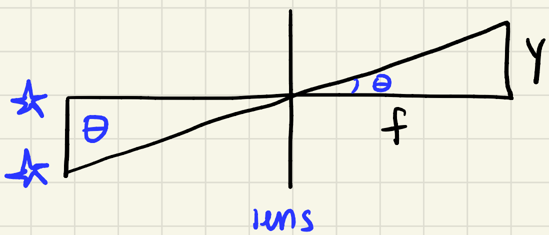
specifications of a telescope:

Plate scales: (chromey 5.3.2)

What aspects of a telescope determine the platescale? That is, the mapping of the sky to the camera, in arcsec/mm?

How many arcseconds does a pixel correspond to?



$$S = \frac{\theta}{y} = \frac{1}{f}$$

θ → in radians

S → plate scale

$\tan\theta = y/f$

for small angles, $\tan\theta \approx \theta$

to express the plate scale in arcsec/mm, let y = 1mm:

$$s = \frac{206265}{f} \quad [\text{arcsec/mm}]$$

Focal ratio:

$$\mathcal{R} = \overset{\text{focal length}}{f} / \underset{\text{aperture diameter}}{D}$$

WIRO has a focal ratio of 27, usually written as f/27. Larger $\mathcal{R}$ is "slow", smaller $\mathcal{R}$ is "fast"!

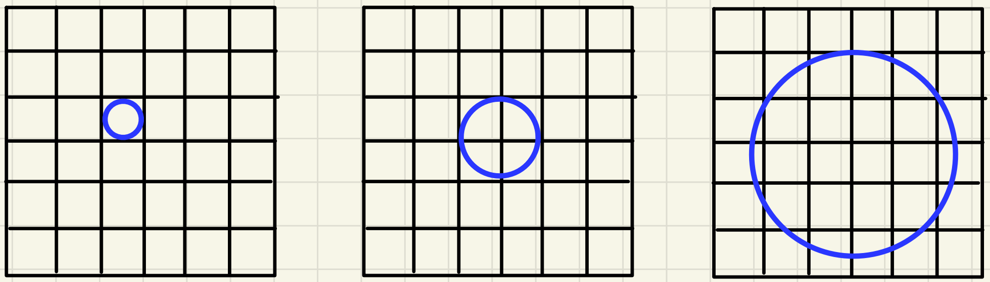
z.B. WIYN at KPNO is an f/6.29 3.5m telescope. What is its platescale?

$$\mathcal{R} = f/D \implies f = \mathcal{R} \cdot D = 6.29 \cdot 3.5\,\text{m} = 22\,\text{m}$$

$$s = \frac{206265}{f} = \frac{206265}{22\,\text{m} \cdot 1000\,\text{mm/m}} = 9.37\ \text{arcsec/mm}$$

- f is always the effective focal length, which can be achieved with a complex optical path. WIYN doesn't have a 22m length!

- the combination of plate scale and detector pixel size need to be carefully chosen so that the data (e.g. star images) are sufficiently well sampled.
- the Nyquist criterion (nyquist sampling) specifies that there need to be two detector elements per resolution element.
- z.B. the full width at half-maximum (FWHM) of the seeing disk (the Point spread function or PSF) is 1 arcsec, then you want to have 0.5 arcsec/pixel or better.



undersampled	Nyquist or critically sampled	oversampled
- poor image definition for point sources - poor separation for close sources - can dither to try to recover shape info	- adequate image reconstruction and source separation	- may allow superior image reconstruction and definition, but also leads to more noise (it's per pixel) and larger flux uncertainty - smaller FOV

Field of view (FOV) is pixel size multiplied by number of pixels.

2. B. Suppose you are observing at WIYN (3.5m, f/6.29) and the seeing is 0.8" at best. What pixel size, in microns, should your detector have in order to achieve Nyquist sampled data?

Need to get pixels with $p = 0.8''/2 = 0.4''$

$R = f/D \Rightarrow f = 6.29 \cdot 3.5m \cdot 10^6 \mu m/m = 22 \times 10^6 \mu m$

