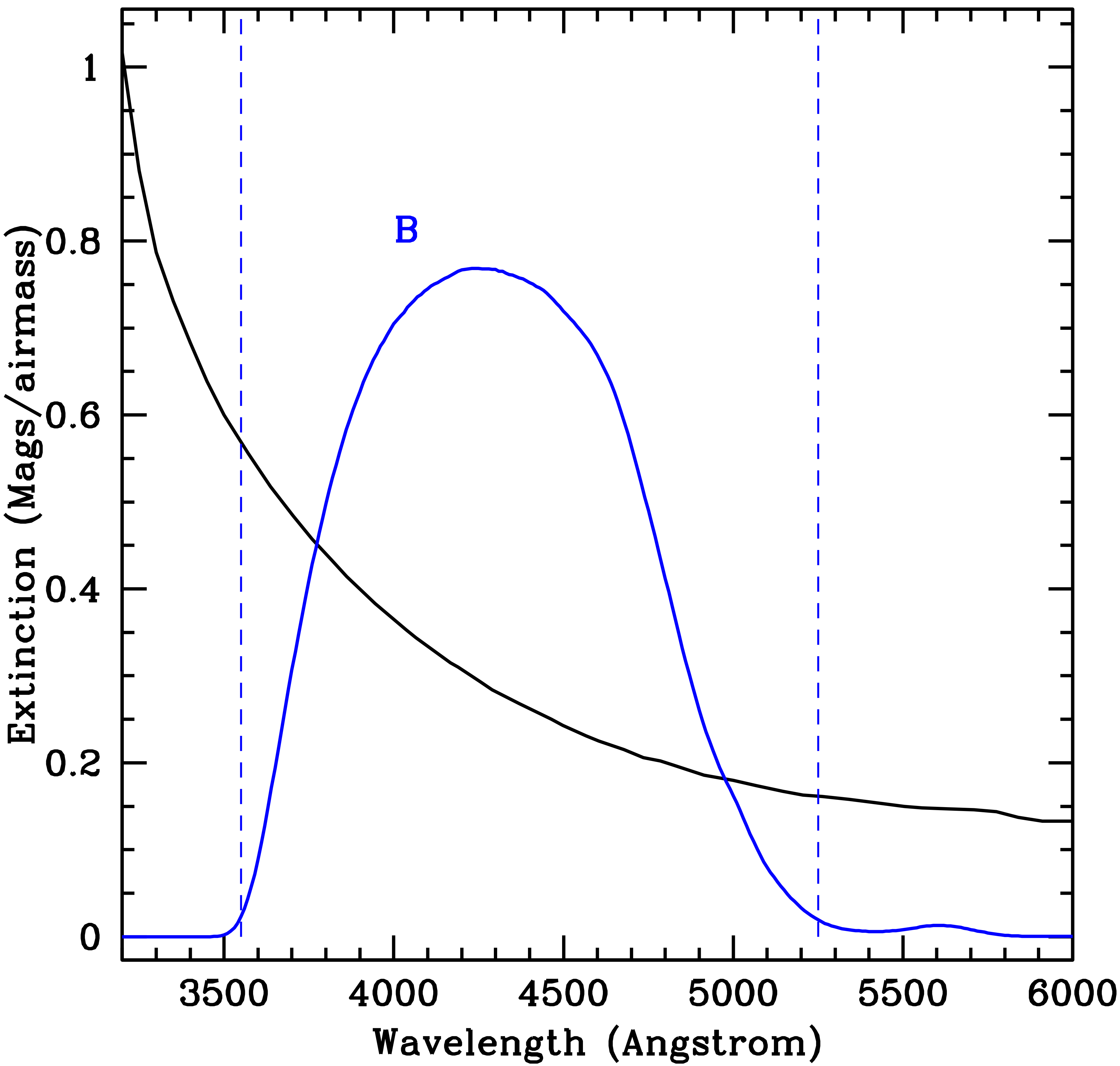
k_I = 0.07 mag/airmass



Extinction (Mags/airmass)
Wavelength (Angstrom)
U
B
V
R
I
0
0.2
0.4
0.6
0.8
1
4000
5000
6000
7000
8000

Atmospheric Extinction

Note, however, that the bandpasses are very wide compared to what's going on with the extinction.


B
1
0.8
0.6
0.4
0.2
0
Extinction (Mags/airmass)
3500
4000
4500
5000
5500
6000
Wavelength (Angstrom)

Atmospheric Extinction

The extinction may depend upon the **color** of the star when observing using wide filters (such as UBVRI), particularly at U and B. May need:

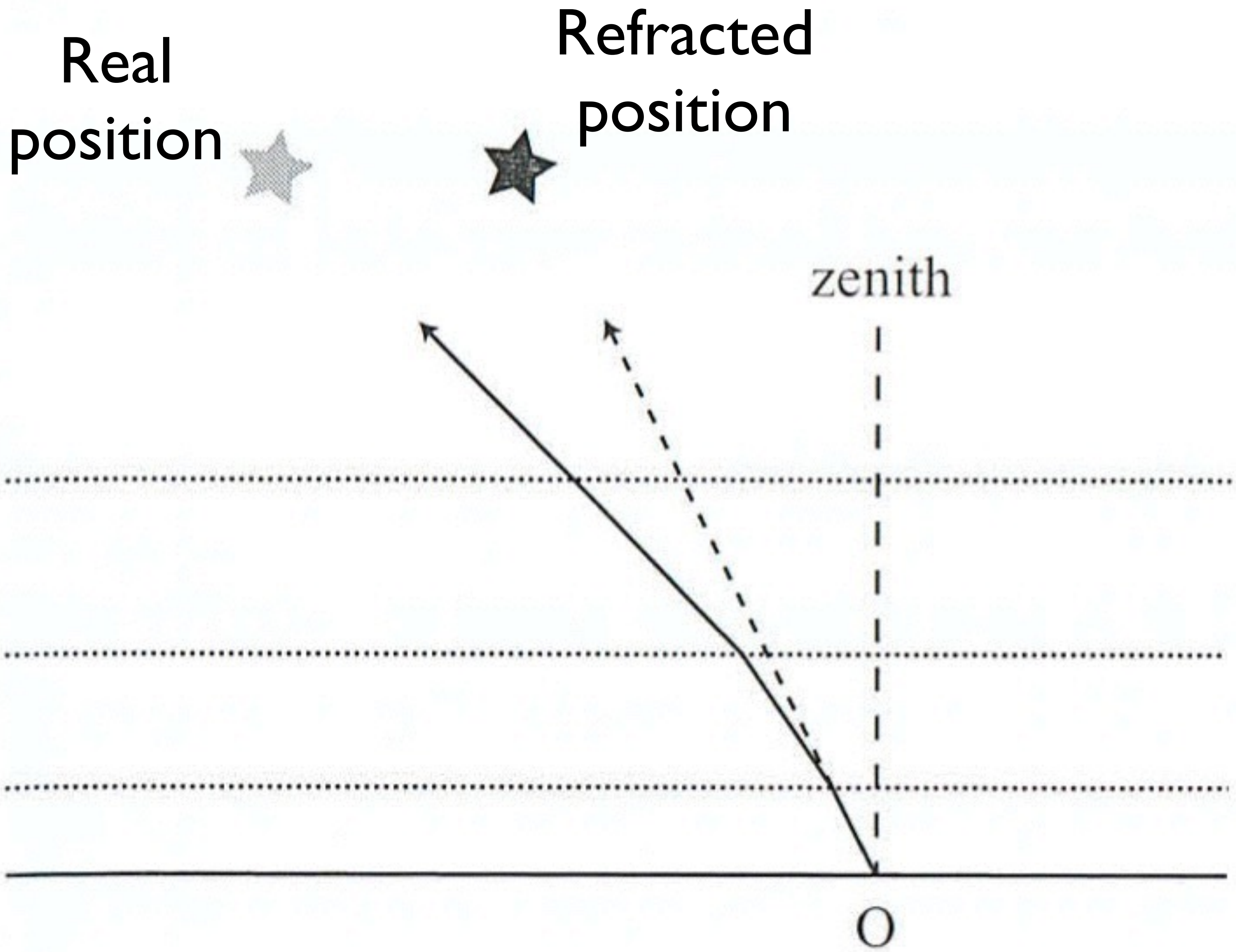
$$\Delta \text{mag} = kX + k'(B-V)X$$

term to correct for extinction rather than just

$$\Delta \text{mag} = kX$$

In practice, I've never had to do this. Staying to reasonably low airmasses ($X \leqslant 1.5$-ish) helps.

