Astronomical Observing Techniques 2018

Lecture 2: Trouble is in the Air

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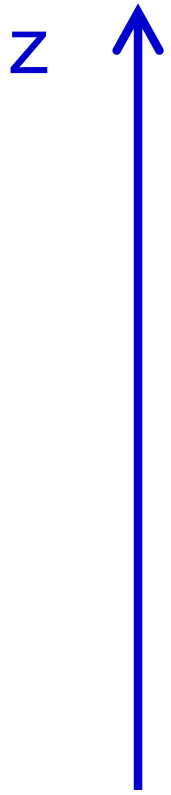
The Earth's Atmosphere: Overview

- Astronomical observations are mostly ground-based
- Earth's atmosphere influences observations:
  - absorption
  - emission
  - scattering
  - refraction
  - dispersion
  - turbulence

Atmospheric Structure: Assumptions

- Assumptions:
  - atmosphere in local radiative equilibrium
  - homogeneous composition
- Hydrostatic equilibrium:
  - static (*v=0*)
  - altitude *z*
  - temperature *T(z)*
  - density *ρ(z)*



Hydrostatic Equilibrium: Pressure

$$dm = \rho \cdot A \cdot dz$$

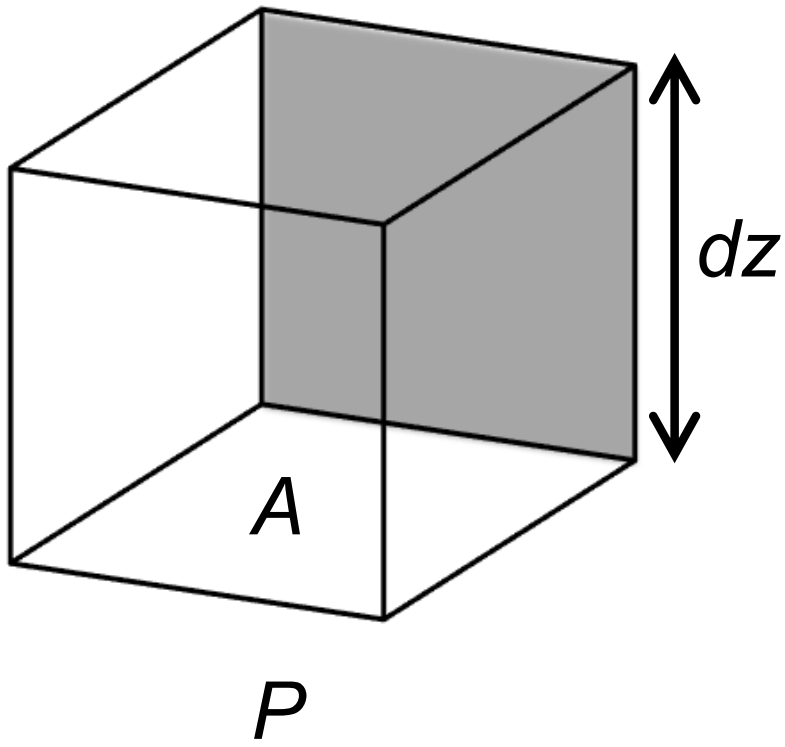
$$dF = -g \cdot dm = -\rho \cdot g \cdot A \cdot dz$$

$$dP = dF / A = -\rho \cdot g \cdot dz$$

$$P = \rho \cdot k \cdot T / \mu, \quad \rho = P \cdot \frac{\mu}{kT}$$

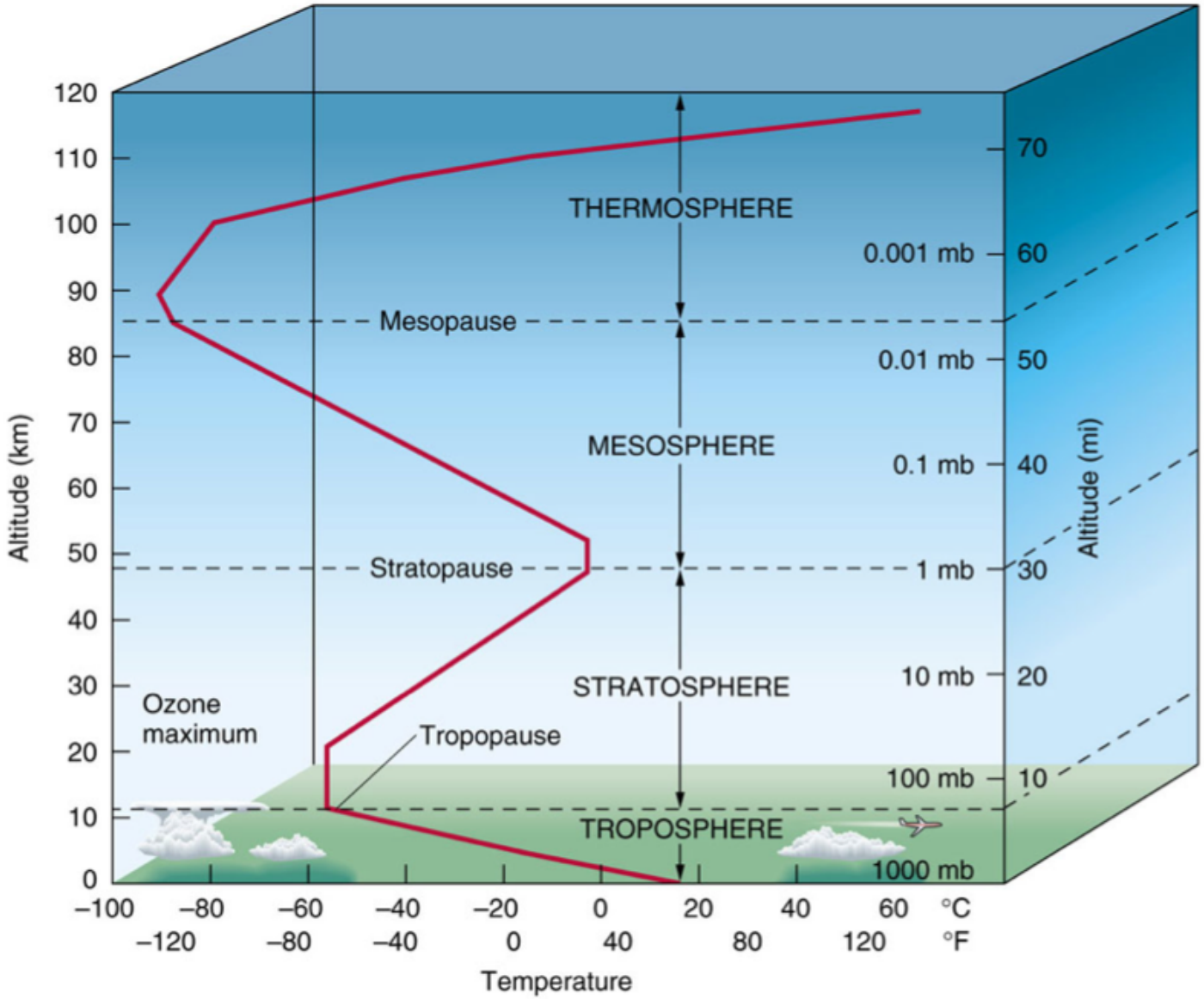
$$dP / dz = -P / H, \quad H = \frac{kT}{\mu g}$$

