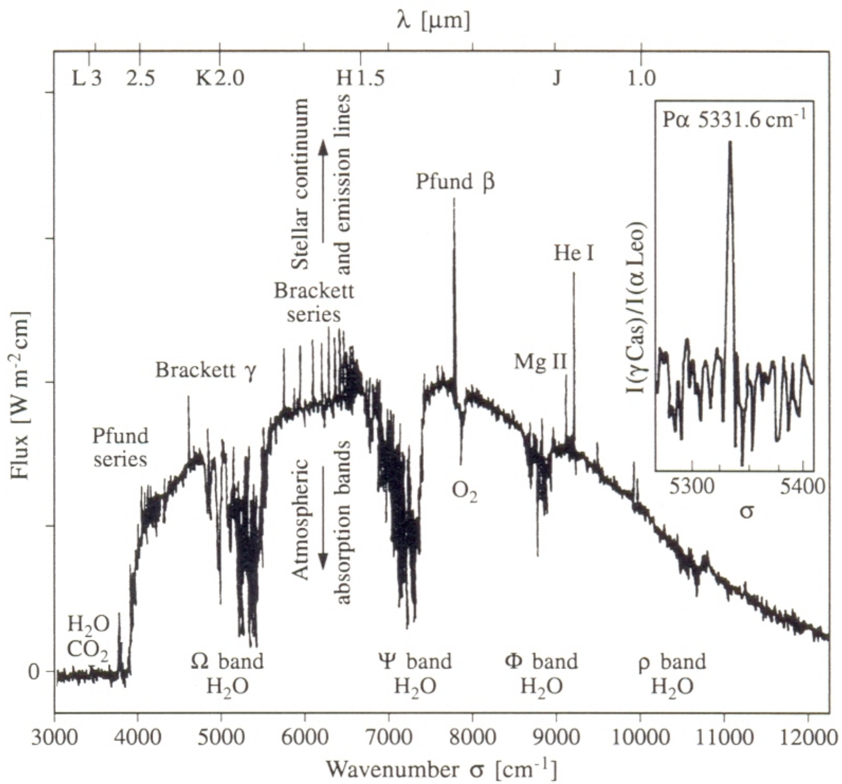
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

based on lectures by Bernhard Brandl



<u>Lecture 2: Earth Atmosphere</u>

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

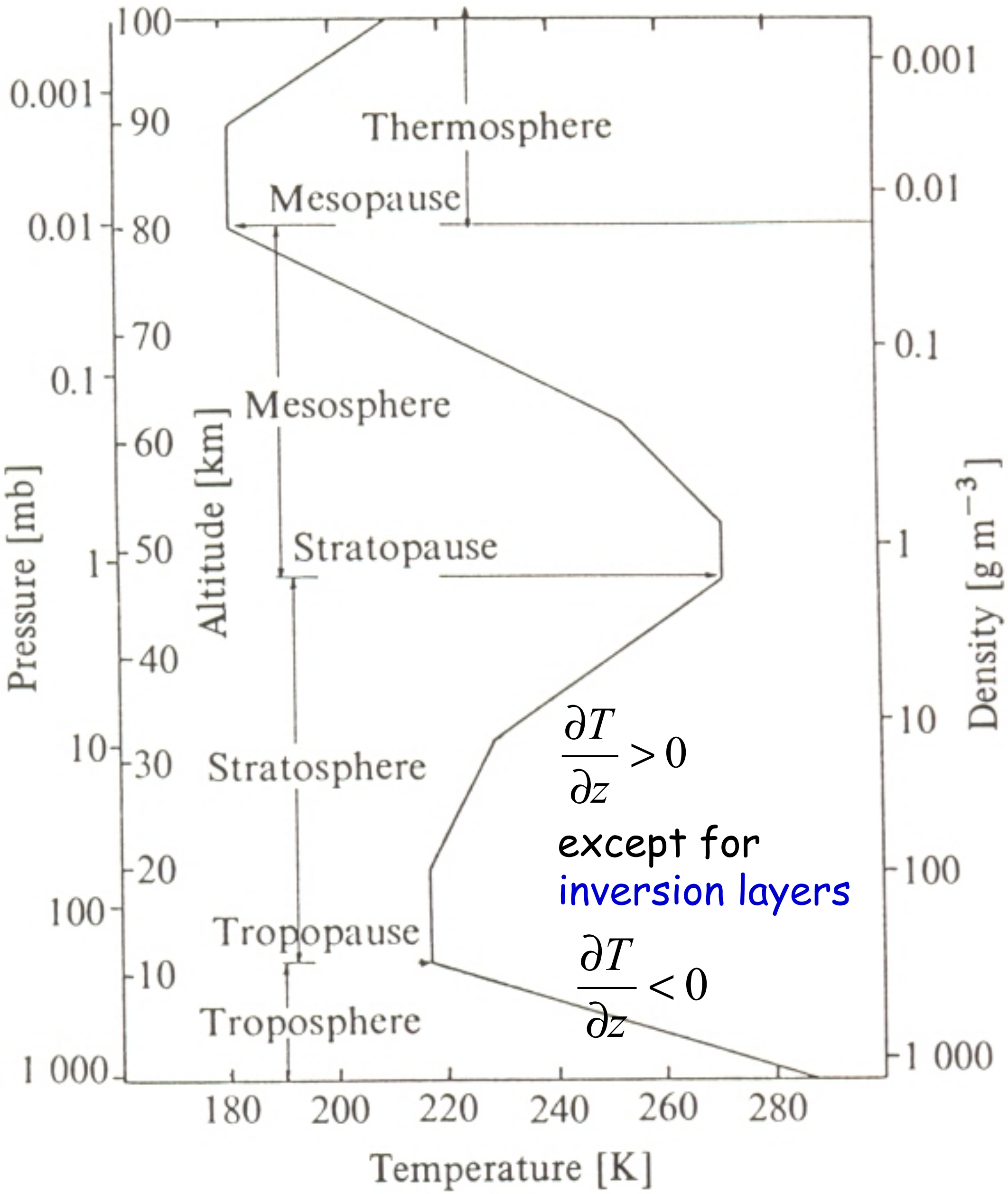
Hydrostatic equilibrium structure described by:

- altitude z
- temperature T(z)
- density ρ(z)

Pressure P(z) described by: $P(z) = P_0 e^{-\frac{z}{H}}, H = \frac{kT}{\mu g}$

H = scale height (~ 8km), μ = mean molecular weight

Vertical Profile

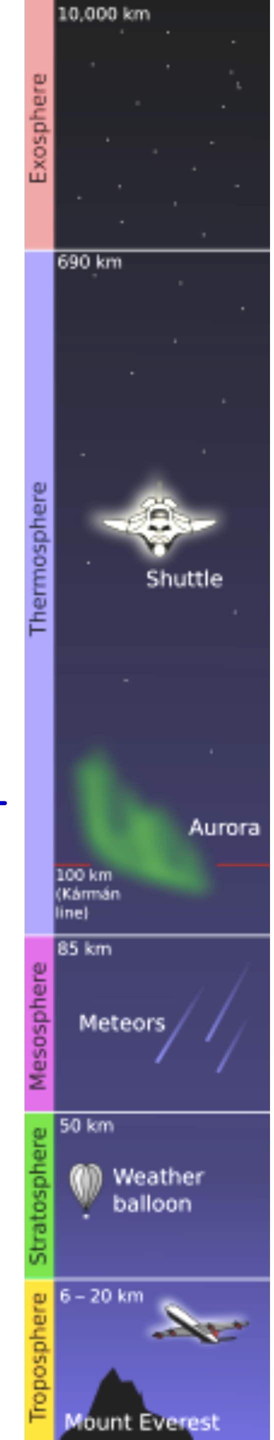


$$\frac{\partial T}{\partial z} > 0$$

except for inversion layers

$$\frac{\partial T}{\partial z} < 0$$

Ionosphere



Atmospheric Composition

- Main constituents: O_2 and N_2
  relative constant proportions (78.1% N_2, 20.9% O_2) up to 100 km

- Ozone – mainly absorbs in UV
  - distribution depends on latitude and season
  - maximum concentration around 16 km height

- CO_2 – important component for (mid)IR absorption
  - mixing independent of altitude (similar to N_2, O_2)

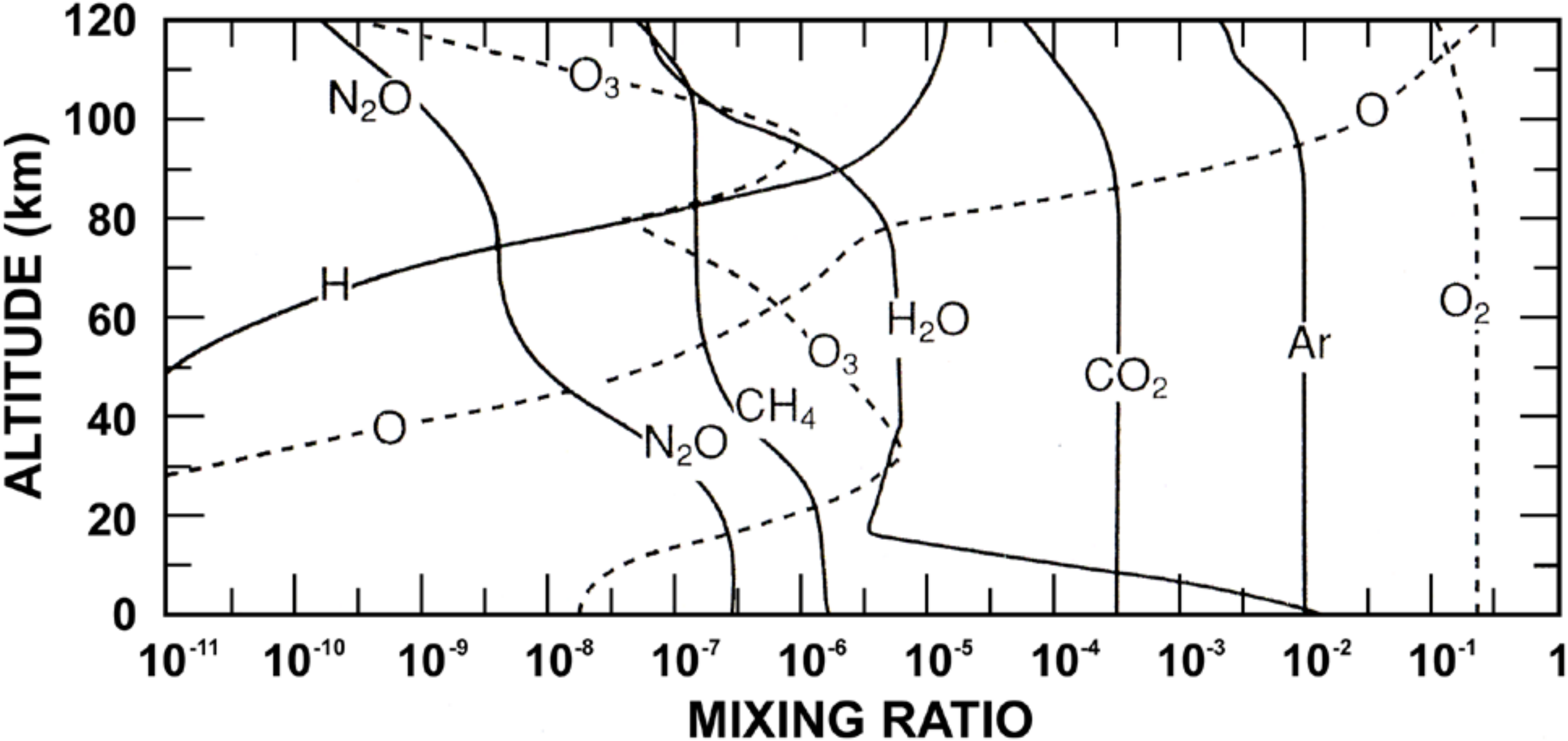
- Ions – varies strongly with altitude and solar activity
  - relevant above 60km where reactions with UV photons occur:

$$\mathrm{O_2} + h\nu \rightarrow \mathrm{O_2^{+*}} + \mathrm{e^-} \quad \text{and} \quad \mathrm{O_2} + h\nu \rightarrow \mathrm{O^+} + \mathrm{O} + \mathrm{e^-}$$

  - electron showers along magnetic fields cause Aurora
  - at 100 – 300 km height: $n_e \sim 10^5 - 10^6\ \mathrm{cm^{-3}}$

- Water vapour – highly variable, causes very strong absorption bands

Mixing Ratio of Atmospheric Gases



2. Absorption

Atomic and molecular transitions causing absorption features:

- pure rotational molecular transitions: H_2O, CO_2, O_3,
- rotation-vibrational molecular transitions: CO_2, NO, CO
- electronic molecular transitions: CH_4, CO, H_2O, O_2, O_3, OH
- electronic atomic transitions: O, N, ...

Attenuation at altitude z_0:

$$I(z_0) = I_0(\infty) \cdot \exp\left[-\frac{1}{\cos\theta} \sum_i \tau_i(\lambda, z_0)\right]$$

for *i* absorbing species with optical depth

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

(θ is the zenith distance; κ is the absorption coefficient; ρ_0 is the mass density of air, and $r_i(z)$ the mixing ratio).