Refraction



Refraction

Objects outside the earth's atmosphere will appear higher in the sky than they actually are. At 5000Å, the amount of refraction is roughly

$$R_{5000Å}=60''\tan z$$

where z is technically the **apparent** zenith distance. At large zenith distances need to use something more complicated.

The fact that the amount of refraction depends upon zenith distance is why the sun and moon appear to be **flattened** (17%) when on the horizon.

Refraction

Note: when the lower limb of the sun is apparently just touching the horizon, the entire sun is actually BELOW the horizon!

Refraction

Another example of refraction by Earth's atmosphere

Refraction

Why do we care?

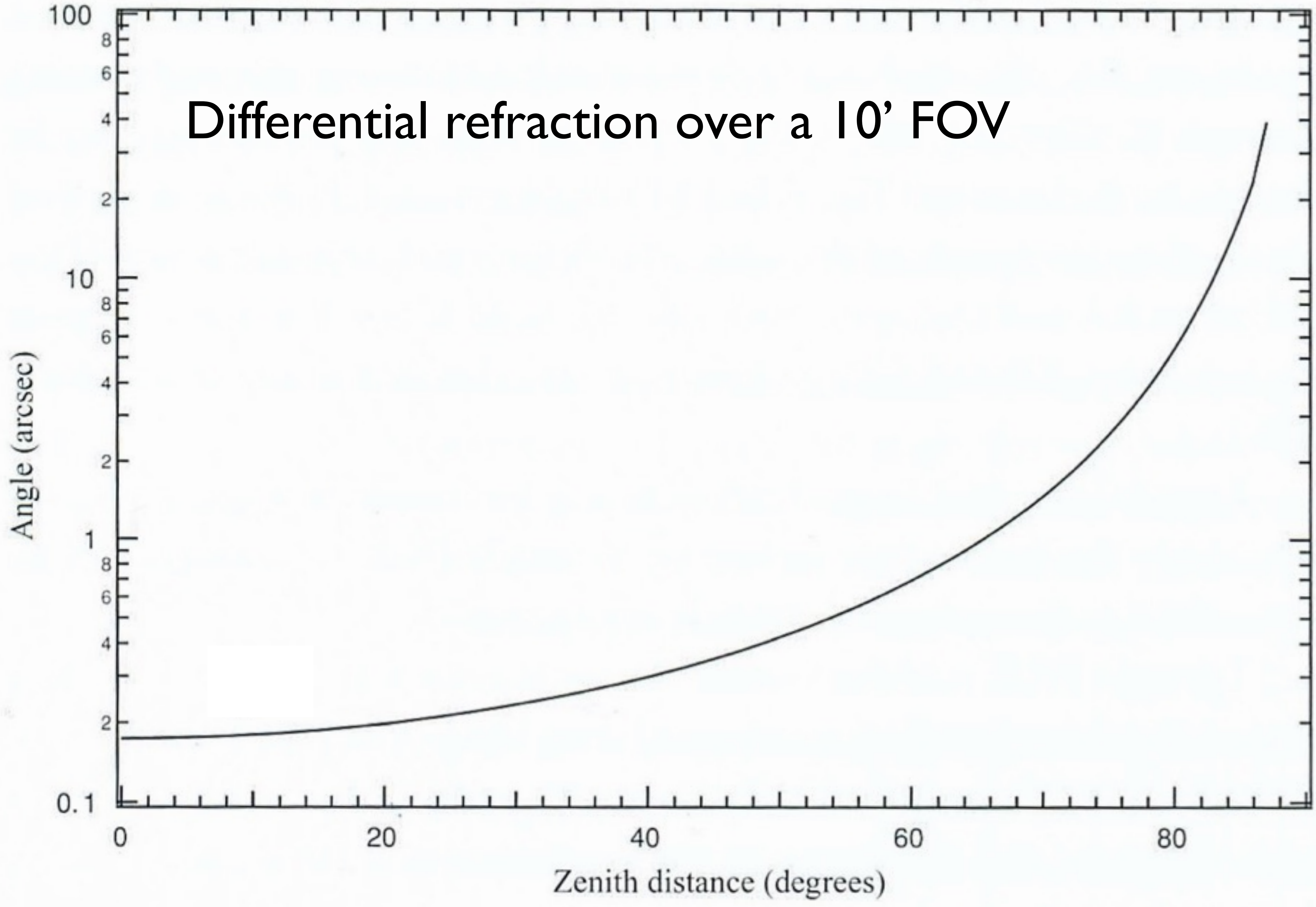
- Refraction amount to 1 **arcminute** at z=45°! That's a lot!!! Must correct for this when pointing telescopes. Note that it changes slowly (check the derivative!); it amounts to 9.9′ an altitude of 5° (z=85°), but 34′ on the horizon.
- Differential refraction: two kinds, both matter!

Refraction

Differential refraction:

- **Spatial** differential refraction. The scale is not quite the same "up and down" as "left and right" if the field of view (FOV) is significant.

Differential refraction over a 10’ FOV



Refraction

Wavelength-dependent refraction, another kind of "differential refraction"

- The atmosphere acts like a prism, dispersing the light from a star into a small rainbow, with blue at the top. The reason is the same: the refractive index n is a function of wavelength both in glass and in air: n decreases with wavelength. So the blue image is refracted more and will be higher than the red image.

