

Astronomical Observing Techniques

Lecture 2: Trouble is in the Air

Christoph U. Keller

keller@strw.leidenuniv.nl

Outline

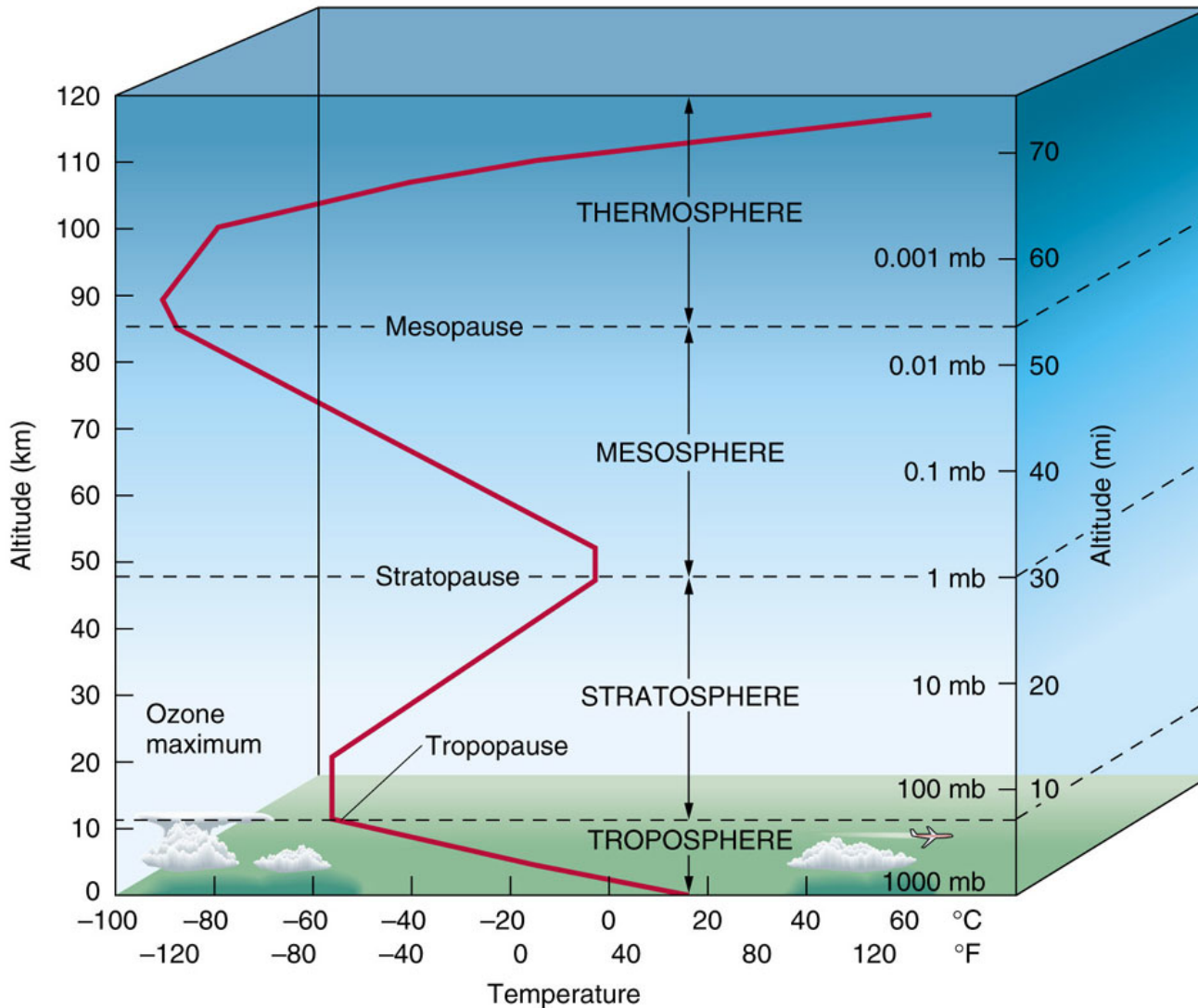
1. Atmospheric Structure
2. Absorption
3. Emission
4. Scattering, Refraction & Dispersion
5. Turbulence & Seeing

1. Atmospheric Structure

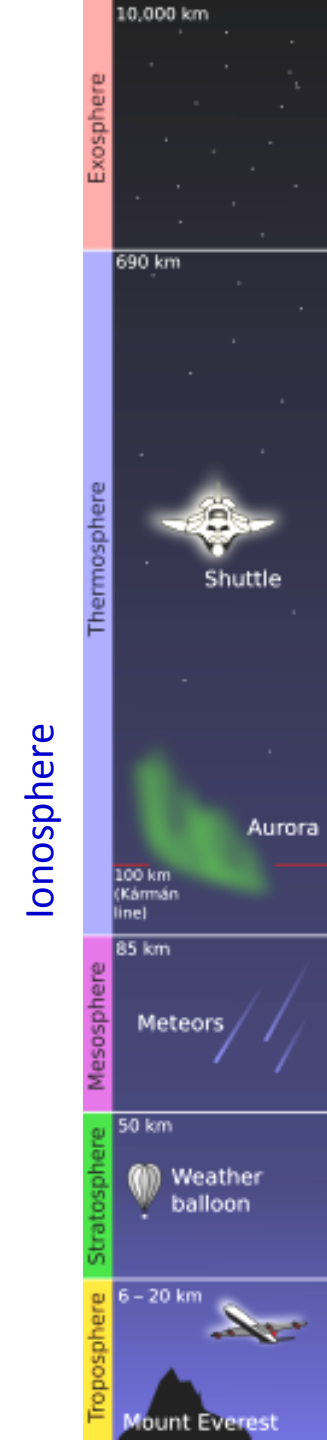
- Assumptions:
 - atmosphere in **local radiative equilibrium**
 - homogeneous composition
- Hydrostatic equilibrium structure described by:
 - altitude z
 - temperature $T(z)$
 - density $\rho(z)$
- **Pressure $P(z)$** described by:
$$P(z) = P_0 e^{-\frac{z}{H}}, \quad H = \frac{kT}{\mu g}$$

$H =$ **scale height** (about 8km), $\mu =$ mean molecular weight

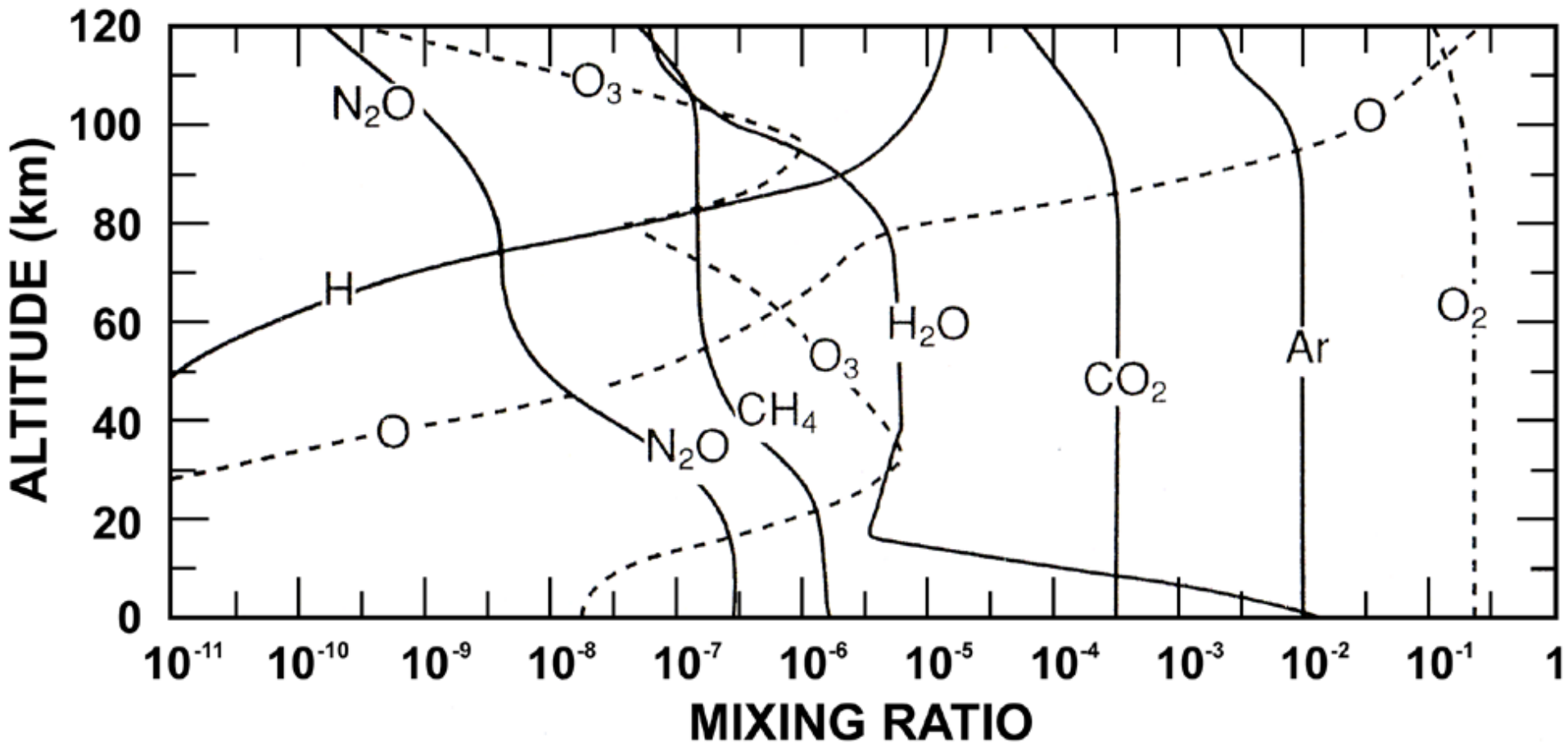
Vertical Profile



www.geog.ucsb.edu/~joel/g110_w08/lecture_notes/stability/agburt01_09.jpg



Mixing Ratio of Atmospheric Gases



ruc.noaa.gov/AMB_Publications_bj/2009%20Schlatter_Atmospheric%20Composition%20and%20Vertical%20Structure_eae319MS-1.pdf

Atmospheric Composition

- O_2 , N_2 main constituents, constant proportions up to 100 km
- Ozone – mainly absorbs in UV
 - distribution depends on latitude, season
- CO_2 – important component for (mid)-infrared absorption
 - mixing independent of altitude
- Ions – vary strongly with altitude and solar activity
 - relevant > 60km (reactions with UV photons)
$$O_2 + h\nu \rightarrow O_2^{+*} + e^- \quad \text{and} \quad O_2 + h\nu \rightarrow O^+ + O + e^-$$
 - electron showers along magnetic fields cause Aurora
 - at 100 – 300 km height: $n_e \sim 10^5 - 10^6 \text{ cm}^{-3}$
- H_2O – highly variable, very strong absorption bands

2. Absorption

- Atomic, molecular transitions -> absorption features:
 - pure **rotational** molecular transitions: H₂O, CO₂, O₃,
 - **rotation-vibrational** molecular transitions: CO₂, NO, CO
 - **electronic molecular** transitions: CH₄, CO, H₂O, O₂, O₃, OH
 - **electronic atomic** transitions: O, N, ...