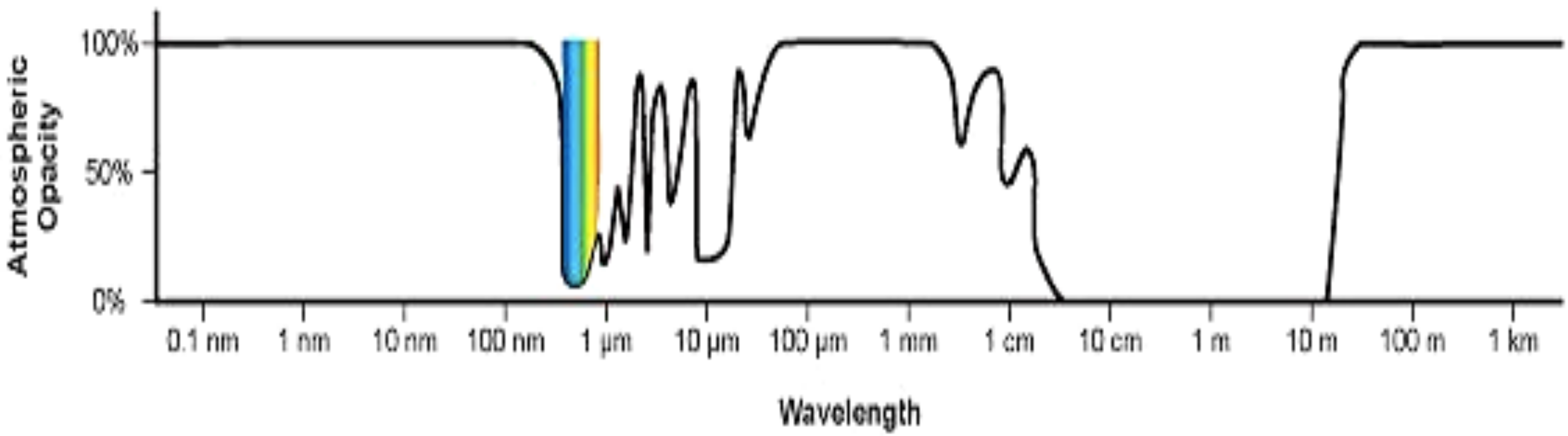
Atmospheric Bands

Two cases of absorption:

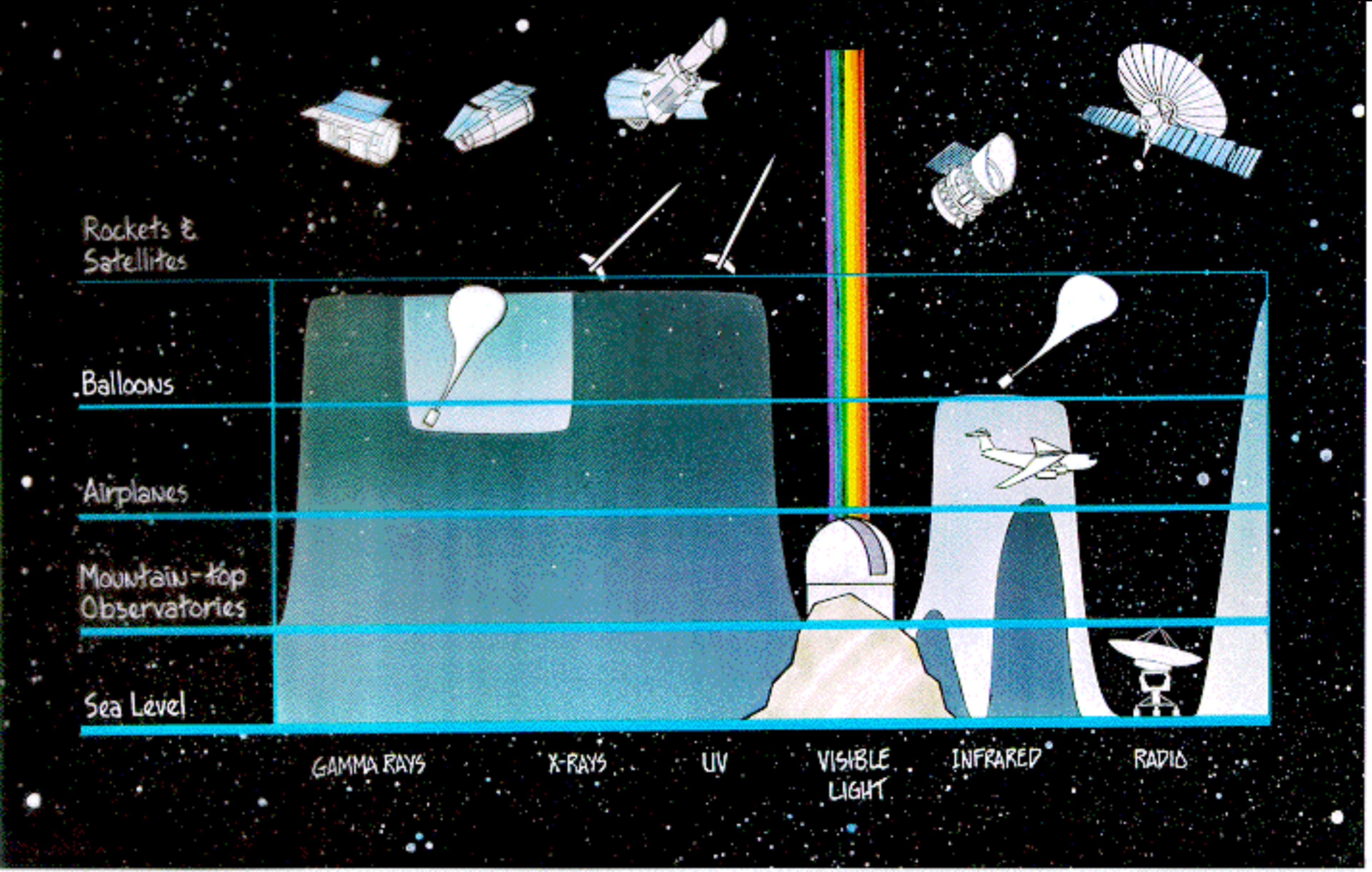
- total absorption → atmospheric transmission windows
- partial absorption → reduced transmission due to narrow telluric* absorption features

**Telluric* = related to the Earth; of terrestrial origin*

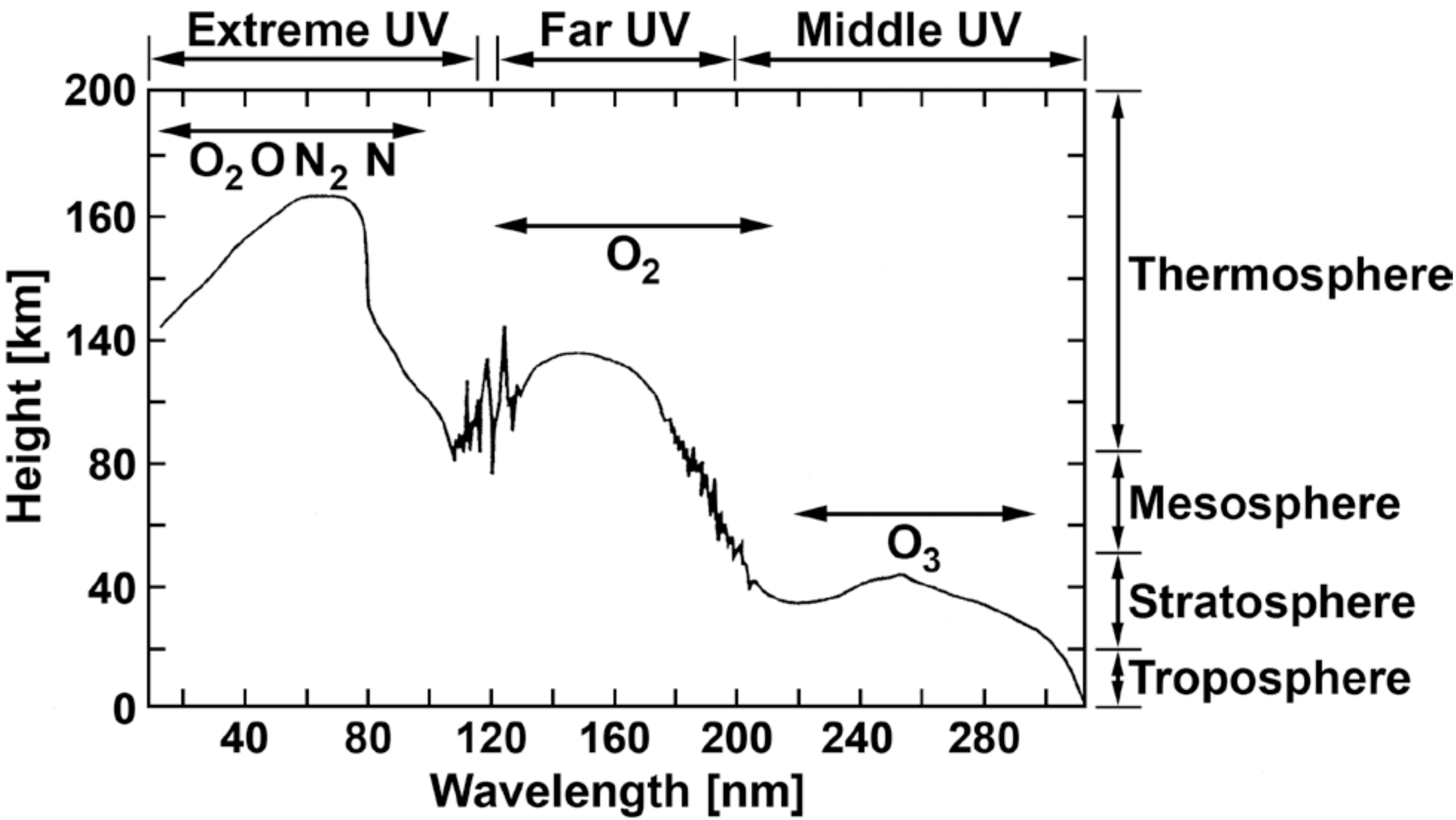
Atmospheric opacity defines atmospheric transmission bands (wavelengths accessible to ground-based observations)



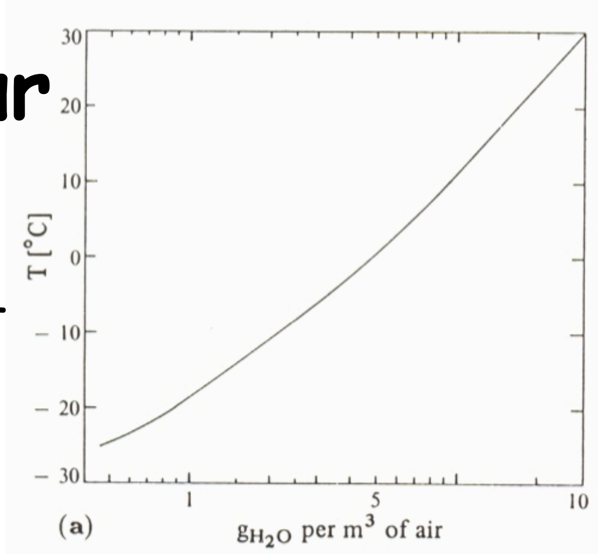
Ground based astronomy is limited to visible, near/mid-IR and radio wavelengths.
Space astronomy provides access to γ-rays, X-rays, UV, FIR, sub-mm



UV Absorption



Absorption by Water Vapour

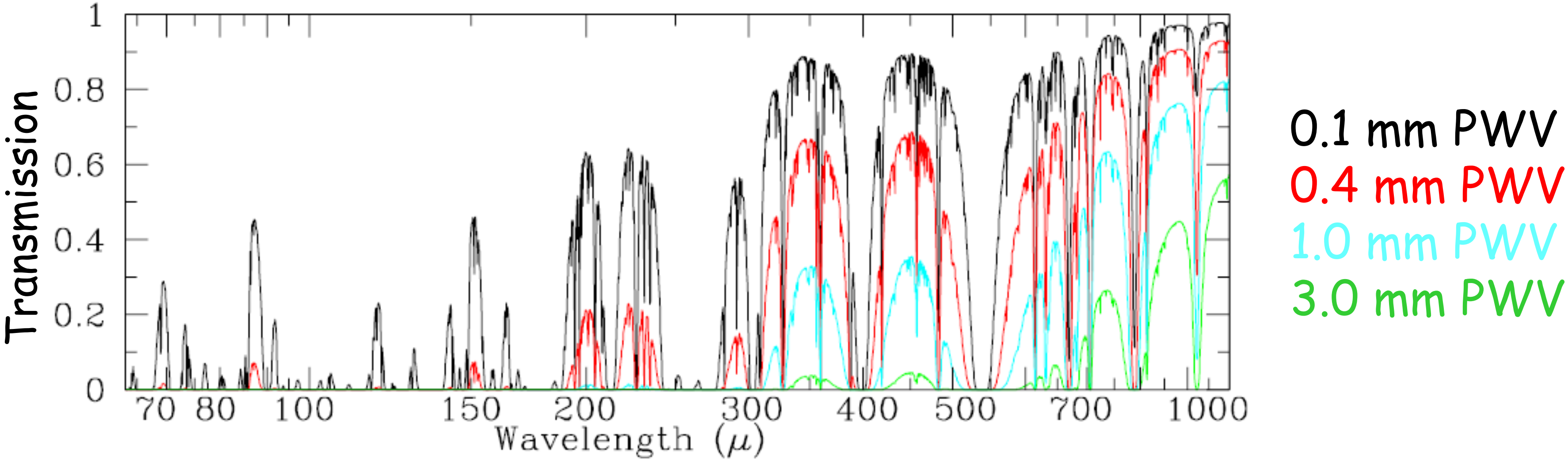


Water vapor is strong function of T and z.