Refraction

$$R(\lambda) = R(\lambda) - R(5000) = 206265\ [(n(\lambda) - n(5000)]\tan z$$

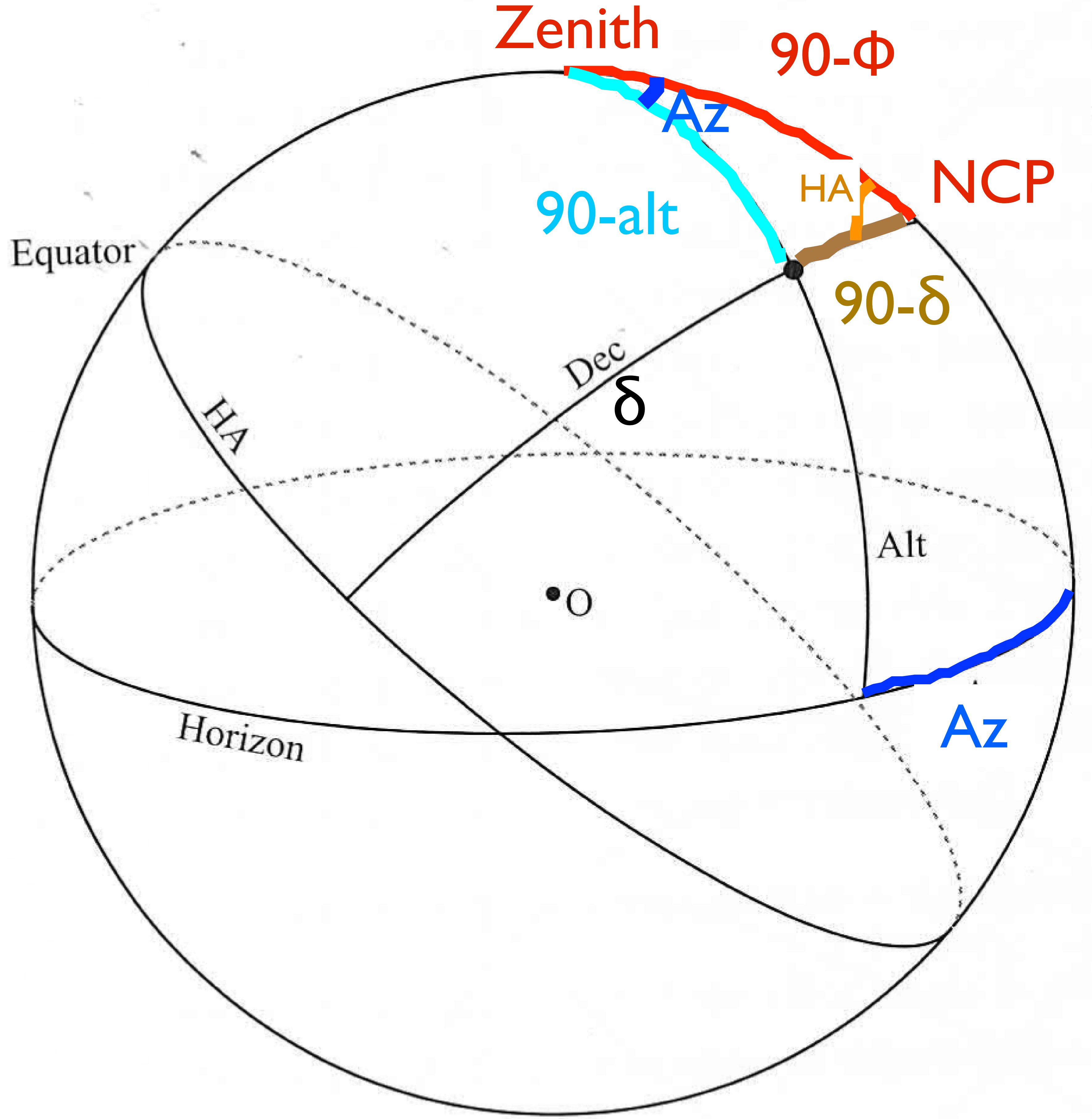
Table I

Atmospheric differential refraction at an altitude of 2 km (arcseconds)

Sec z	Wavelength (Ångstroms) 3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.05	0.68	0.38	0.20	0.08	0.00	-0.06	-0.11	-0.14	-0.17	-0.19	-0.21	-0.23
1.10	0.97	0.55	0.29	0.12	0.00	-0.09	-0.15	-0.20	-0.24	-0.28	-0.30	-0.32
1.15	1.20	0.68	0.36	0.15	0.00	-0.11	-0.19	-0.25	-0.30	-0.34	-0.38	-0.40
1.20	1.40	0.80	0.42	0.17	0.00	-0.13	-0.22	-0.30	-0.35	-0.40	-0.44	-0.47
1.25	1.59	0.90	0.48	0.20	0.00	-0.14	-0.25	-0.33	-0.40	-0.45	-0.50	-0.53
1.30	1.76	1.00	0.53	0.22	0.00	-0.16	-0.28	-0.37	-0.44	-0.50	-0.55	-0.59
1.35	1.92	1.09	0.58	0.24	0.00	-0.17	-0.30	-0.40	-0.48	-0.55	-0.60	-0.64
1.40	2.07	1.18	0.62	0.26	0.00	-0.19	-0.33	-0.44	-0.52	-0.59	-0.65	-0.69
1.45	2.22	1.26	0.67	0.28	0.00	-0.20	-0.35	-0.47	-0.56	-0.63	-0.69	-0.74
1.50	2.37	1.34	0.71	0.29	0.00	-0.21	-0.37	-0.50	-0.60	-0.68	-0.74	-0.79
1.55	2.51	1.42	0.75	0.31	0.00	-0.23	-0.40	-0.53	-0.63	-0.72	-0.78	-0.84
1.60	2.64	1.50	0.80	0.33	0.00	-0.24	-0.42	-0.56	-0.67	-0.75	-0.83	-0.88
1.65	2.78	1.58	0.84	0.34	0.00	-0.25	-0.44	-0.59	-0.70	-0.79	-0.87	-0.93
1.70	2.91	1.65	0.88	0.36	0.00	-0.26	-0.46	-0.61	-0.73	-0.83	-0.91	-0.97
1.75	3.04	1.73	0.92	0.38	0.00	-0.27	-0.48	-0.64	-0.77	-0.87	-0.95	-1.02
1.80	3.17	1.80	0.95	0.39	0.00	-0.29	-0.50	-0.67	-0.80	-0.90	-0.99	-1.06
1.85	3.29	1.87	0.99	0.41	0.00	-0.30	-0.52	-0.69	-0.83	-0.94	-1.03	-1.10
1.90	3.42	1.94	1.03	0.42	0.00	-0.31	-0.54	-0.72	-0.86	-0.98	-1.07	-1.14
1.95	3.54	2.01	1.07	0.44	0.00	-0.32	-0.56	-0.75	-0.89	-1.01	-1.11	-1.19

Refraction

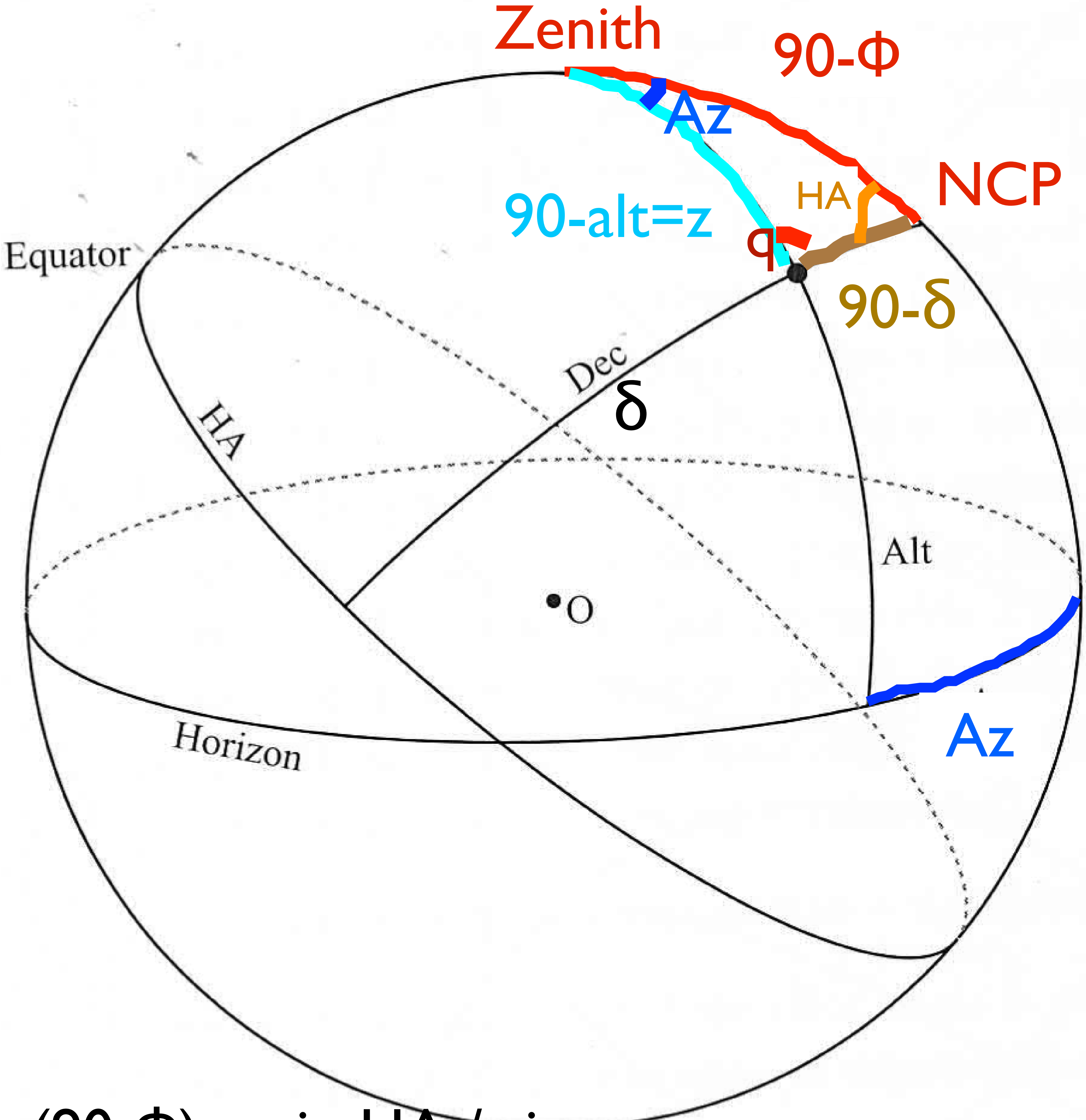
If you're observing with a narrow (1″) spectrograph slit that is oriented the wrong way, then not all wavelengths are entering the slit. The trick is to orient the slit at the parallactic angle.