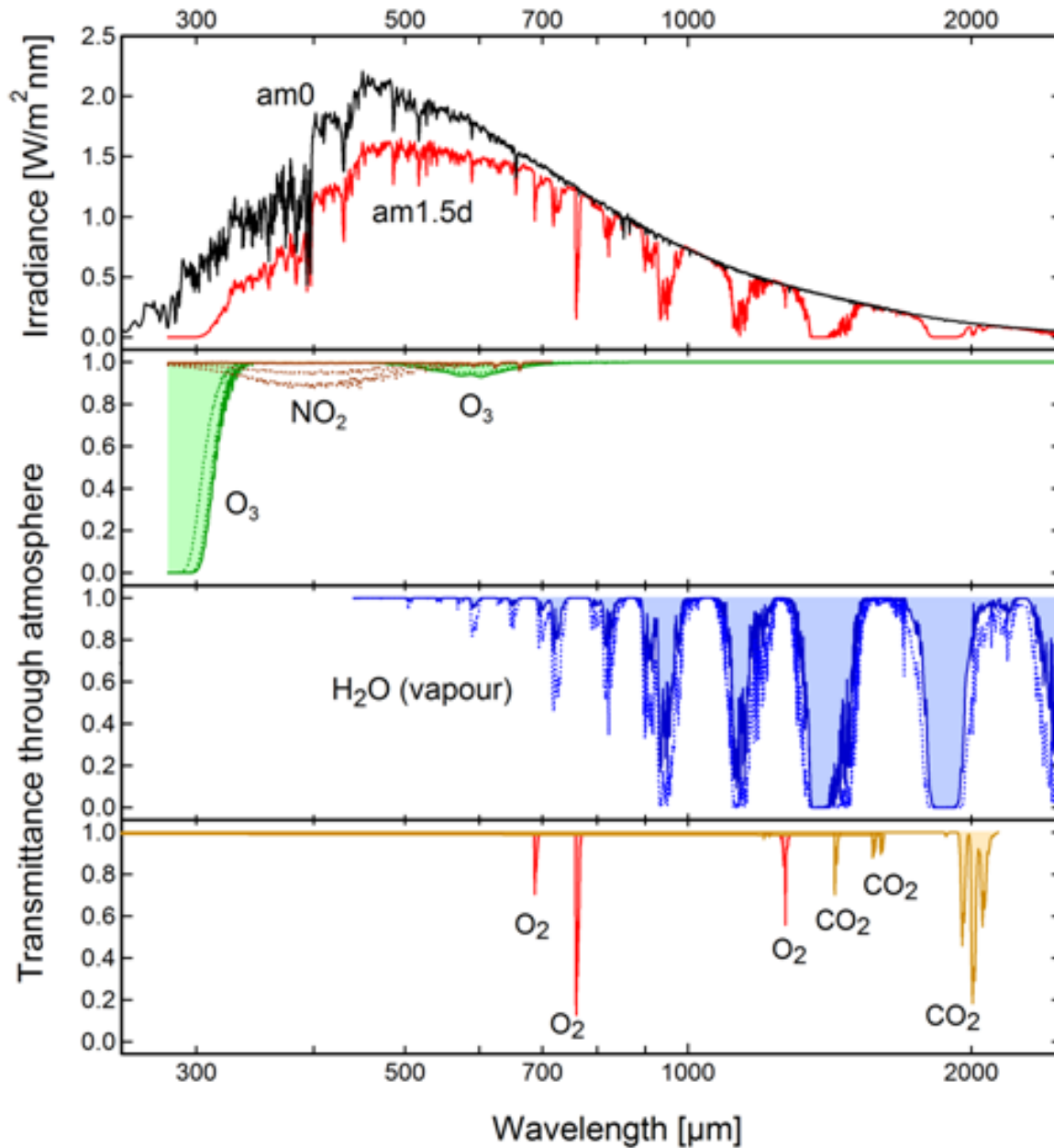
- Attenuation at altitude z_0 and zenith distance θ :
$$I(z_0) = I_0(\infty) \cdot \exp\left[-\frac{1}{\cos\theta} \sum_i \tau_i(\lambda, z_0)\right]$$

- for i absorbing species with optical depth τ_i

$$\tau_i(\lambda, z_0) = \int_{z_0}^{\infty} r_i(z) \rho_0(z) \kappa_i(\lambda) dz$$

κ : absorption coefficient; ρ_0 : mass density of air;

$r_i(z)$ the mixing ratio $r_i = n_i / (n_{\text{tot}} - n_i)$ where n is the amount in mol



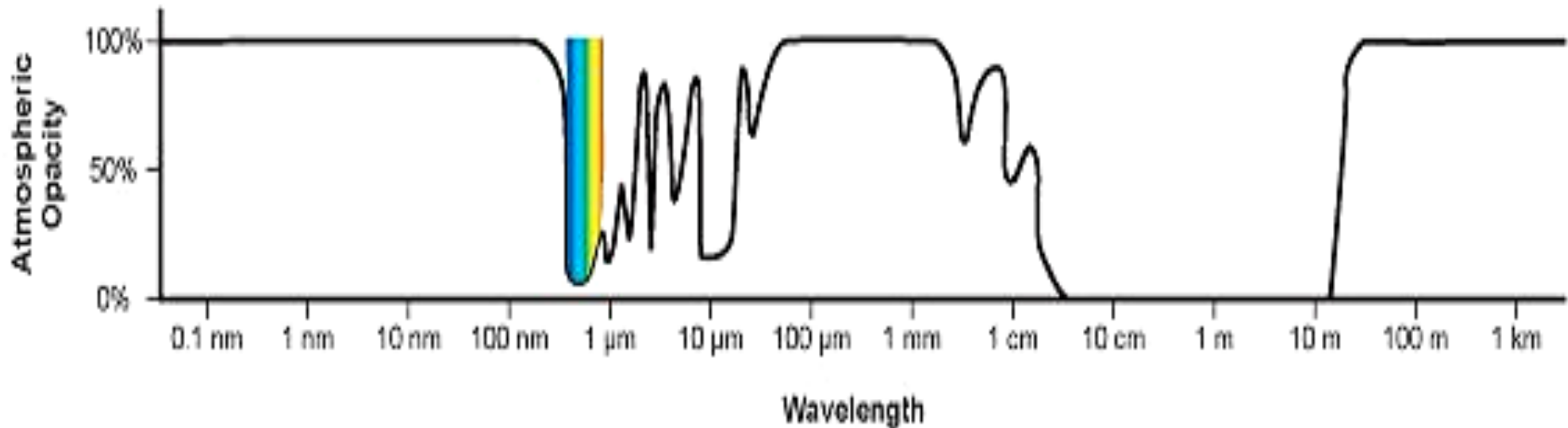
www.pvlighthouse.com.au/resources/courses/altermatt/The%20Solar%20Spectrum/figures/Sources%20of%20absorption%20in%20AM1-5d.png

Atmospheric Bands

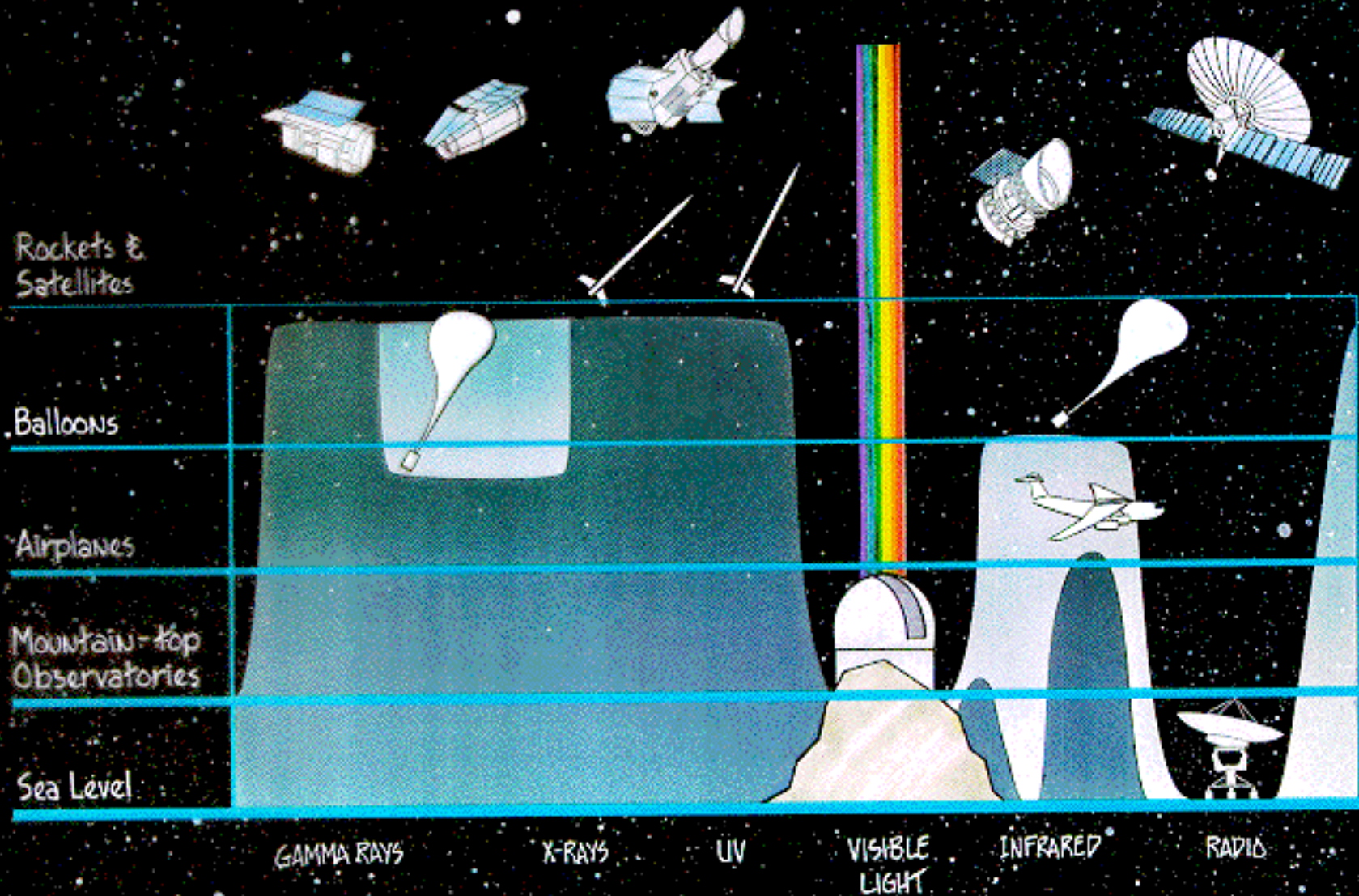
Two cases of absorption:

- total** absorption → atmospheric **transmission windows**
- partial** absorption → reduced transmission due to narrow **telluric lines** of terrestrial origin

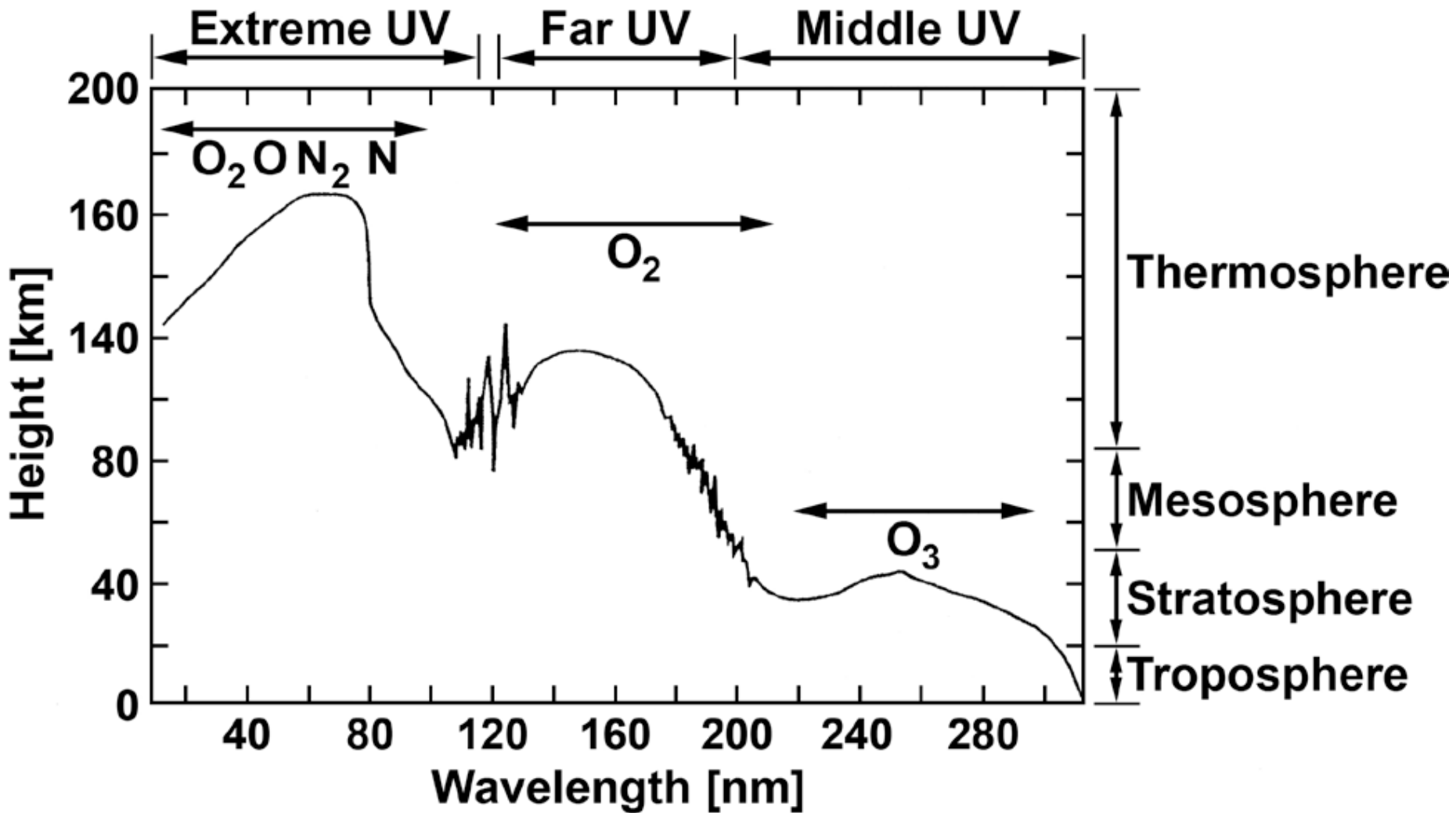
Atmospheric opacity defines **atmospheric transmission bands**
(wavelengths accessible to ground-based observations)