$\text{platescale} = \frac{206265}{22 \times 10^6} = 0.00937 \, ''/\mu m$

$p = \frac{0.4''}{0.00937''/\mu m} = 42.2 \mu m$

What sized pixels will oversample the data? smaller

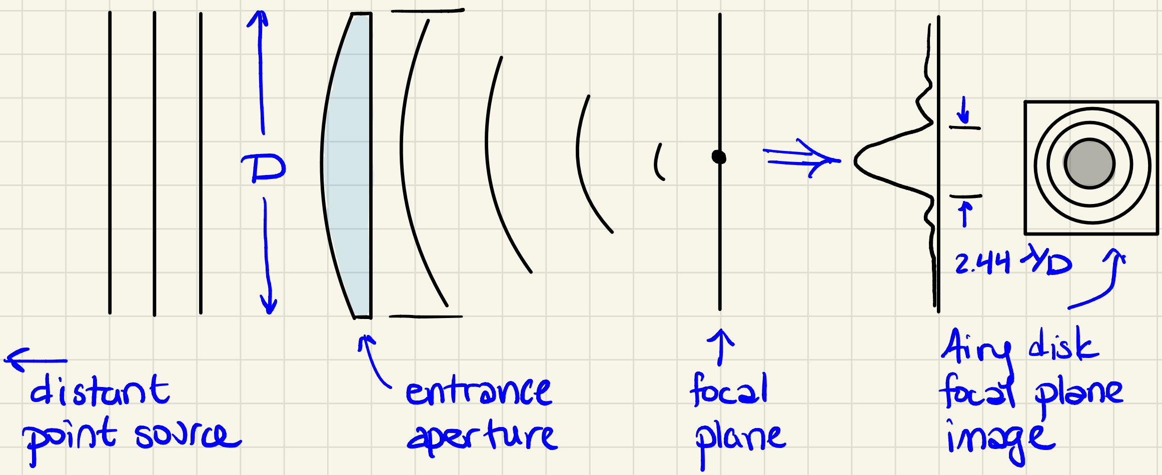
undersample? bigger

What would the FoV be for a 2048 x 2048 detector?

$FoV = p \cdot N_{pix} = 0.4'' \cdot 2048 = 819.2'' = 13.6'$

Angular Resolution (Chromey ch. 5.4)

There is a limit to the image quality you can achieve due to the wave nature of light.



The wavefront from distant astronomical sources will arrive perfectly planar and parallel at the telescope aperture.

They will encounter the entrance aperture of the telescope, usually the primary mirror or lens, with diameter D.

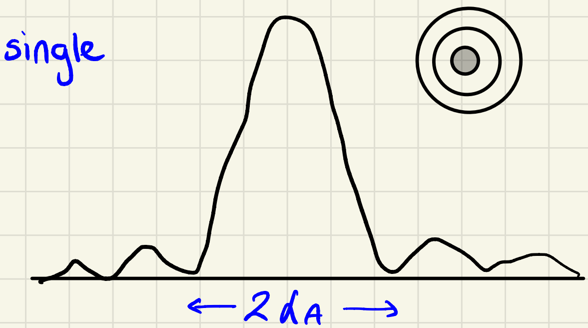
The calculation of how the planar wavefront interacts with this pupil is a problem first worked out by George Airy. Effectively, you will get a bullseye pattern, now called an Airy disk, which is the Fourier transform of a circular aperture.

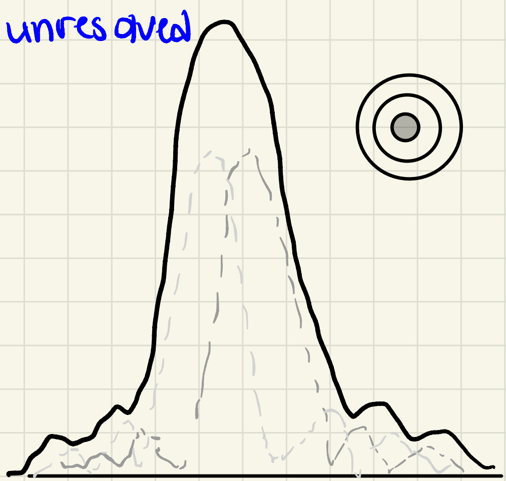
The size of this Airy disk is the diffraction limit of the telescope, and will be the minimum size of a point source.

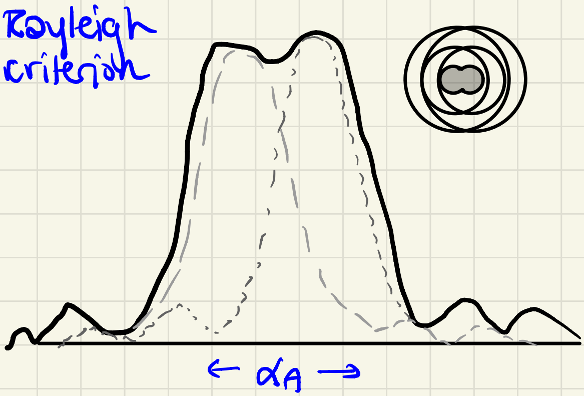
The angular radius of the first dark ring is

$$\alpha_A = \frac{1.22\lambda}{D} \text{ [radians]} = \frac{0.252\lambda}{D} \text{ [arcsec m } \mu m^{-1}\text{]}$$

The FWHM of the Airy disk is $0.9\,\alpha_A$. If two sources are too close, they may look like one. To resolve two sources, you need them to be separated by at least α_A, the angular radius of the central disk. This is called the Rayleigh Criterion. In this limiting resolution scenario, the maximum of one pattern coincides with the first dim minimum in the other.