$$P(z) = P_0 \cdot e^{-\frac{z}{H}}$$



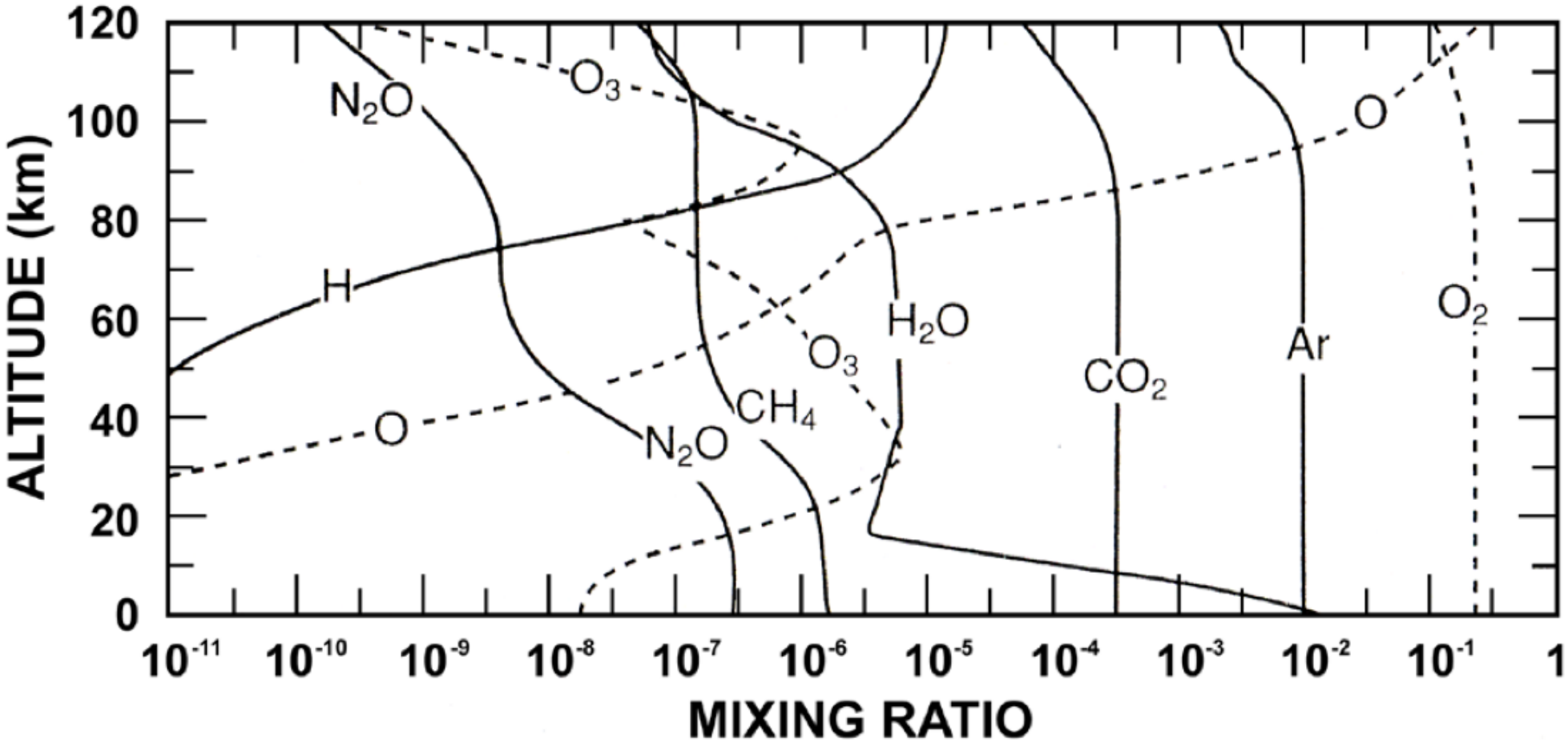
ρ: density, *A*: surface, *g*: gravitational acceleration,
F: force, *k*: Boltzmann constant, *T*: temperature,
μ: mean molecular weight. *H*: scale height ≈ 6-8 km

Atmospheric Structure: Temperature



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

Atmospheric Composition: Mixing Ratios



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 ratio independent of altitude
- H_2O – highly variable, very strong absorption bands

Ionosphere

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: $n_e \sim 10^5 - 10^6$ cm^{-3}

Atmospheric Absorption

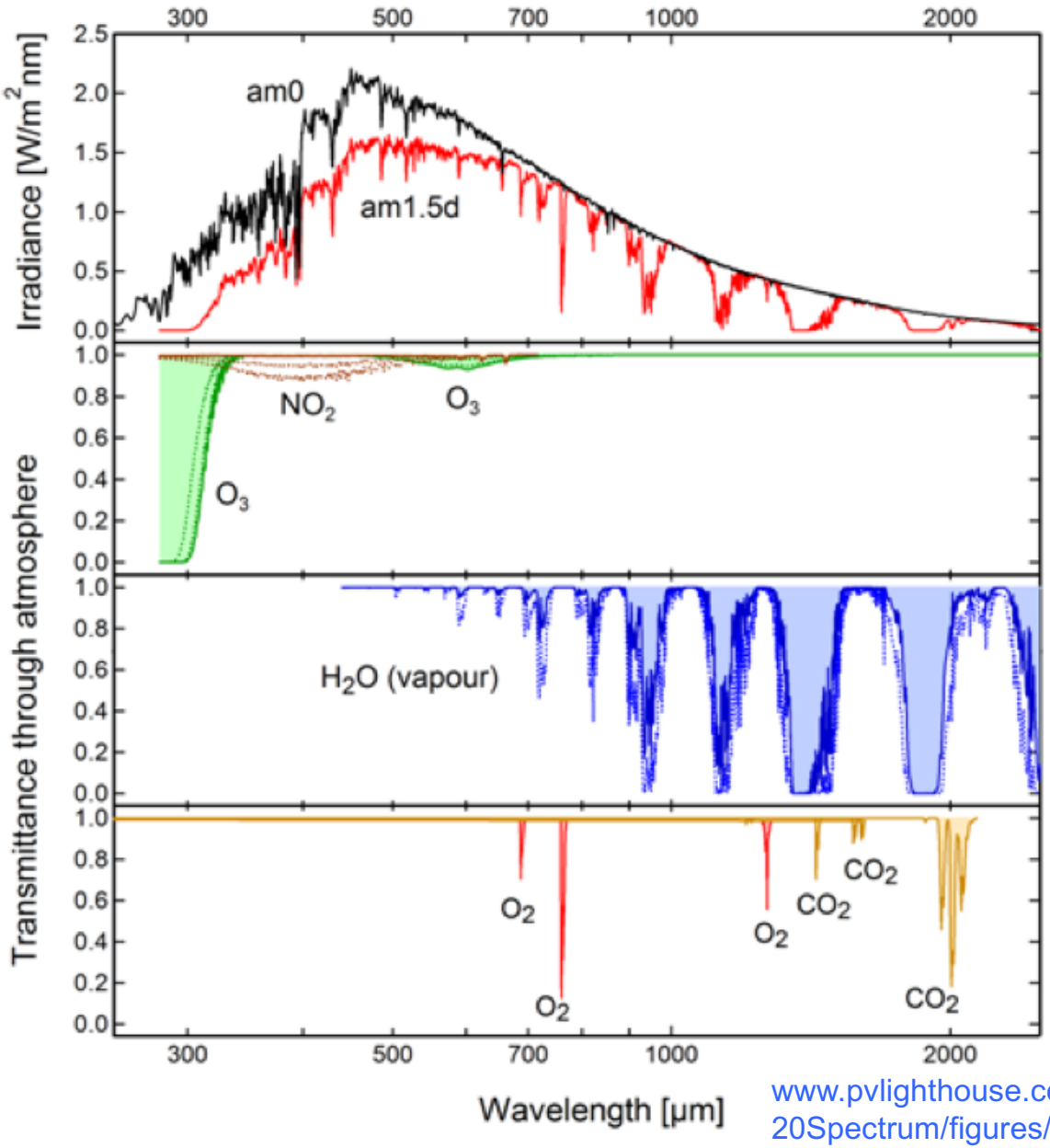
- atomic, molecular transitions -> absorption features:
- individual atomic absorption lines
- molecular absorption bands
- Attenuation at altitude z_0 and zenith distance θ:
- for *i* absorbing species with optical depth τ_i

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

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

κ: absorption coefficient; ρ_0: mass density of air;
$r_i(z)$ the mixing ratio $r_i = n_i/(n_{tot}-n_i)$ where n is the amount in mol