Ground based astronomy is limited to visible, near/mid-IR and radio wavelengths.
Space astronomy provides access to γ -rays, X-rays, UV, FIR, sub-mm



UV Absorption



ruc.noaa.gov/AMB_Publications_bj/2009%20Schlatter_Atmospheric%20Composition%20and%20Vertical%20Structure_eae319MS-1.pdf



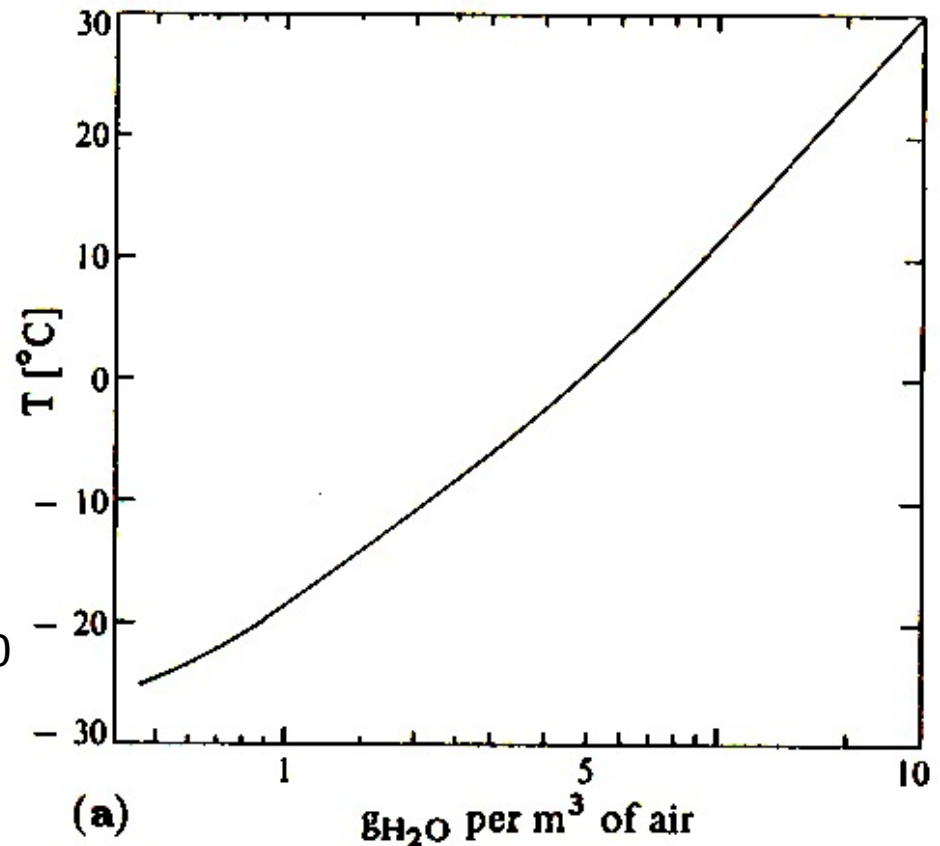


Absorption by Water Vapour

- Water vapor strongly depends on T and z
- Precipitable water vapor (PWV) = depth of water in column of atmosphere (if liquid)
- PWV w above altitude z_0

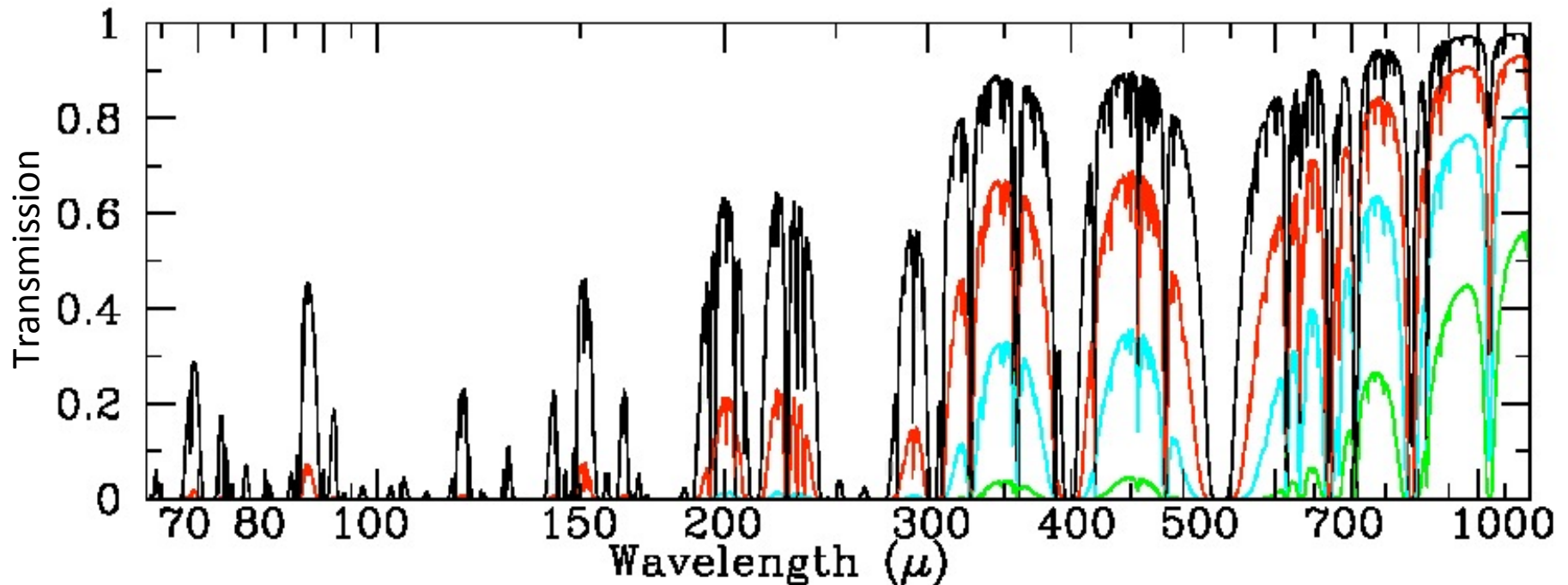
$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz ,$$

$$N_{H_2O} [\text{m}^{-3}] = 4.3 \times 10^{25} \frac{P}{P_0} \frac{T}{T_0} r(z)$$



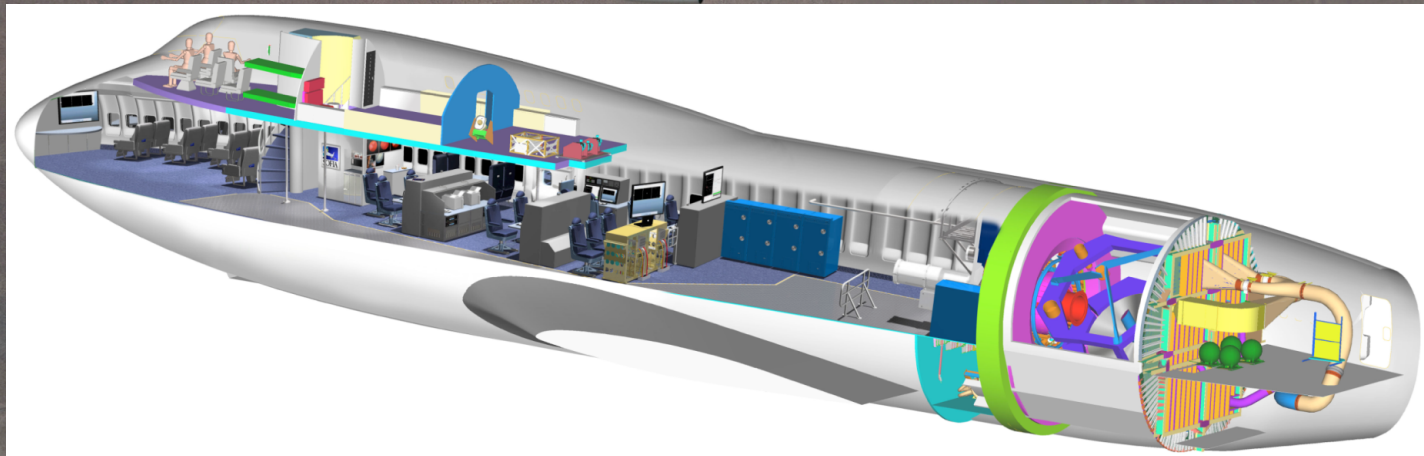
Absorption by Water Vapour

Scale height for PWV is only ~ 3 km
→ observatories at **high altitudes**



0.1 mm PWV, 0.4 mm PWV, 1.0 mm PWV, 3.0 mm PWV

FIR/sub-mm astronomy is also possible from airplanes, e.g. the Stratospheric Observatory for Infrared Astronomy (SOFIA)