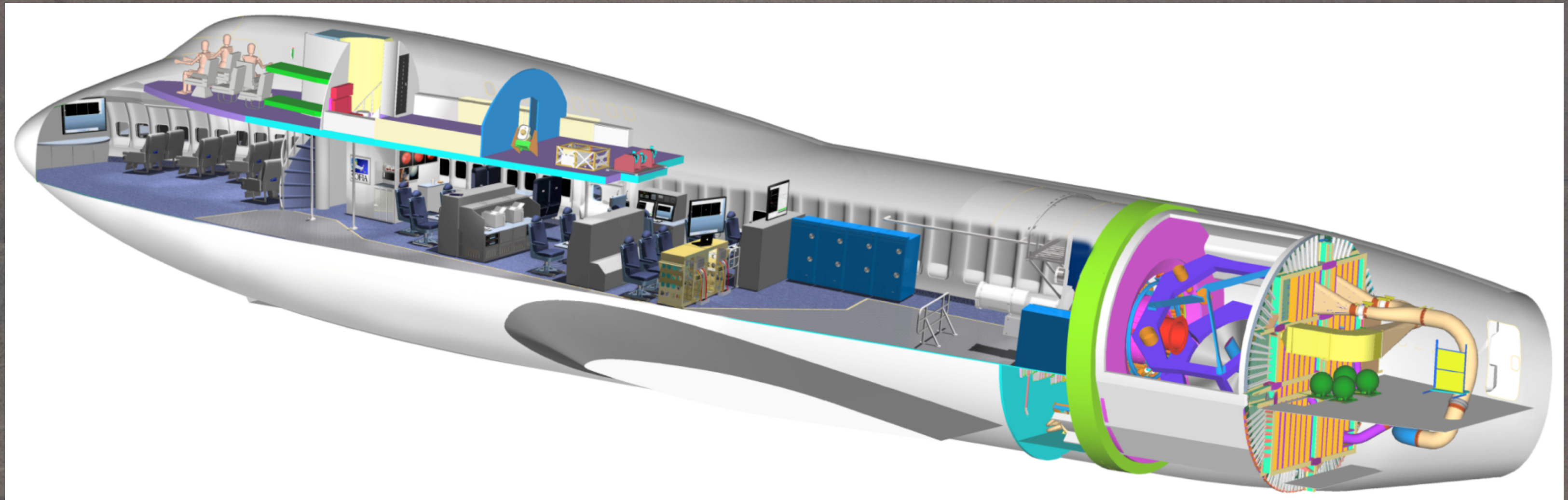
Precipitable water vapor (PWV) is depth of amount of water in column of atmosphere if all water in that column were precipitated as rain.
The amount of PWV above an altitude z_0 is:

$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O}\, dz \,, \quad \text{where} \qquad N_{H_2O}\left[\mathrm{m}^{-3}\right] = 4.3\times 10^{25}\, \frac{P}{P_0}\frac{T}{T_0}\, r(z)$$

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



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



3. Atmospheric Emission

A. Fluorescent Emission

Fluorenscence = recombination of electrons with ions.

Recombination probability low; takes several hours → night time

- Produces both continuum + line emission = airglow
- Occurs mainly at ~ 100 km height
- Main sources of emission: O I, Na I, O_2, OH (←NIR), H

Emission intensity measured in Rayleigh:

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

B. Thermal Emission

Up to 60 km atmosphere in local thermodynamic equilibrium (LTE), i.e., the excitation levels are thermally populated.

Calculating specific energy received requires full radiative transfer calculation (see below), but for $\tau \ll 1$ one can use the approximation:

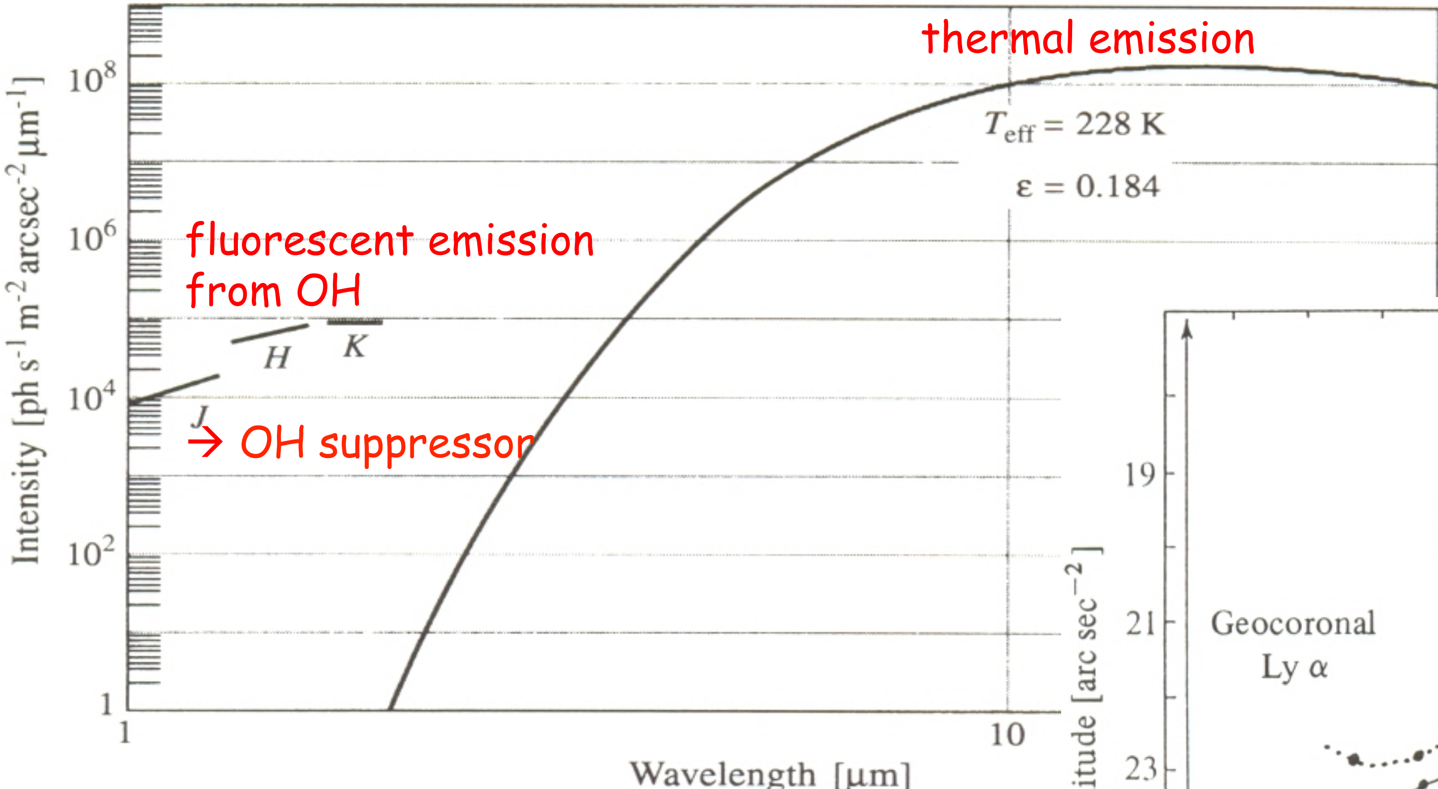
$$I_\lambda(z) = \tau_\lambda B_\lambda(\bar{T}) \frac{1}{\cos\theta}$$

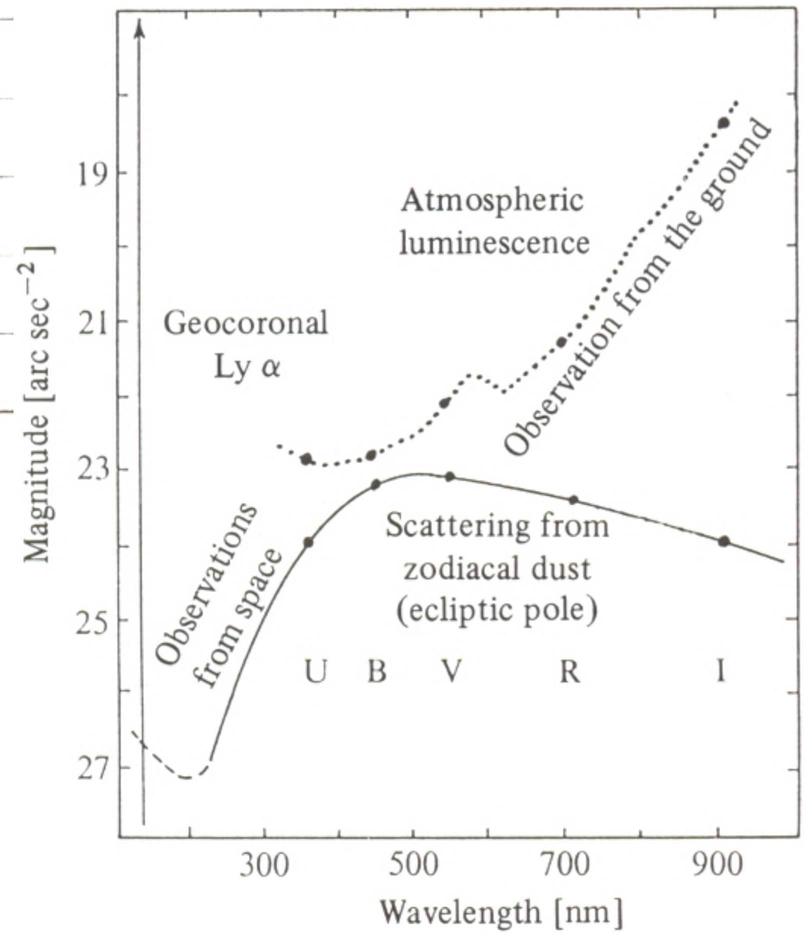
where B(T) is the Planck function at mean temperature of atmosphere.

For $\bar{T}$ = 250 K and θ = 0:

Spectral band	L	M	N	Q
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	2 100

Fluorescent and Thermal Emission

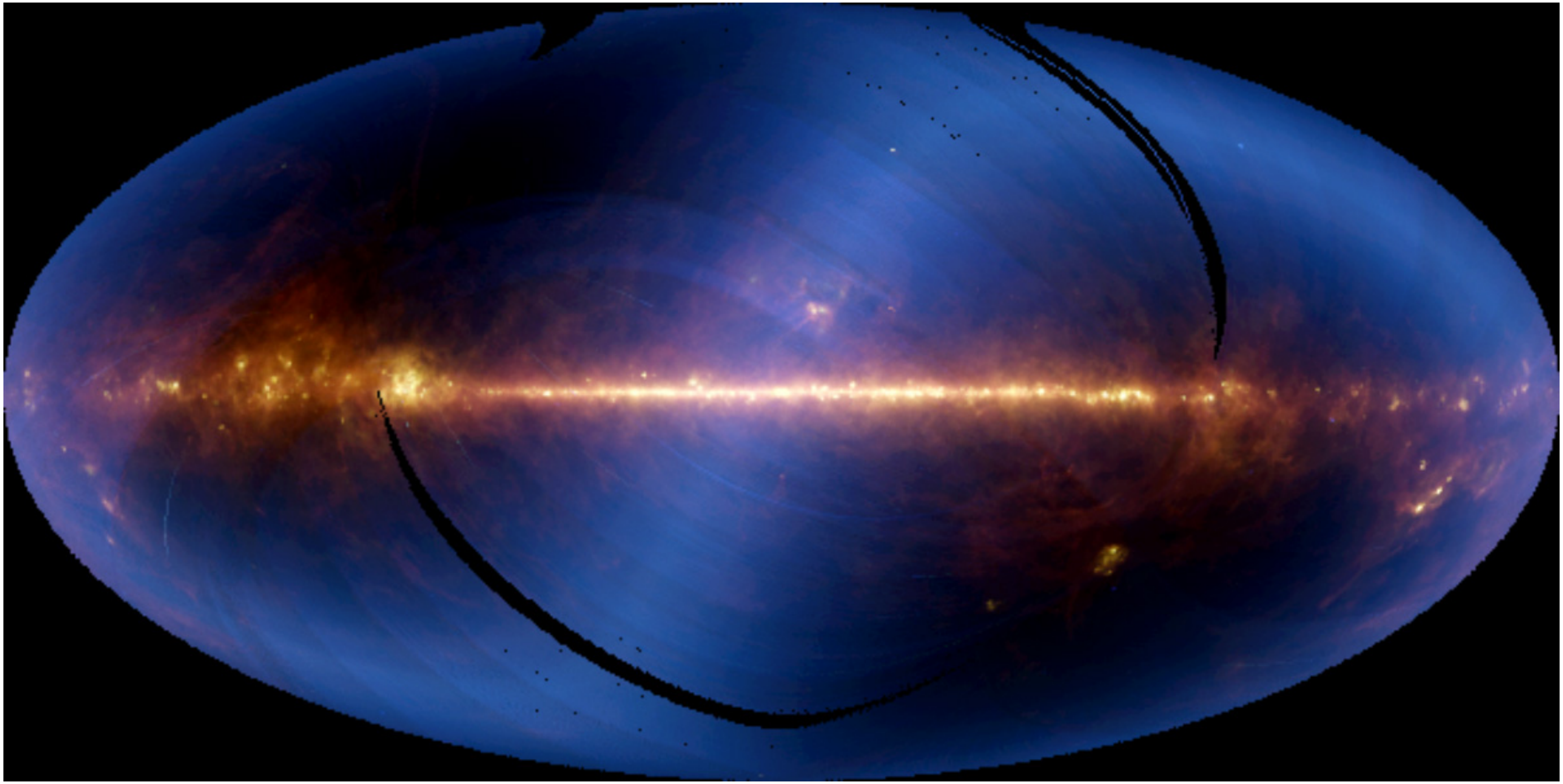




Sky surface brightness.