Atmospheric Absorption: Bands



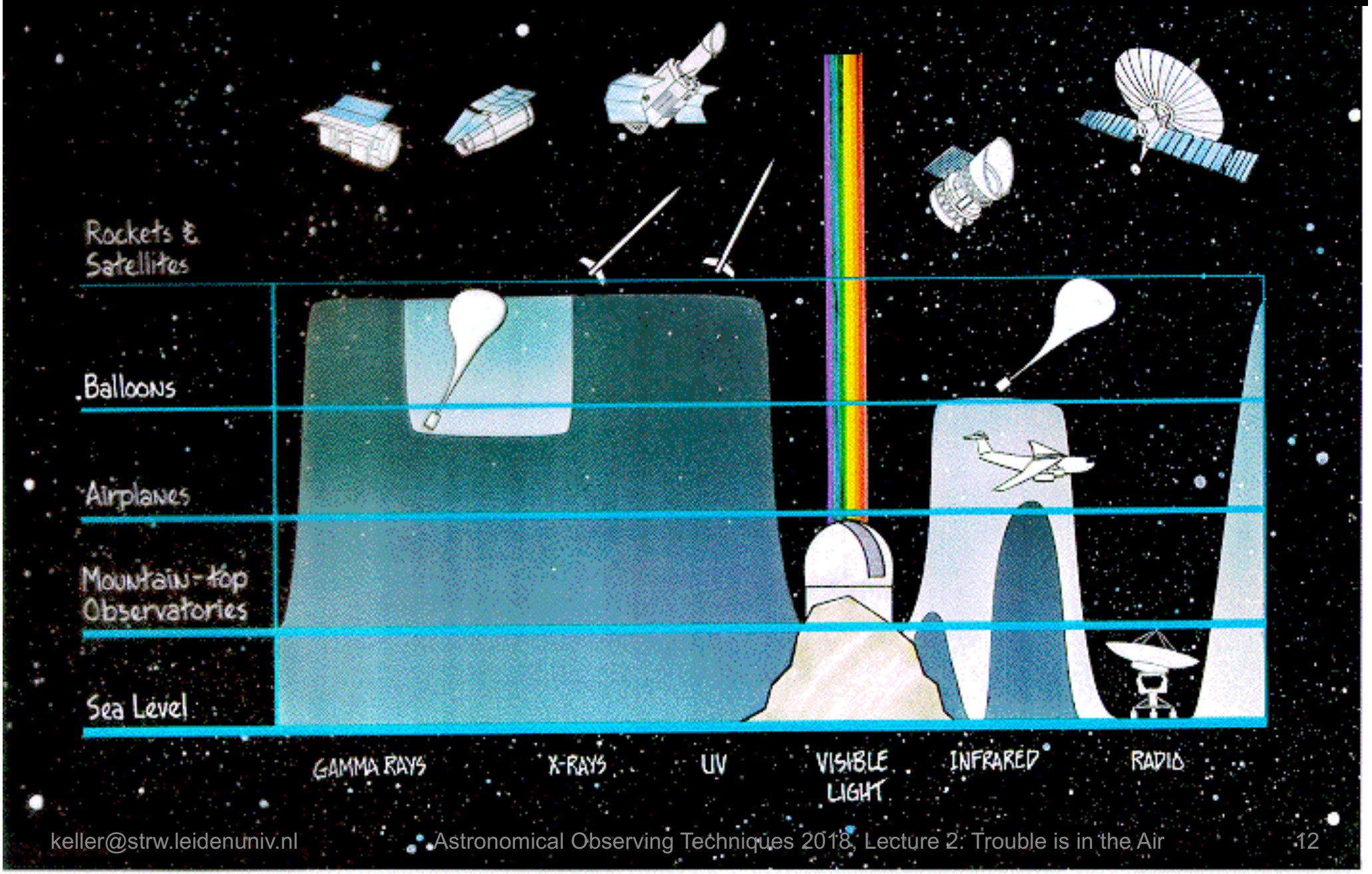
Total absorption → atmospheric transmission windows

Partial absorption → reduced transmission due to narrow telluric lines of terrestrial origin

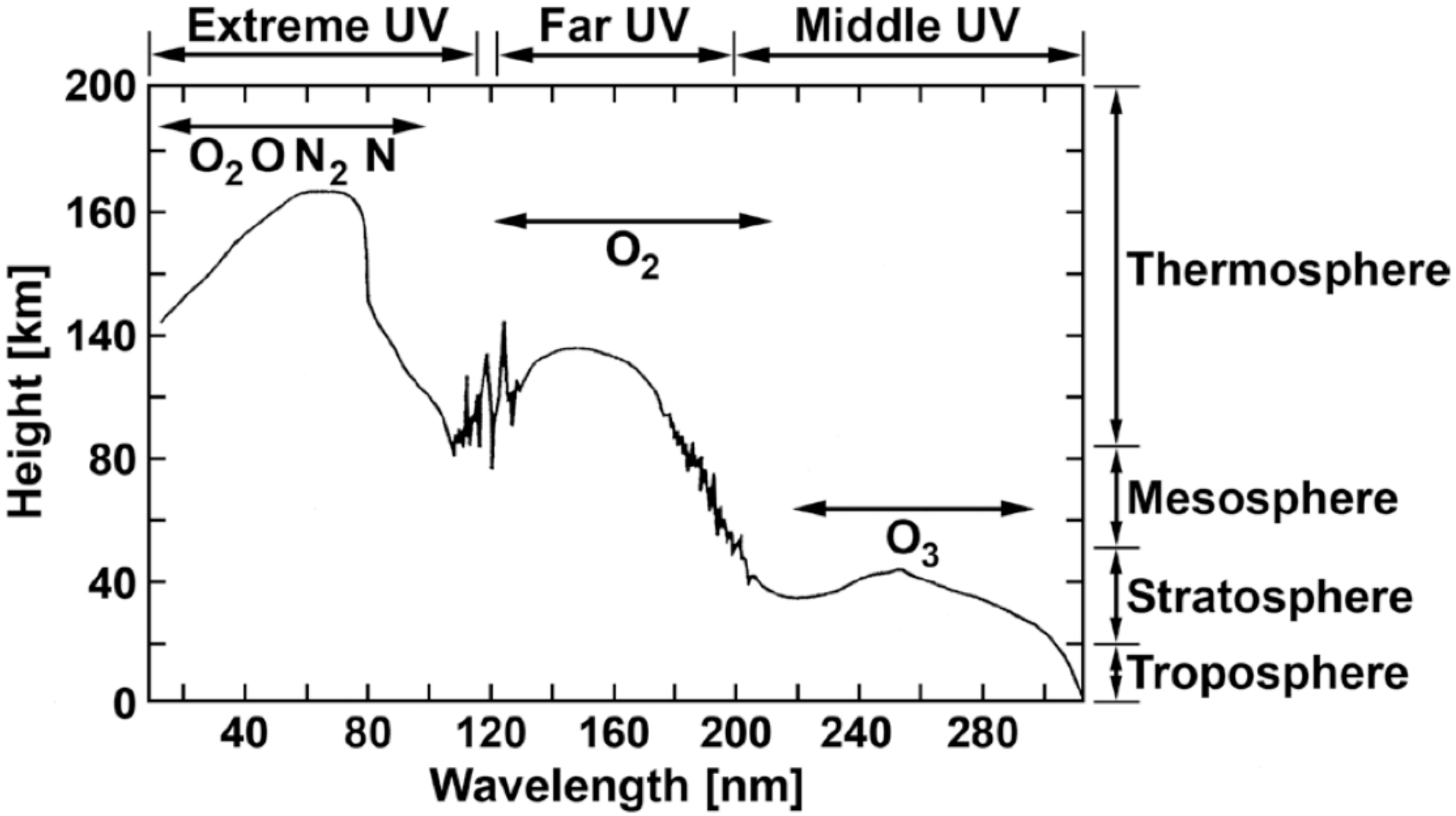
Atmospheric opacity defines atmospheric transmission bands (wavelengths accessible to ground-based observations)

