ASTR 535 : Observational Techniques

Effects of the Earth’s atmosphere

Four atmospheric effects

Learning objectives

- Understand the effects of the Earth's atmosphere (+) that we will discuss: emission, absorption, refraction, and seeing

Four effects of Earth’s atmosphere

- Emission : atmosphere emits light, with flux a function of wavelength
  - Also will discuss other sources of “background” light
- Absorption : atmosphere absorbs light, with fraction absorbed a function of wavelength and also a function of airmass
- Refraction : atmosphere causes direction of light to be changed slightly, and this shift is a function of wavelength and also airmass
- Seeing : atmosphere blurs images
  - Also will discuss typical blurring function and how seeing is characterized

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Effects of the Earth’s atmosphere

Atmospheric emission

Learning objectives

- Understand the nature of sources that contribute to the sky “background”, including their origin, wavelength dependence, and dependence on location and time

Emission from Earth’s atmosphere

- sources
  - airglow : excitation of molecules in atmosphere
  - thermal emission of atmosphere
  - zodiacal light : scattered light from dust in solar system (not from atmosphere!)
  - unresolved stars/galaxies
  - moonlight
  - sunlight
  - aurorae
  - light pollution
- All are function of wavelength
- Most are function of time
- Most are function of position

Zodiacal light

- Not from Earth’s atmosphere!
- Dust in the plane of the solar system scatters sunlight
  - Brighter near ecliptic
- Continuous emission with solar-like spectrum
- Surface brightness in optical (V band) ranges from 22-23.5 mag/square arcsec
- Provides “base” background emission
  - True even from orbit!

Emission spectrum

- Baseline emission is from zodiacal light
- Without moonlight, most atmospheric emission is in lines
- Predominantly, emission is from airglow
    - OH: the “OH forest”
    - Others, e.g. [OI] 5577
- Strong function of wavelength, increasing towards longer wavelengths

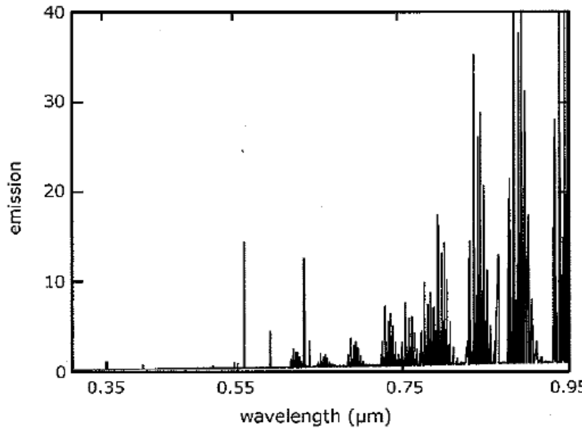


Figure 1.7. Sky brightness in the visible and near-infrared. Based on Rouss[elot] et al. (2000).

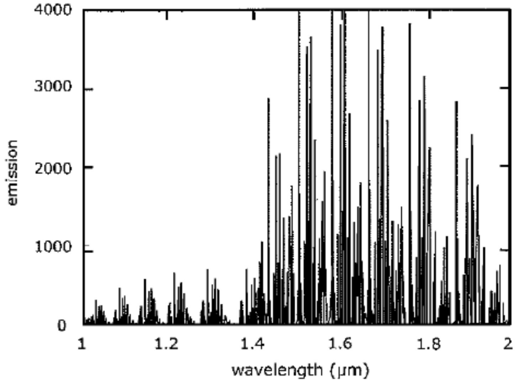


Figure 1.8. Sky brightness from 1 to 2 μm. The vertical scale has been made 100 times larger than in Figure 1.7. Based on Rousselot *et al.* (2000).

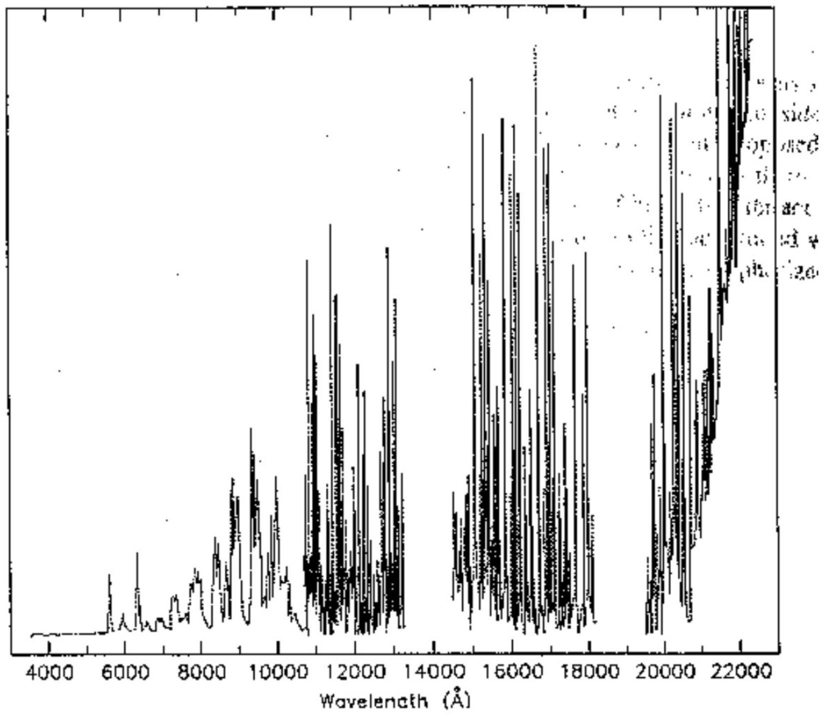


Fig 3. The night sky from 4000 A to 2.2 μm (courtesy D. Crampton), showing the strong night sky emission. The rise in the integrated night sky background is actually less frightening: The sky $(I\text{-}H)_{AB}$ ~ 3.3, comparable to the rise between B and I, where the sky $(B\text{-}I)_{AB}$ ~ 2.5.

Lunar sky brightness

Lunar sky brightness is a function of wavelength (blue!), phase of the Moon, and distance from Moon in the sky

Days from New Moon	*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

- Because of significant effect of Moon, observing time usually split into:
  - dark time: Moon below horizon
  - grey time (various definitions) : above horizon, < 50% illuminated
  - Bright time : above horizon, > 50% illuminated

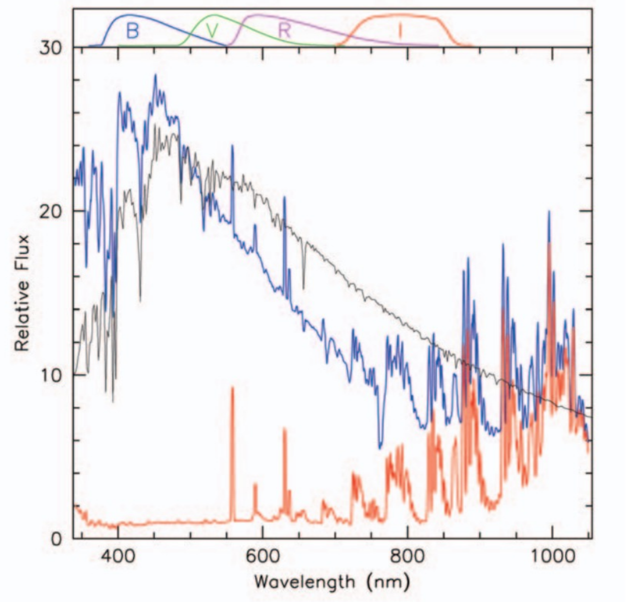


Figure 2: Comparison between the night sky spectrum during dark time (red line, Patat 2003) and bright time (blue line). The latter was obtained with FORS1 on September 1, 2004 using the low dispersion grism 150I and no order sorter filter. Due to the very blue continuum, the spectral region at wavelengths redder than 650 nm is probably contaminated by the grism second order. Both spectra have been normalized to the continuum of the first one at 500 nm. For comparison, the model spectrum of a solar-type star is also plotted (black line). For presentation, this has been normalized to the moonlit night sky spectrum at 500 nm. The upper plot shows the standard *BVRI* Johnson-Cousins passbands.