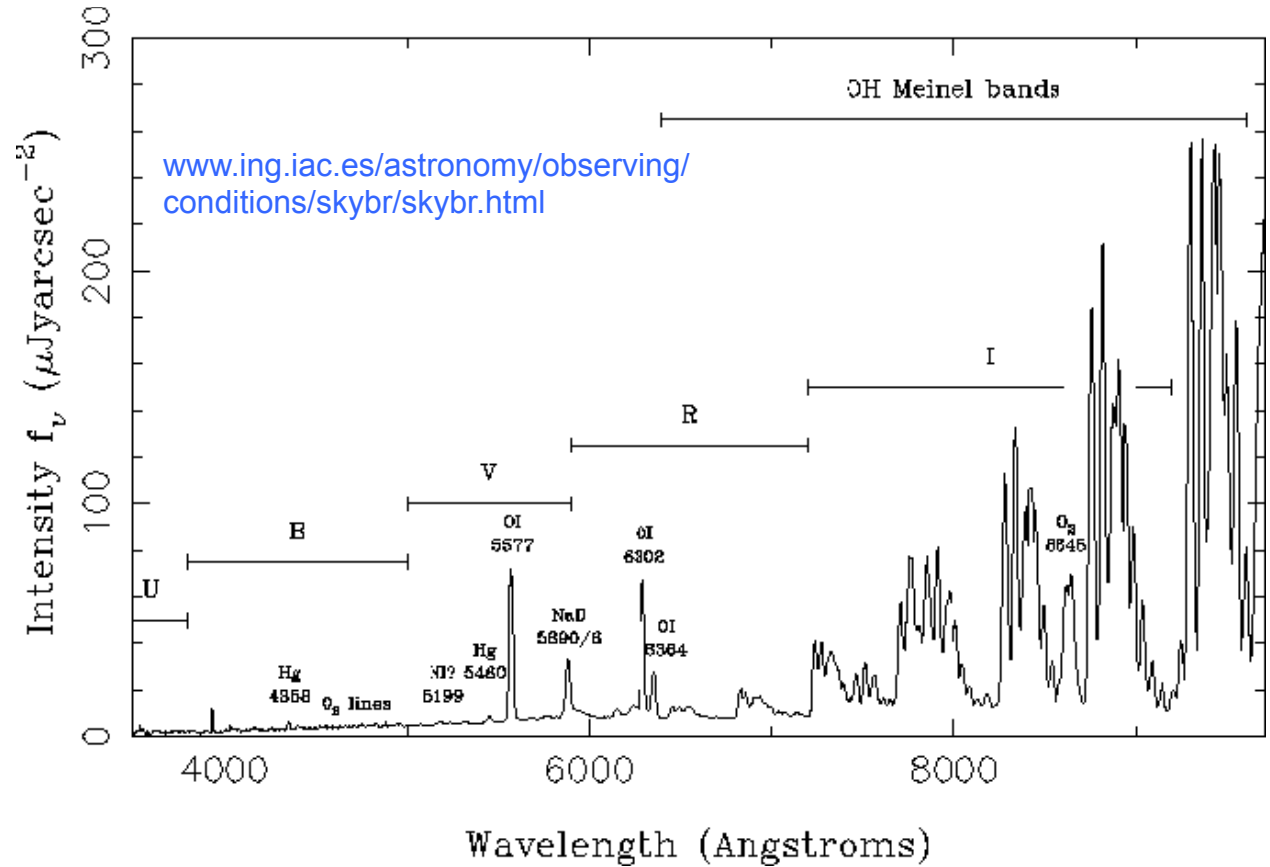


3. Atmospheric Emission

- **Fluorescence** = recombination of electrons with ions
- Recombination probability low; takes several hours → part of night
 - Produces both continuum + line emission = **airglow**
 - Occurs mainly at ~ 100 km height
 - Main sources of emission: O I, Na I, O₂, OH (in NIR), H
- Emission intensity measured in **Rayleigh**:

$$1 \text{ Rayleigh} = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} = \frac{1.58 \cdot 10^{-11}}{\lambda[\text{nm}]} \text{ W cm}^{-2} \text{ sr}^{-1}$$

Airglow



NASA/Dan Burbank - <http://spaceflight.nasa.gov/gallery/images/station/crew-30/html/iss030e015472.html>

Thermal Atmospheric Emission

- Atmosphere in **local thermodynamic equilibrium (LTE)** <60 km, i.e. excitation levels are thermally populated
- **Full radiative transfer calculation** needed
- For $\tau \ll 1$ use **approximation**:

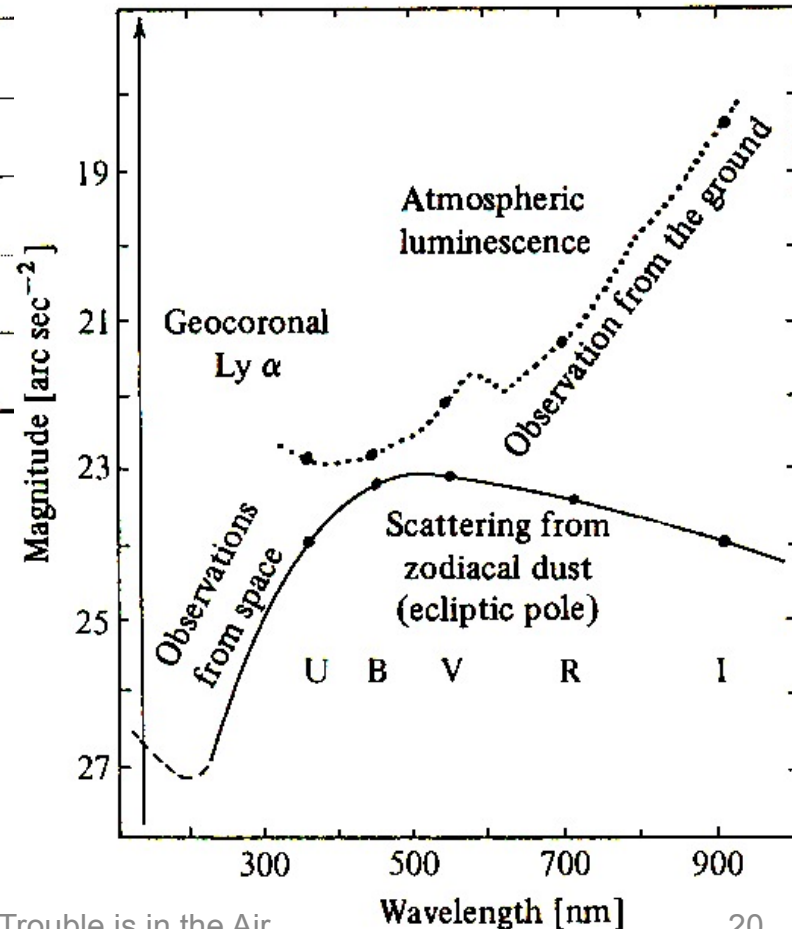
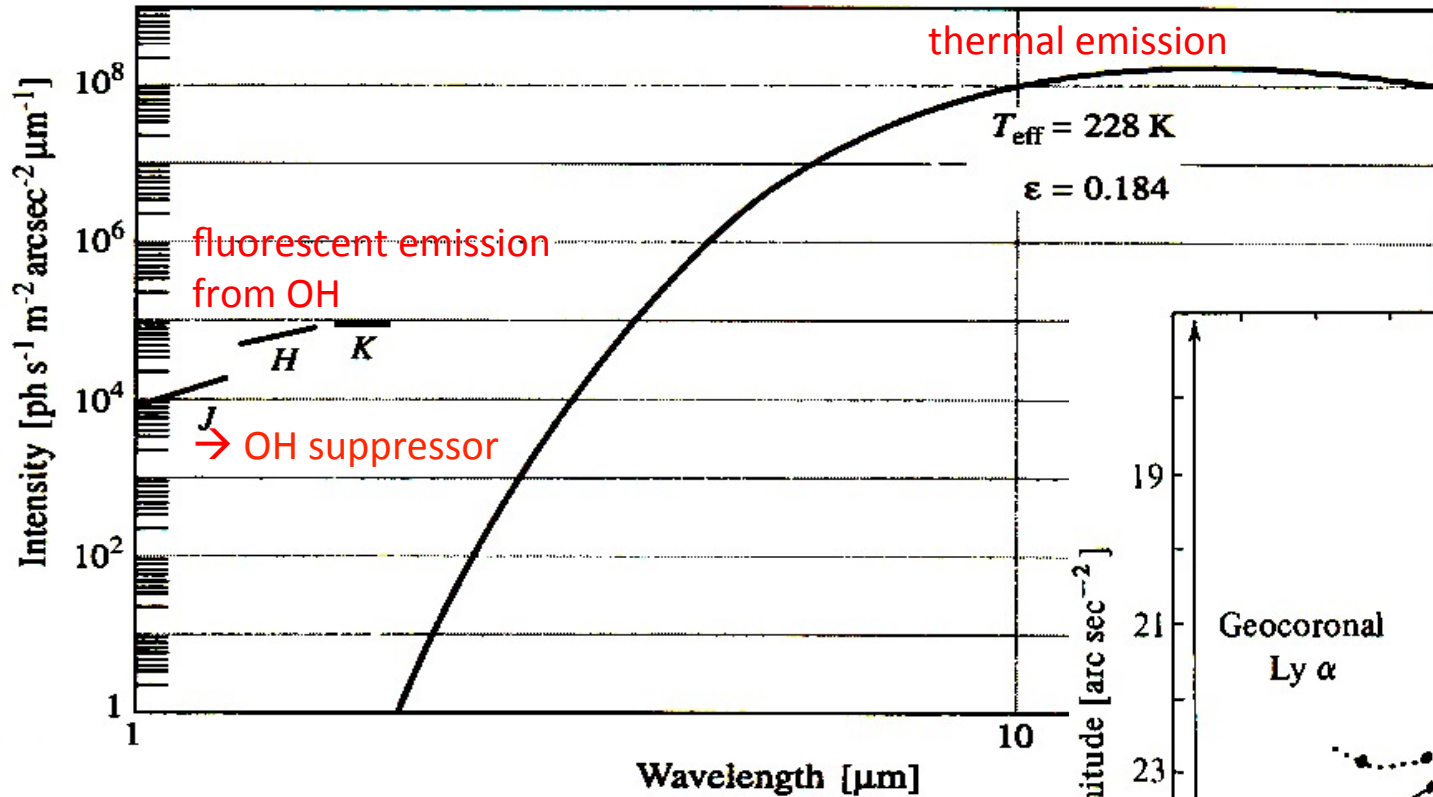
$$I_{\lambda}(z) = \frac{\tau_{\lambda} B_{\lambda}(T_{\text{mean}})}{\cos\theta}$$

For $T = 250$ K and $\theta = 0$

$B_{\lambda}(T_{\text{mean}})$: Planck function at mean temperature T_{mean} of atmosphere

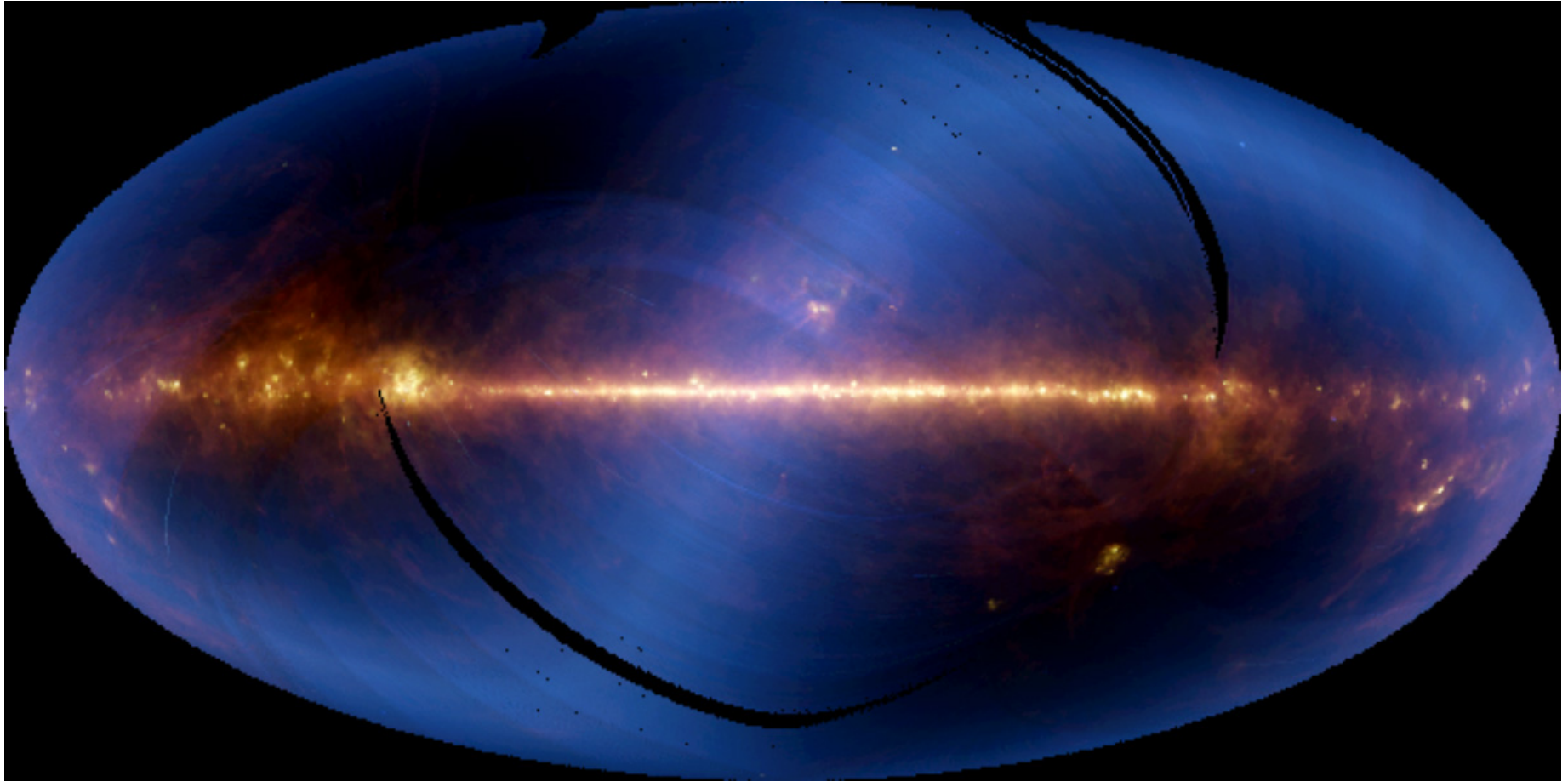
Spectral band (cf. Sect. 3.3)	<i>L</i>	<i>M</i>	<i>N</i>	<i>Q</i>
Mean wavelength [μm]	3.4	5.0	10.2	21.0
Mean optical depth τ	0.15	0.3	0.08	0.3
Magnitude [arcsec ⁻²]	8.1	2.0	-2.1	-5.8
Intensity [Jy arcsec ⁻²] ^a	0.16	22.5	250	2100