Zenith
90-Φ
Az
NCP
HA
90-alt
Equator
90-δ
Dec
δ
HA
Alt
O
Horizon
Az

Parallactic angle

The position angle is always the angle from north through east. It's the missing angle in this diagram!



$\sin q / \sin(90-\Phi) = \sin HA / \sin z$

$\sin q = \cos\Phi \sin HA / \sin z$

Atmospheric Dispersion Compensation

For a fiber spectrograph, such as Hectospec, there's nothing practical to be done. Fibers are 1.5" in diameter.

Hectospec and 6.5-m MMT for M31, M33

MMT photo by Kathryn Neugent

Table I

Atmospheric differential refraction at an altitude of 2 km

Sec z	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500
						Wavelength (Ångstroms)				
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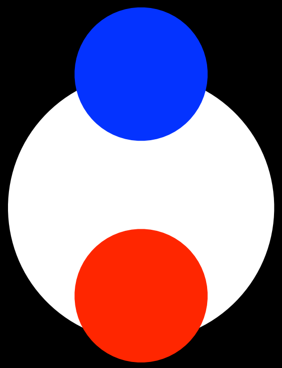
1.05	0.68	0.38	0.20	0.08	0.00	-0.06	-0.11	-0.14	-0.17	-0.19
1.10	0.97	0.55	0.29	0.12	0.00	-0.09	-0.15	-0.20	-0.24	-0.28
1.15	1.20	0.68	0.36	0.15	0.00	-0.11	-0.19	-0.25	-0.30	-0.34
1.20	1.40	0.80	0.42	0.17	0.00	-0.13	-0.22	-0.30	-0.35	-0.40
1.25	1.59	0.90	0.48	0.20	0.00	-0.14	-0.25	-0.33	-0.40	-0.45
1.30	1.76	1.00	0.53	0.22	0.00	-0.16	-0.28	-0.37	-0.44	-0.50
1.35	1.92	1.09	0.58	0.24	0.00	-0.17	-0.30	-0.40	-0.48	-0.55
1.40	2.07	1.18	0.62	0.26	0.00	-0.19	-0.33	-0.44	-0.52	-0.59
1.45	2.22	1.26	0.67	0.28	0.00	-0.20	-0.35	-0.47	-0.56	-0.63
1.50	2.37	1.34	0.71	0.29	0.00	-0.21	-0.37	-0.50	-0.60	-0.68
1.55	2.51	1.42	0.75	0.31	0.00	-0.23	-0.40	-0.53	-0.63	-0.72
1.60	2.64	1.50	0.80	0.33	0.00	-0.24	-0.42	-0.56	-0.67	-0.75
1.65	2.78	1.58	0.84	0.34	0.00	-0.25	-0.44	-0.59	-0.70	-0.79
1.70	2.91	1.65	0.88	0.36	0.00	-0.26	-0.46	-0.61	-0.73	-0.83
1.75	3.04	1.73	0.92	0.38	0.00	-0.27	-0.48	-0.64	-0.77	-0.87
1.80	3.17	1.80	0.95	0.39	0.00	-0.29	-0.50	-0.67	-0.80	-0.90
1.85	3.29	1.87	0.99	0.41	0.00	-0.30	-0.52	-0.69	-0.83	-0.94
1.90	3.42	1.94	1.03	0.42	0.00	-0.31	-0.54	-0.72	-0.86	-0.98
1.95	3.54	2.01	1.07	0.44	0.00	-0.32	-0.56	-0.75	-0.89	-1.01

At an airmass of 1.5, the image at 4000Å will be shifted up by 0.7", and the image at 6500Å will be shifted down by 0.5" wrt 5000Å. What to do?