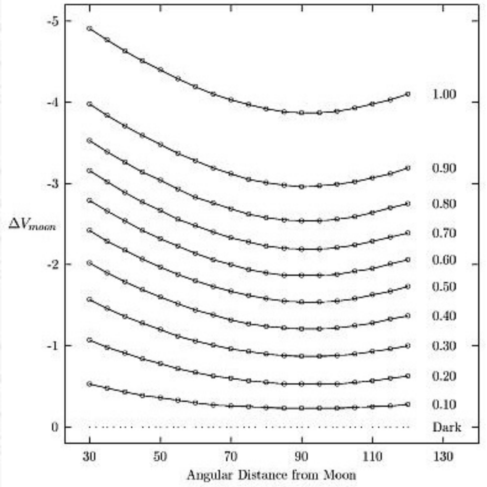
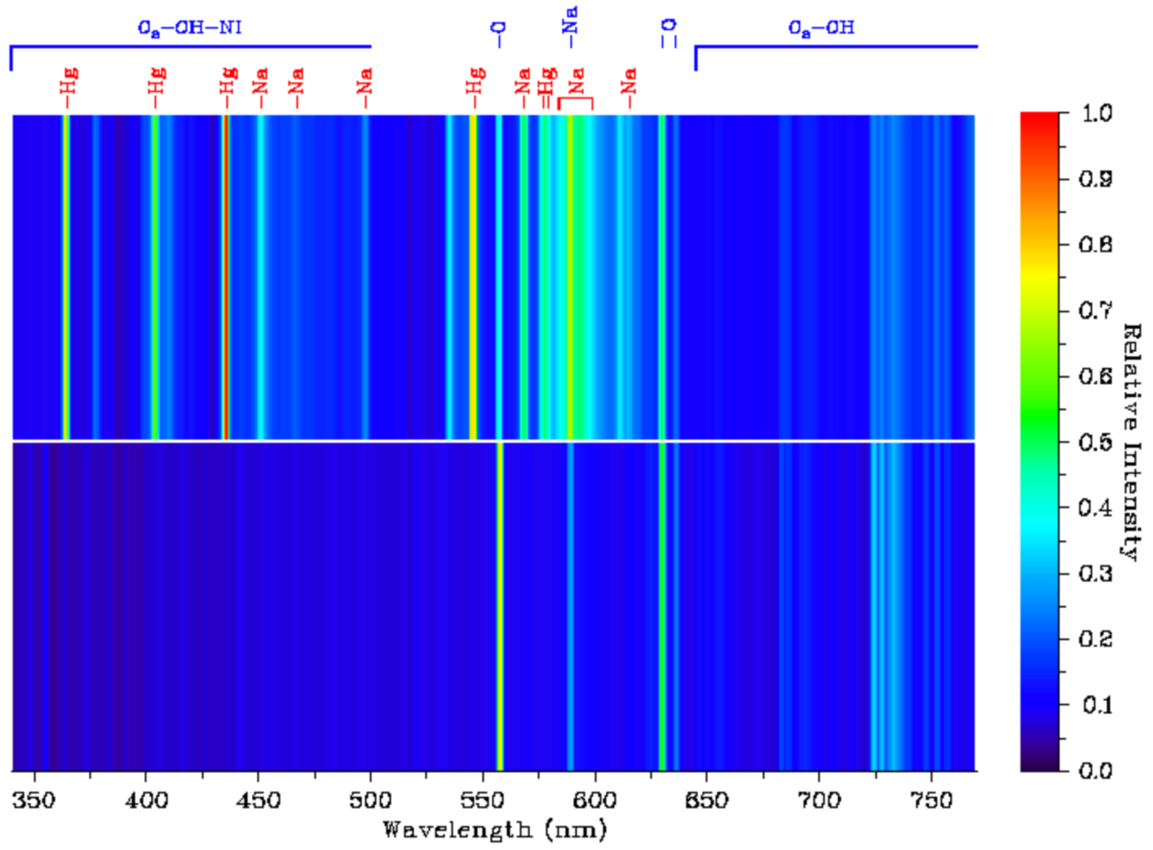


Figure 1. The brightening of the dark sky (V_{sky}=21.9 mag/arcsec^2, corresponding to low airmass, high ecliptic and galactic latitude, and solar minimum) by scattered moonlight, calculated as a function of fractional lunar illumination and angular distance from the Moon. [JPEG / TIFF]

Sunlight and twilight

- Surface brightness from sunlight depends on distance of Sun below horizon
- Note definitions:
  - Sunset : sun goes below horizon
  - Civil twilight: 6 degrees below
  - Nautical twilight: 12 degrees below
  - Astronomical twilight: 18 degrees below (fully dark)
- Lots of useful stuff can be done before astronomical twilight!
  - Twilight flat fields
  - Brighter star calibration
  - Brighter star observations
- Observing: be prepared at sunset!

Light pollution



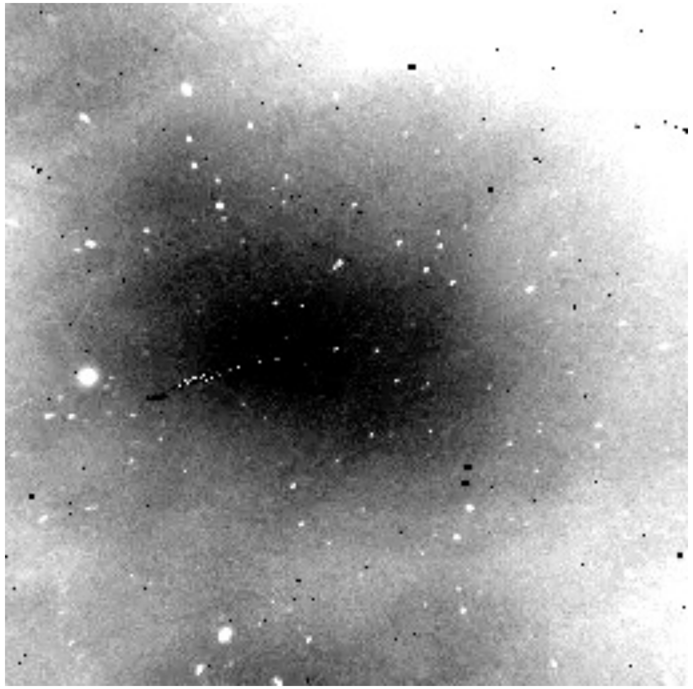
Comparison between a night sky spectrum taken at Cerro Paranal-Chile during dark time (lower panel) and one taken in Asiago-Italy (upper panel). Light pollution is clearly visible in the form of Sodium and Mercury emission lines in the blue/visible part of the spectrum.

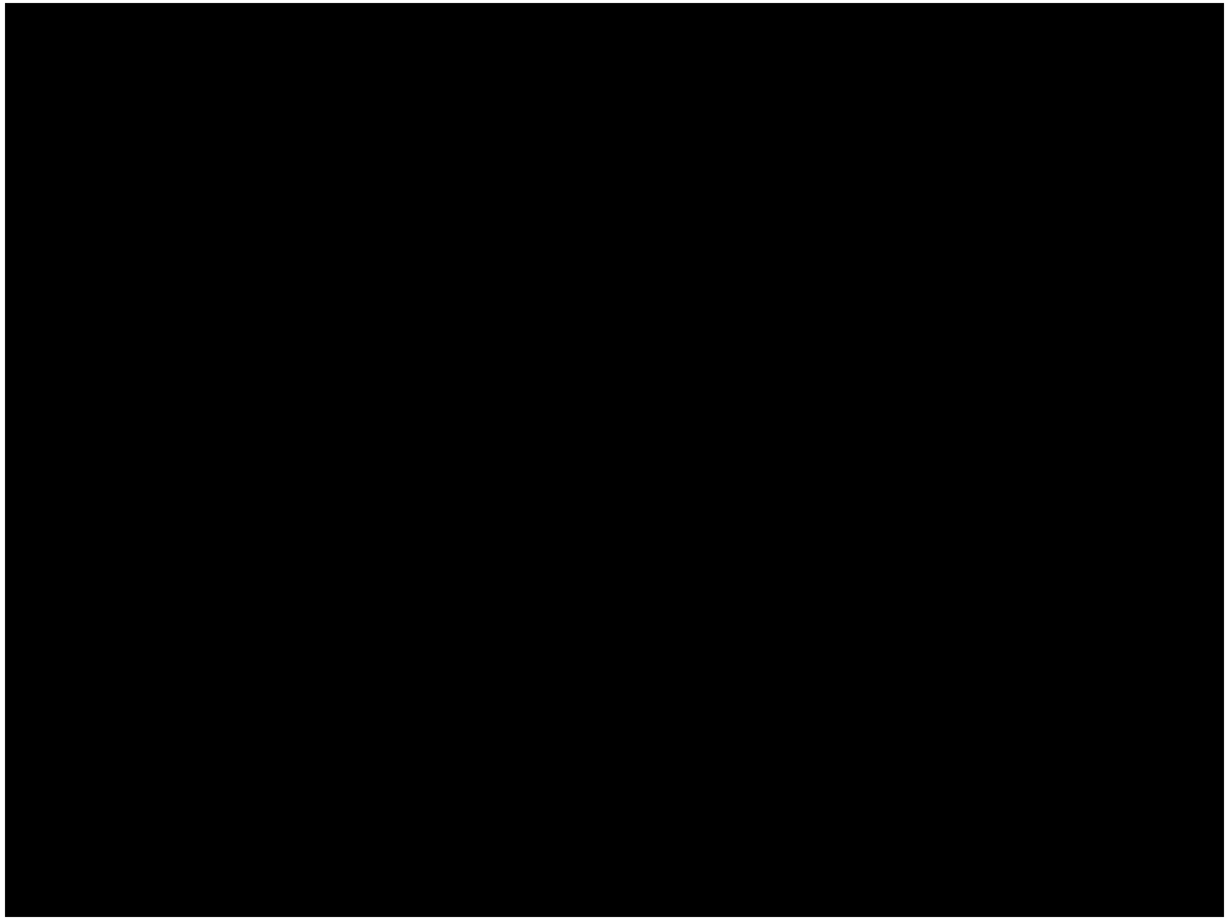
Variability of sky

Sky emission in variable!