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

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



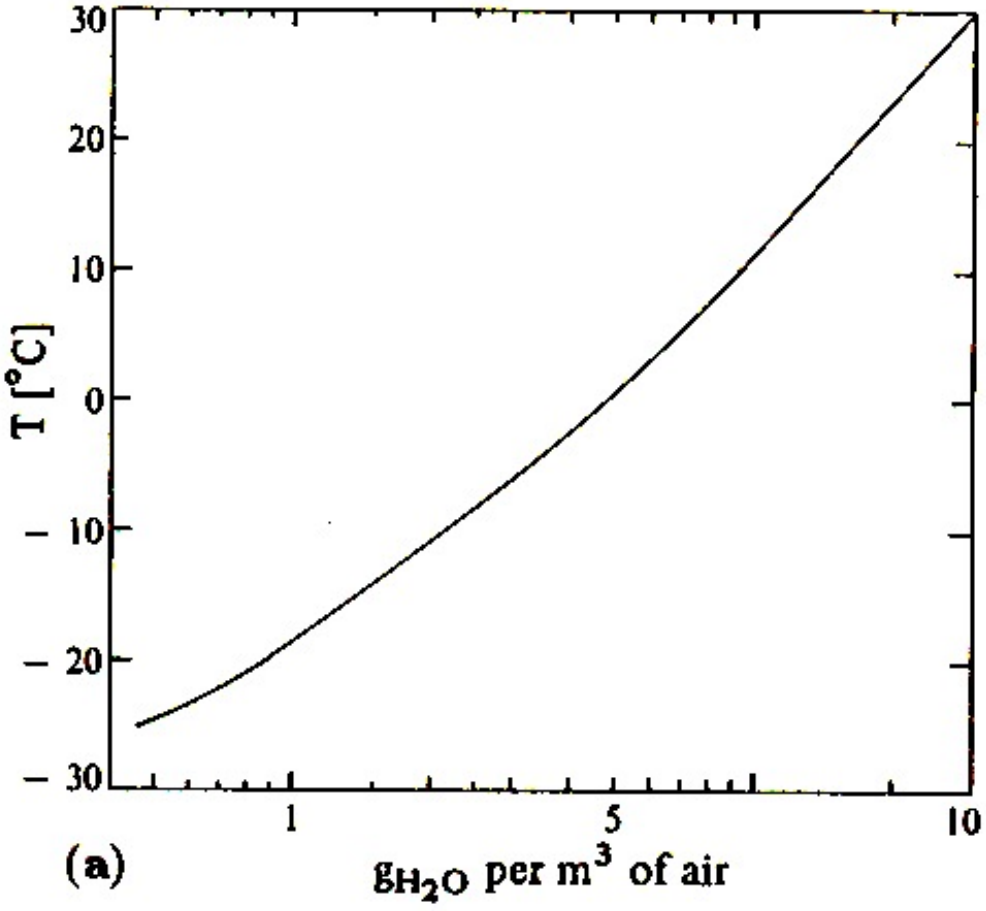
Atmospheric Absorption: UV



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

Atmospheric Absorption: Water Vapour

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

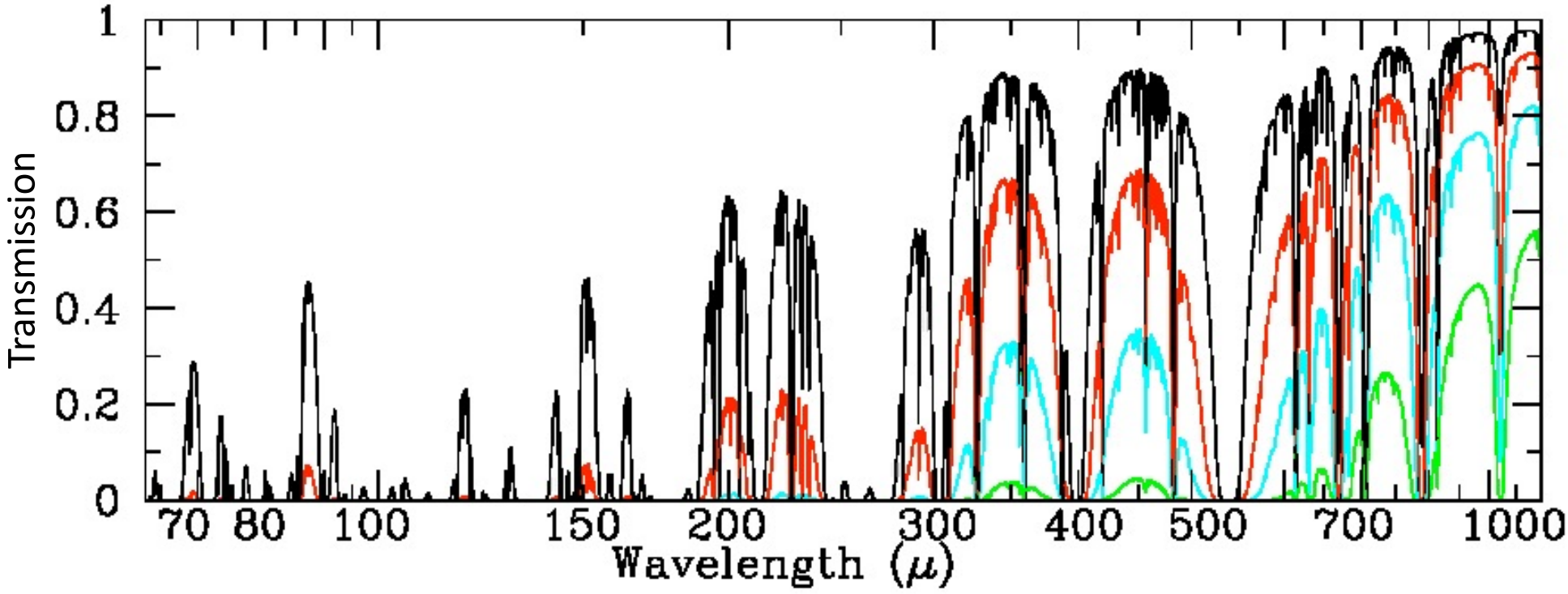


$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz \,,$$

$$N_{H_2O}\left[\mathrm{m}^{-3}\right] = 4.3\times10^{25}\,\frac{P}{P_0}\,\frac{T}{T_0}\,r(z)$$

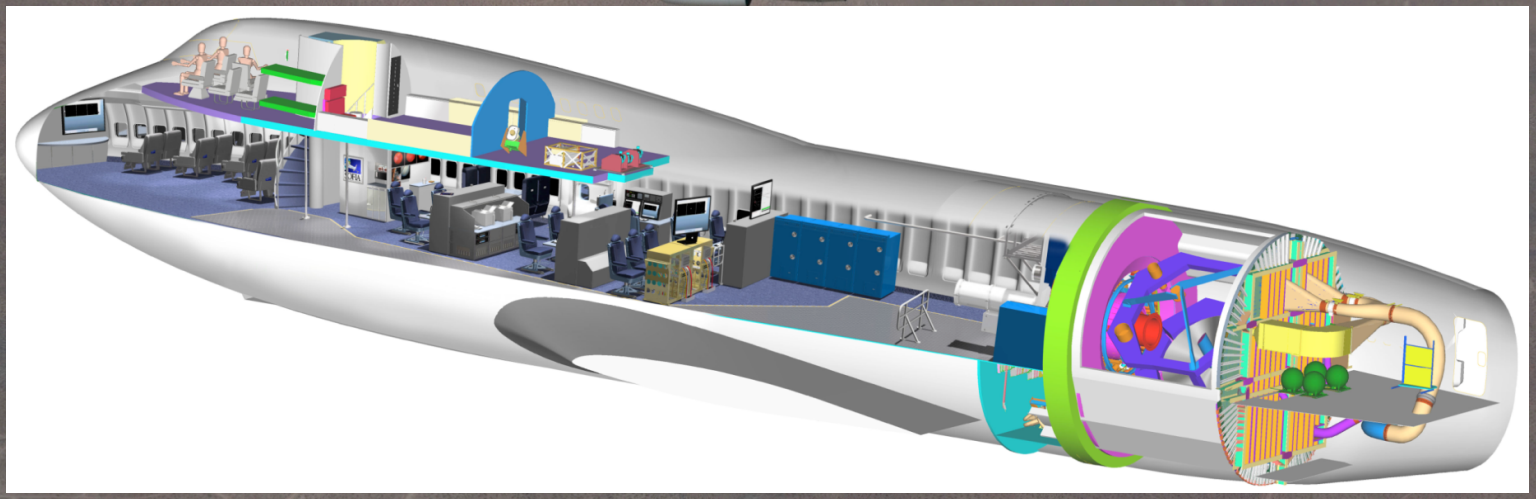
Absorption by Water Vapour

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)