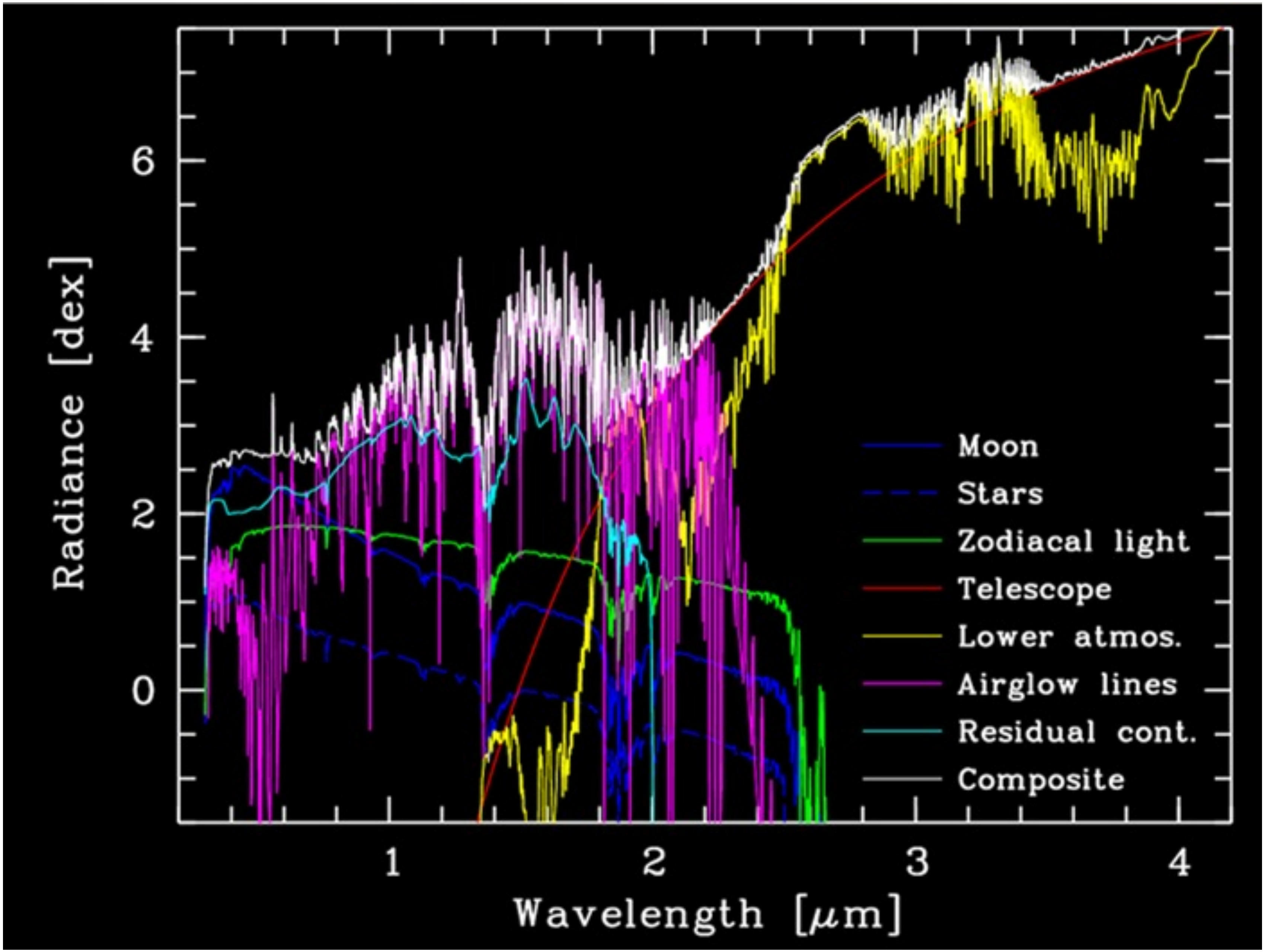
Important as even an unresolved point source has a finite angular diameter when viewed through a telescope.

Emission from Space



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

Total Emission in near-infrared



4. Scattering, Refraction and Dispersion

A. Scattering by Air Molecules

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

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

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).

Remember, Rayleigh scattering is not isotropic: $I_{scattered} = I_0 \frac{3}{16\pi} \sigma_R \left(1 + \cos^2\theta\right) d\omega$

B. Aerosol Scattering

Aerosols (sea salt, hydrocarbons, volcanic dust) are much bigger than air molecules → Rayleigh scattering does *not* apply.

Instead, scattering is described by Mie's theory (from classical electrodynamics, using a "scattering efficiency factor" Q):

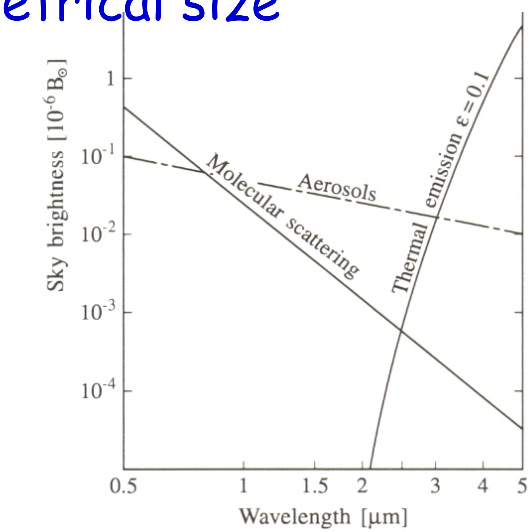
$$Q_{\text{scattering}} = \frac{\sigma_M}{\pi a^2} = \frac{\text{scattering cross section}}{\text{geometrical cross section}}$$

If $a \gg \lambda$ then $Q_{\text{scattering}} \sim Q_{\text{absorption}}$ and:

- the scattered power is equal to the absorbed power
- the effective cross section is twice the geometrical size

If $a \sim \lambda$ then $Q_s \sim 1/\lambda$ (for dielectric spheres):

- the scattered intensity goes with $1/\lambda$

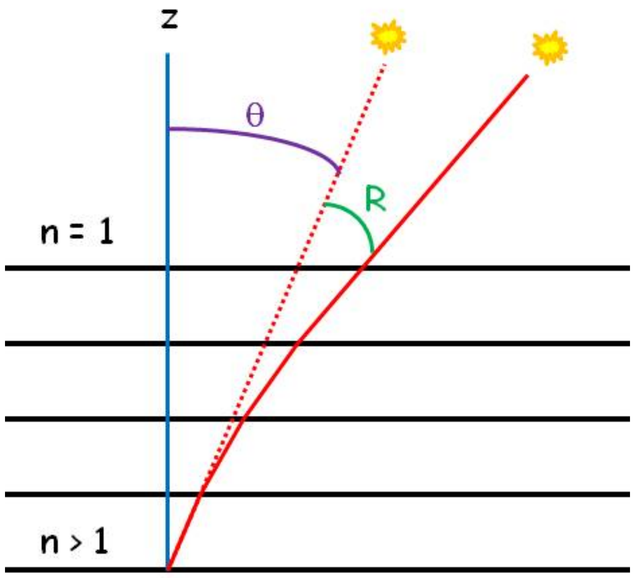


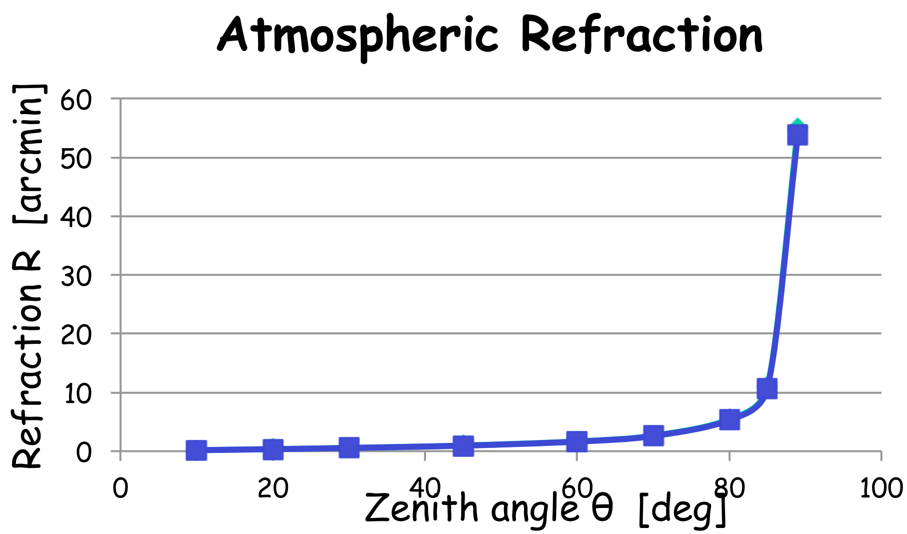
Refraction

Atmospheric Refraction

Due to atmospheric refraction, the *apparent* location of a source is significantly altered (up to half a degree near the horizon)
→ telescope pointing model.

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



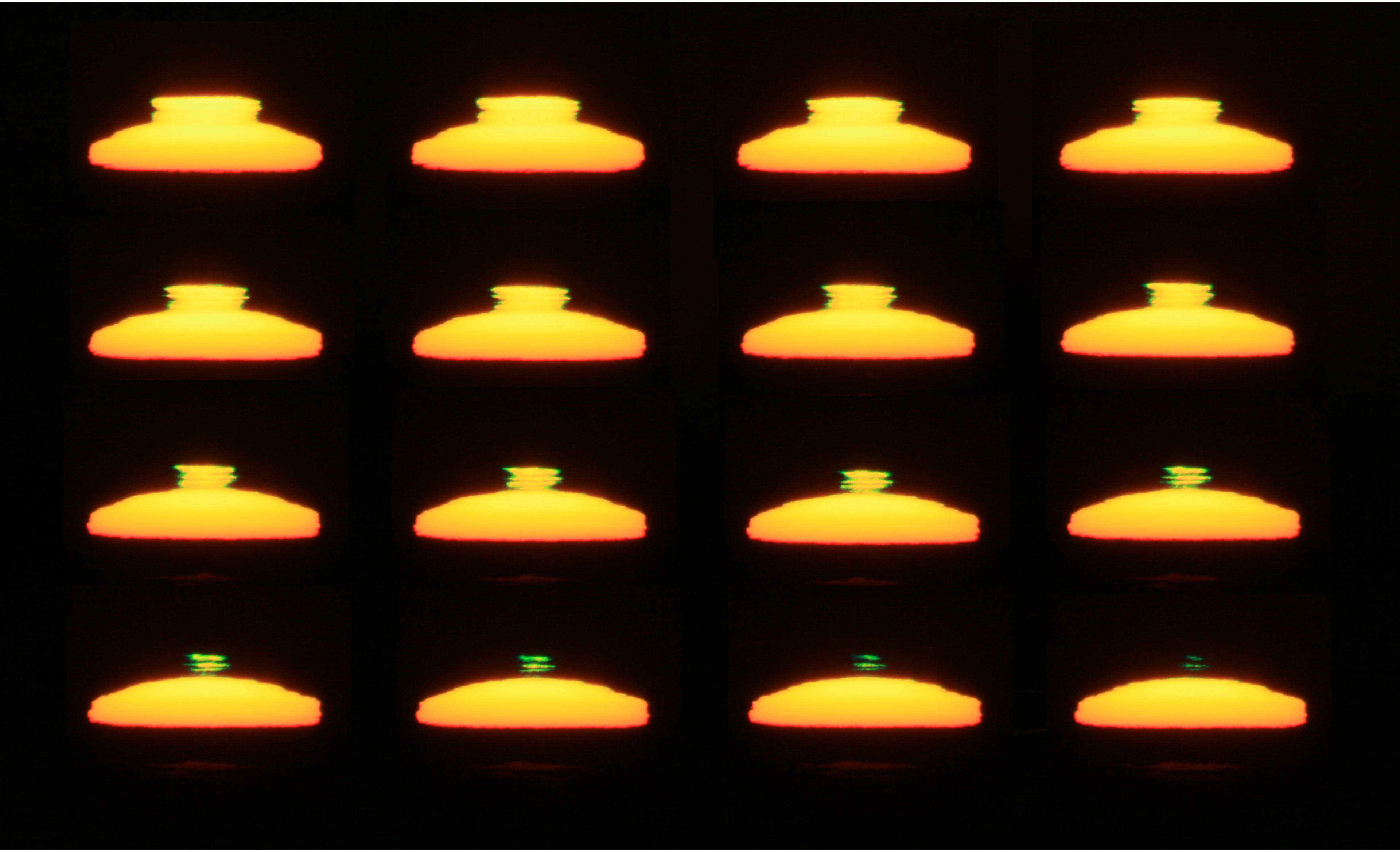


Note that the refractive index of air depends on the wavelength λ:

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

(valid for dry air, 1 atm pressure, T ~ 290K and λ_0 in [μm]).