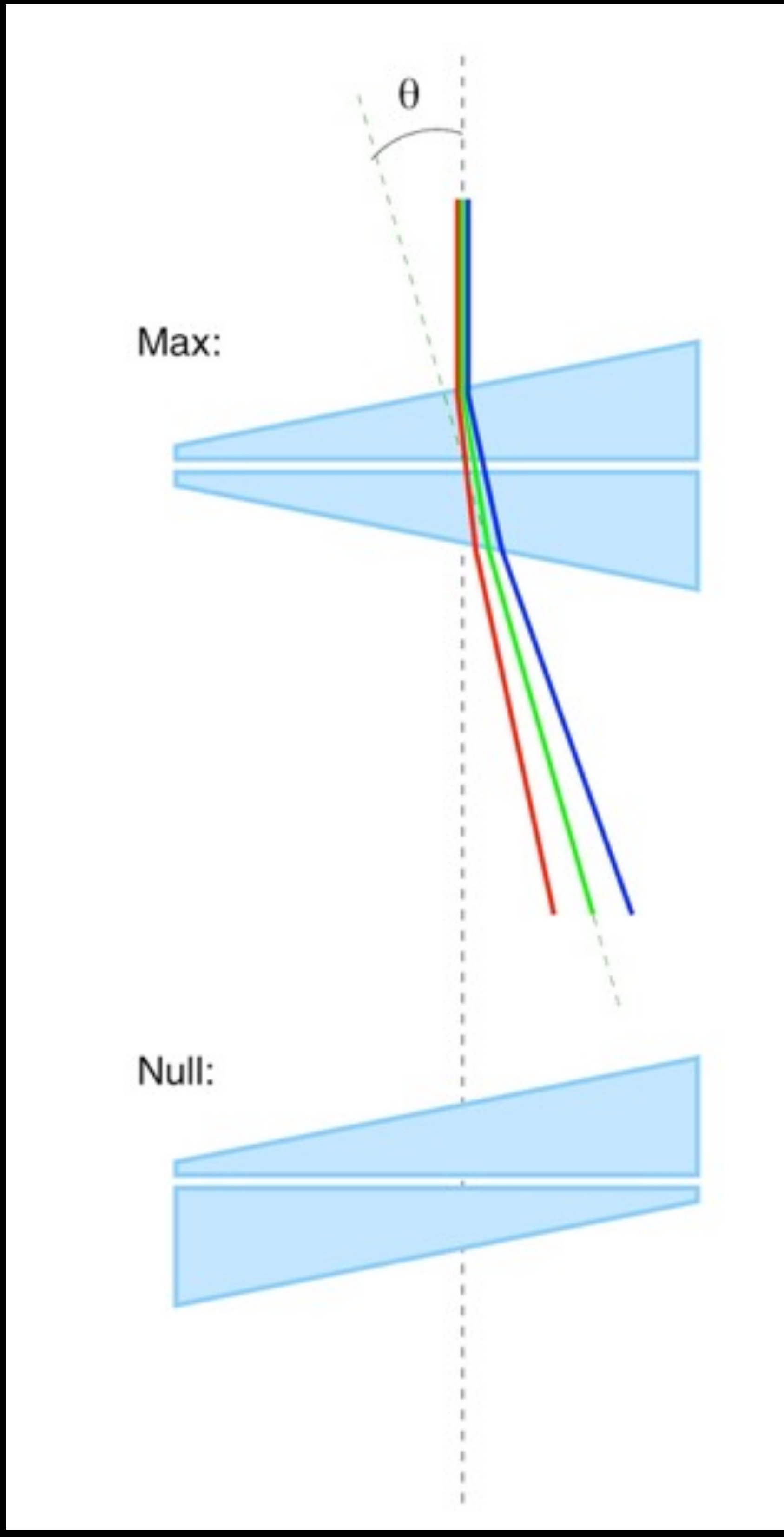
Atmospheric Dispersion Compensator



True to scale: fiber is 1.5″ diameter, seeing is assume to be 0.75″, and observation is made at an airmass of 1.5. Blue image is 4000Å, red image is 6500Å.

Atmospheric Dispersion Compensator

Simplest concept is pair of rotating prisms:



Humor…

One of the Lowel astronomers was taking images with the DCT. He switched from a red filter to a blue filter and was astonished to find that the stars had all shifted by about 5 pixels on the detector. What was up with that?

Discuss!

Seeing

The Earth's atmosphere is a turbulent place, with air of different temperatures being mixed. The result at sea level is:

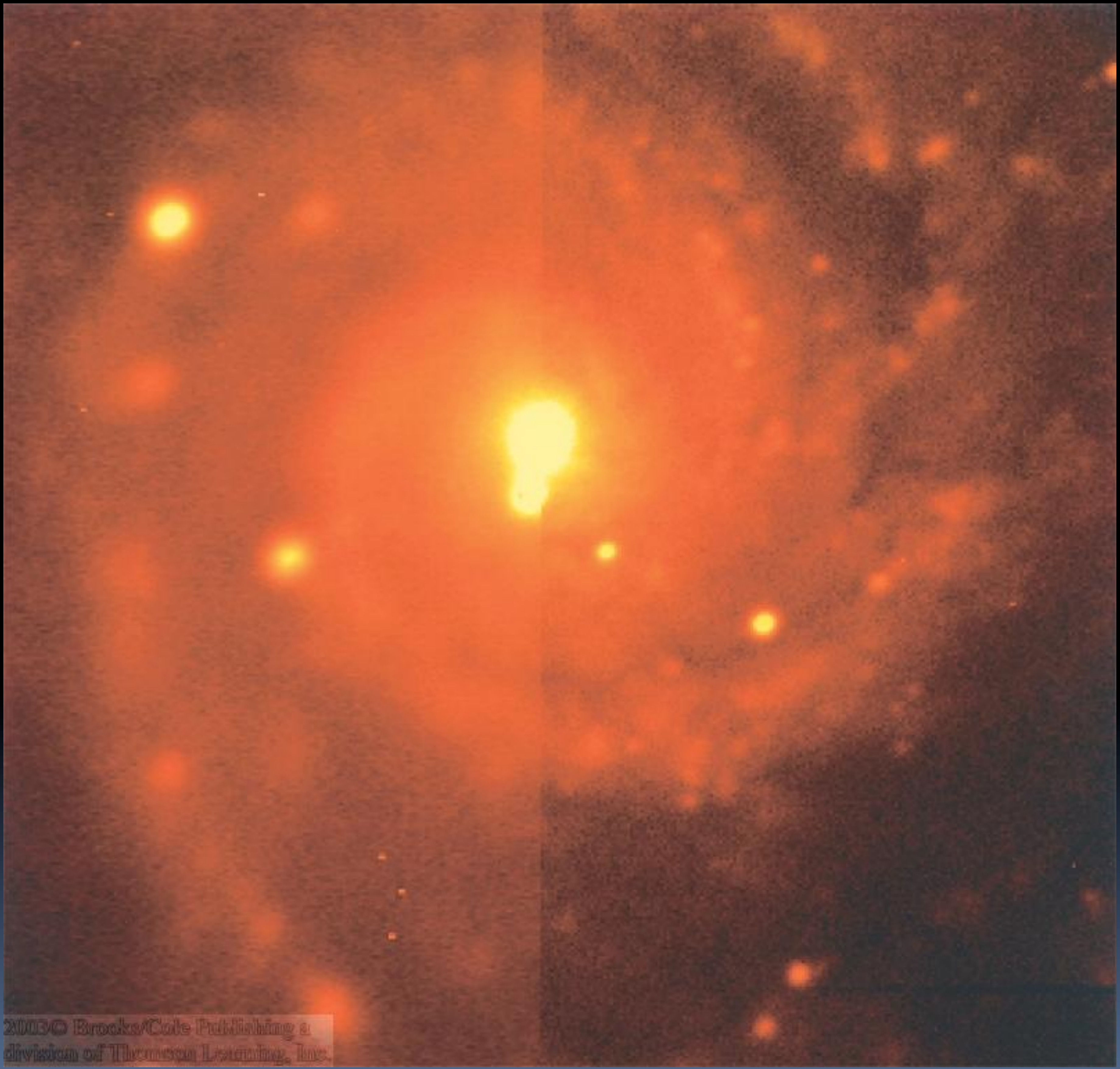
- A star in a small telescope (<5-inches) might jitter around by a few arcseconds.
- A star in a large telescope (>20-inches) will show a "pulsating blob" with a diameter of a few arcseonds.