Z.B. Find the angular resolution of the Hubble Space Telescope at 1200Å (about the bluest it can go). HST is a 2.5m.

$$\alpha\,[\text{radians}] = \frac{1.22 \cdot 1200\text{Å}}{2.5\text{m} \cdot \times 10^{10}\,\text{Å/m}} = 5.865\times 10^{-6}\ \text{rad} \cdot \frac{206265''}{\text{radian}}$$

$\alpha = 0.012''$

HST is the best resolution you will get without adaptive optics or an interferometer.

Z.B. What is the best resolution you can get with Gemini/GMOS, an 8.1m that operates at 360–1030 nm?

$$\alpha\,[\text{radians}] = \frac{1.22 \cdot 360\,\text{nm}}{8.1\text{m} \cdot 10^{9}\,\text{nm/m}} = 5.422\times 10^{-8}\ \text{rad}$$

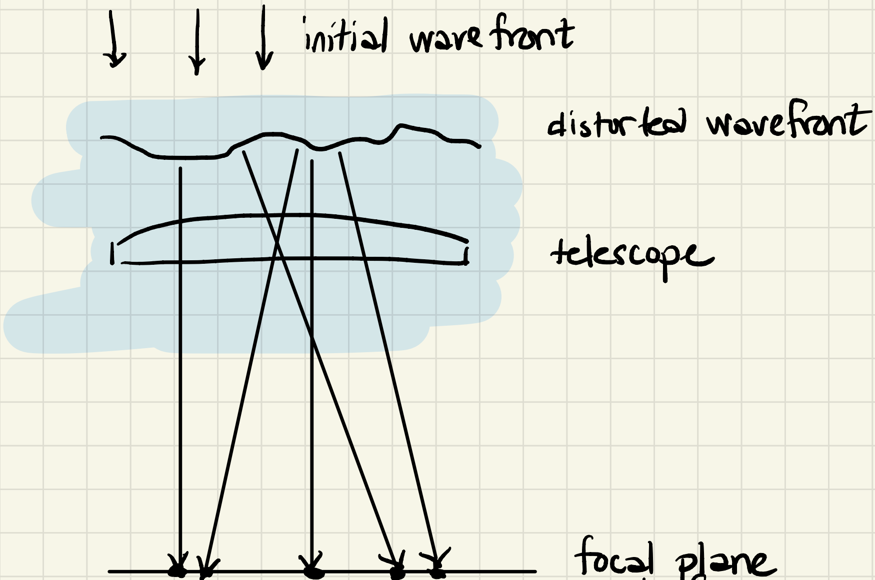
$\alpha = 0.011''$

Typical seeing at the Gemini N site is ~0.75''. So you can see that ground-based optical telescopes are not usually diffraction limited.

Earth's Atmosphere

Atmospheric Blur (Chromey Ch. 6.5)

"Seeing" is caused by turbulence in the atmosphere. Temperature gradients and bubbles will create cells with different indices of refraction. The wavefront from a source which arrived as a plane will be distorted by the time it reaches the telescope.



In a short exposure this causes speckles to form in the image. This speckle pattern reforms quickly, so in longer exposures it blurs into the seeing disk.