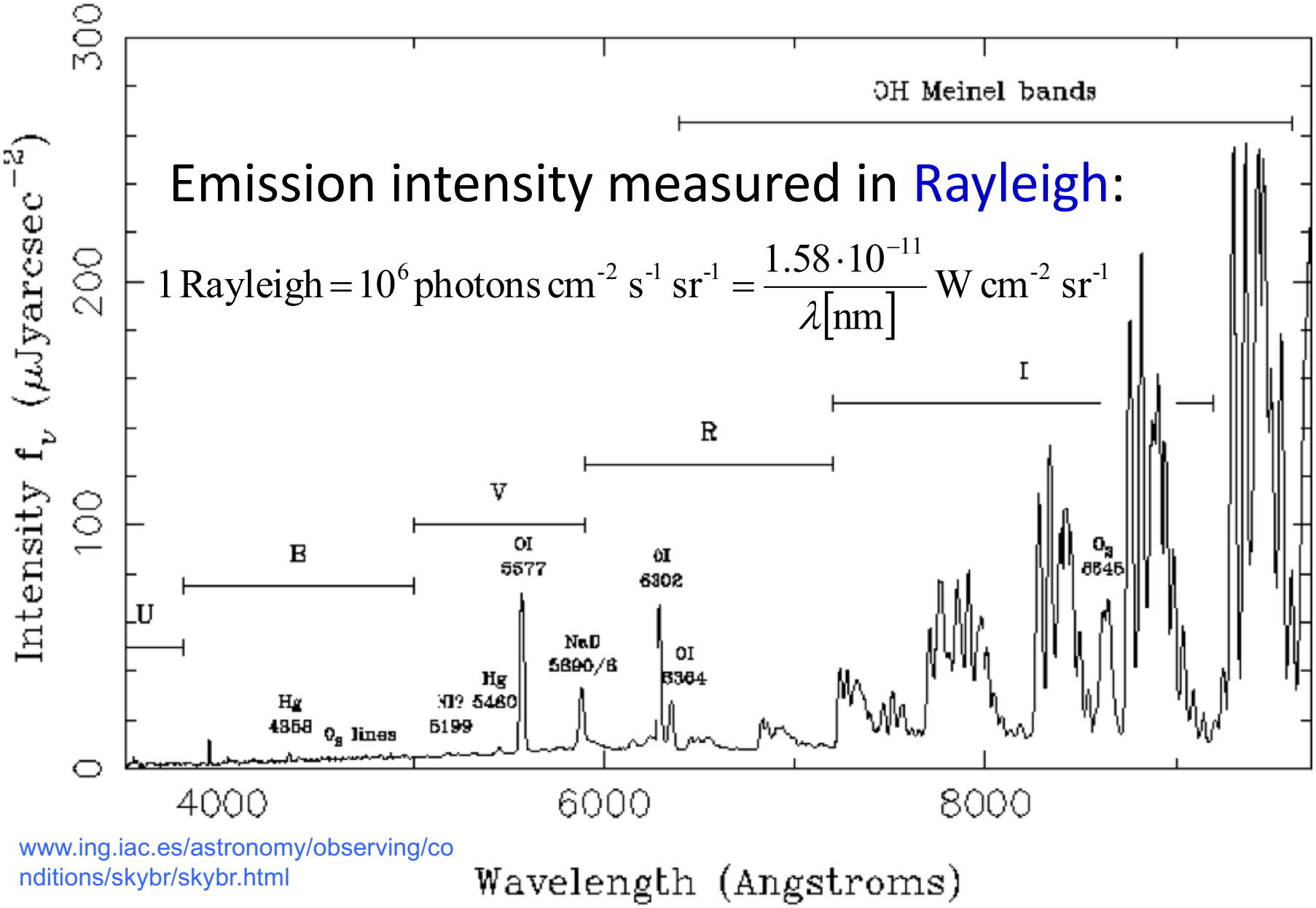


Atmospheric Emission: Airglow

- Fluorenscence = recombination of electrons and ions
- Recombination probability low; takes several hours
- Produces both continuum + line emission = airglow
  - Occurs mainly at ~ 100 km height
  - Main sources of emission: O I, Na I, O_2, OH (in NIR), H

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

Atmospheric Emission: Airglow



Emission intensity measured in Rayleigh:

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

www.ing.iac.es/astronomy/observing/conditions/skybr/skybr.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 $\tau << 1$ use approximation:

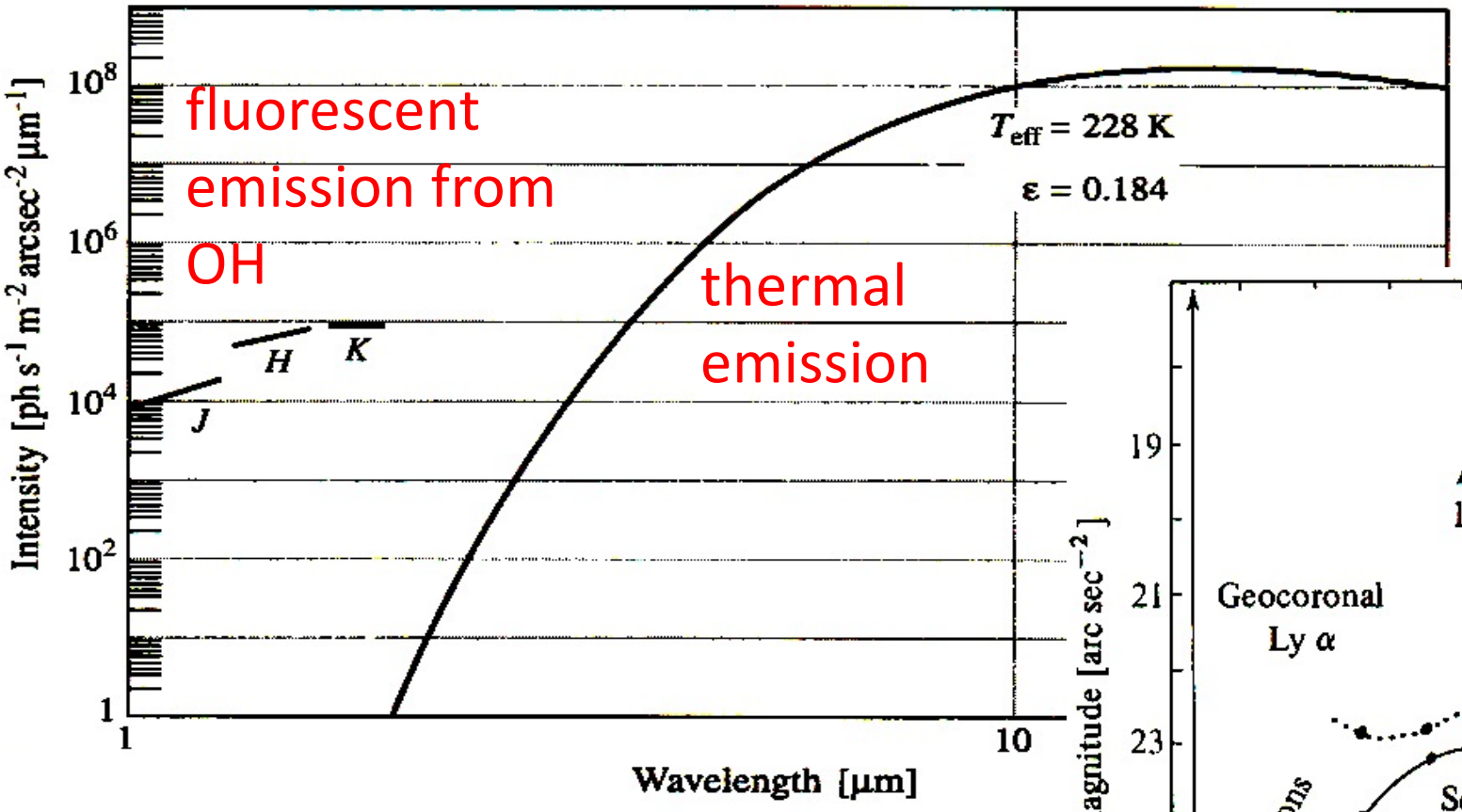
$$I_\lambda(z) = \frac{\tau_\lambda B_\lambda(T_{\text{mean}})}{\cos\theta}$$

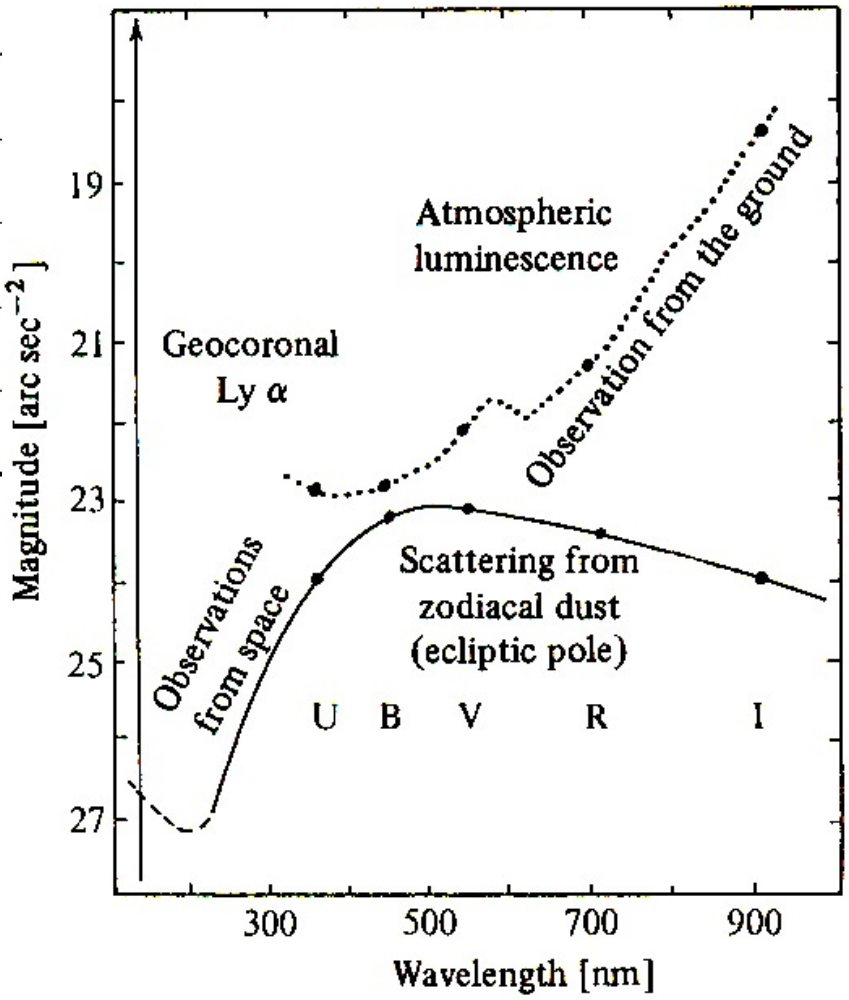
$B_\lambda(T_{\text{mean}})$: Planck function at mean temperature T_{mean} of atmosphere