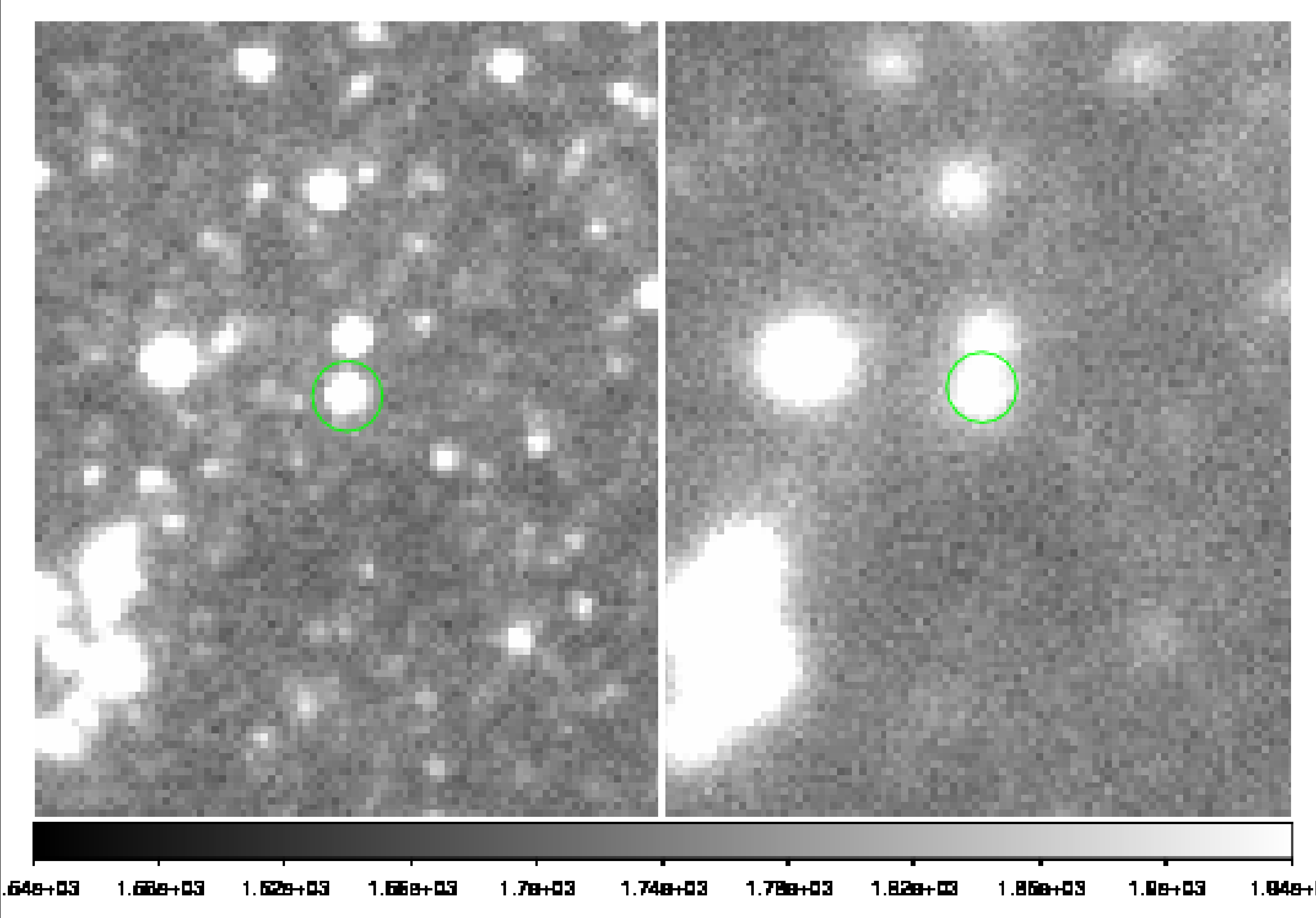
Seeing

In a “good seeing” site (on top of a mountain with steady air flow), the images might jigger by <1”. For instance, at the DCT, our typical seeing is 0.7” or better.

Good seeing matters!

Bad Seeing Good Seeing





Good image quality matters if your objects are 2 million light-years away!

Seeing

Zenith distance dependence:

$$S=S_o X^{0.6}$$

where S_o is the seeing at zenith.

Wavelength dependence:

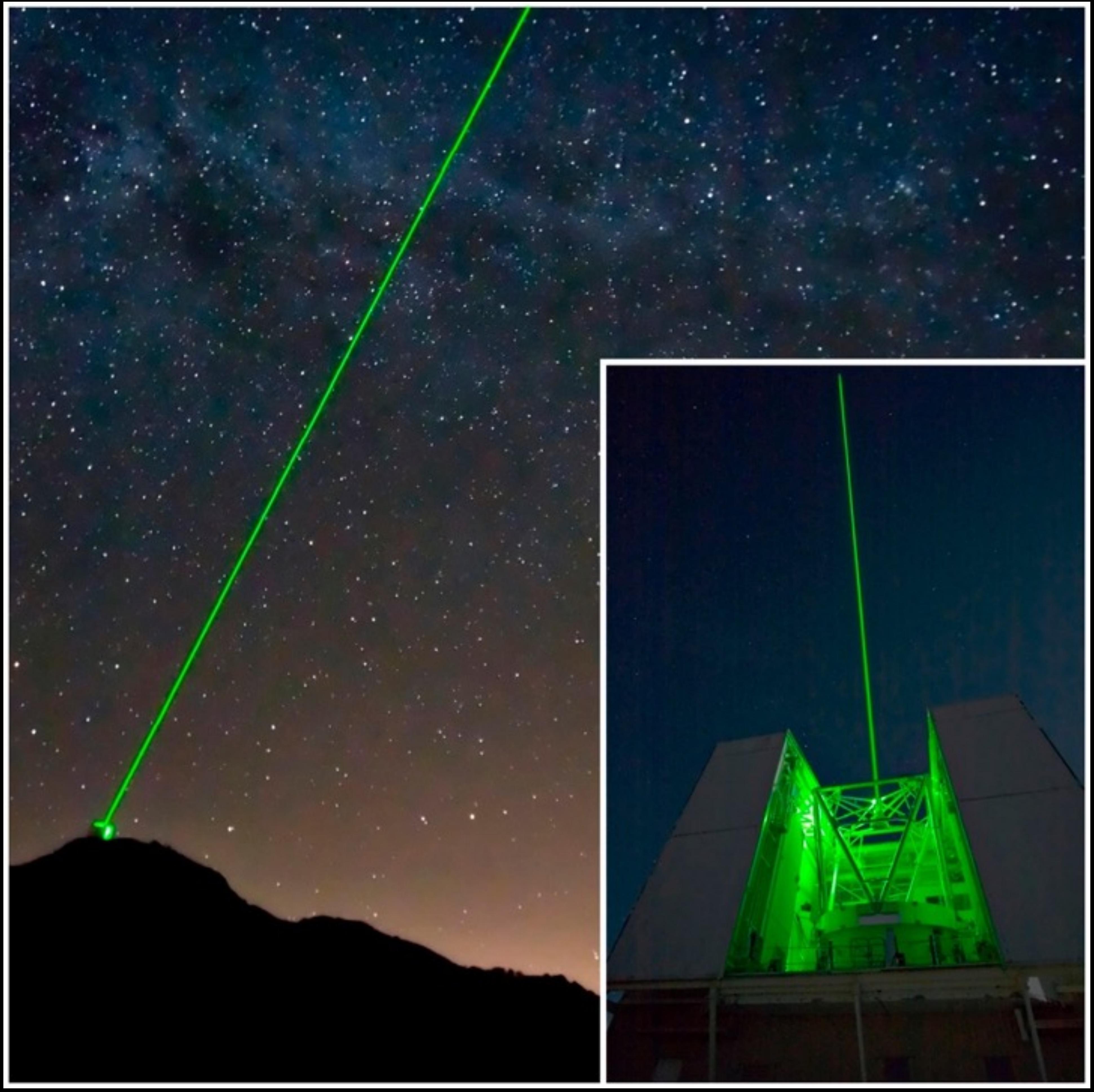
$$S=S_o \lambda^{-0.2}$$

Seeing

In point of a fact, a lot of "seeing" isn't from the earth's atmosphere, but due to thermal issues at the telescope. Need to keep the primary mirror at the ambient temperature. Hotter, and you get convection cells. Colder, and you get cold air "wedges" above the mirror.

Adaptive Optics

Rather than "active optics" (changing the mirror shape a few times a minute) you could, in principle, change the mirror shape a few hundred times per second to compensate for image motion/ blurring. You need a bright star in the field, and there often isn't one. So, some astronomers create their own star....