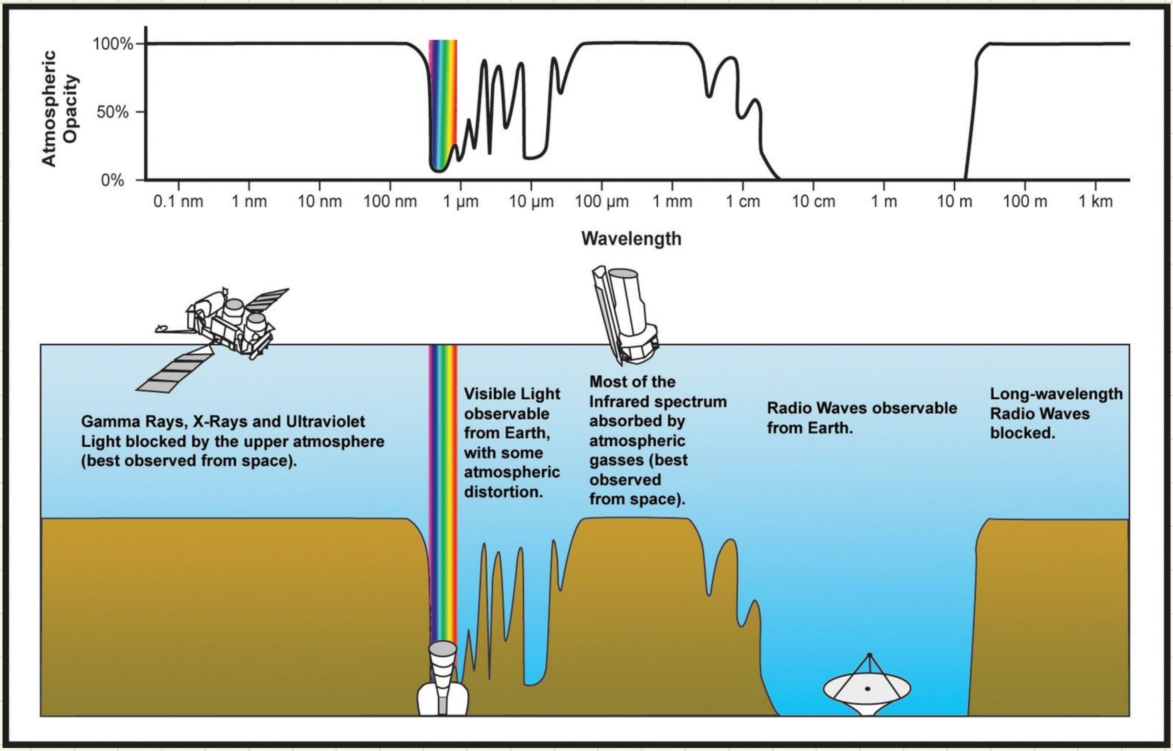
Observations will be seeing limited if the segment of wavefront that can be treated as a wave is bigger than the telescope diameter;

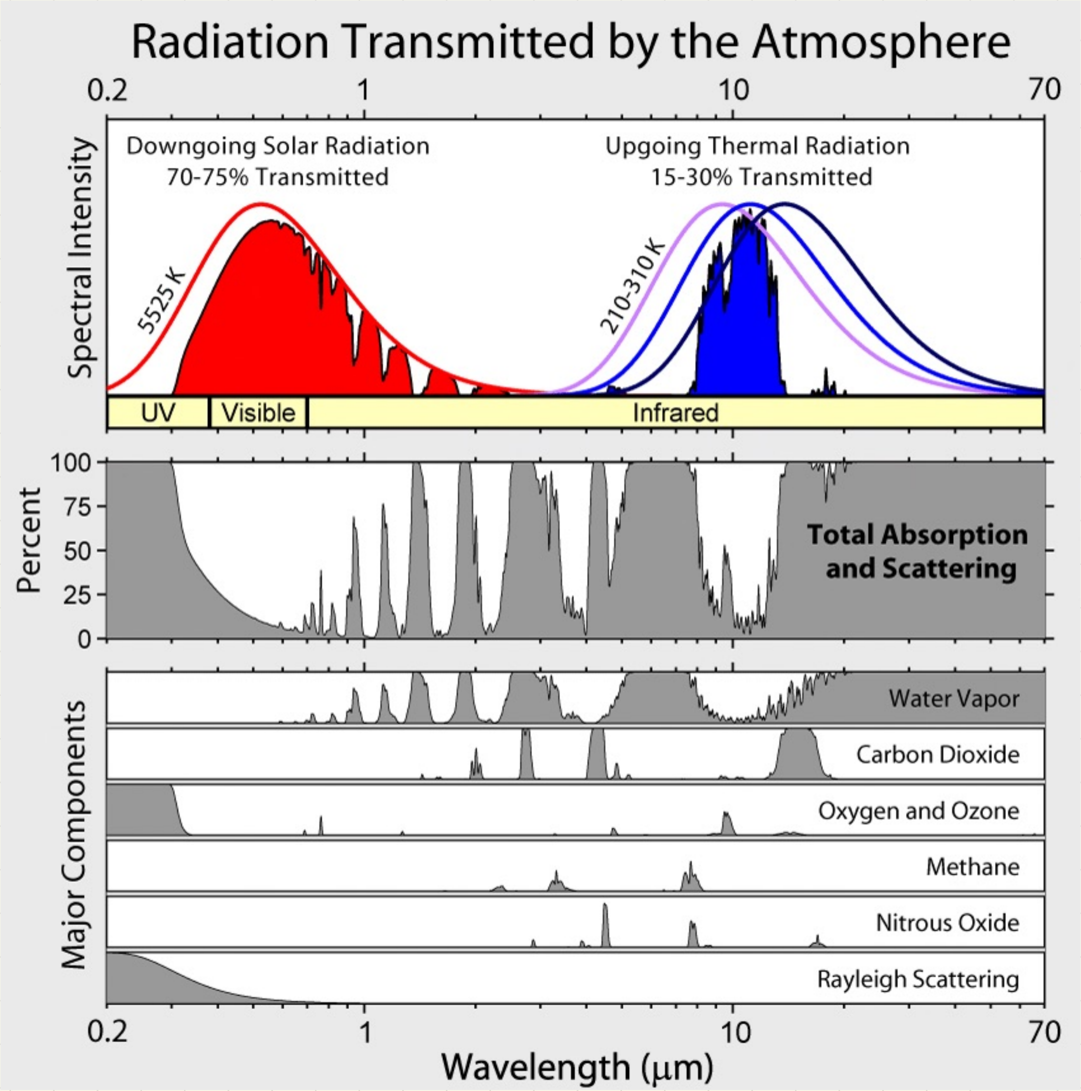
$$\theta \text{ (seeing, in arcsec)} \approx 0.2 \frac{\lambda [\mu m]}{r_{0\lambda} [m]}$$