Need to measure ~simultaneously to remove

Also can be spatially variable





Quantitative sky brightness

- Sky simulators are now available:
  - ESO Sky calculator
- Sky contributes noise to observations!
  - Amount of sky noise depends on sky brightness
  - Amount of sky noise depends on image quality

Impact on observations

- Optical broadband imaging
  - Sky surface brightness between 17 and 22.5 mag / square arcsec, depending on moon
  - “Fainter” objects achieve much better S/N in dark time
- Optical spectroscopy
  - Moon produces continuum emission
  - “fainter” objects require dark time
- Near-IR broadband imaging: brightness and time variation
  - Sky is much brighter : between 12 and 13.5 mag / square arcsec. Background limited except for ”bright” objects
  - Leads to different strategies for data collection and reduction
  - Moon contributes relatively little
  - Bright time!
- Near-IR spectroscopy
  - Sky significant in lines
  - Again, moon contributes relatively little

ASTR 535 : Observational Techniques

Effects of the Earth's atmosphere

Atmospheric absorption

Learning objectives

- Understand the nature of sources that contribute to absorption in the Earth's atmosphere, including their origin, wavelength dependence, and dependence on location and time
- Understand the basic radiative transfer of absorption and the definition of airmass and extinction coefficients
- Understand how atmospheric absorption is corrected for in imaging and spectroscopy

Atmospheric absorption

- Sources
  - Rsyleigh scattering, mostly off molecules in atmosphere
  - Aerosols : particulates in the atmosphere, e.g. salt, dust, ash
  - Molecular absorption : O_3, O_2, H_2O, CO_2, CH_4, etc.
- All are functions of wavelength
- All a functions of position
- Some are functions of time

Absorption wavelength dependence

Optical:
- Ozone provides short wavelength cutoff
- largely continuous from scattering
- Some molecular absorption, e.g. A and B bands

Near-IR
- Molecular absorption, esp H2O, dominates
- H2O absorption leads to atmospheric windows

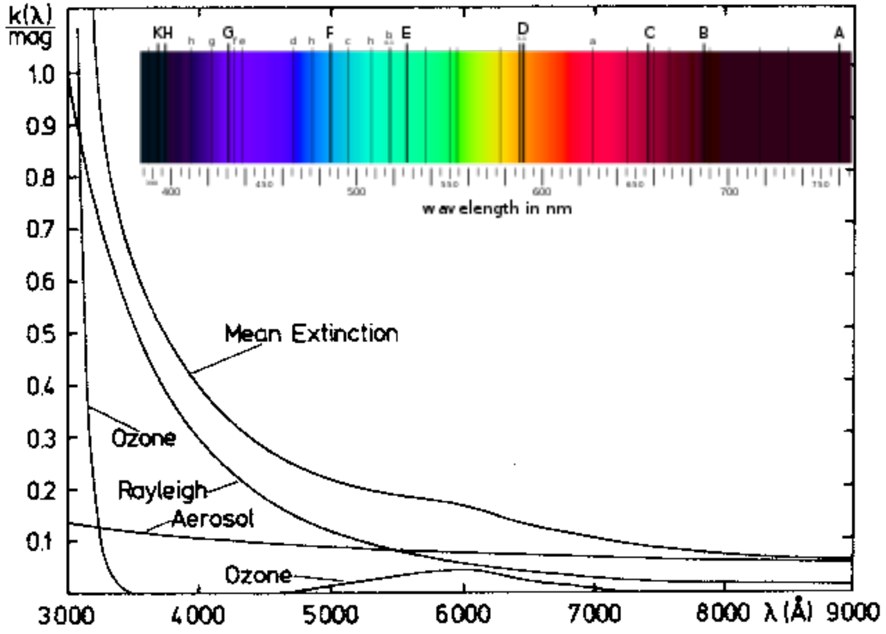


Fig. 1. Mean vertical extinction at Flagstaff, Arizona, in May-June 1976. The assumed ozone and Rayleigh co... separately

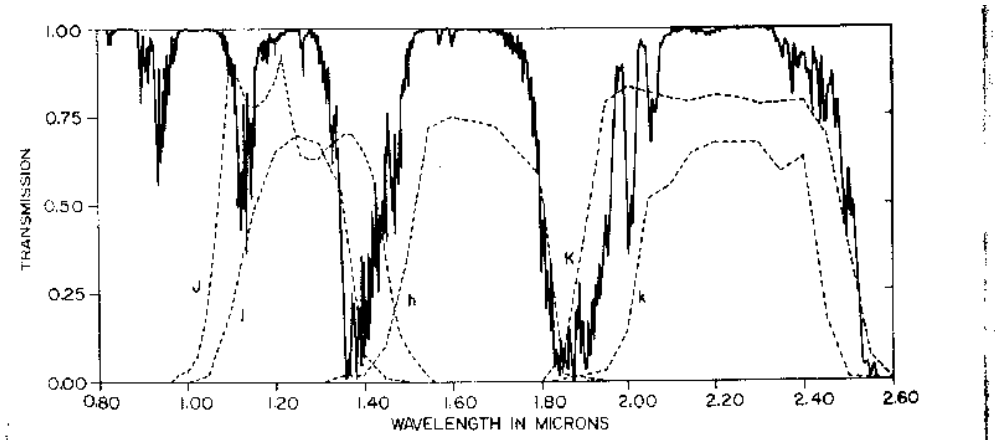
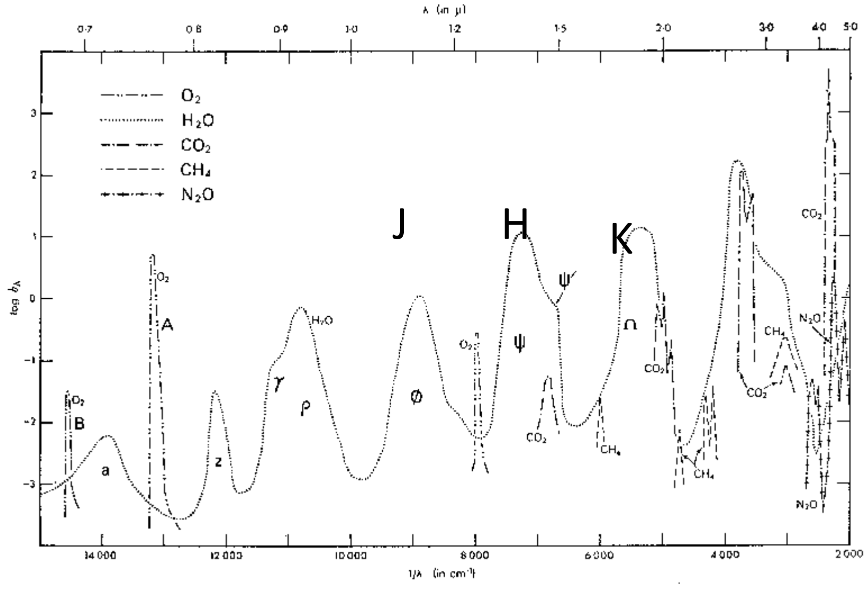


FIG. 1.—The adopted Kitt Peak summer atmospheric transmission is plotted as a function of wavelength. The sensitivity functions of the John... I and K filters (Johnson 1965b) and the currently used Kitt Peak J, H, K filters identified as j, h, and k; are also plotted.