Green Flash

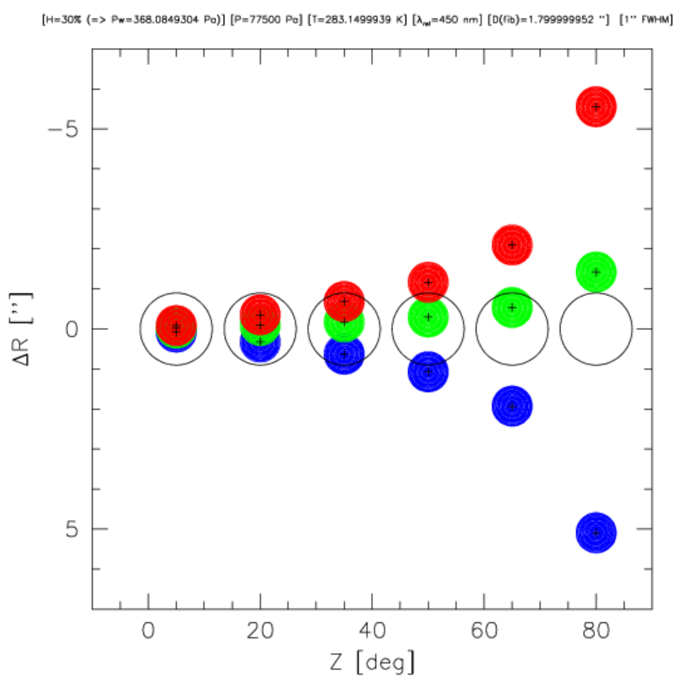


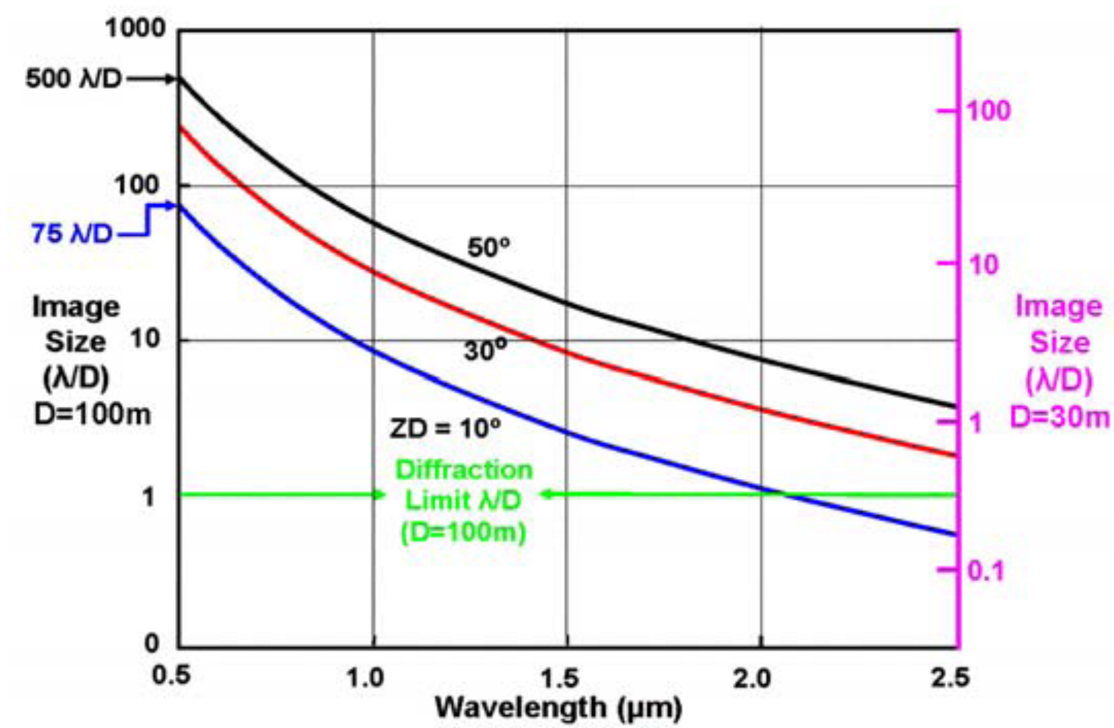
http://upload.wikimedia.org/wikipedia/commons/2/2b/Development_of_Green_Flash.jpg

Atmospheric Dispersion

Dispersion: The elongation of points in broadband filters due to n(λ) [→ "rainbow"].
The magnitude of the dispersion is a strong function of airmass and wavelength.

No problem is dispersion < λ/D ← o.k. for small or seeing limited telescopes, but big problem for large, diffraction limited telescopes

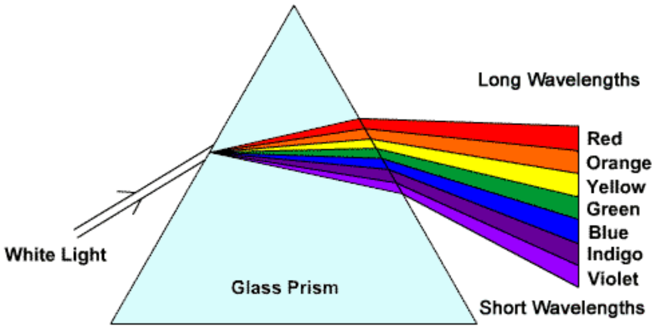


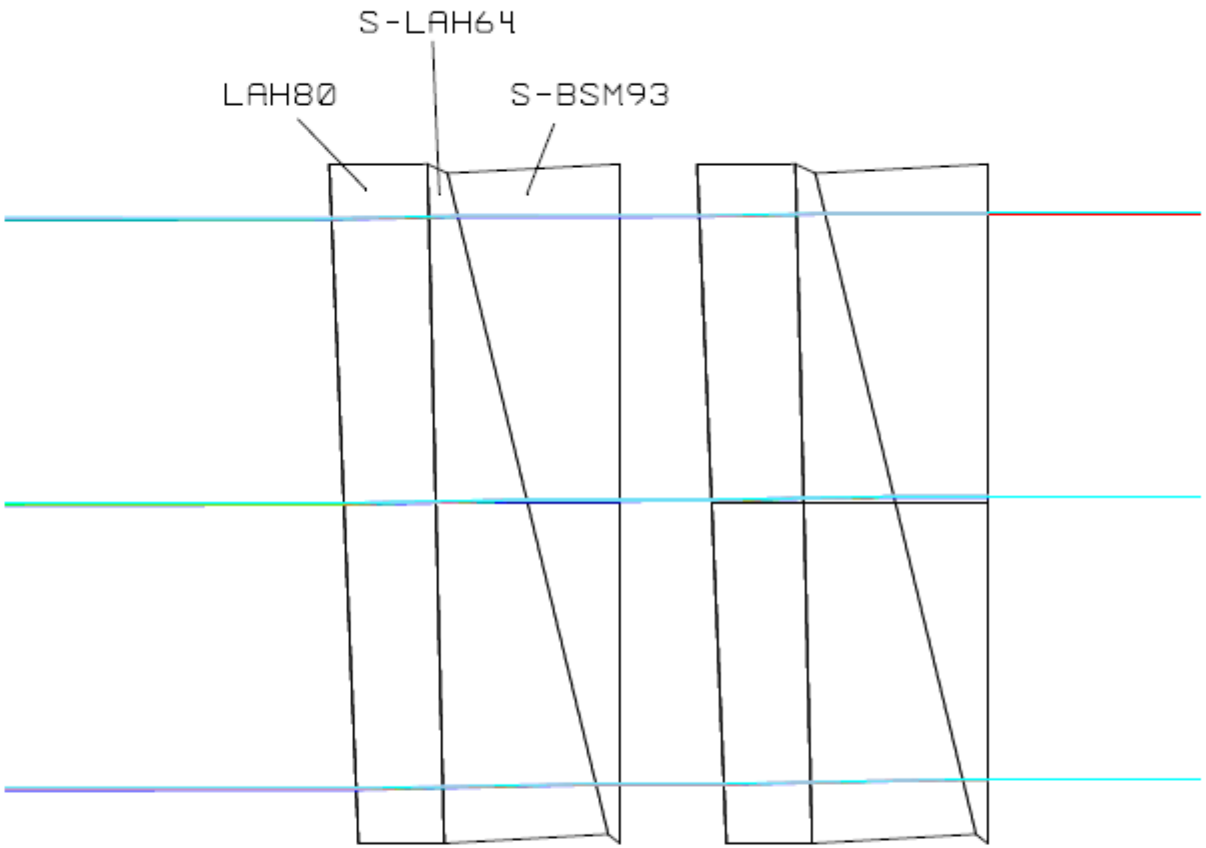


Atmospheric Dispersion Corrector

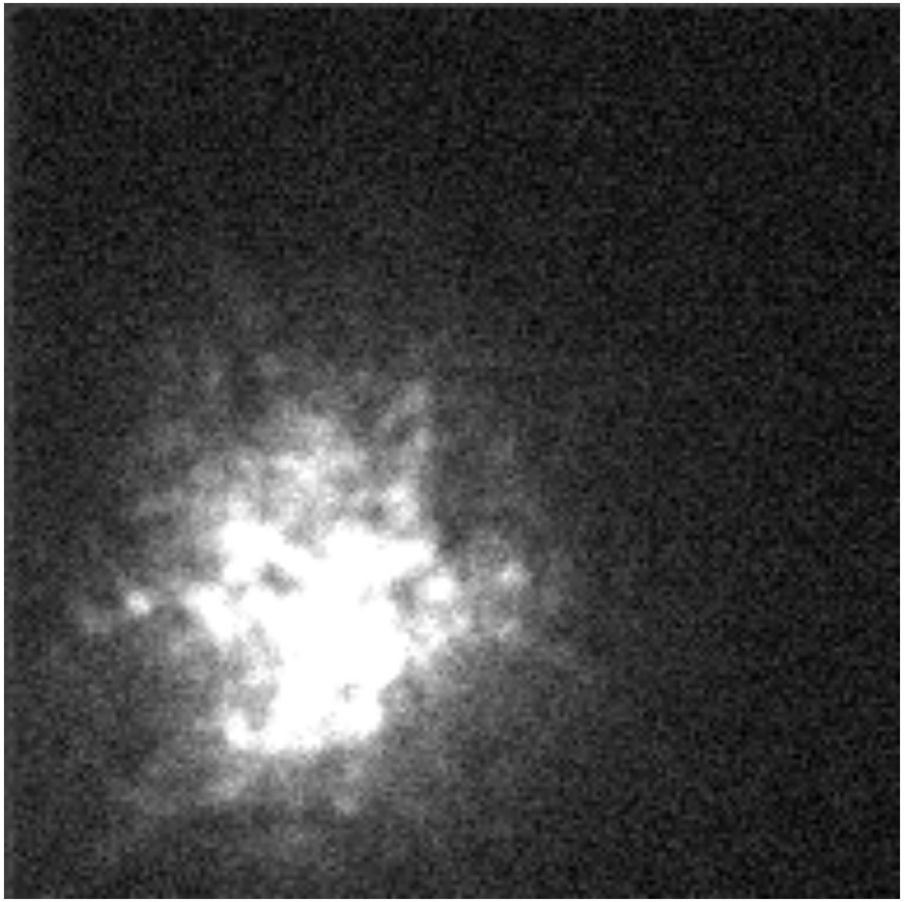
To counterbalance atmospheric dispersion use:

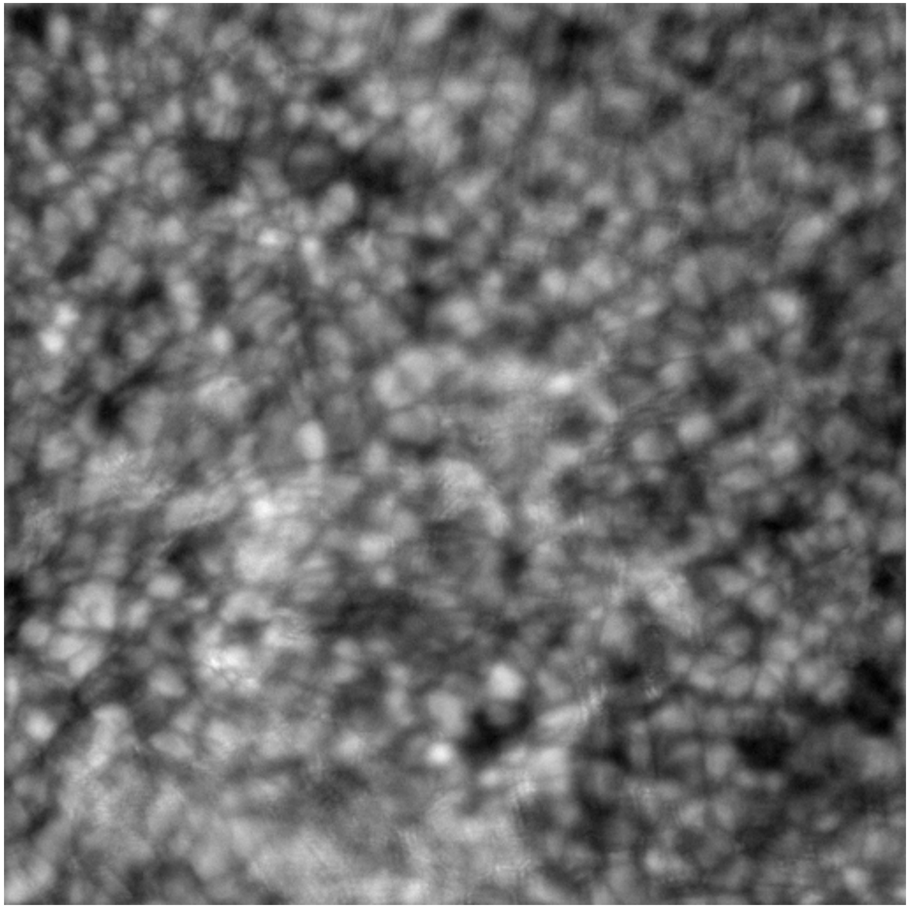
1. a refractive element (e.g., prism)
2. a second prism (different material with different dispersion) to maintain the optical axis
3. use a second (identical) double prism assembly to adjust the strength of the correction for different zenith angles.