$r_{0\lambda}$ → Fried parameter, length that can be treated as plane

Usually, though, you don't know $r_{0\lambda}$, so you can't calculate seeing. More often, you'll observe it in your data. Typical values are ~1". Values like 0.25" – 0.75" are good, whereas >2" is possible (and bad).

Extinction / Absorption





Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption
and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (μm)

Main contributions to continuum extinction in optical:

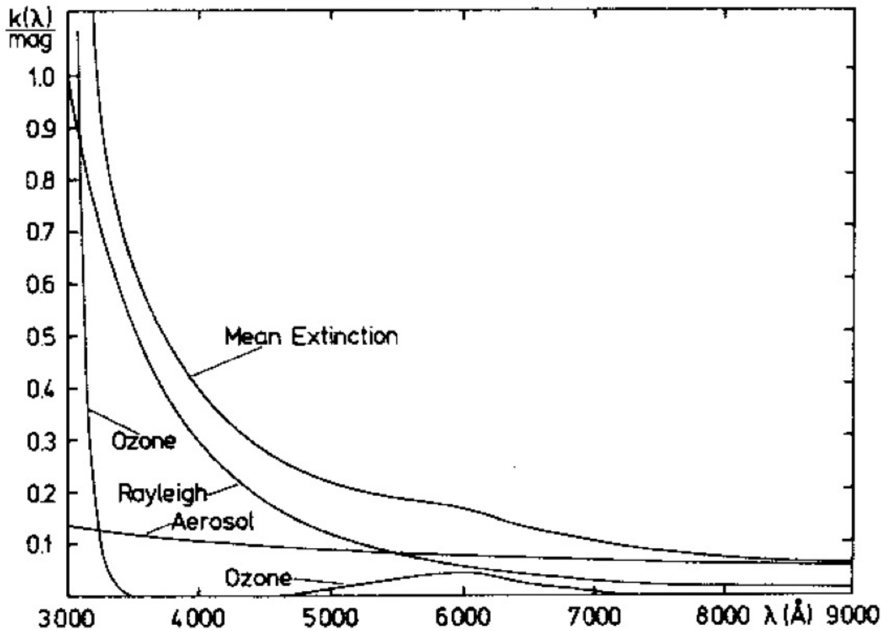


Fig. 1. Mean vertical extinction at Flagstaff, Arizona, in May-June 1976. The assumed ozone and Rayleigh contributions are shown separately