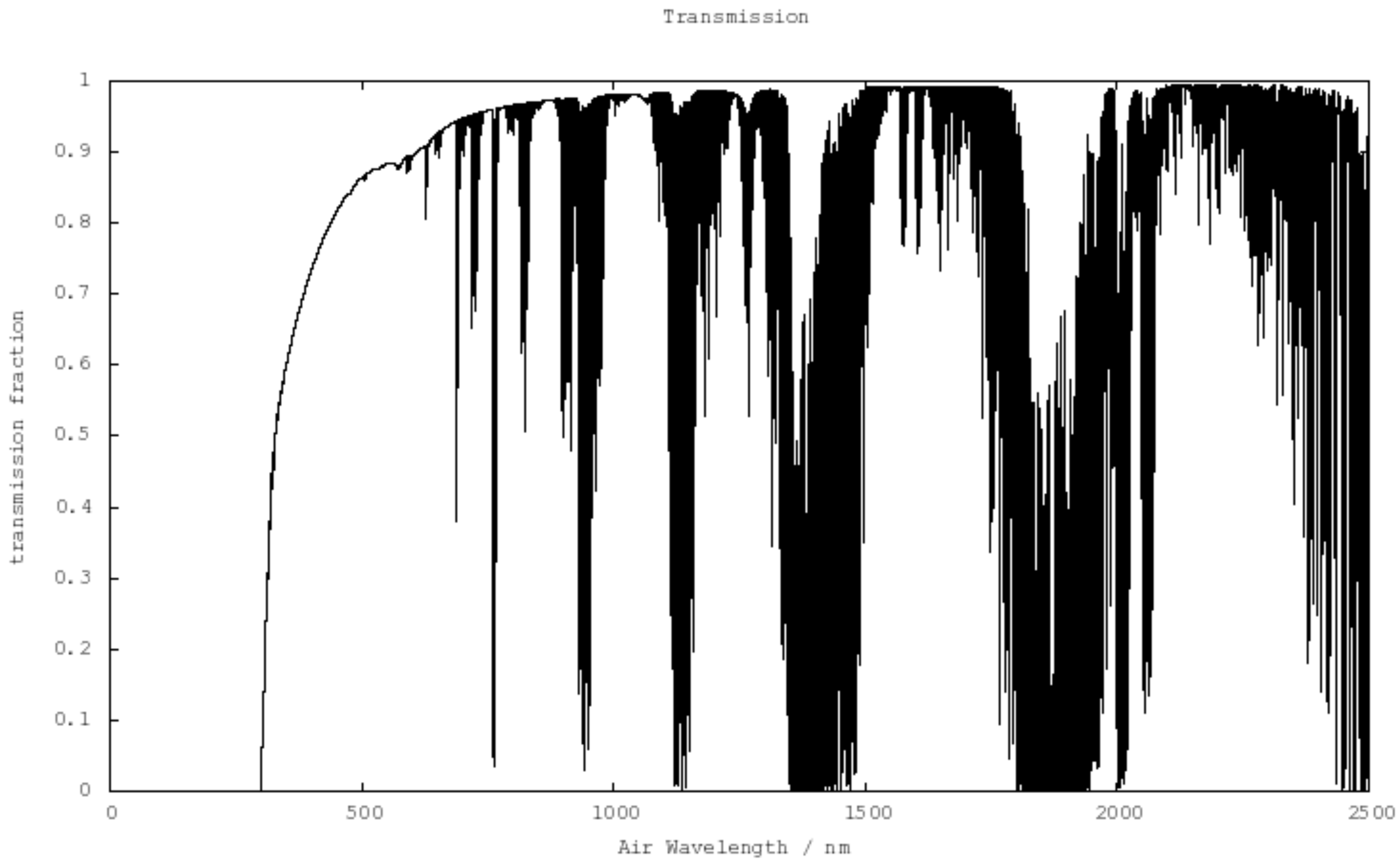


Infrared band absorption of atmospheric gases

I	806 nm
Z	900 nm[4]
Y	1020 nm
J	1220 nm
H	1630 nm
K	2190 nm
L	3450 nm
M	4750 nm
N	10500 nm
Q	21000 nm[5]

Modeling of absorption

- Also in ESO Sky calculator



Quantitative light loss through atmosphere

- Depends on how much air light passes through
  - Parameterized by the airmass

$$X \sim \sec z$$

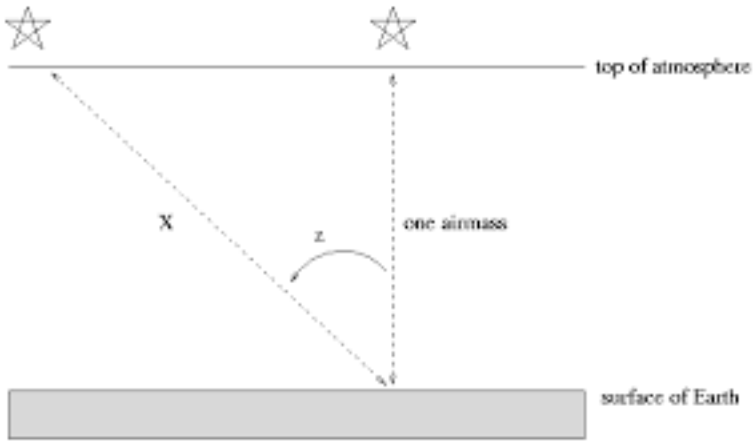
where z is the zenith distance, which can be calculated for an observation:

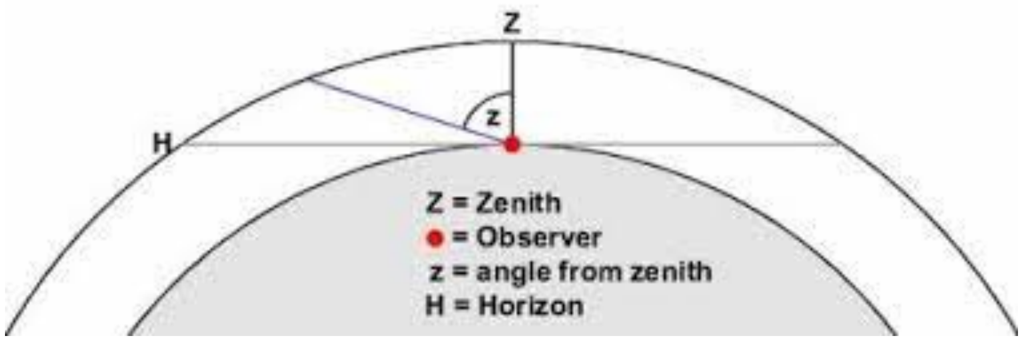
$$\sec z = (\sin \varphi \sin\delta + \cos\varphi\cos\delta\cos h)^{-1}$$

where φ is latitude, δ is declination, h is hour angle

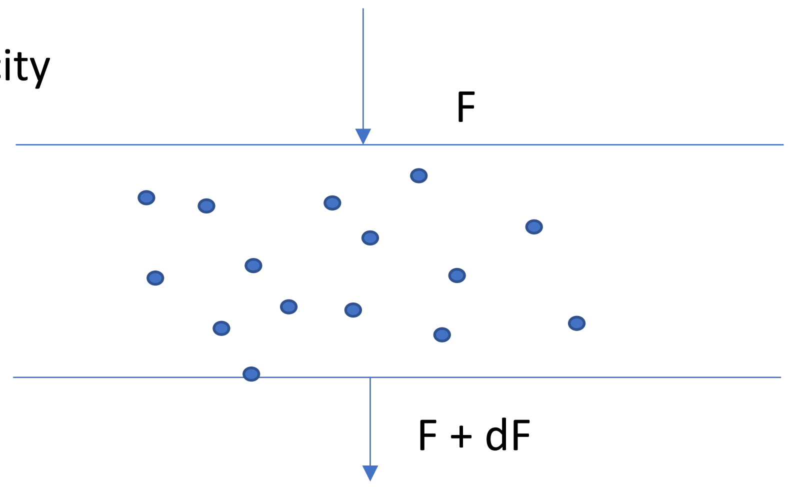
Taking into account curvature (relevant only for higher airmass) :

$X = \sec z - 0.0018167(\sec z - 1) - 0.002875(\sec z - 1)^2 - 0.0008083(\sec z - 1)^3$





Quantitative light loss through atmosphere



Consider a thin slab of atmosphere with incident flux F and absorber opacity

$$\kappa = N\,\sigma$$

Simple radiative transfer equation :

$$dF = -\,\kappa F dx$$

with solution

$$F = F_{top}e^{-\kappa dx} \equiv F_{top}e^{-\tau}$$

where τ is the optical depth. Scaling with airmass:

$$\tau(X) \sim \tau_0 X$$

we get

$$F = F_{top}e^{-\tau_0 X}$$

Expressed in magnitudes

$$m = m_0 + 1.086\tau_0 X$$

$$m_0 = m + k_\lambda X$$

Where the *extinction coefficient, k,* is defined as:

$$k_\lambda \equiv -1.086\tau_0$$

Atmospheric absorption and photometry

- All sky photometry
  - Required conditions : photometric so that there is uniform dependence on airmass
  - Solve for extinction only
    - First and second order extinction coefficients

      $m_0 = m + k_\lambda X + k_{2\lambda} \text{ (color) } X$
    - Observe one (or more) stars at a range of airmasses, determine k
    - Apply extinction correction to instrumental magnitudes
  - Solve simultaneously for extinction plus transformation, observing a set of stars of known magnitude over a range of colors and a range of airmasses

$$M_i = m_i + k_i X + t_i(M_i - M_j) + z_i$$

solve for surface to determine k, t, z. Then for science targets, apply!
  - In a single field (differential photometry), zeropoint accounts for extinction, but only to the extent to which the extinction is constant over the field

Atmospheric absorption and spectroscopy

- Mean extinction coefficients
- telluric absorption and spectroscopy
  - “telluric standards”, usually hot stars