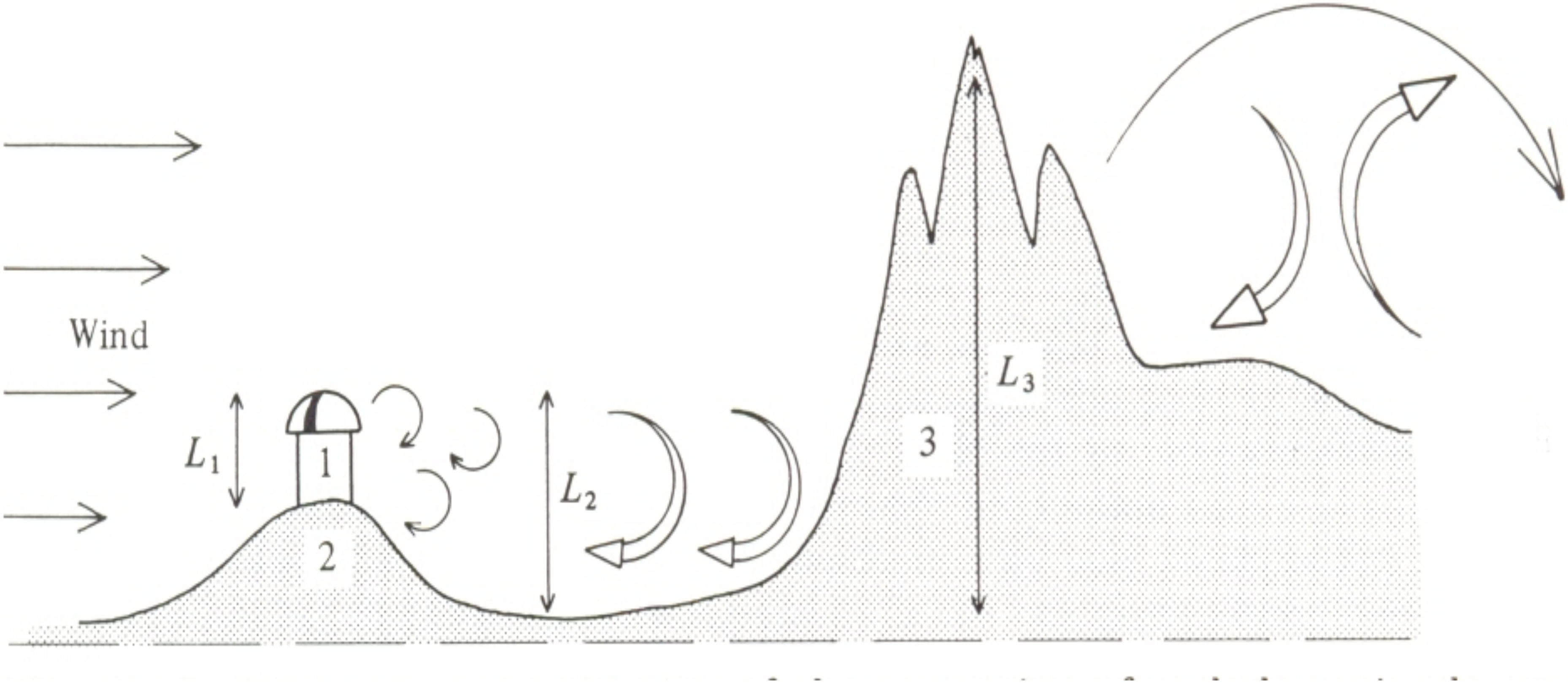


Seeing





5. Atmospheric Turbulence



The scales L_1, L_2, L_3 are characteristic of the outer (external) scales of turbulence caused by the wind around the obstacles 1, 2, 3.

Reynolds Number

Turbulence develops in a fluid when the Reynolds number *Re*

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$

exceeds a critical value.

V is the flow velocity
μ is the dynamic viscosity
ν the kinematic viscosity of the fluid ($\nu_{air}=1.5\cdot10^{-5}$ m^2 s^{-1})
L the characteristic length, e.g. a pipe diameter.

At Re ~ 2200 the transition from laminar to turbulent flow occurs.

Example: wind speed ~ 1 m/s, L = 15m → Re = 10^6 → turbulent!

Power Spectrum of Turbulence

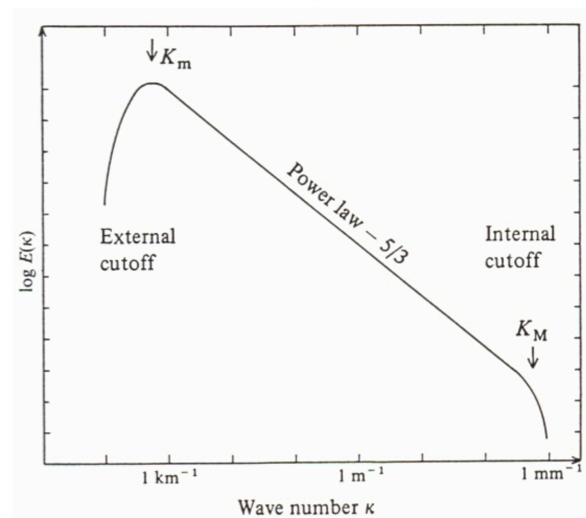
The kinetic energy of large scale (~*L*) movements is gradually transferred to smaller and smaller scales, down to a minimum scale length l_0, at which the energy is dissipated by viscous friction.

The local velocity field can be decomposed into spatial harmonics of the wave vector $\boldsymbol{\kappa}$.
The reciprocal value $1/\boldsymbol{\kappa}$ represents the scale under consideration.

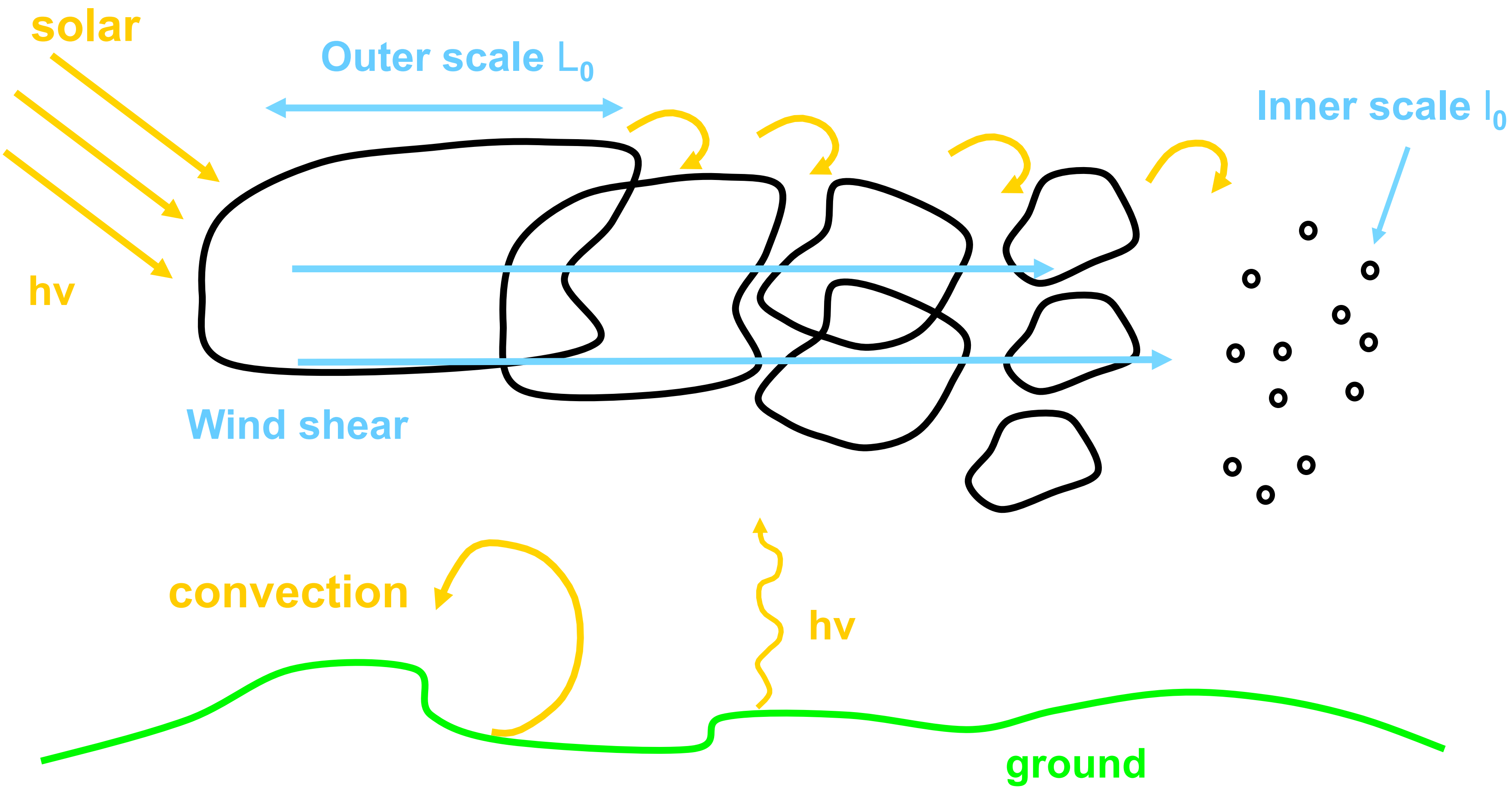
The mean 1D spectrum of the kinetic energy, or Kolmogorov spectrum, is:

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

where l_0 is the inner scale, L_0 the outer scale of the turbulence, and $L_0^{-1} < \kappa < l_0^{-1}$



Kolmogorov Turbulence



Air Refractive Index Fluctuations

Winds mix layers of different temperature → fluctuations of temperature T → fluctuations of density ρ→ fluctuations of refractive index *n*.

Of interest: difference between *n*(r) at point r and *n*(r+ρ) at a nearby point r+ρ. The variance of the two values is given by:

$$D_n(\rho) = \left\langle \left| n(r) - n(r+\rho) \right|^2 \right\rangle = C_n^2 \rho^{2/3}$$

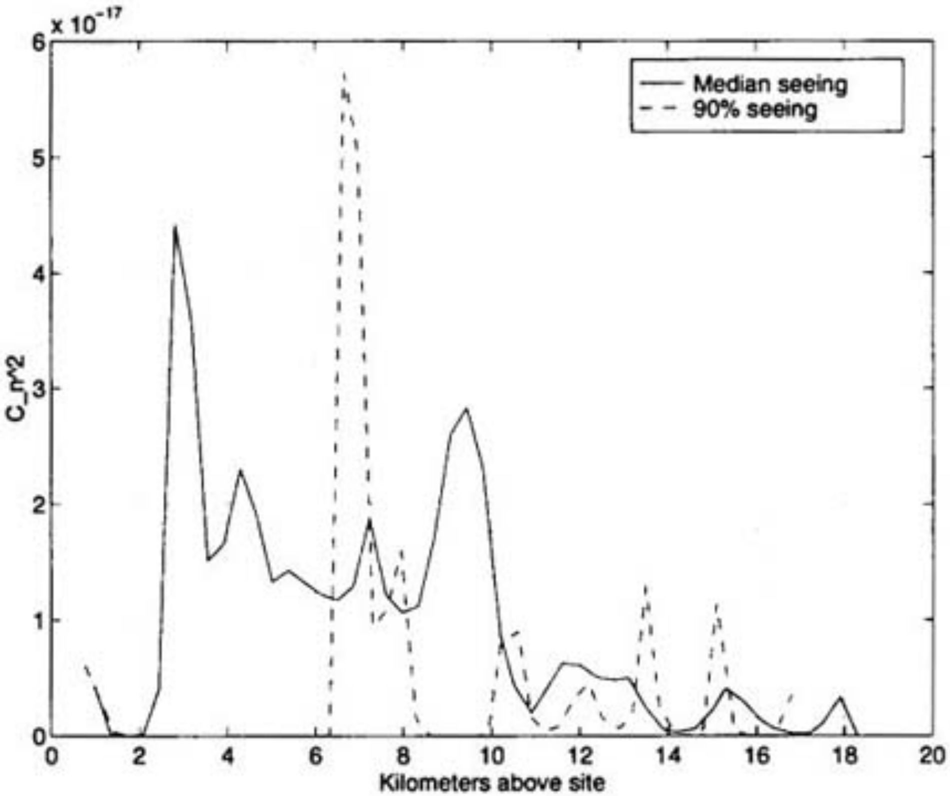
where $D_n(\rho)$ is the index structure function and C_n^2 is the index structure coefficient or structure constant of the refractive index.

Air Refractive Index Fluctuations (2)

Usually, one is only interested in the *integral* of fluctuations along the line of sight: $C_n^2 \cdot \Delta h$.

Typical value: $C_n^2 \cdot \Delta h \sim 4 \cdot 10^{-13}$ cm$^{1/3}$ for a 3 km altitude layer

But: there are always several layers of turbulence



Median seeing conditions on Mauna Kea are taken to be $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are taken to be $r_o \sim 0.40$ meters. Figure taken from a paper by Ellerbroek and Tyler (1997).