Fluorescent and Thermal Emission



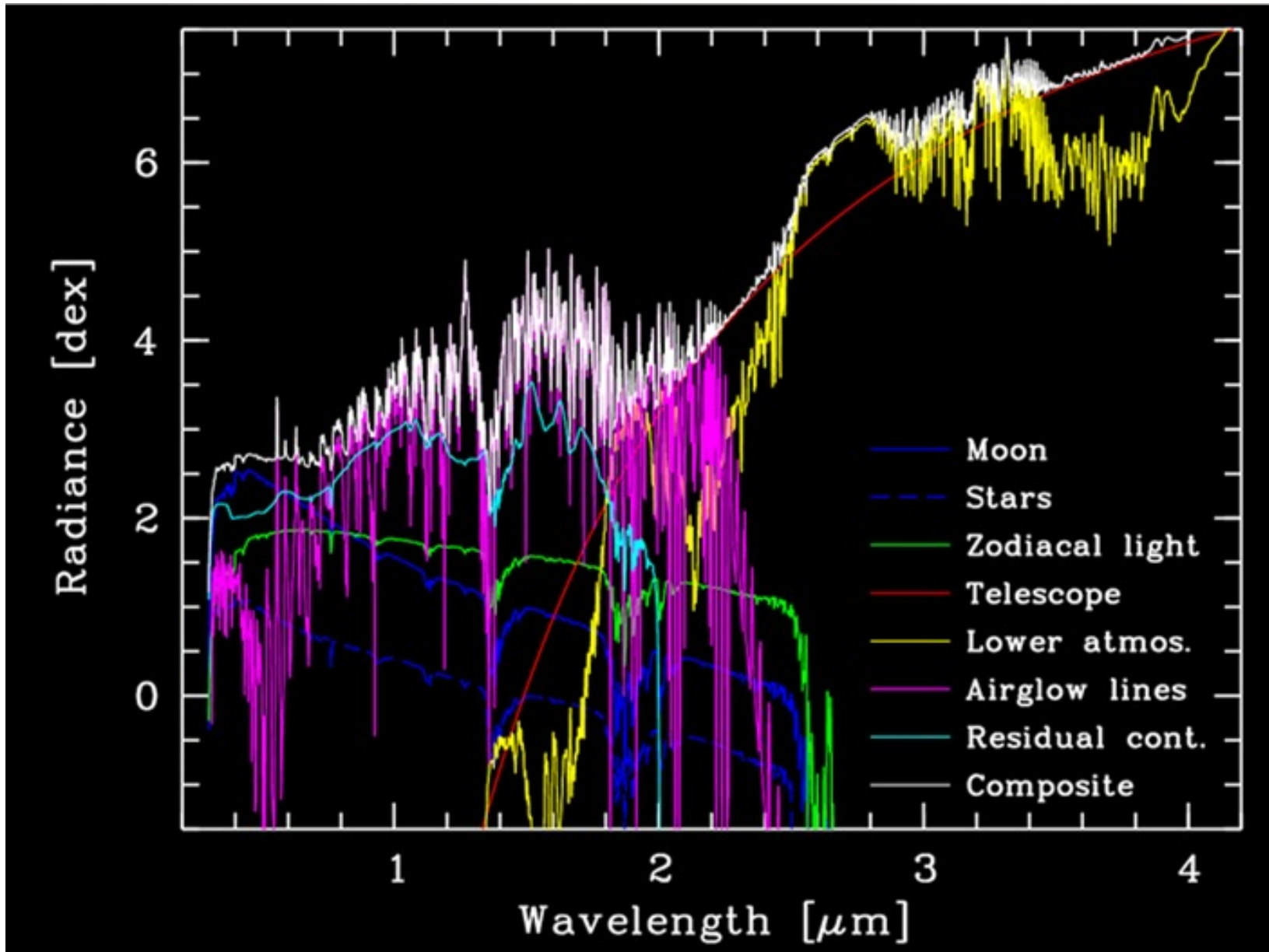
Sky **surface brightness** is important as even an unresolved point source has a finite angular diameter when viewed through a telescope.

Emission from Space



www.ipac.caltech.edu/Outreach/Gallery/IRAS/allsky.html

Total Emission in Near-Infrared





Molecular Scattering

- Molecular scattering in visible and NIR is **Rayleigh scattering**; scattering cross-section given by:

$$\sigma_R(\lambda) = \frac{8\pi^3}{3} \frac{(n^2 - 1)^2}{N^2 \lambda^4}$$

where N is the number of molecules per unit volume and n is the refractive index of air ($n-1 \sim 8 \cdot 10^{-5} P/T$).

- Rayleigh scattering is **not isotropic**:

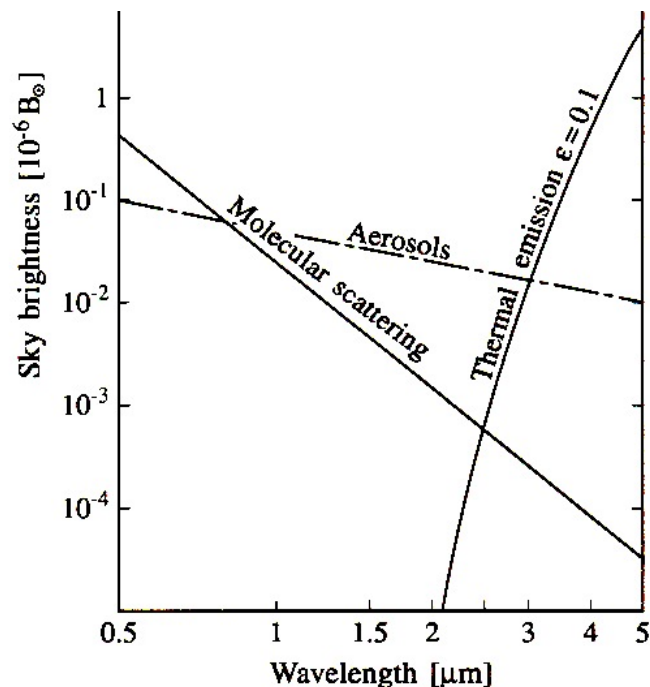
$$I_{scattered} = I_0 \frac{3}{16\pi} \sigma_R (1 + \cos^2 \theta) d\omega$$

Aerosol Scattering

- Aerosols (sea salt, hydrocarbons, volcanic dust) much larger diameter d than than air molecules \rightarrow NOT Rayleigh scattering
- Aerosol scattering described by **Mie theory** (classical electrodynamics, “scattering efficiency factor” Q):

$$Q_{\text{scattering}} = \frac{\sigma_M}{\pi a^2} = \frac{\text{scattering cross section}}{\text{geometrical cross section}}$$

- $d \gg \lambda$: $Q_{\text{scattering}} \sim Q_{\text{absorption}}$
 - scattered power equal to absorbed power
 - **effective cross section is twice the geometrical size**
- $d \sim \lambda$: $Q_s \sim 1/\lambda$ (for dielectric spheres):
 - **scattered intensity goes with $1/\lambda$**



Refraction

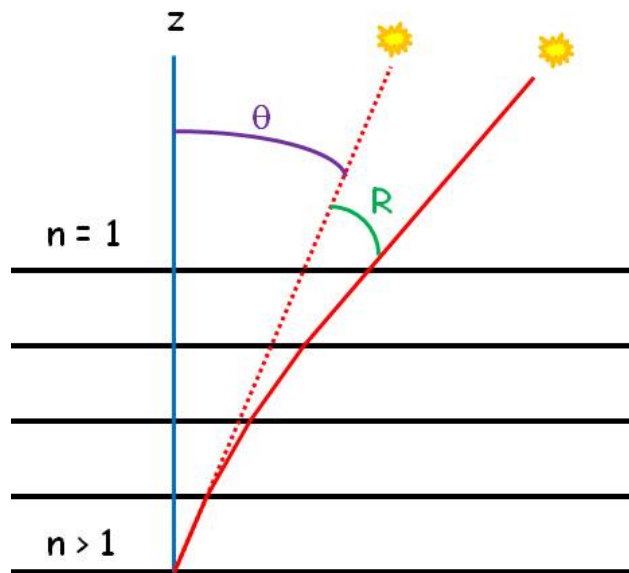


Atmospheric Refraction

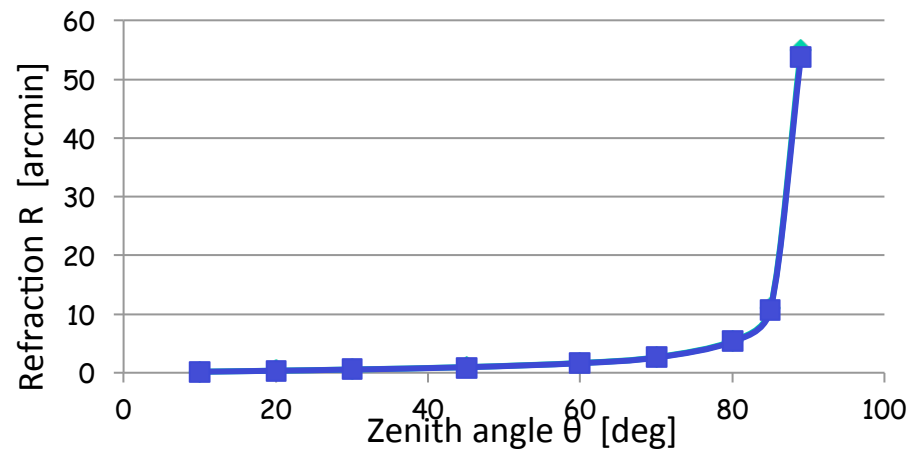
Atmospheric refraction -> *apparent* location of source significantly altered (up to 0.5 degree near horizon) → telescope pointing must correct for refraction

Refraction

$$R = (n(\lambda) - 1) \tan \theta$$



Atmospheric Refraction



Refractive index of air depends on wavelength λ :

$$[n(\lambda) - 1] \times 10^6 = 64.328 + \frac{29498.1}{146 - \frac{1}{\lambda_0^2}} + \frac{255.4}{41 - \frac{1}{\lambda_0^2}}$$