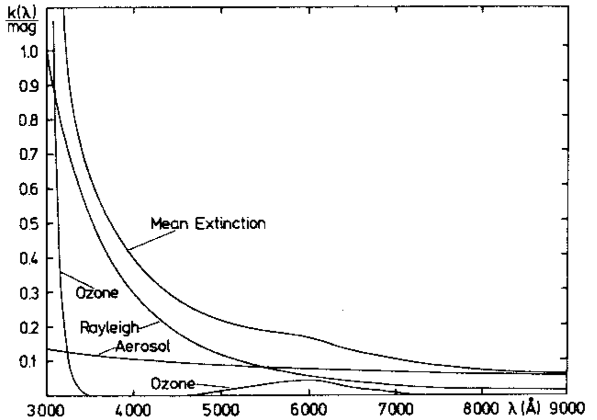
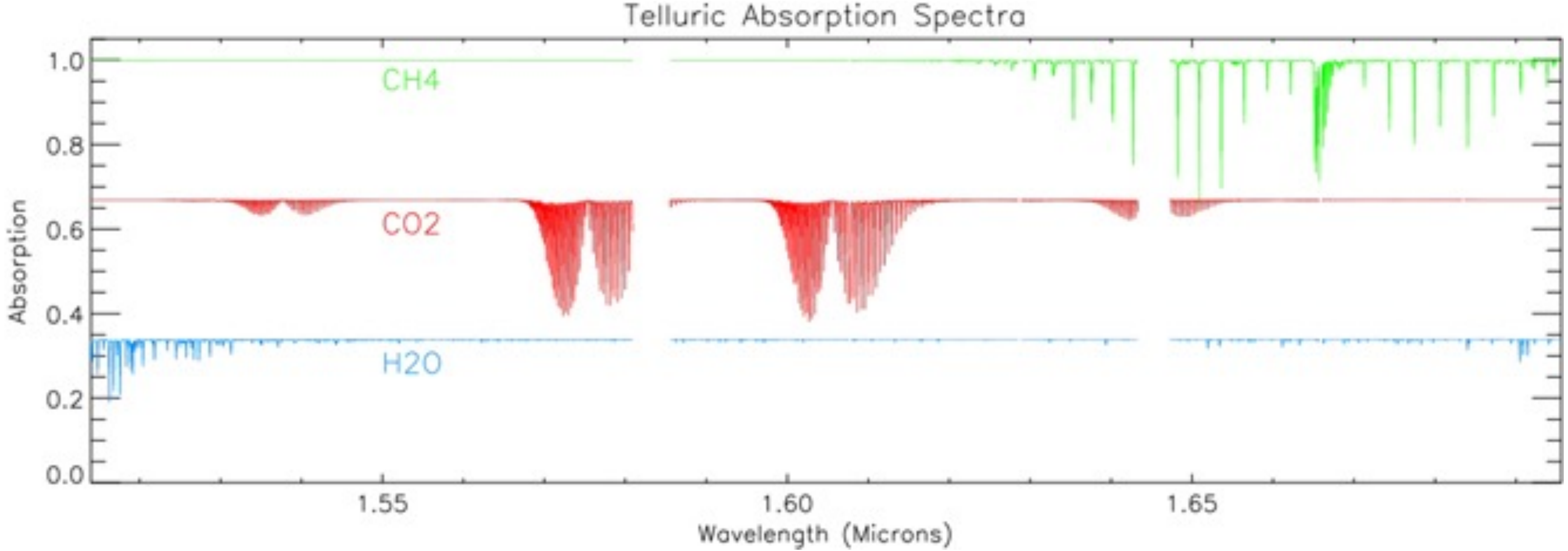


Fig. 1. Mean vertical extinction at Flagstaff, Arizona, in May-June 1976. The assumed ozone and Rayleigh contributions are shown separately



ASTR 535 : Observational Techniques

Effects of the Earth’s atmosphere

Atmospheric refraction

Learning objectives

- Understand how refraction from the Earth's atmosphere causes the direction of light from astronomical objects to be deflected
- Understand the terms astronomical refraction and constant of refraction
- Understand that refraction varies with wavelength, leading to differential refraction
- Understand some of the implications of refraction and differential refraction

Atmospheric refraction

- Refraction and Snell's law
- Application to the Earth's atmosphere (n_{air} ~ 1.00029)

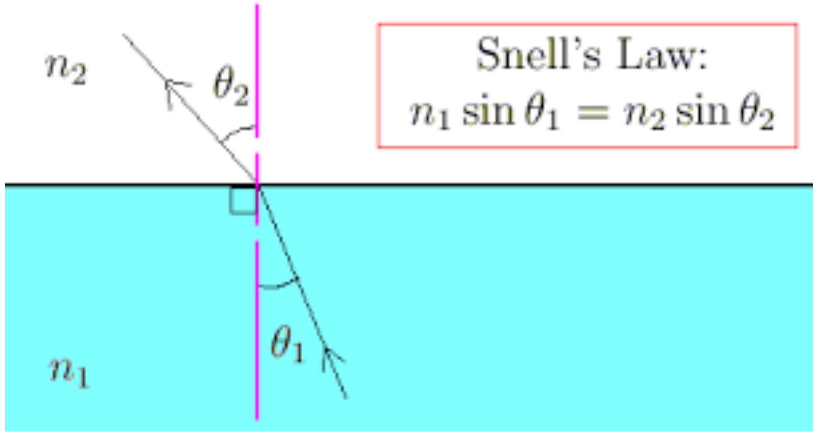
$$\frac{\sin z_0}{\sin z_N} = \frac{\mu_N}{1}$$

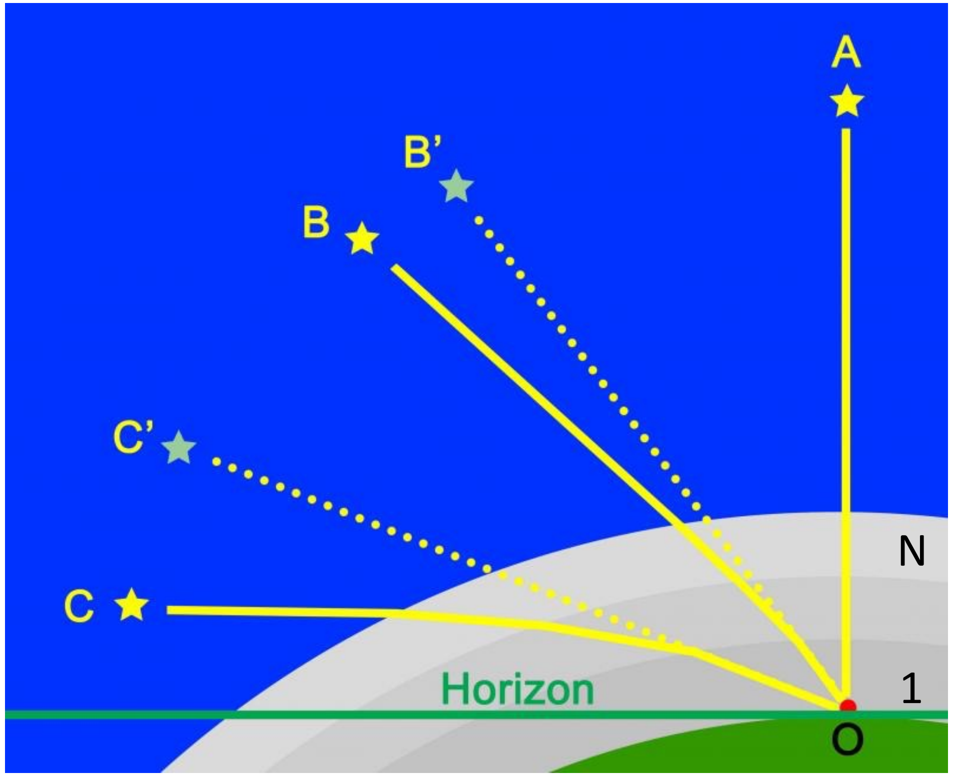
$$\frac{\sin z_N}{\sin z_{N\_1}} = \frac{\mu_{N\_1}}{\mu_N}$$

....

$$\frac{\sin z_1}{\sin z} = \frac{\mu}{\mu_1}$$

--> $\sin z_0 = \mu \sin z$





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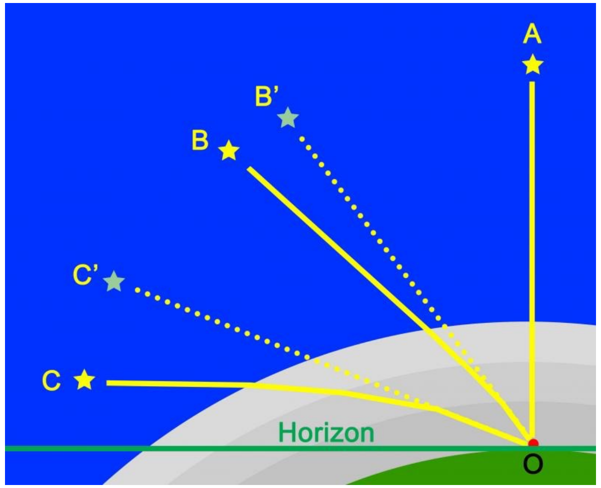
Atmospheric refraction



- Astronomical refraction, r, is the amount the object is displaced

$$\sin(z + r) = \mu \sin z$$

Since r is small

$$\sin z + r \cos z = \mu \sin z$$

$$r = (\mu - 1)\tan z \equiv R \tan z$$

where R is the "constant of refraction" and is determined by the index of refraction of air.

  - This breaks down at larger airmass, where a more complicated formula is required