For T = 250 K and θ = 0

Spectral band (cf. Sect. 3.3)	*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

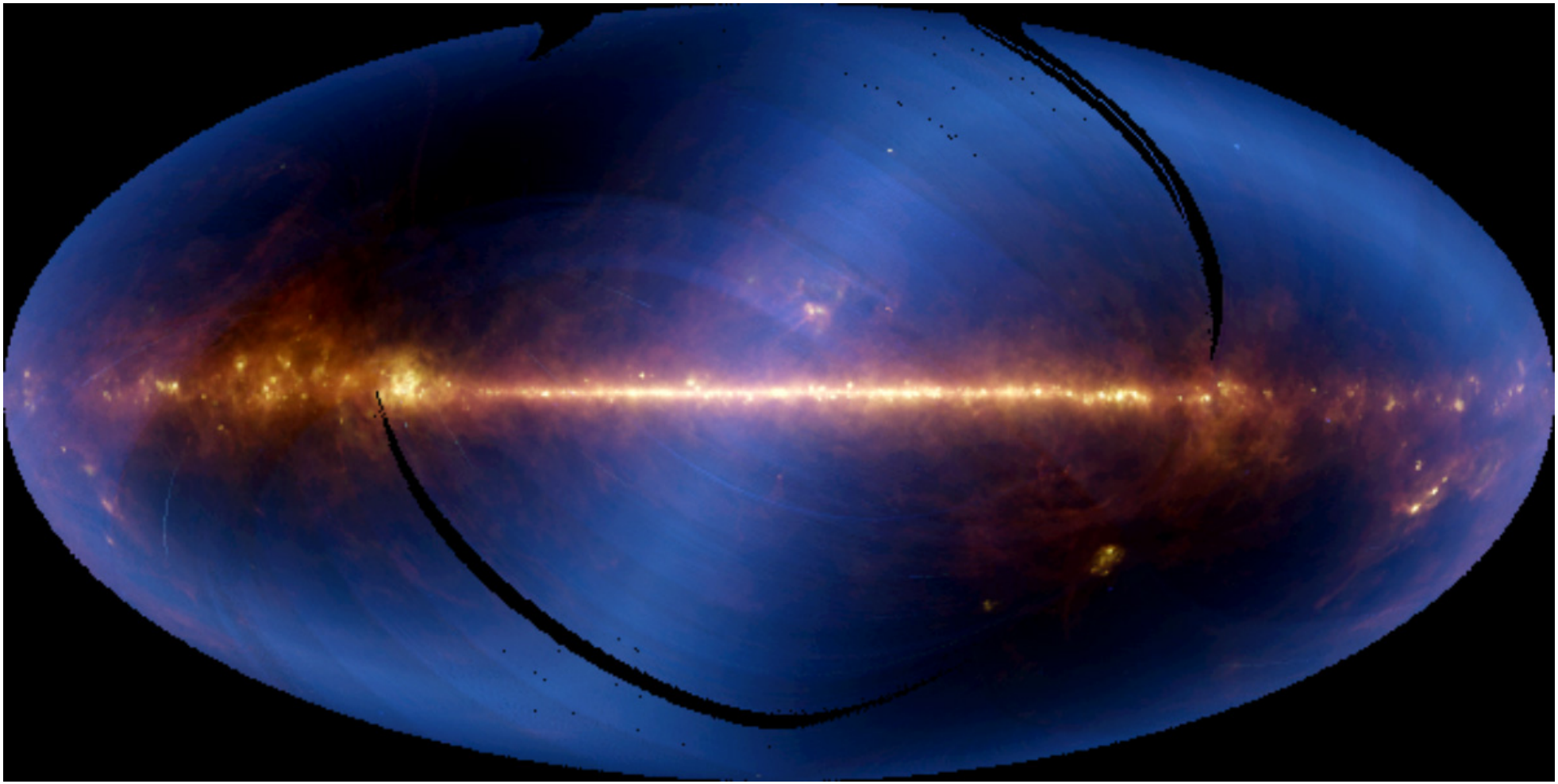
Fluorescent and Thermal Emission





Sky surface brightness 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

Molecular Scattering

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

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

where *N* is the number of molecules per unit volume and *n* is the refractive index of air ($n\text{-}1 \sim 8\cdot10^{-5}\ P/T$).

- Rayleigh scattering is not isotropic:

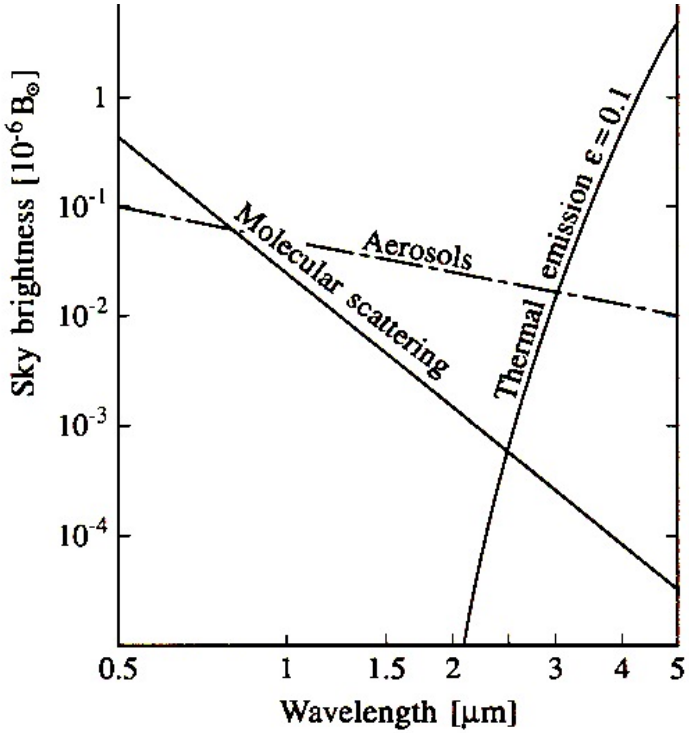
$$I_{scattered} = I_0\frac{3}{16\pi}\sigma_R\left(1+\cos^2\theta\right)d\omega$$

Aerosol Scattering

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

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

- $d >> \lambda$: $Q_{scattering} \sim Q_{absorption}$
  - 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 $1/\lambda$