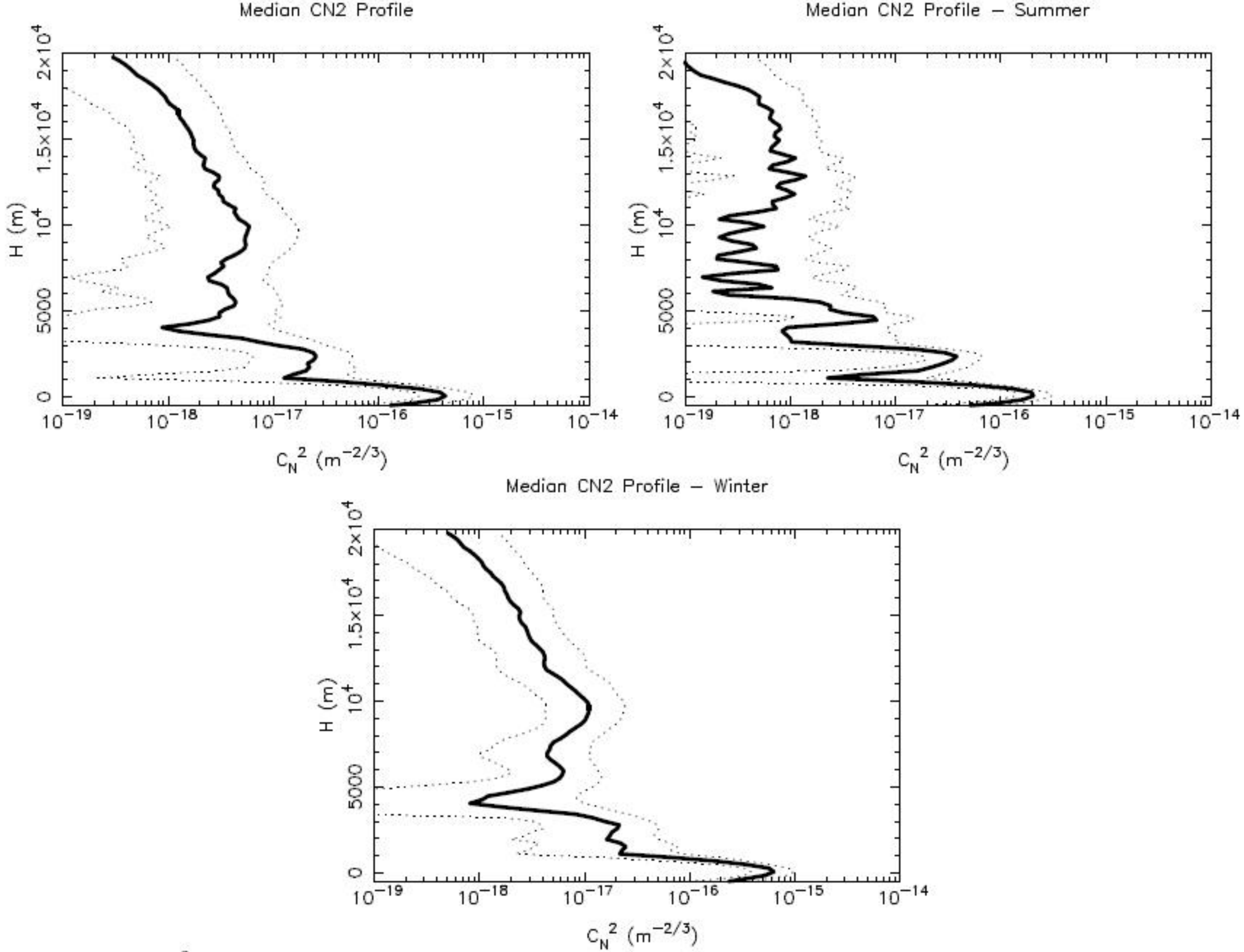
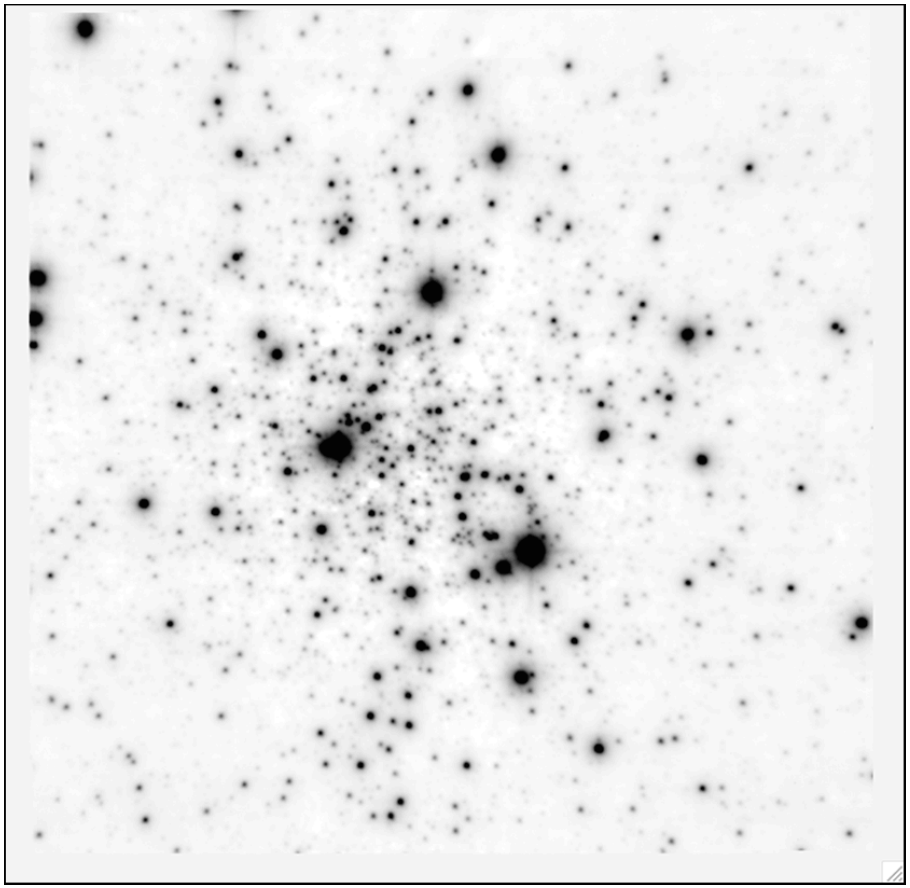
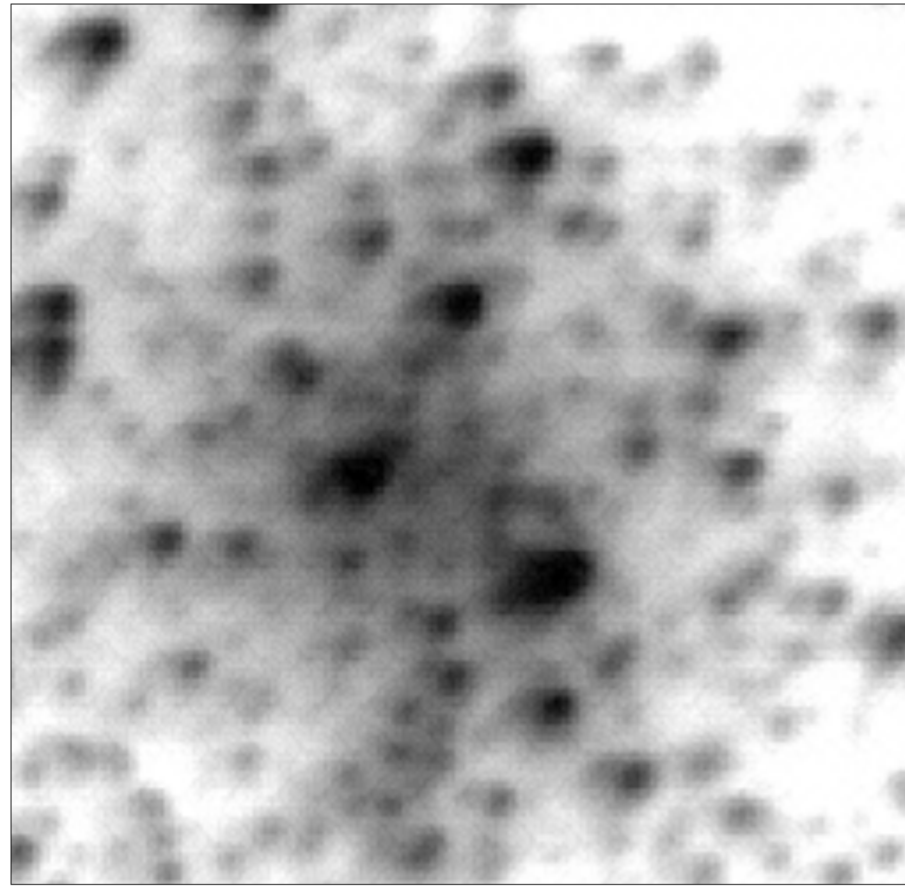


Figure 2. Median C_N^2 profile obtained with the complete sample of 43 nights, the summer [April-June] and winter [October-March] time samples. Results are obtained with the standard GS technique.

Image Degradation by the Atmosphere
...and why we care ...!

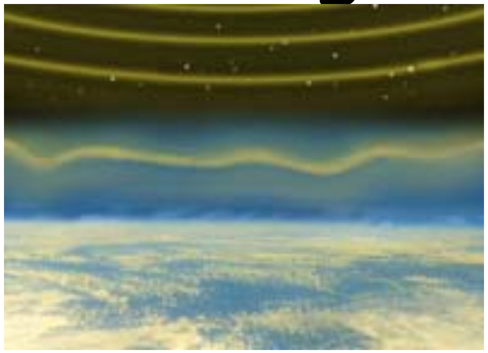


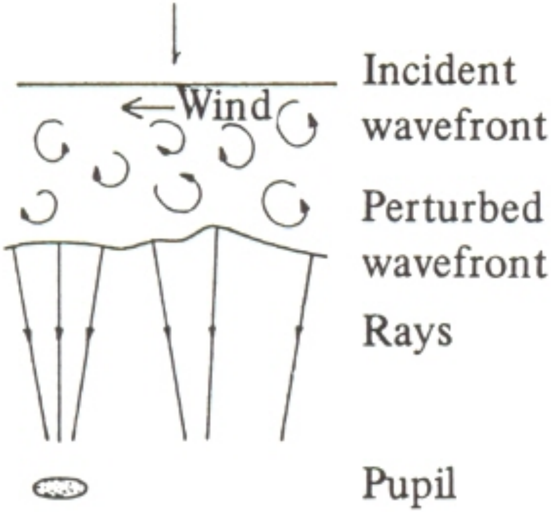


PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM

WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

Aspects of Image Degradation





Scintillation – the energy received by the pupil varies in time

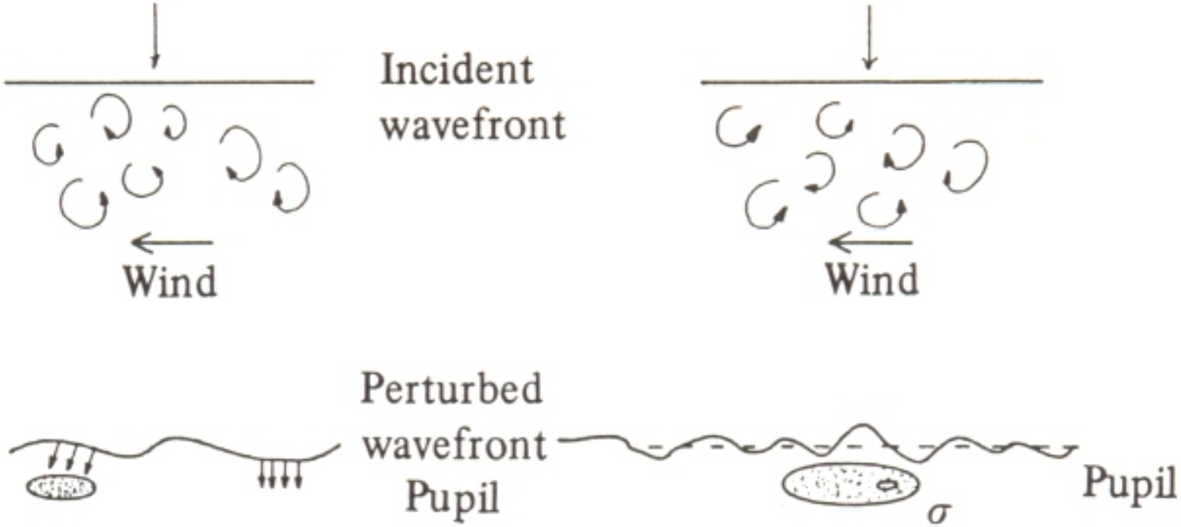


Image motion – the average slope of the wavefront at the pupil varies ("tip-tilt")

Image blurring – the spatial coherence of the wavefront is reduced ("seeing")

The Fried Parameter r_0

The radius of the spatial coherence area is given by the so-called Fried parameter r_0 :

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

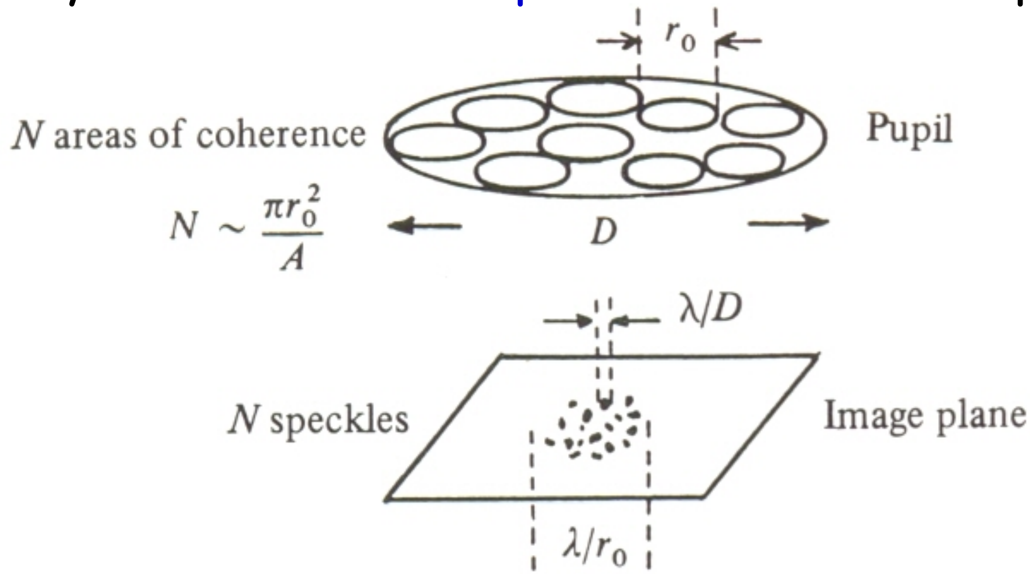
Note that r_0 increases as the 6/5 power of the wavelength and decreases as the -3/5 power of the air mass.