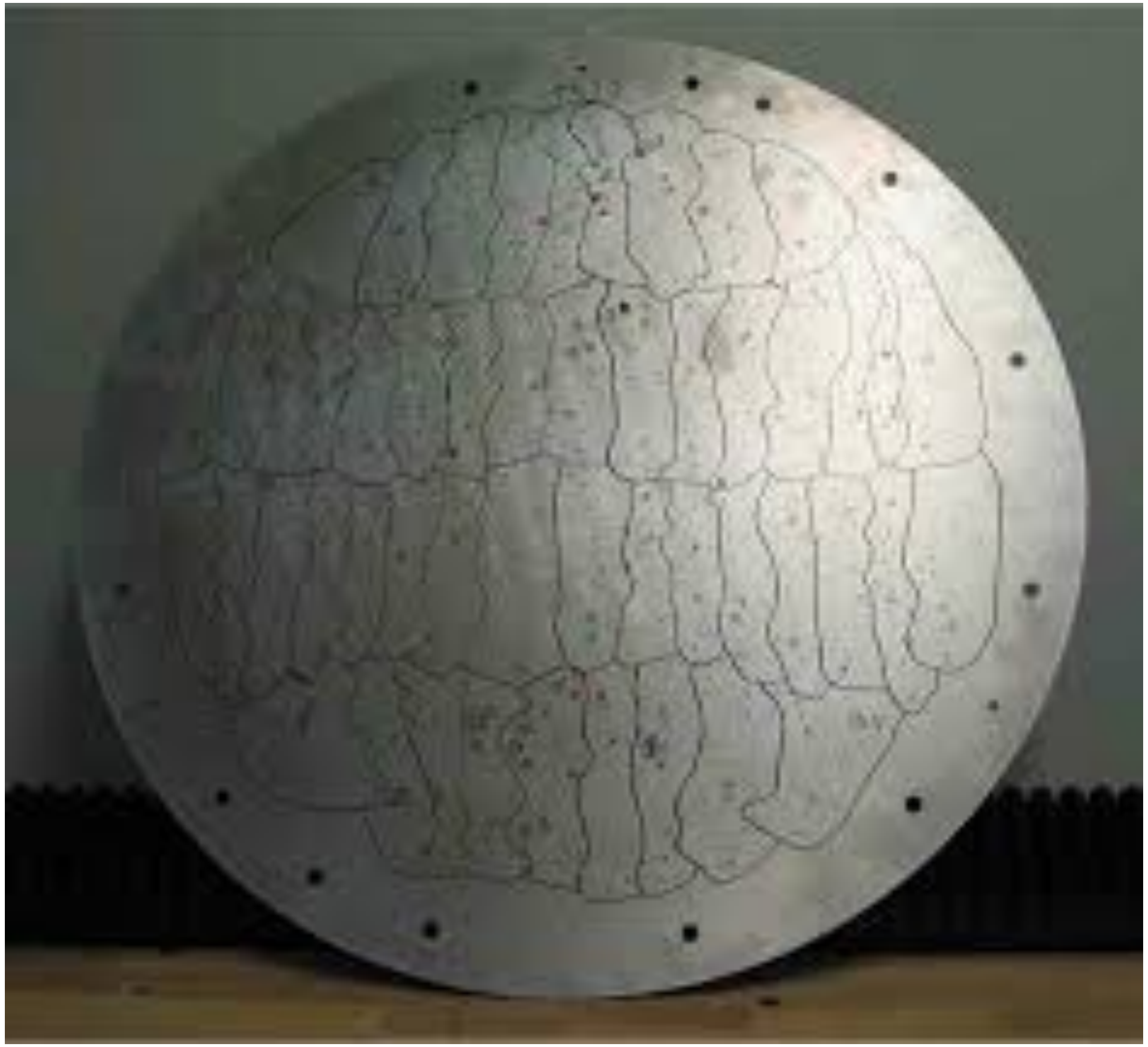
- Index of refraction is a function of wavelength, but typical value in the mid-optical is μ = 1.00029, which gives R ≈ 60 arcsec, so objects are displaced about 1 arcminute
- Direction of displacement is towards the zenith, which can be a combination of motion in both right ascension and declination
  - Displacement is along the parallactic angle, which is the angle between N and the zenith

Some impacts of refraction

- Need to know to point telescopes
- Need to know when determining actual positions of objects across the sky (all-sky astrometry)

Refraction and wide field spectroscopy

- Across a ”wide” field, refraction varies, so if you need to precisely locate where the relative positions of objects are, you may need to do so for a particular position in the sky
- Example: SDSS plug plates where multiple plates needed to be made for the *same* field, depending on hour angle of observation!



Differential refraction and spectroscopy

Index of refraction of air is a function of wavelength

λ (Å)	R (")
3000	63.4
4000	61.4
5000	60.6
6000	60.2
7000	59.9
10000	59.6
40000	59.3

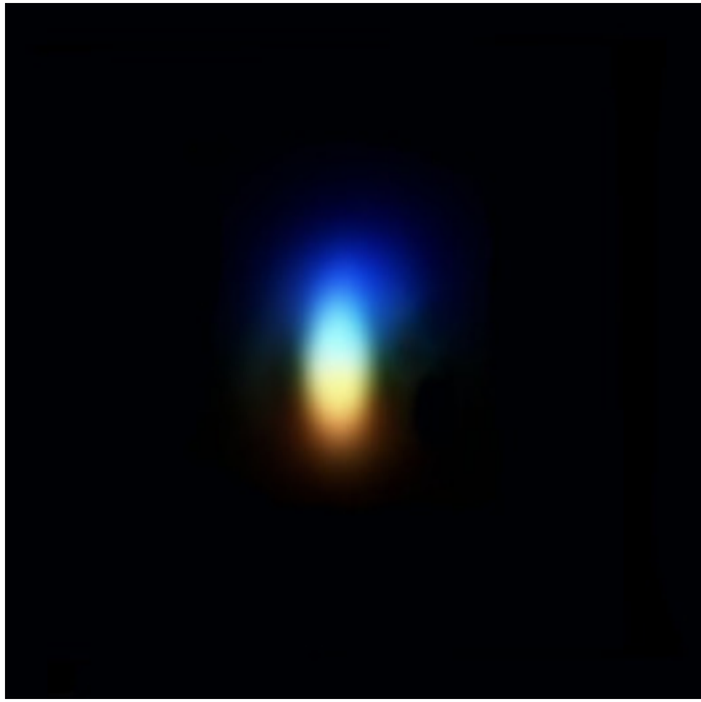


Figure 5. An image of Polaris at high magnification showing atmospheric dispersion. Image courtesy of Martin Lewis https://britastro.org/node/17066

→ Atmosphere acts as a prism : differential refraction

- Implication for aperture or slit spectroscopy
  - Will get different fraction of light depending on wavelength, leading to inability to accurately do relative flux calibration, i.e. get large scale shape of spectrum correct
  - For slit spectroscopy, can be alleviated by positioning slit along the parallactic angle
  - It is possible to build atmospheric dispersion (ADC) corrector to counteract the effect, but this must include a moving component, since amplitude changes with zenith distance

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Effects of the Earth's atmosphere

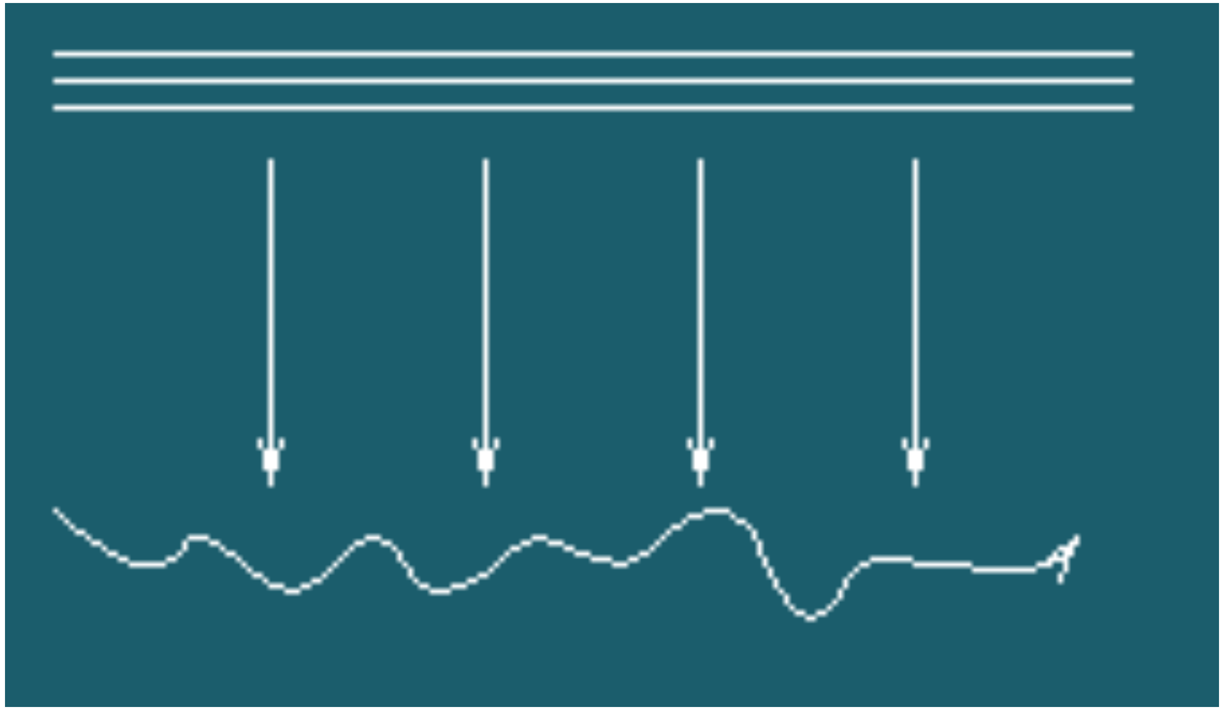
Atmospheric seeing

Learning objectives

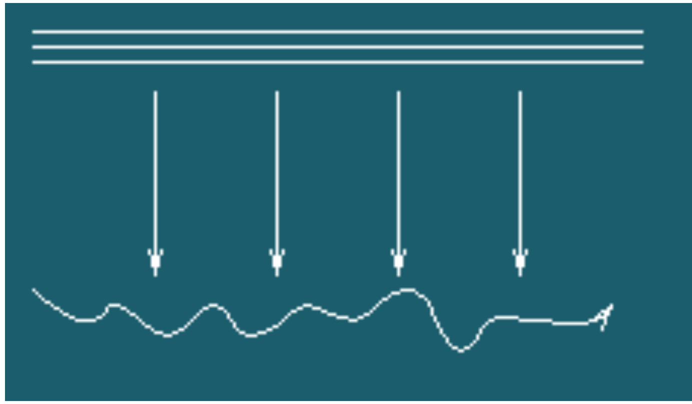
- Understand the basic concept of scintillation and seeing. Know the terminology of the coherence length (r_0) and the isoplanatic patch, and know what typical values are.
- Understand the multiple man-made sources of seeing.
- Know the terminology for describing/characterizing image shape: FWHM, PSF, MTF, EE, and Strehl ratio.
- Understand how the PSF extends to large distances and does not depend on the brightness of the star, although your ability to recognize it might.