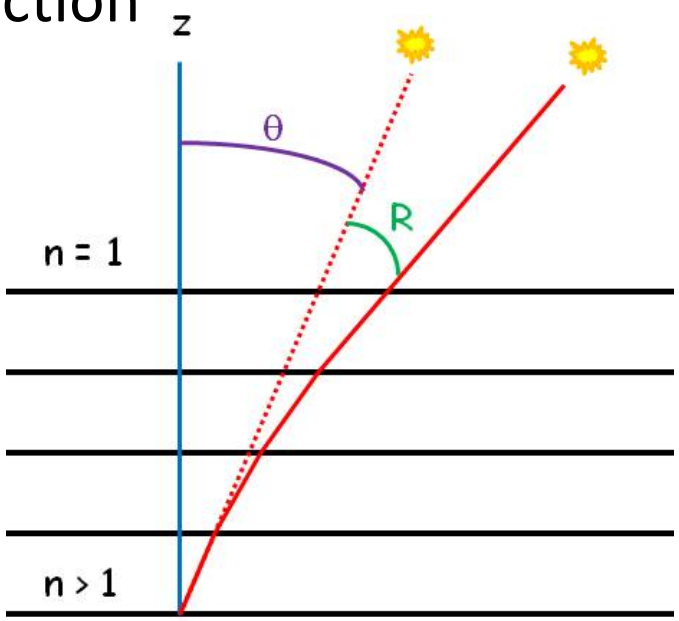


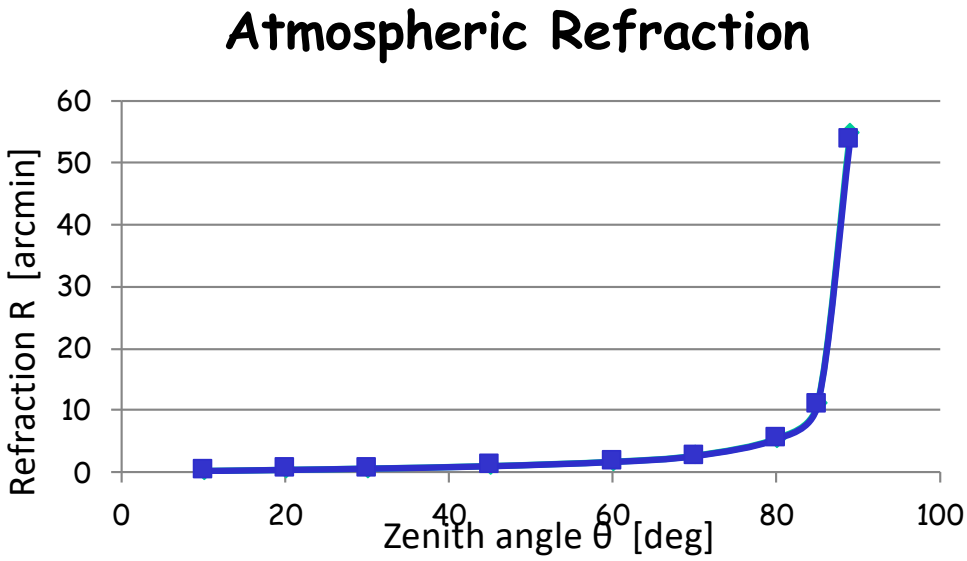
Atmospheric Refraction

Atmospheric Refraction: Equations

Atmospheric refraction -> *apparent* location of source significantly altered (up to 0.5 degree near horizon) → telescope pointing must correct for refraction $R = (n(\lambda) - 1)\tan\theta$

Refraction



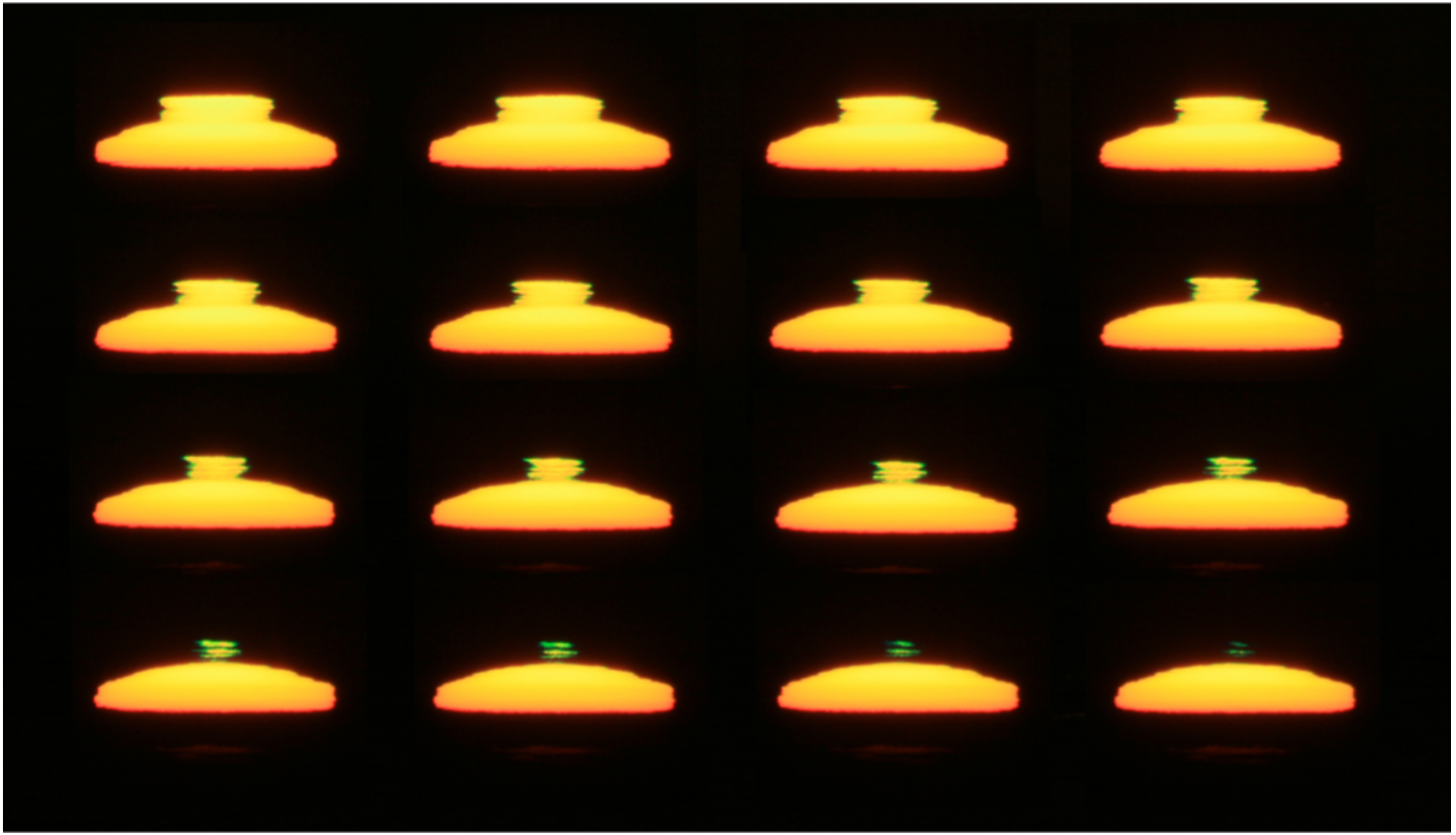


Refractive index of air depends on wavelength λ:

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

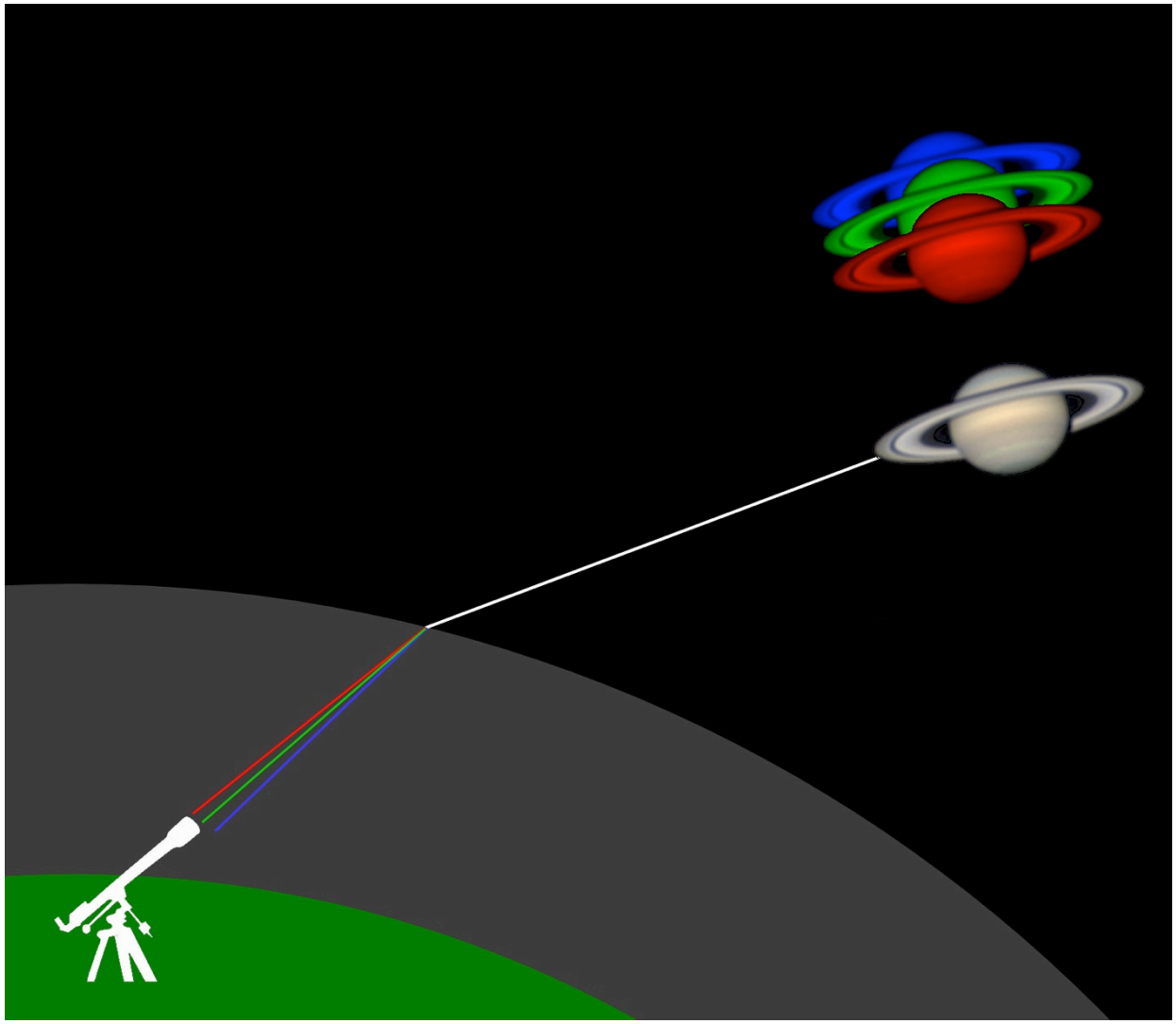
(dry air, 1 atm pressure, T ~ 290K, λ_0 in [μm])