Another "definition" is that r_0 is the average turbulent scale over which the RMS optical phase distortion is 1 radian.

The angle $\Delta\theta = \dfrac{\lambda}{r_0}$ is often called the atmospheric seeing.

Short Exposures through Turbulence

Random intensity distribution of speckles in the focal plane:



The observed image from some source is given by the convolution of I_0 with the MTF or pupil transfer function T(θ):

$$I(\theta) = I_0(\theta) * T(\theta) \quad \text{or} \quad \left\langle |I(\omega)|^2 \right\rangle = |I_0(\omega)|^2 \left\langle |T(\omega)|^2 \right\rangle$$

If a point source is observed as reference through the same r_0 we can calculate:

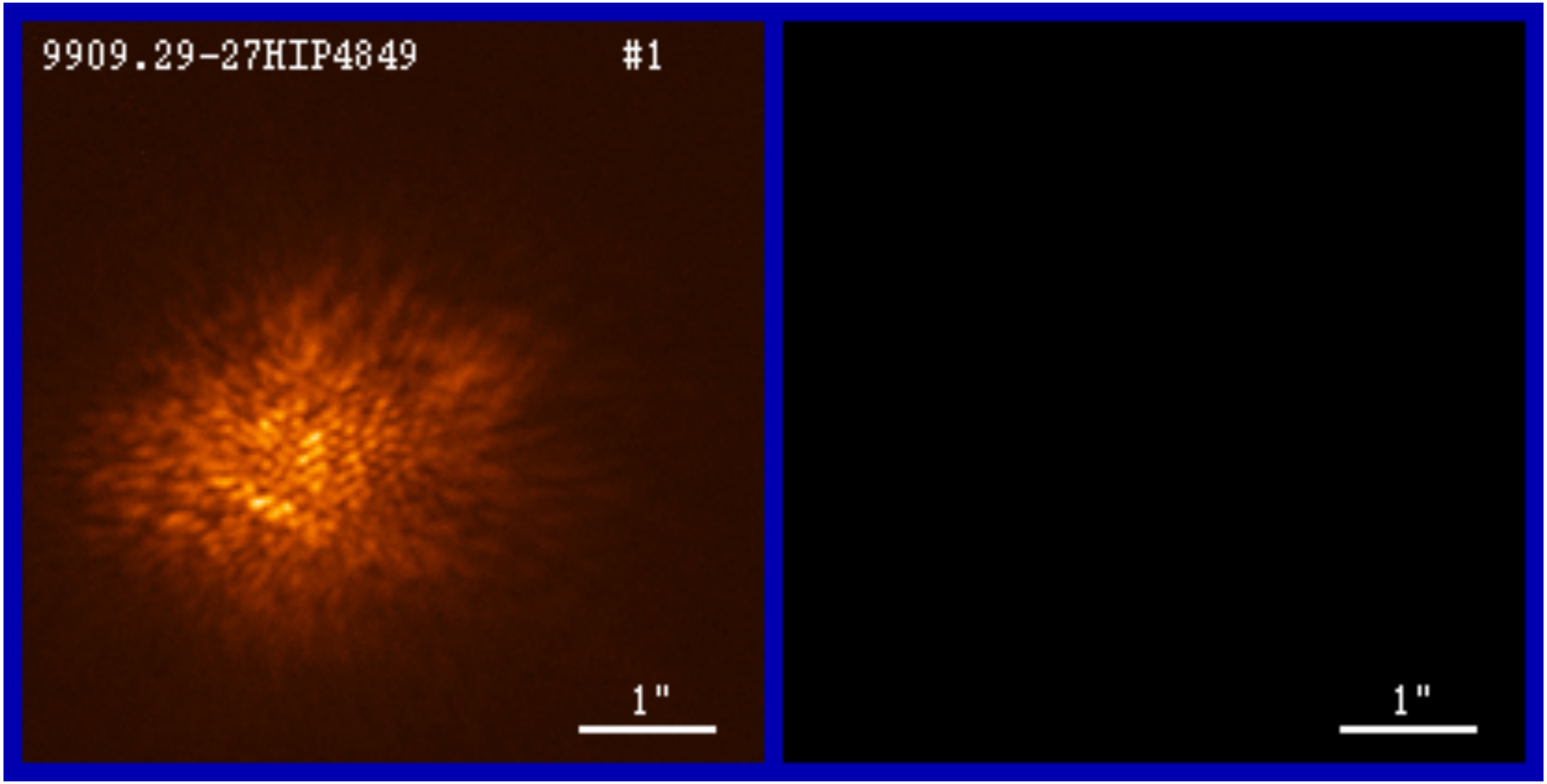
$$|I_0(\omega)| = \left(\frac{\left\langle |I(\omega)|^2 \right\rangle_{obs}}{\left\langle |T(\omega)|^2 \right\rangle_{obs}} \right)^{1/2}$$

This is called speckle interferometry.

Speckle Interferometry

Example: Real-time bispectrum speckle interferometry: 76 mas resolution.

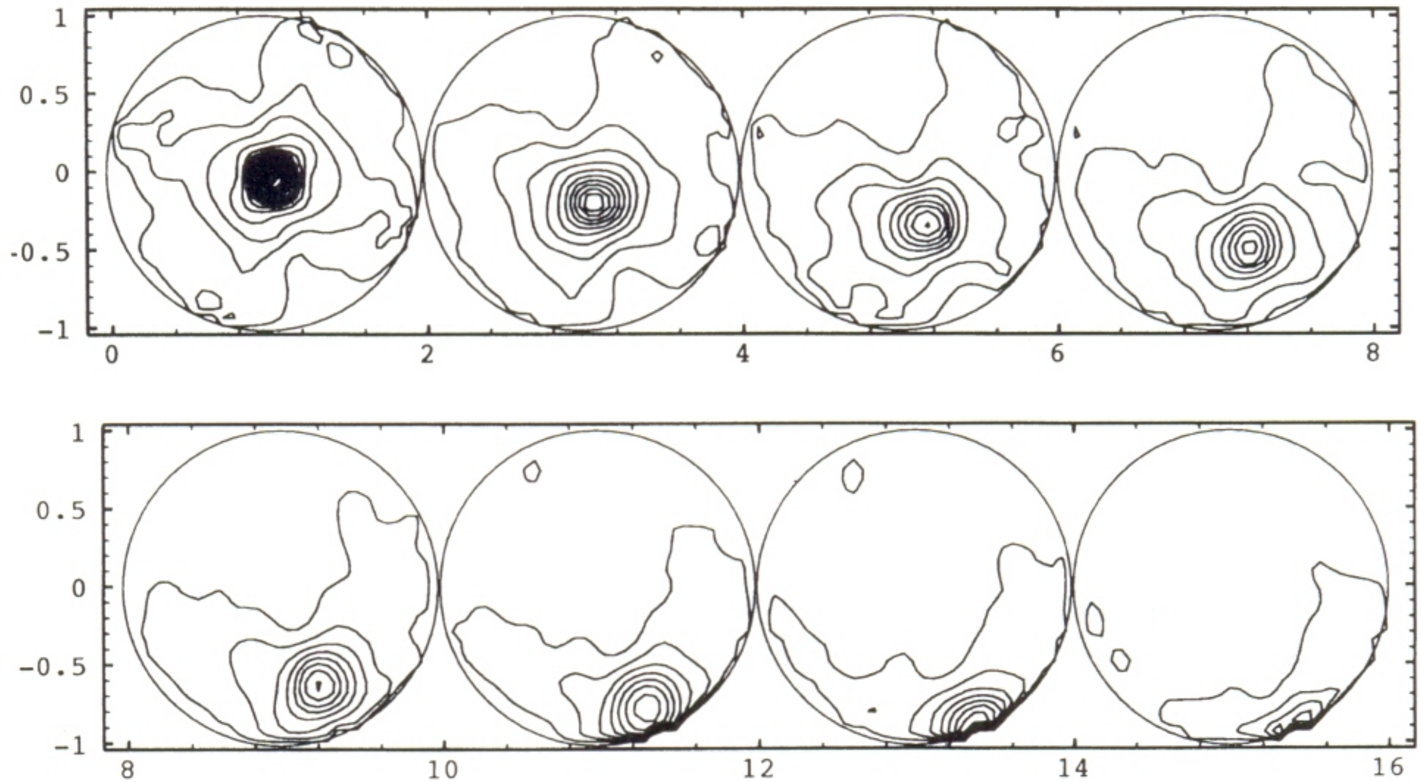
http://www3.mpifr-bonn.mpg.de/div/ir-interferometry/movie/speckle/specklemovie.html



Several related techniques do exist, e.g., Shift-and-add, Lucky Imaging, bispectrum analysis, Aperture masking, Triple correlation, …

Turbulence Correlation Time τ_c

Time series of a patch of atmosphere above the 3.6m telescope aperture (Gendron 1994)



Two effects:

1. The turbulence does not change arbitrarily fast but with a correlation time or coherence time τ_c.
2. Often, the turbulent time scales >> time for the turbulent medium to pass the telescope aperture (wind speed) → "frozen turbulence"

Summary: r_0, seeing, τ_0, θ_0

The Fried parameter $r_0(\lambda) = 0.185\lambda^{6/5}\left[\int_0^\infty C_n^2(z)dz\right]^{-3/5}$ is the radius of the spatial coherence area.
It is the average turbulent scale over which the RMS optical phase distortion is 1 radian. *Note that r_0 increases as $\lambda^{6/5}$.*

$\Delta\theta = \dfrac{\lambda}{r_0} \sim \lambda^{-1/5}$ is called the seeing. At good sites r_0 (0.5µm) ~10 - 30 cm.

The atmospheric coherence (or Greenwood delay) time is: $\tau_0 = 0.314\dfrac{r_0}{\bar{v}}$
It is the maximum time delay for the RMS wavefront error to be less than 1 rad (where *v* is the mean propagation velocity).

The isoplanatic angle $\theta_0 = 0.314\cos\zeta\dfrac{r_0}{\bar{h}}$ is the angle over which the RMS wavefront error is smaller than 1 rad.

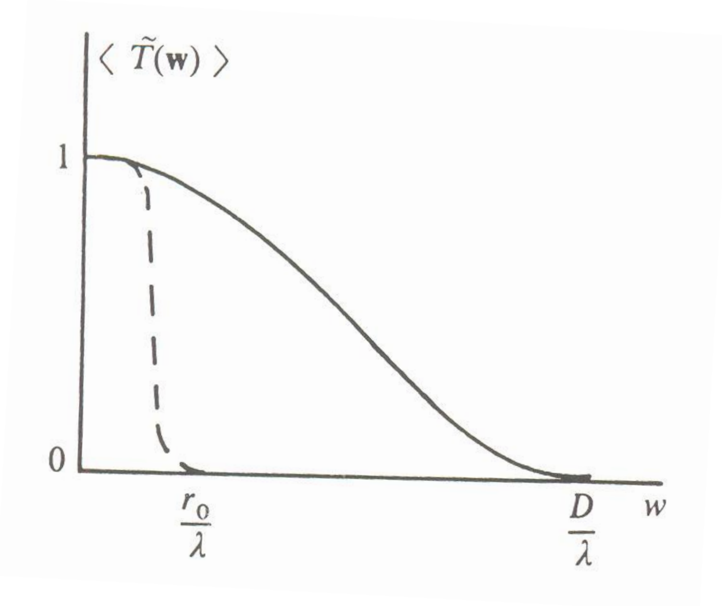
Long Exposures through Turbulence

When $t_{int} >> \tau_c$ the image is the mean of the instantaneous intensity:

$$I(\theta) = \langle I_0(\theta) * T(\theta, t) \rangle$$

With the mean modulation transfer function (MTF):

$$\left\langle \tilde{T}(\omega) \right\rangle \approx \exp\left[-1.45 k^2 C_n^2 \Delta h \, (\lambda\omega)^{5/3}\right]$$



➔ The image is smeared or spatially filtered (loss of high spatial frequencies).

The angular dimension now has order of λ/r_0 rather than λ/D.

In other words:
As long as $D > r_0$, bigger telescopes will *not* provide sharper images.