Atmospheric seeing

- For an incoming plane wave of light, a perfect optical system will make a diffraction-limited image
- Variations in the index of refraction over the scale of the cylinder of light coming into the telescope cause small deviations from a plane wave
- Causes two effects:
  - Scintillation : integrated intensity variations
  - Seeing: positional and image quality variations

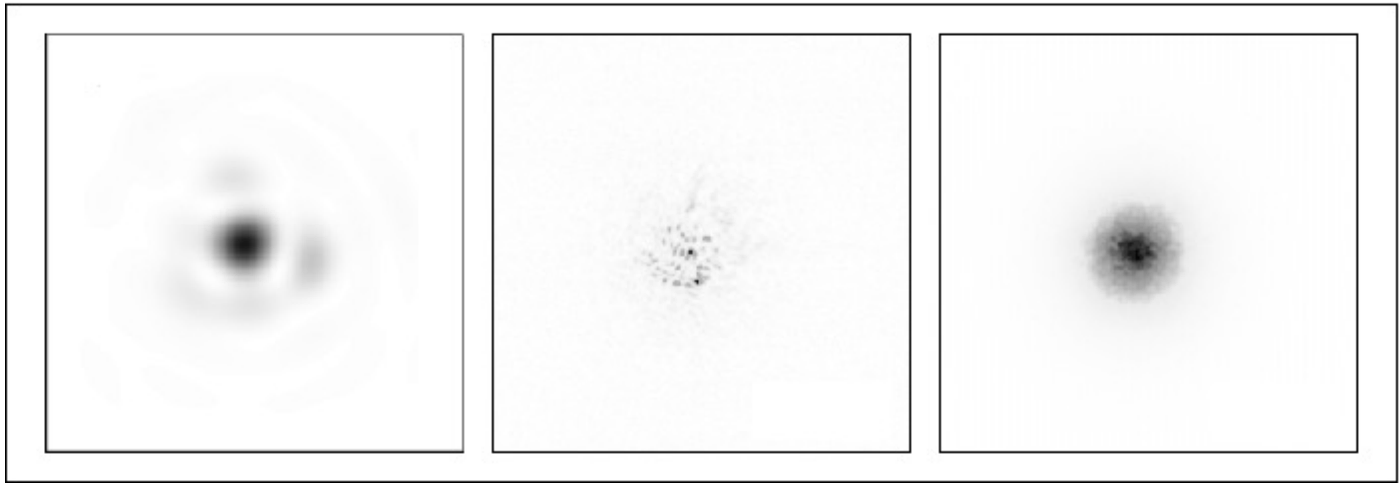


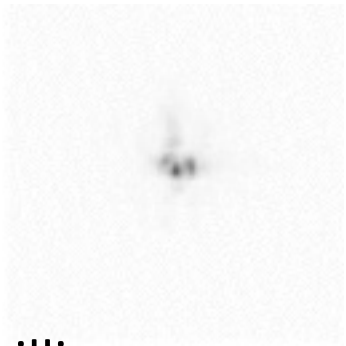
Atmospheric seeing: effects



Observation:

- scintillation small for larger apertures
- In small apertures (<~ 10cm), one sees diffraction limited images in short exposures (<10-100 msec), but they move around
- In larger apertures, one sees “speckles” in short exposures, which move around
- In longer exposures, both give similar images, typically around 1” FWHM





Implication:

- Wavefront in ~flat on scales of 10-20 cm,
- Instantaneous slopes vary by ~1 arcsec on scales of tens of millisec

Atmospheric seeing: theory

- Seeing comes from atmospheric turbulence, theory worked out by Kolmogorov, Fried and others
- Interested here just in recognizing some vocabulary!
- Turbulent fields described by a structure function

$$D_N(x) \equiv < | N(r + x) - N(r)|^2 >$$

- Kolmogorov turbulence gives index of refraction structure function:

$$D_n(x) = C_n{}^2 x^{2/3}$$

where C_n is the refractive index structure constant

- This leads to phase structure function:

$$D_\varphi(x) = 6.88 \left(\frac{x}{r_0}\right)^{5/3}$$

where the coherence length, r_0, is given by:

$$r_0 = .185\ \lambda^{6/5} \cos^{3/5} z \left(\int C_n{}^2\, dh\right)^{-3/5}$$

Image size from seeing

- Physically, r_0 is roughly inversely proportional to image size (d) from seeing

$$d \sim \lambda / r_0$$

  bigger r_0 is better!

- For diffraction, image size is given by

$$d \sim \lambda / D$$

- Seeing dominates when $r_0 < D$; a larger r_0 means better seeing. Diffraction more important for smaller apertures.
- Seeing is more important than diffraction at shorter wavelengths (and for larger apertures) since r_0 scales roughly with wavelength. Diffraction more important at longer wavelengths
- effects of diffraction and seeing cross over in the IR for most astronomical-sized telescopes (∼5 microns for 4m); the crossover falls at a shorter wavelength for smaller telescope or better seeing.

Where in atmosphere does seeing arise?

- Amplitude of r_0 comes from $(\int C_n^2\, dh)^{-3/5}$
- as you might expect, this varies from site to site and also in time.
- At most sites, there seems to be three regimes of ``surface layer" (wind-surface interactions and manmade seeing), ``planetary boundary layer" (influenced by diurnal heating), and ``free atmosphere" (10 km is tropopause: high wind shears
- typical astronomical site has $r_0 \sim$10-20 cm at 5000Å
  - Roughly matches empirical data of when speckles are seen

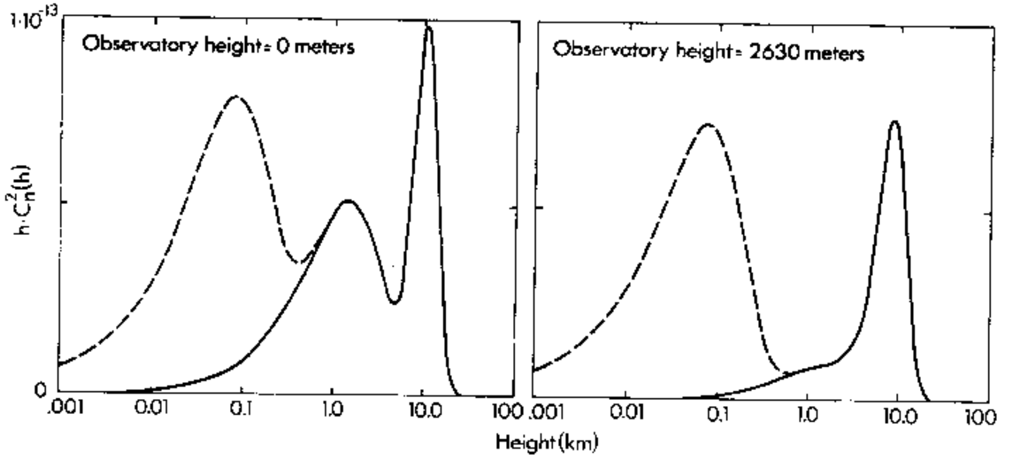
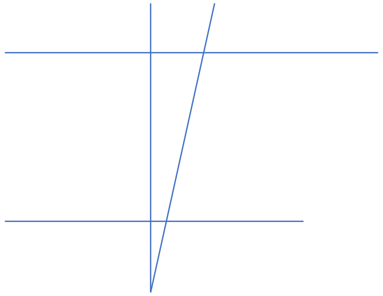


Figure 2 Average C_n^2 profile with local height h_L (in km). (*Left*) Profile for a sea level site. (*Right*) Profile for a 2630 meter high mountain site. The solid curve follows the expression given by Valley (1980) for height h above sea level: $C_n^2 = [2.05 \times 10^{-23} \cdot h^{10} \cdot \exp(-h) + 0.93 \times 10^{-16} \cdot \exp(-h/1.5)]\ m^{-2/3}$. It ignores near ground, local seeing. It is scaled to give 0.5 arcsec seeing at $= 0.55\ \mu m$ at sea level. The dashed line corresponds to $C_n^2 = (2.17 \times 10^{-15} + 5 \times 10^{-17} \cdot h_L^{-2/3}) \cdot \exp(-h_L/0.08)$ which also results in 0.5 arcsec seeing by itself. It approximates this local nighttime seeing. For the sea level site the resulting seeing is 0.76 arcsec; for the mountain site 0.63 arcsec. For daytime condition the local seeing will be worse. The $h \cdot C_n^2$ vs log h presentation was chosen to better visualize the contributions of the different heights to r_o.