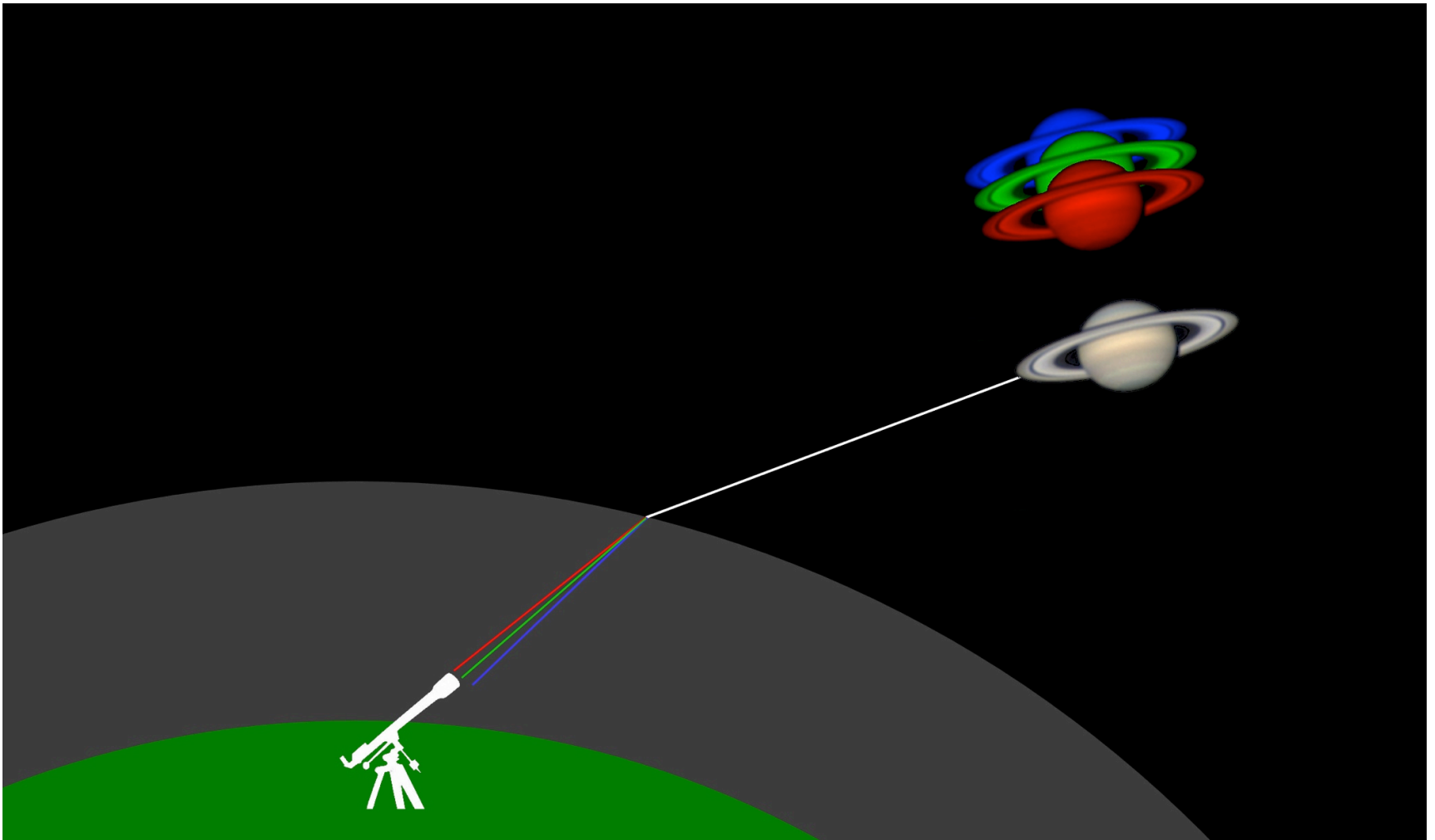
(dry air, 1 atm pressure, $T \sim 290\text{K}$, λ_0 in $[\mu\text{m}]$)

Green Flash



upload.wikimedia.org/wikipedia/commons/2/2b/Development_of_Green_Flash.jpg

Atmospheric Dispersion

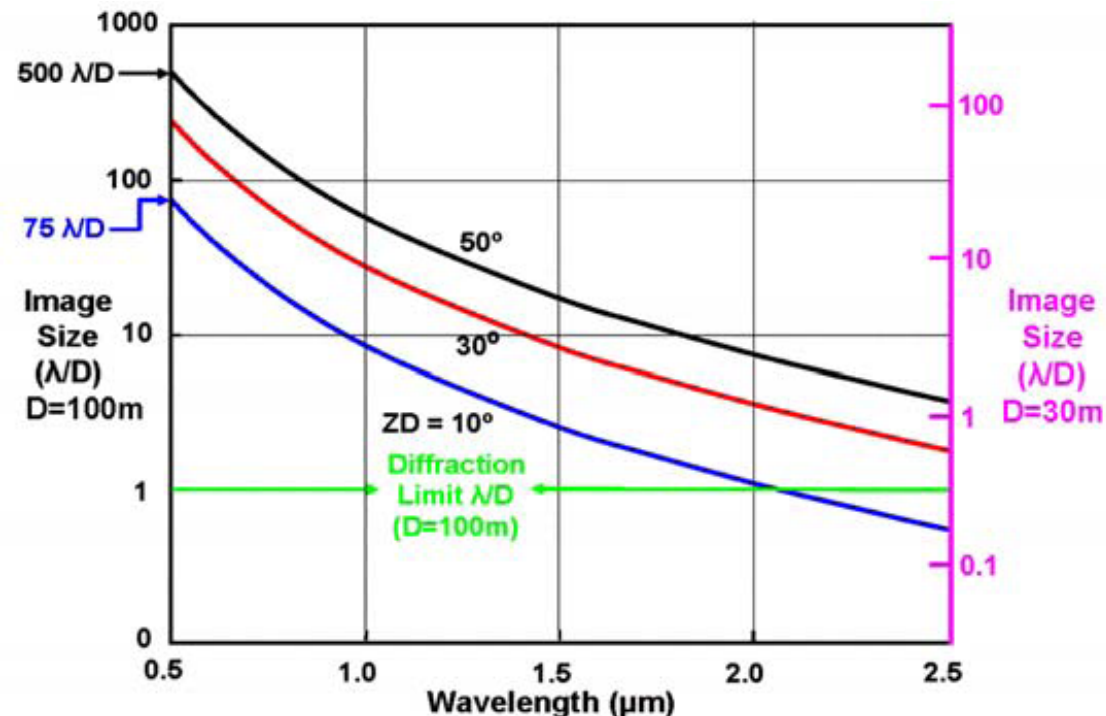
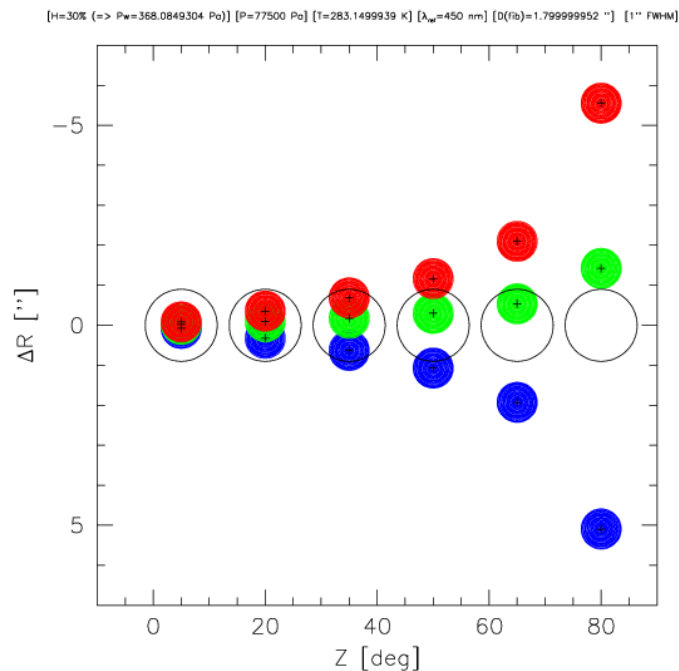


[www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC\(2587060\).htm](http://www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm)

Atmospheric Dispersion

Dispersion: Elongation of points in broadband filters due to $n(\lambda)$ [\rightarrow “rainbow”]. The magnitude of the dispersion is a strong function of airmass and wavelength.

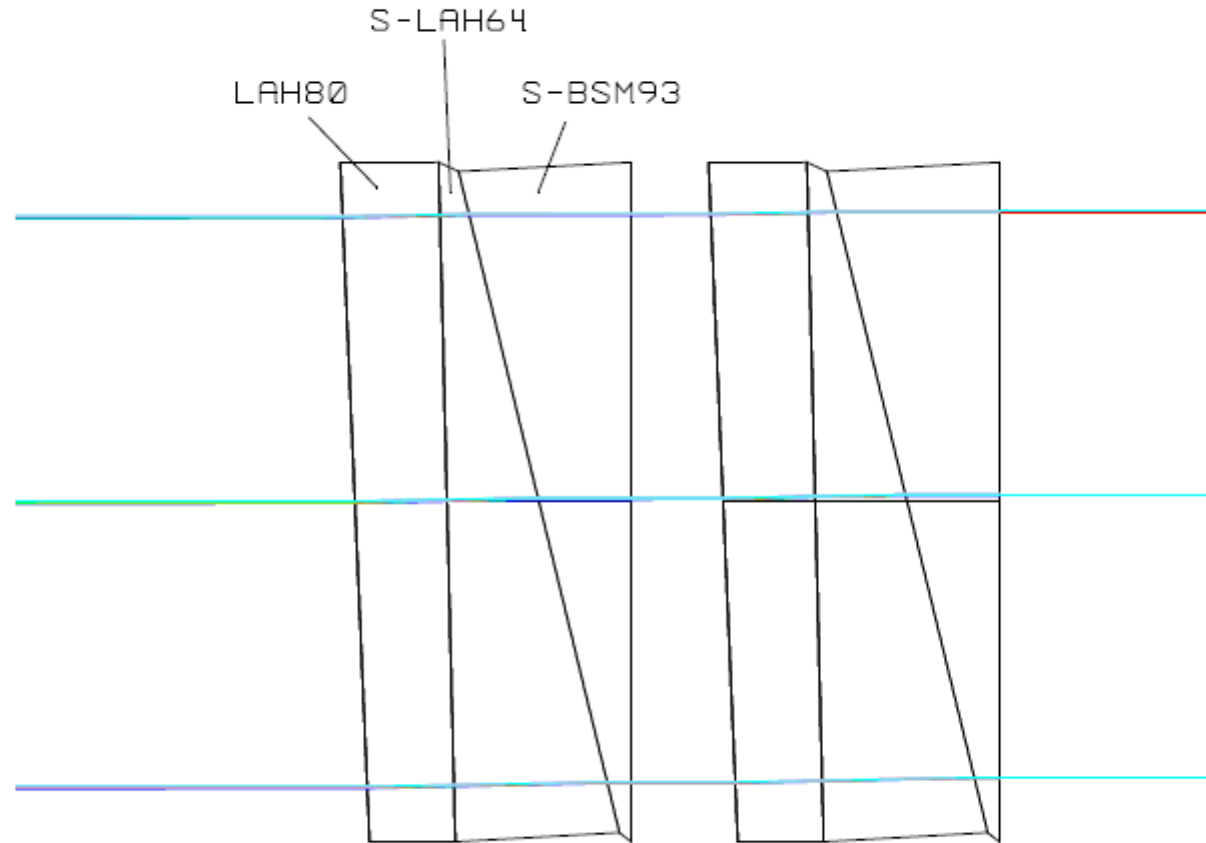
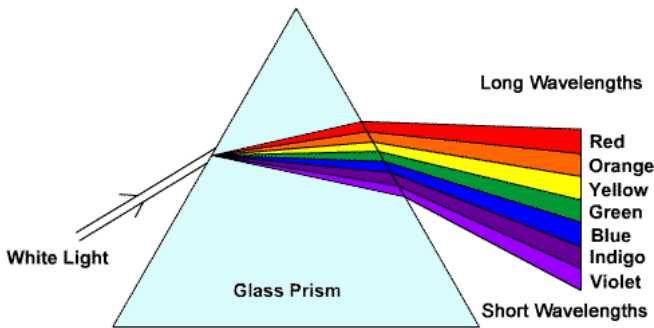
No problem if dispersion $< \lambda/D \leftarrow$ o.k. for small or seeing limited telescopes, but big problem for large, diffraction limited telescopes