ETHAN TWEEDIE | PHOTOGRAPHY

Laser Guide Star AO

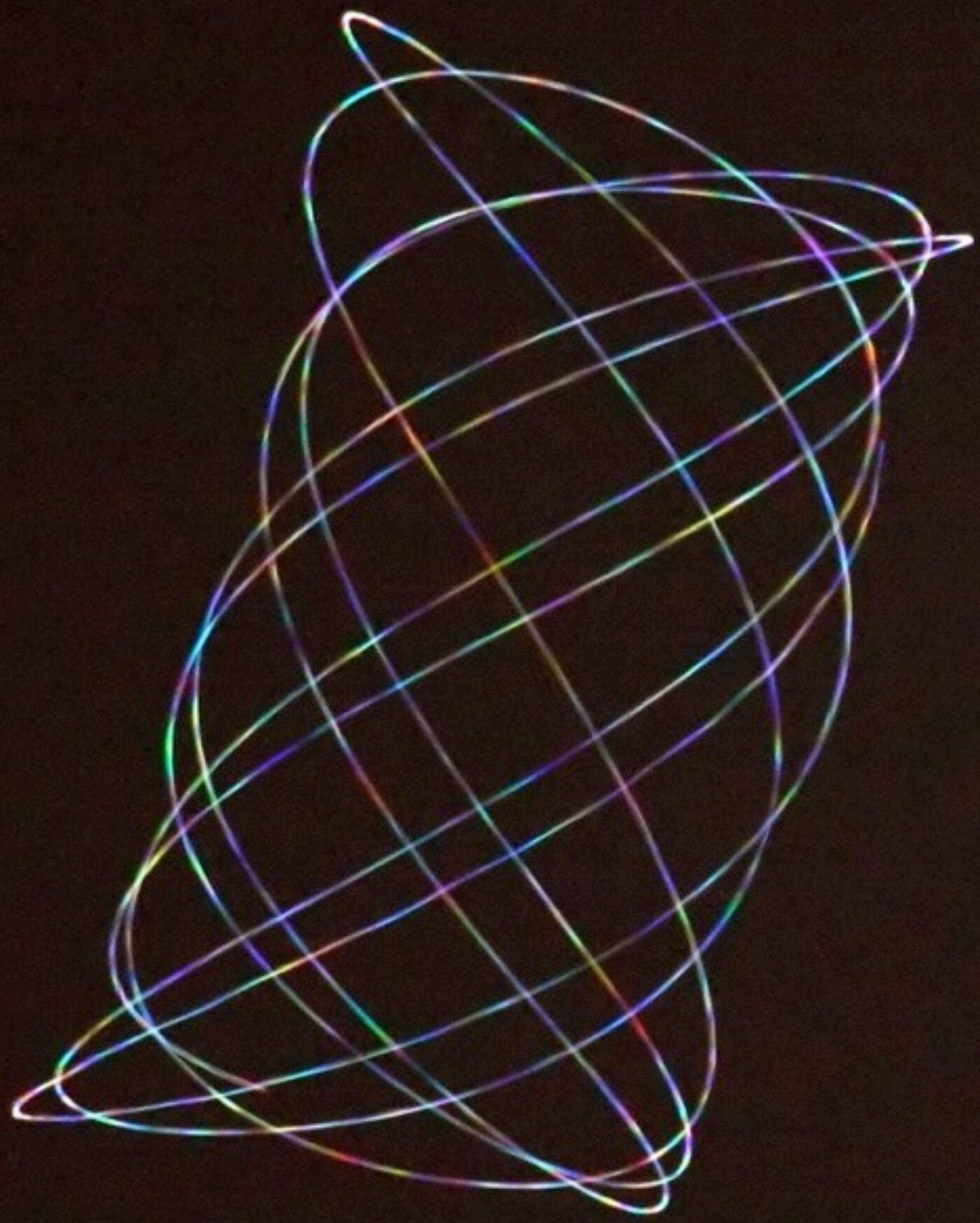
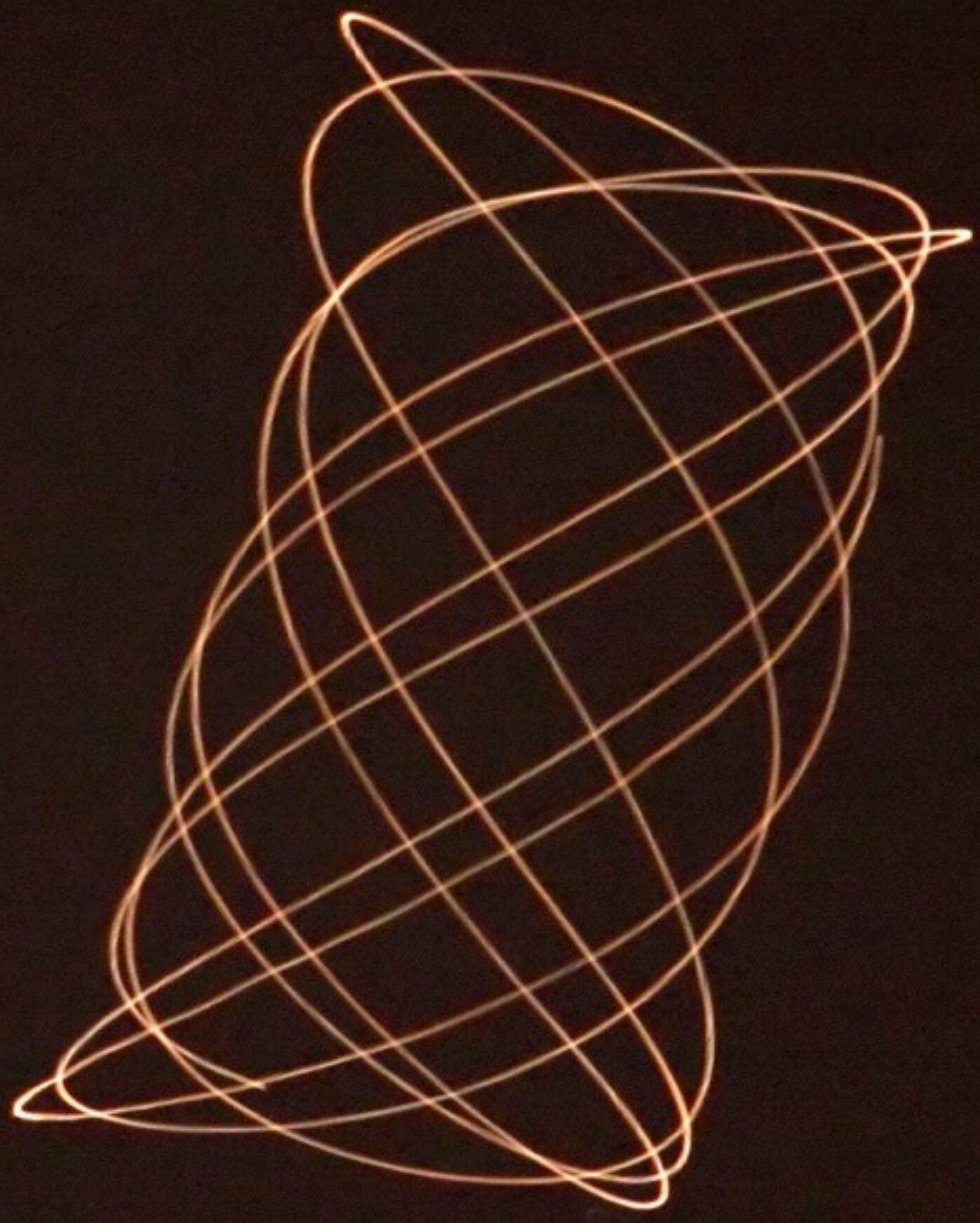
A laser is tuned to 5892Å and makes an artificial star by exciting sodium atoms at an altitude of 90 km. (This is above most of the atmosphere; remember jets fly at an altitude of about 10 km.)