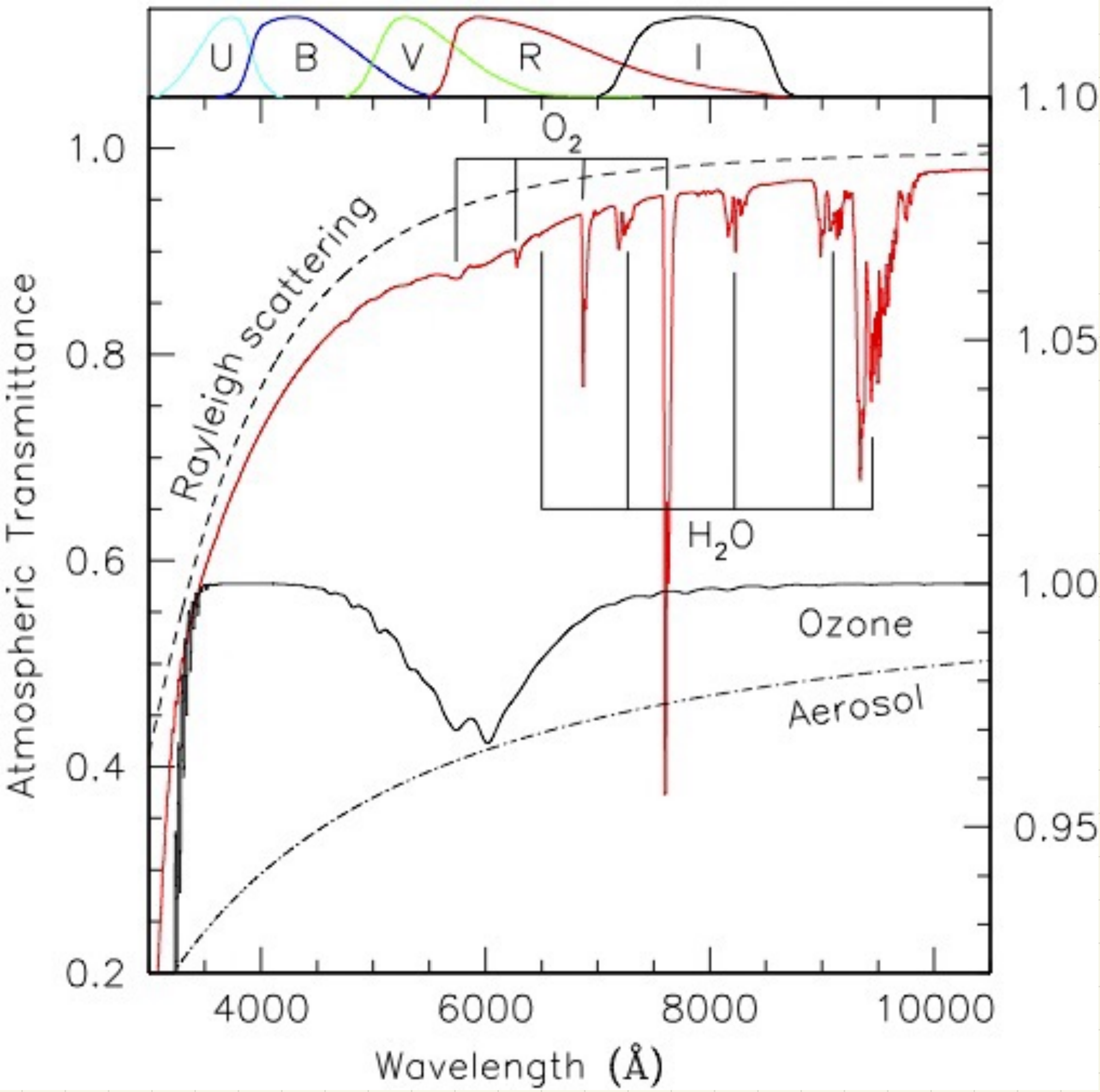
Rayleigh – particles with sizes smaller than λ scatter light. Amount of scattering depends on λ^{-4}, so shorter wavelengths are preferentially scattered – this is why the sky looks blue.

Ozone (O_3) – effective at short wavelengths, especially the UV (this is why the ozone layer is so important).

Some typical extinction coefficients:

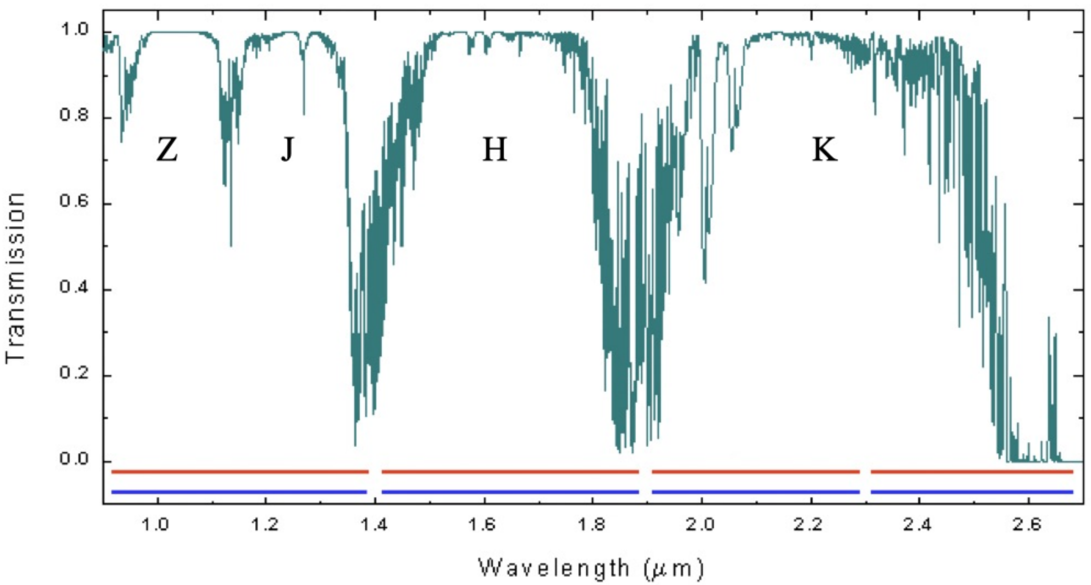
$B = 0.4$ mag/airmass, $V = 0.2$ mag/airmass, $I = 0.1$ mag/airmass

· depends on location, season, fires, volcanoes ...


U
B
V
R
I
O_2
H_2O
Rayleigh scattering
Ozone
Aerosol
Atmospheric Transmittance
Wavelength (Å)
1.0
0.8
0.6
0.4
0.2
1.10
1.05
1.00
0.95
4000
6000
8000
10000

.

Infrared sky transmission (based on Lord 1992 AIRTRAN)



IR observations are often done from space to avoid the IR extinction.

Approximate IR transmission bands:

Z ~1.1 μm
J ~1.1–1.4 μm
H ~1.4–1.8 μm
K ~2.0–2.5 μm
L ~3.0 μm
M ~4.1 μm

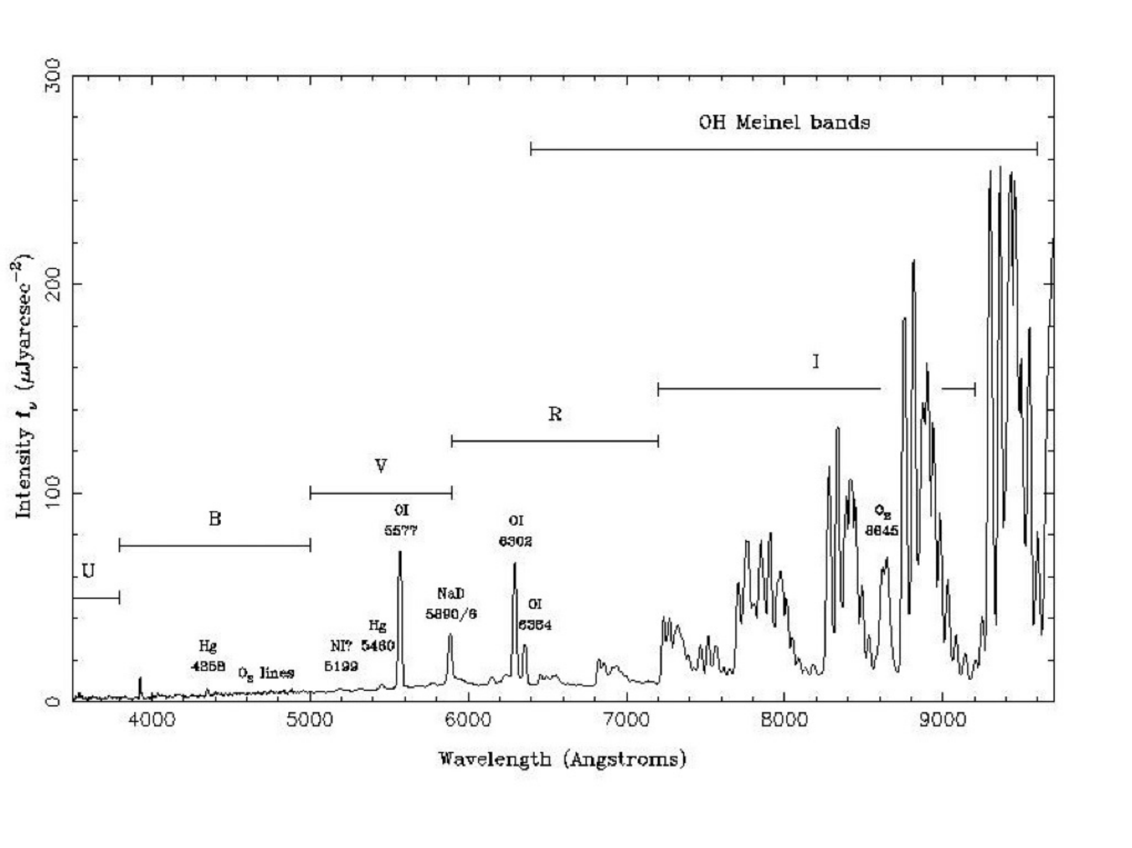
Emission:

The night sky also emits a background light from e.g.:

Natural
Airglow (O, Na, OH Meinel, continuum)
Zodiacal light (sunlight scattered by dust)
Starlight
Extragalactic light (e.g. CMB)

Human:
Light pollution
(Na, Hg, Ti)

Optical / IR sky brightness:



Optical sky brightness:

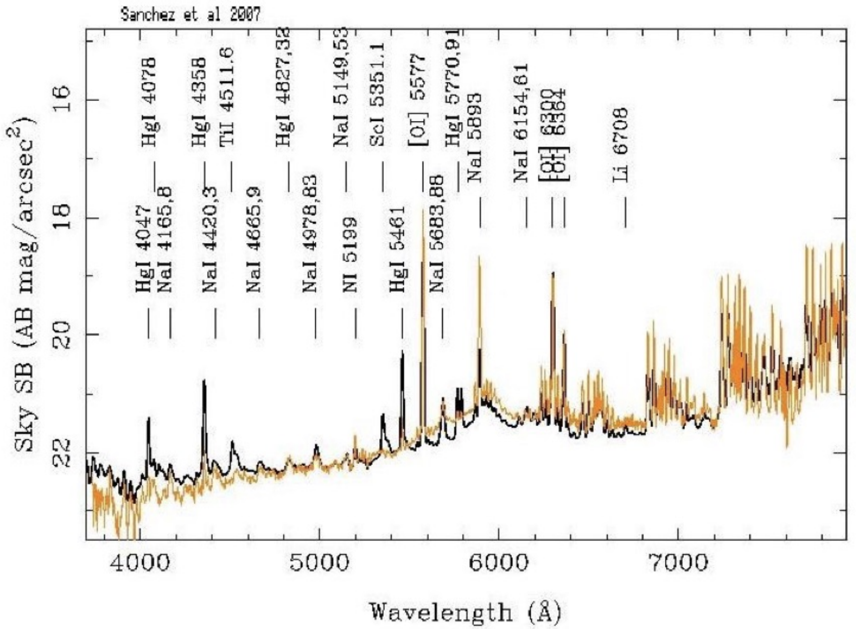


FIG. 1.— Night-sky spectrum at the Calar Alto Observatory in the optical wavelength range (3700-7950Å), obtained after averaging 10 spectra of 6 moonless nights pointing near the zenit (Black solid-line). The intensity has been scaled to that of the darkest moonless night in the V-band. Several emission lines are indentified in the spectrum. The most relevant ones have been labeled with its corresponding name and wavelength. In addition, the broad-emission band of NaI centred at ~5900Å, and the water vapor Meinel bands are clearly identified in the spectrum. For comparison purposes we included the night sky spectrum at the Kitt Peak observatory derived by Massey & Foltz (2000), obtained from their webpage: *http://www.lowell.edu/users/massey/nightsky.html* (Orange dotted-line). It is appreciated how strong are the pollution lines at Calar Alto, in comparison with that observatory.

Sky brightness depends on eg location, especially lunar phase

Sky brightness in mag/arcsec^2:

lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Redshift

Topics: Doppler shift, cosmological redshift

sources: Chromey Ch. 10.8, 11.9

$$1+z = \frac{\lambda_{obs}}{\lambda_{emit}}$$

Doppler Shift

Change in wavelength because source has a velocity through space.

$$1+z = \sqrt{\frac{1+\beta}{1-\beta}}, \quad \beta = \frac{v_r}{c}$$ Relativistic Doppler Shift

$$z \approx \frac{v_r}{c}$$ Non-relativistic limit

Cosmological Redshift

Change in wavelength because space is expanding as light travels through it.

$$1+z = \frac{a(t_0)}{a(t)} = \frac{1}{a(t)}$$

These effects stack:

$$1+z_{cosmo} = \frac{\lambda_{stretch}}{\lambda_{emit}}, \quad 1+z_{Doppler} = \frac{\lambda_{obs}}{\lambda_{stretch}}$$

$$\Longrightarrow 1+z = (1+z_{cosmo})(1+z_{Doppler})$$