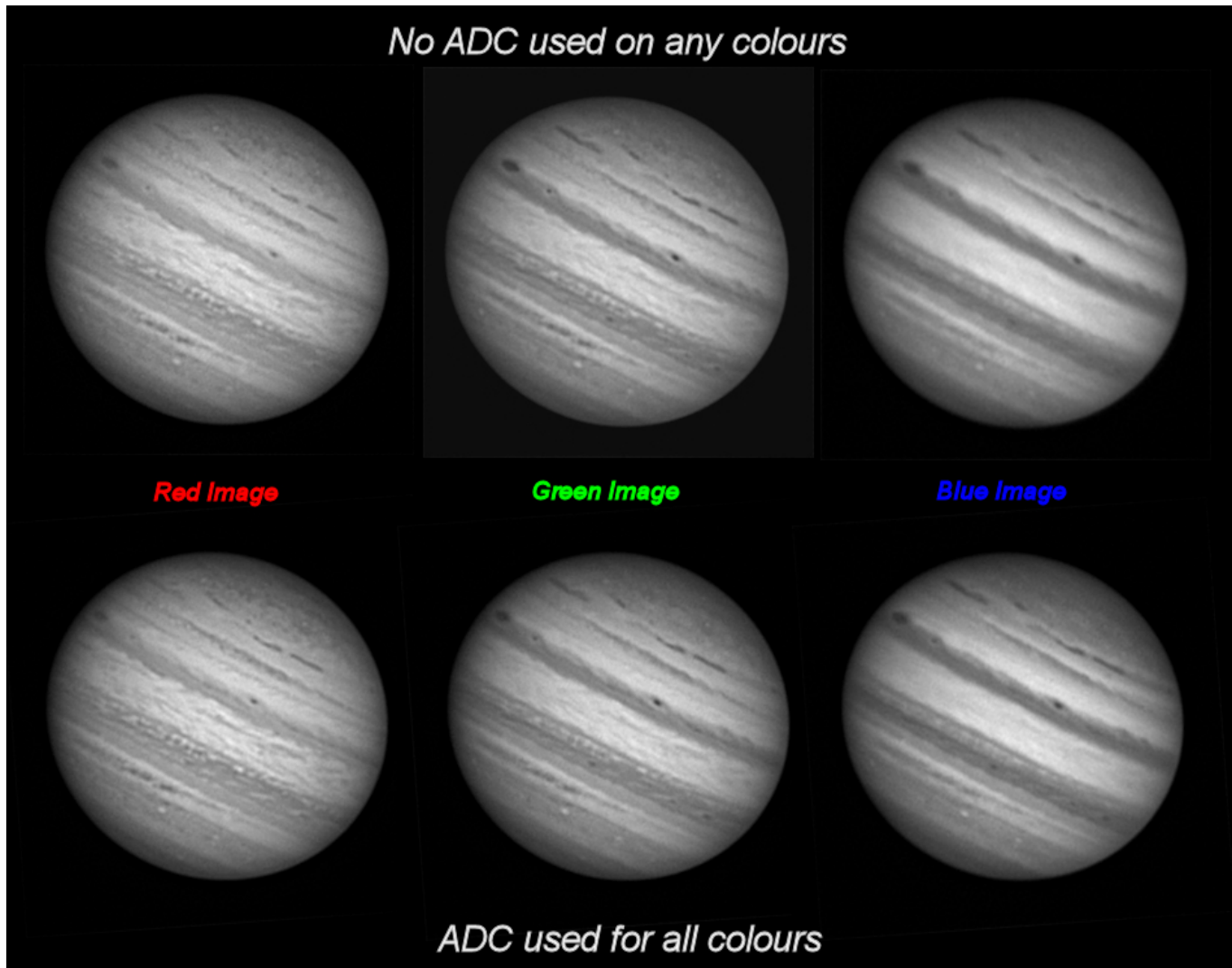
Atmospheric Dispersion Corrector

To counterbalance atmospheric dispersion use:

1. a refractive element (e.g., prism)
2. a second prism (different material with different dispersion) to maintain the optical axis
3. use a second (identical) double prism assembly to adjust the strength of the correction for different

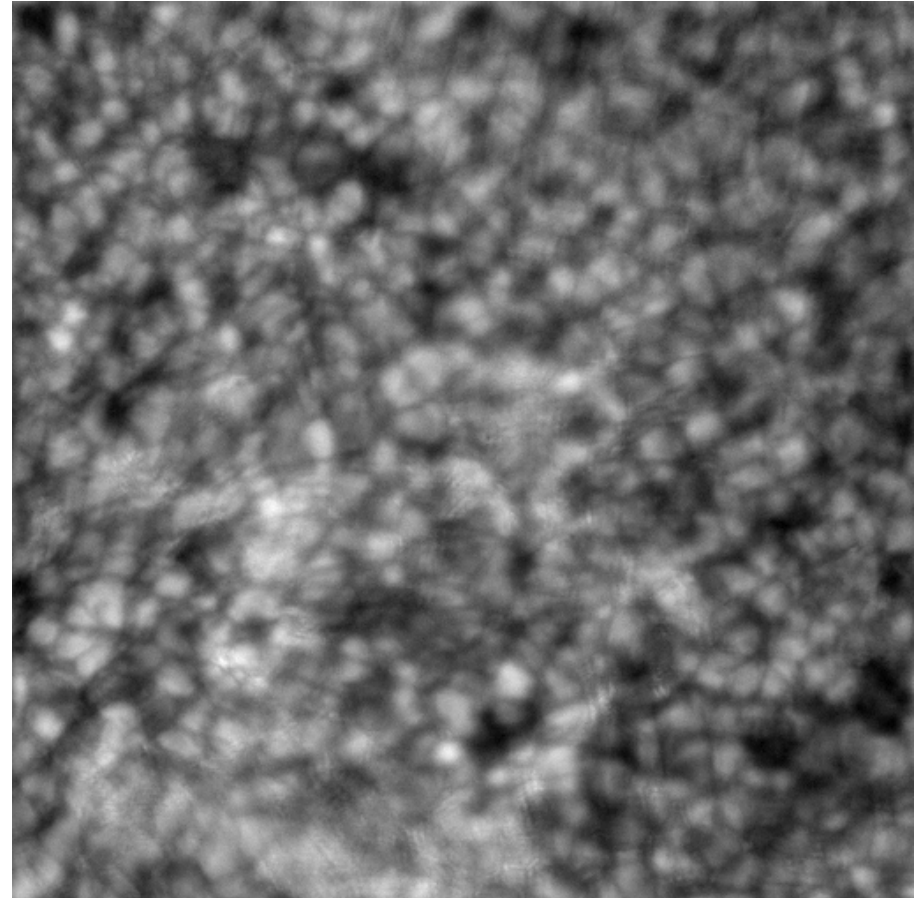
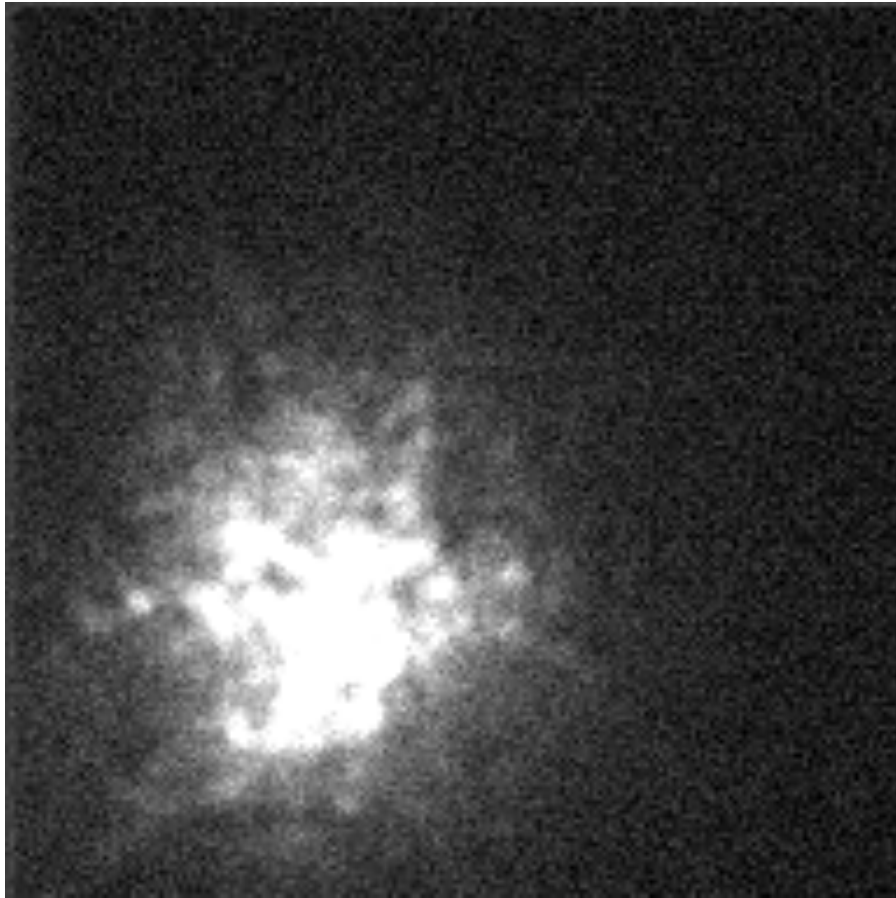


Benefits of ADC

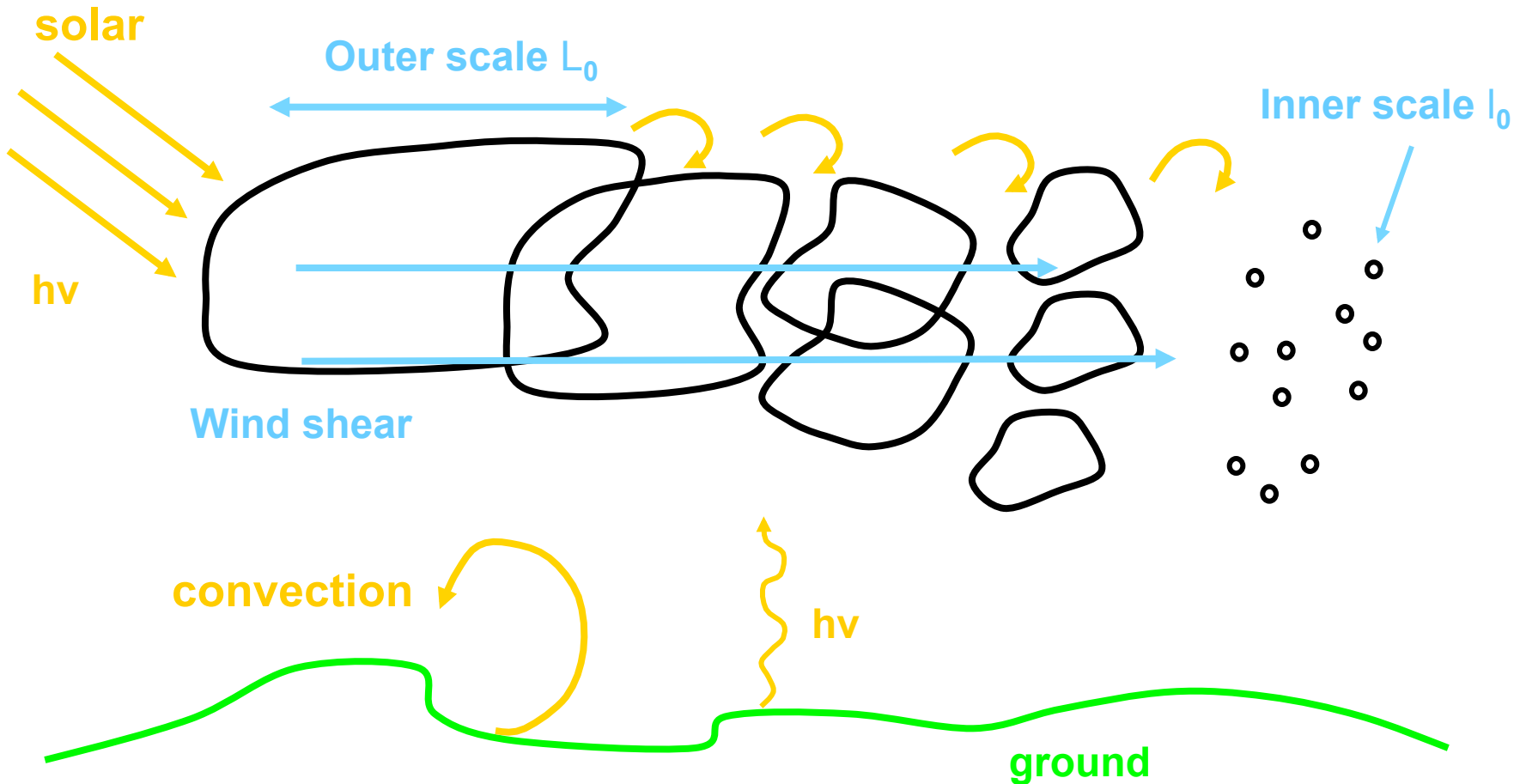


[www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC\(2587060\).htm](http://www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm)