There are simplier things you can do: tip-tilt mirror that moves to take out low-order effects.

Full AO can produces images that are comparable to what you would obtain from space, at least in the near-IR.

Scintillation

The stars twinkle to your bare eye. This means their brightness is changing quickly and randomly, due to varying refraction. Planets don't twinkle because they're not points, and hence average over multiple cells in the atmosphere.

Regulus

Mars

Scintillation

If you're making very short exposures in a small telescope, you might catch a star when it's a bit fainter (or brighter!) than it really is. This adds "scintillation noise" But not a problem with reasonable exposure times or large telescopes.

Very approximately:

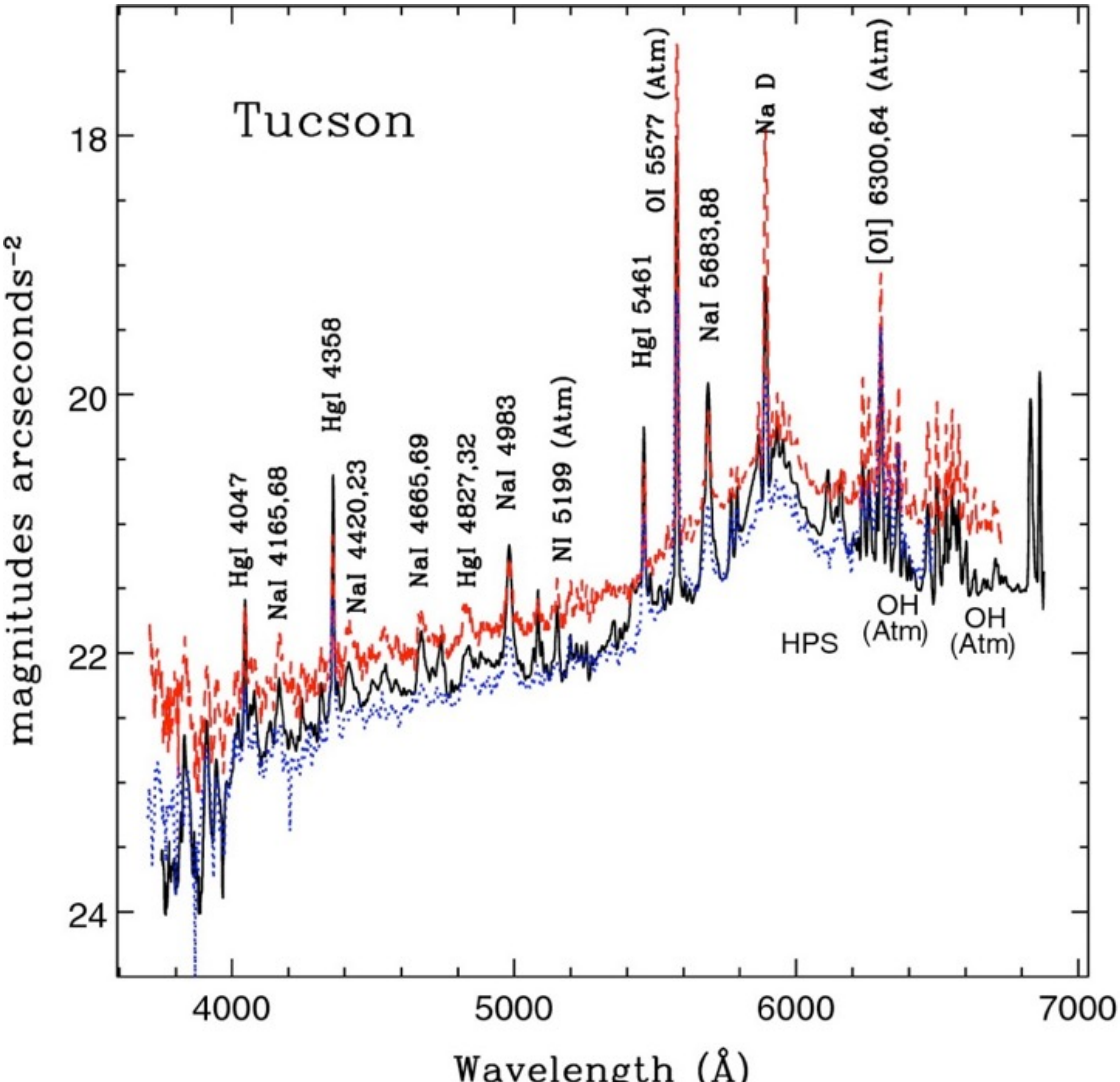
$$S = 0.06\, d^{-2/3}\, X^{1.8}\, t^{-0.5}\, e^{-(h/ho)}$$

where d is the mirror diameter in cm, X is the airmass, t is the integration time in seconds, h is the height of the observatory, and h_o=8000 meters.

The night sky

The night sky is not entirely dark, due to airglow and scattered light.

- Airglow is emission from atoms and molecules in the Earth's upper atmosphere. Features include:
  - ★ oxygen at 5577Å, 6300Å, 6364Å
  - ★ sodium at 5890Å, 5896Å
  - ★ OH molecular bands which dominate the sky brightness longwards of 7000Å.
- Scattering of natural sources
- Light pollution (continuum and emission at sodium and mercury)



From Neugent & Massey (2010, PASP, 122, 1246

Sky Brightness

In the blue, it's about 22.5 mag/arcsec^2

In the red, it's about 21.5 mag/arcsec^2

ISM and reddening

We've been talking about the effects of the Earth's atmosphere on astronomical observations. But what about the effects of the interstellar medium (ISM)?

ISM and reddening

The ISM consists of of multiple components:

- **dust** preferentially scatters blue light, leaving (most) of the red light behind
- sparse **atoms** (mostly H, but a traces of others, producing Ca II and Na absorption
- **molecules**

ISM and reddening

E(B–V) = the observed B–V minus the intrinsic B–V:

$$(B-V)-(B-V)_0$$

$$A_V=3.1\ E(B-V)$$

Shape of reddening law:

$$E(U-B)=(U-B)-(U-B)_0$$

$$E(U-B)/E(B-V)=0.72$$

Mysterious HW

(1) Phil uses the Swope with a 3000x3000 CCD. The scale of the telescope is 0.435"/pixel at zenith. If he observes a field on the meridian at an airmass of 2.0:

a) How different will the scale be along the meridian than perpendicular to it?

b) How different will the refraction be at the top and the bottom of the field.

Hint: what is the **derivative** of the refraction law? You might be surprised.

Mysterious HW

2\. a) What is the parallactic angle for a star on the meridian?

b) What is the parallactic angle for a star rising due east?

3\) You take an image through a V-band filter at zenith and measure a seeing full-width-at-half-maximum of 0.7". If you then take an exposure through the B-band at and airmass of 2, what size images should you expect?

Assume effective wavelength of V-band is 5400Å and that of the B-band is 4420Å.

Mysterious HW

4 a) What is the scintillation noise of a 1-second exposure with a 3-inch (7.6-cm) telescope at zenith at an observatory located at 2000 meters (roughly Flagstaff's elevation).

b) What's the scintillation noise from a 1-second exposure with the Barry Lutz telescope? (0.5m=50 cm) at zenith at an observatory located at 2000 meters

c) What's the scintillation noise from a 10-sec exposure with the 4.3-meter DCT?