Isoplanatic patch



- Can also consider the coherence of the same turbulence pattern over the sky. This coherence angle is called the *isoplanatic angle* (solid angle over which wavefront is ~ the same). Theory gives

  $\vartheta \sim 0.314 r_0/H$

  where H is the typical distance to seeing layer

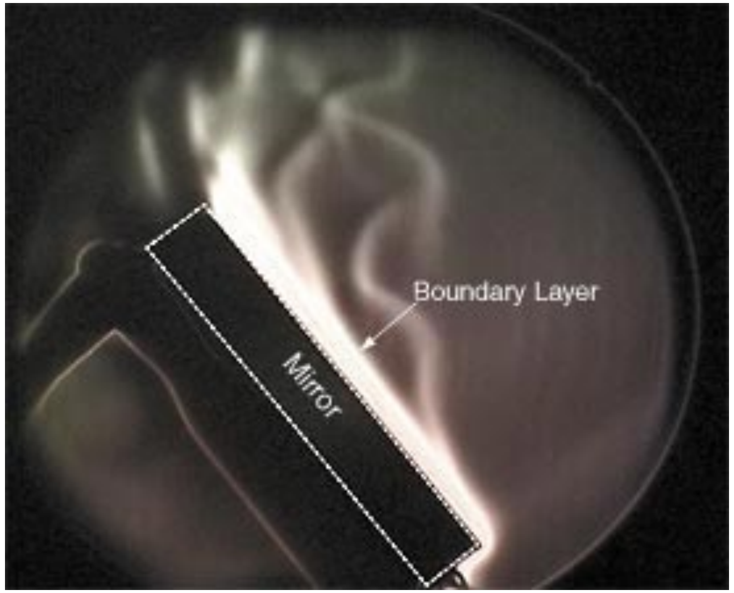
  $H = \sec z \left(\int C_n^2 h^{5/3}\, dh \,/ \int C_n^2\, dh\right)^{3/5}$
- region over which the turbulence pattern is the same is called the *isoplanatic patch*.
- relevant to adaptive optics, where we will try to correct for the differences across the telescope aperture; if we do a single correction, how large a field of view will be corrected?
- For r_0 = 10 cm (e.g. in optical) $H \sim 5000$ m , $\vartheta \sim 1.3$ arcsec. In the infrared $r_0 \sim 70$ cm, $H \sim 5000$ m, $\vartheta \sim 9$ arcsec, i.e. for free atmosphere.
  - For boundary layer, however, isoplanatic patch is considerably larger (part of motivation for ground-layer AO).
- Note that the ``isoplanatic patch for image motion" (not wavefront) is $\sim 0.3 D/H$.
  - For D = 4 m, $H \sim 5000$ m, ϑ_{kin} = 50 arcsec.
  - relevant for low-order atmospheric correction, i.e., tip-tilt, where one is doing *partial* correction of the effect of the atmosphere.

Seeing and site location

- Seeing varies from night to night
- Better seeing with less turbulence
- Laminar air flow is less turbulent, so often observatories located along leading edge in direction of prevailing winds
- atmospheric turbulence is not directly correlated with the presence of clouds. In fact, the seeing is often better with thin cirrus than when it is clear!

Other sources of image degradation

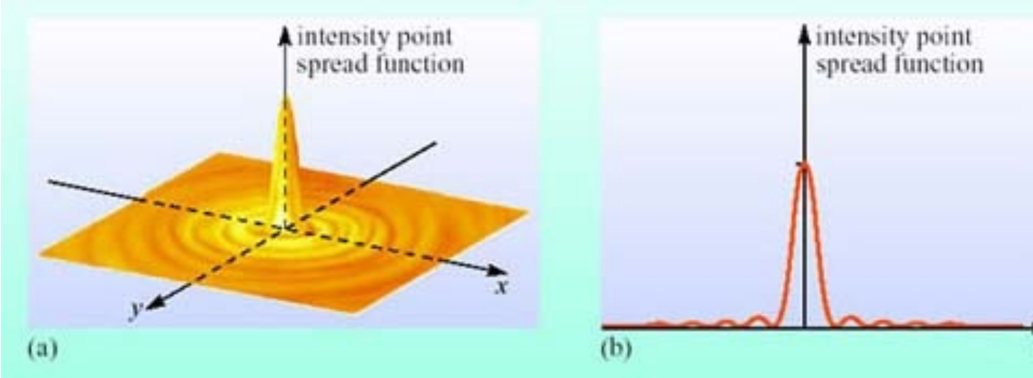
- Man-made seeing
  - Dome: turbulence at slit
  - Mirror: turbulence at mirror
- Telescope motion
  - Wind
  - Tracking
- Optical design / fabrication



Characterizing image shape

- Point spread function (PSF) : full 2D function
- Under assumption of azimuthal symmetry
  - Full width at half maximum (FWHM)
  - Encircled energy (EE) : integral of PSF
- Modulation Transfer Function (MTF) : Fourier transform of PSF

  $MTF(v) = \exp[-3.44(\lambda v/r_o)^{5/3}]$
  - Note that this is close to Gaussian
- Strehl ratio
  - Often used to describe AO performance
  - Ratio of peak to peak of diffraction limited image



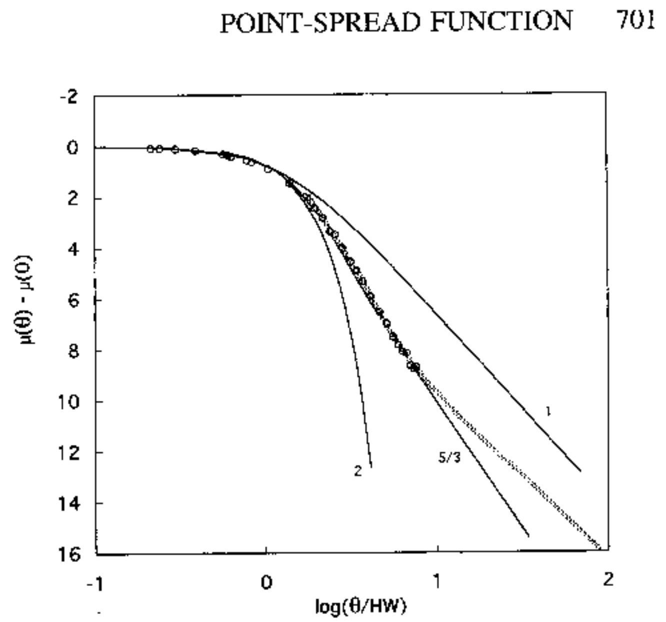


FIG. 2—The observed PSF (open circles, stippled line) is compared to theoretical models for MTFs of different indices n.

Empirical PSF

- PSF has more extended wings than Gaussian
- Well characterized by a Moffat function or, even better, by two

- Note that PSF extends "forever"

- Wings are "lost" in the background

- Fainter star wings are lost at smaller radii, but the PSF of faint and bright stars are the same

- Fainter stars are not "smaller" than brighter stars!

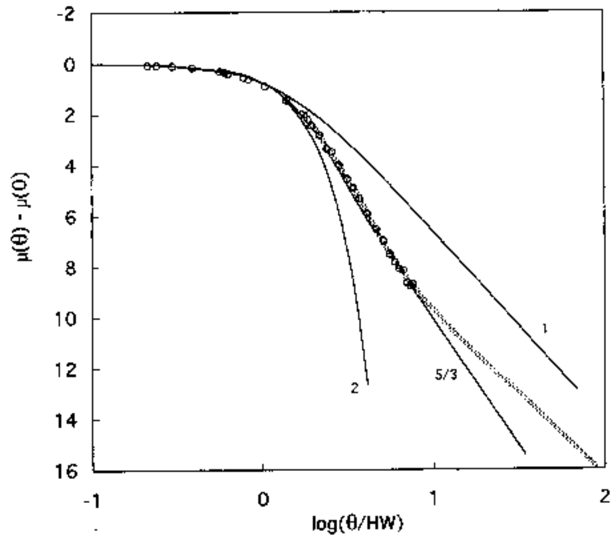


FIG. 2—The observed PSF (open circles, stippled line) is compared to theoretical models for MTFs of different indices n.

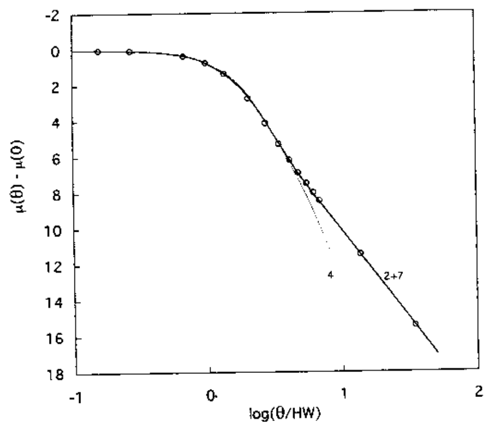


FIG. 3—The Kolmogorov PSF (open circles) fitted by a Moffat function with $\beta=4$ (thin line) and by the sum of two Moffat functions ($\beta_1=7$ and $\beta_2=2$). All functions have the same HW as the PSF.

APO Observing programs

- Observing information page: astronomy.nmsu.edu:8000/apo-wiki/wiki/NMSU/2019 (linked from Canvas page)

- Spectrophotometric standards

- In groups, read through material, present:
  - Science context and goal
  - Instrument and instrument configuration
  - Targets : location, slit position?
    - When are they observable? Use skycalc or some other observation planning tool
    - TUI catalogs
  - Required conditions
  - Exposure times / criteria
  - Calibrations
  - Other?
  - Outstanding questions