Seeing



5. Atmospheric Turbulence



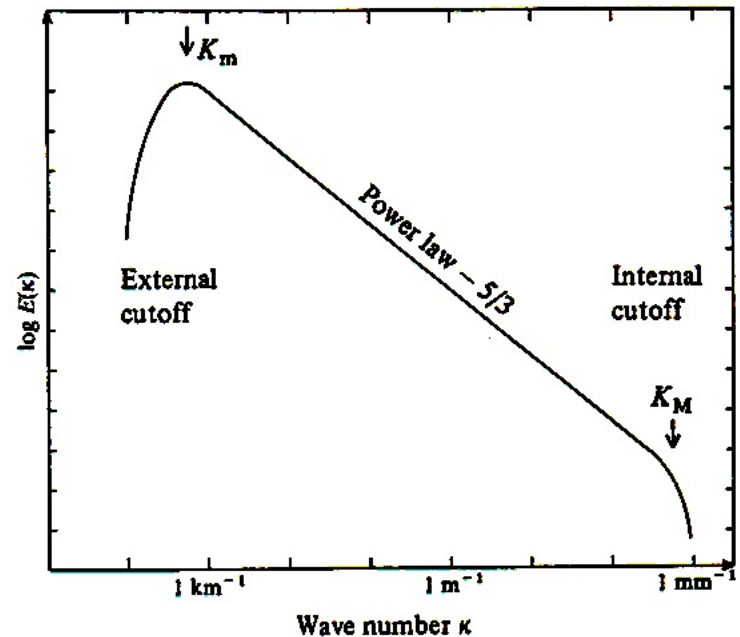
Komogorov Turbulence

- kinetic energy of large scale ($\sim L$) movements transferred to smaller and smaller scales, down to minimum scale length l_0 , where energy is dissipated by viscous friction
- local velocity field decomposed into spatial harmonics of wave vector κ (Fourier domain)
- $1/\kappa$ is length scale under consideration
- mean spectrum of kinetic energy (Kolmogorov spectrum)

$$E(\kappa) \propto \kappa^{-5/3}$$

- $l_0 =$ inner scale, $L_0 =$ outer scale with

$$L_0^{-1} < \kappa < l_0^{-1}$$

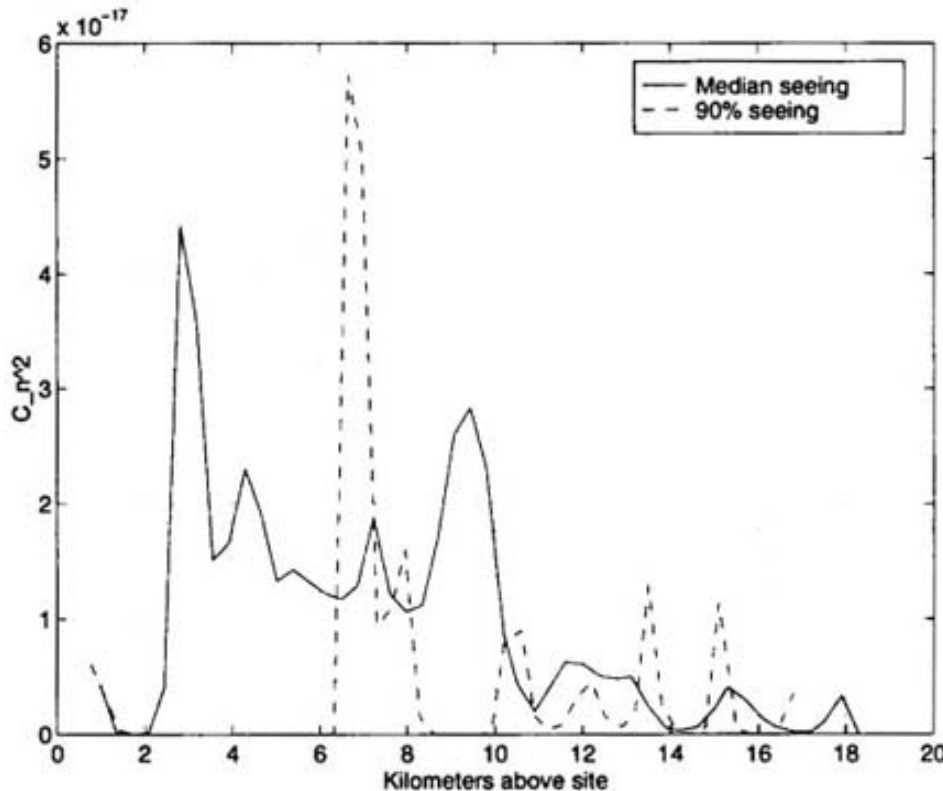


Air Refractive Index Fluctuations

- winds mix layers of different temperature → fluctuations of temperature T → fluctuations of density ρ → fluctuations of refractive index n
- 1K temperature difference changes n by 1×10^{-6}
- variation of 0.01K along path of 10km:
 $10^4 \text{ m} \times 10^{-8} = 10^{-4} \text{ m} = 100 \text{ waves at } 1\mu\text{m}$
- refractive index of water vapour is less than that of air
→ moist air has smaller refractive index

Index Fluctuations with Altitude

- $C_n^2(z) \cdot \Delta z$ is a measure for index fluctuation contributions from layer Δz at altitude z
- typical value: $C_n^2 \cdot \Delta z \sim 4 \cdot 10^{-13} \text{ cm}^{1/3}$ for a 3 km altitude layer
- turbulence often occurs in layers



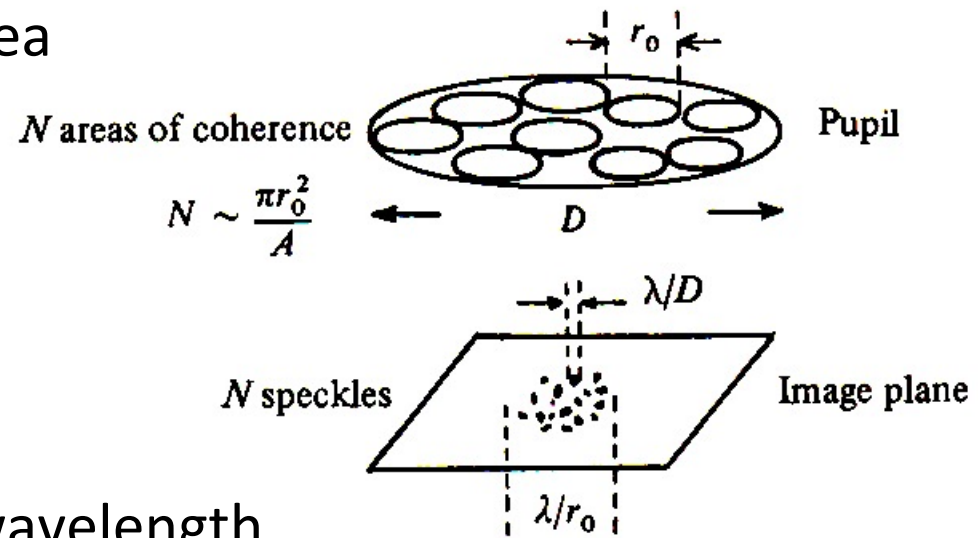
Median seeing conditions on Mauna Kea $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are $r_o \sim 0.40$ m.

www.gemini.edu/sciops/instruments/adaptiveOptics/mk_cn2.jpg

Fried Parameter r_0

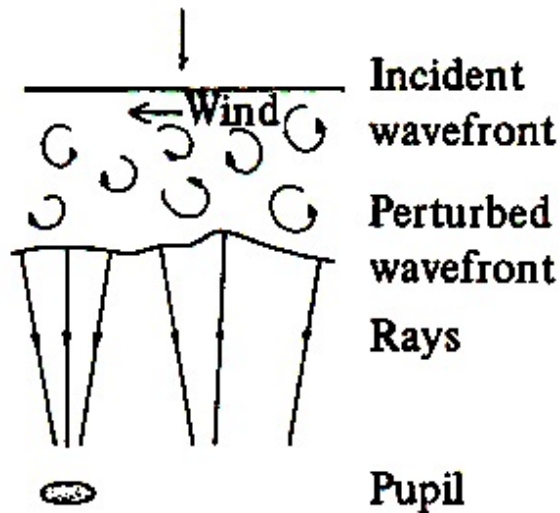
- radius of spatial coherence area (of wavefront) given by Fried parameter r_0 :

$$r_0(\lambda) = 0.185\lambda^{6/5} \left[\int_0^\infty C_n^2(z) dz \right]^{-3/5}$$



- r_0 increases as 6/5 power of wavelength
- r_0 is average scale over which rms optical phase distortion is 1 rad
- angle $\Delta\theta = \lambda/r_0$ is the seeing in arcsec
- r_0 at good sites: 10 - 30 cm (at $0.5\mu\text{m}$)
- seeing is roughly equivalent to FWHM of long-exposure image of a point source (Point Spread Function)

Aspects of Image Degradation



Scintillation

energy received by pupil varies in time (stars flicker)

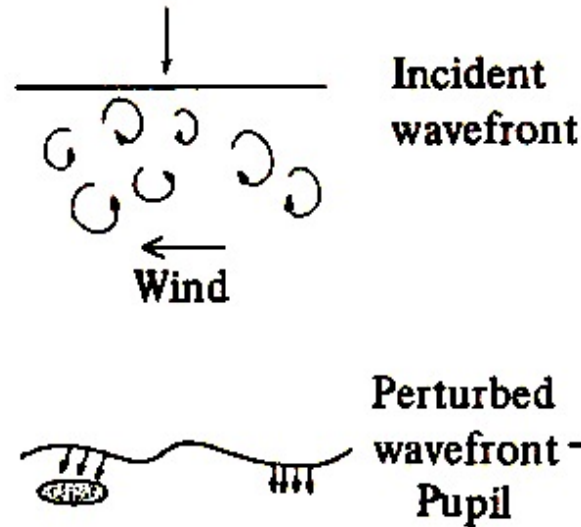


Image Motion

average slope of wavefront at pupil varies ("tip-tilt", stars move around)

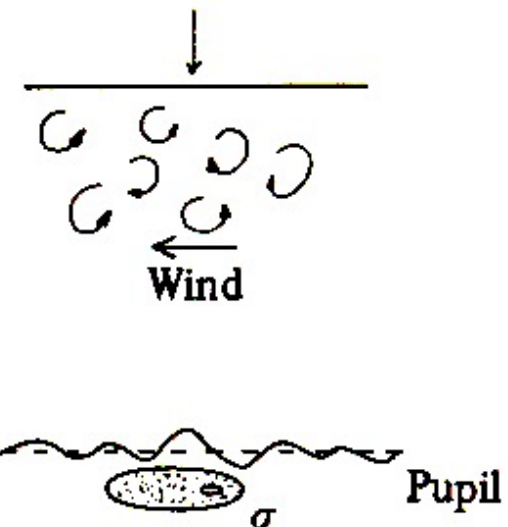


Image Blurring

wavefront is not flat ("seeing")

Long Exposure through Turbulence

- **atmospheric coherence** (or Greenwood delay) **time**: maximum time delay for RMS wavefront error to be less than 1 rad (v is mean wind velocity)

$$\tau_0 = 0.314 \frac{r_0}{\bar{v}}$$

- integration time $t_{\text{int}} \gg \tau_0$
→ image is mean of instantaneous images
- long-exposure image is smeared
- angular resolution $\sim \lambda/r_0$ instead of $\sim \lambda/D$
- for $D > r_0$, bigger telescopes will *not* provide sharper images!