Green Flash



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

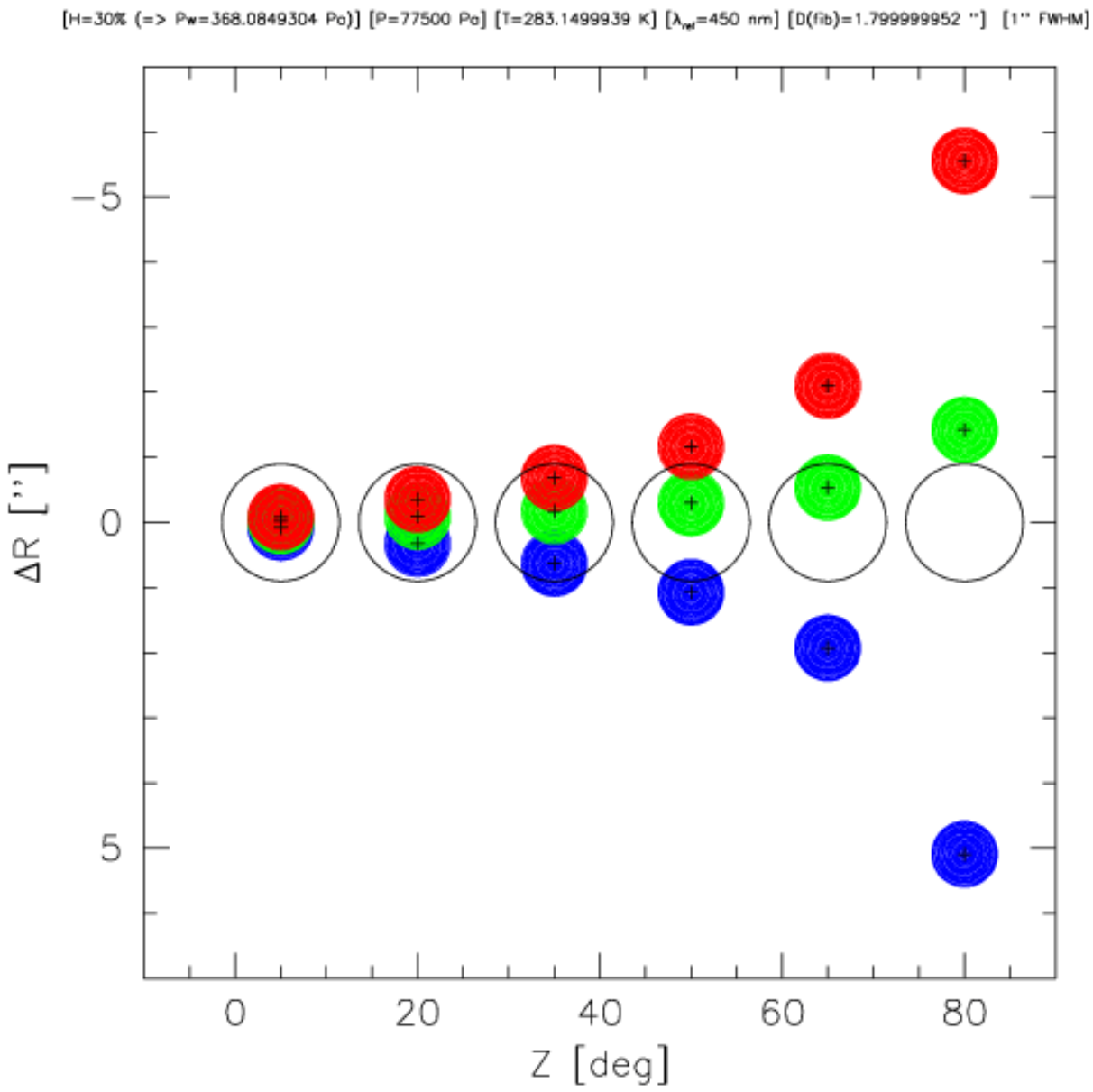
Atmospheric Dispersion



www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm

- Dispersion: Elongation of points in broadband filters due to n(λ) → "rainbow"
- Dispersion depends strongly on airmass and wavelength
- No problem if dispersion < λ/D ← o.k. for small or seeing limited telescopes, but big problem for large, diffraction limited telescopes (e.g. E-ELT)

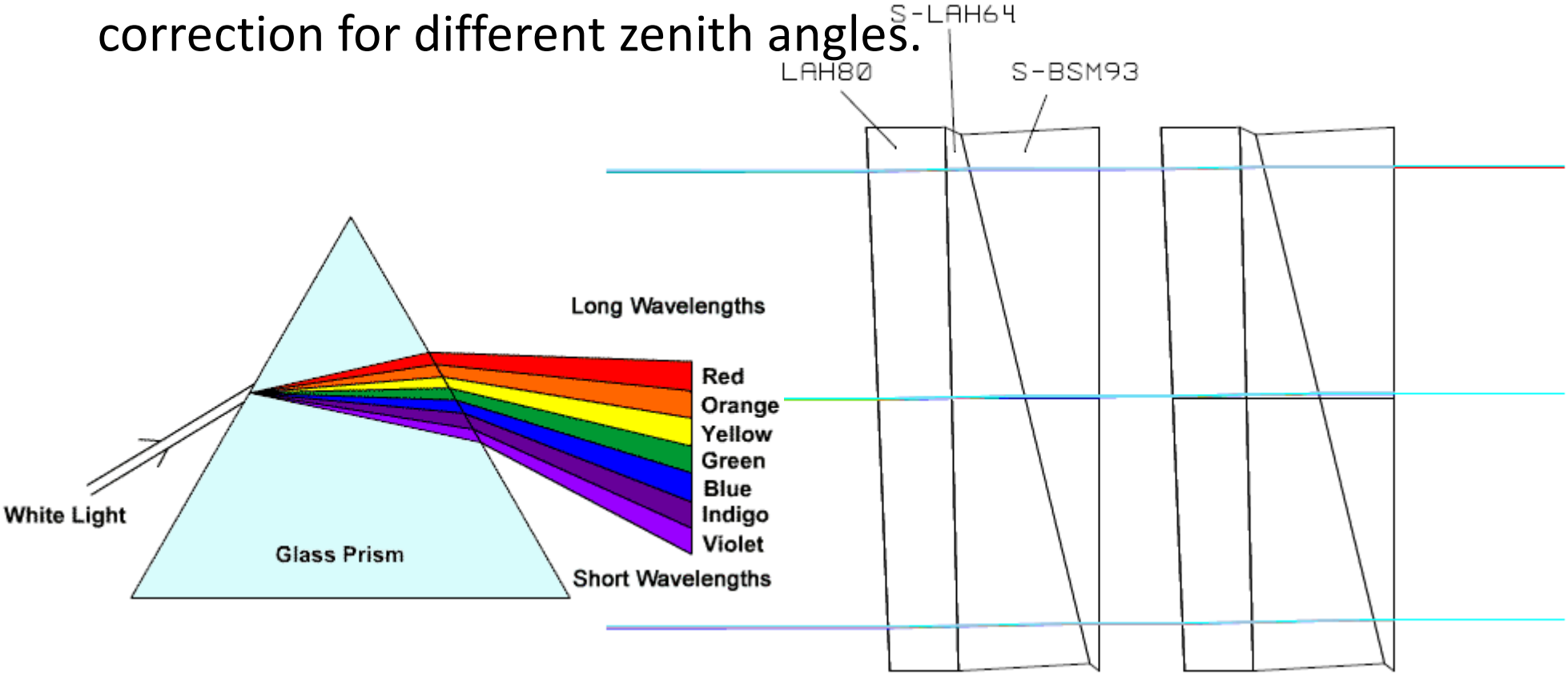
Atmospheric Dispersion



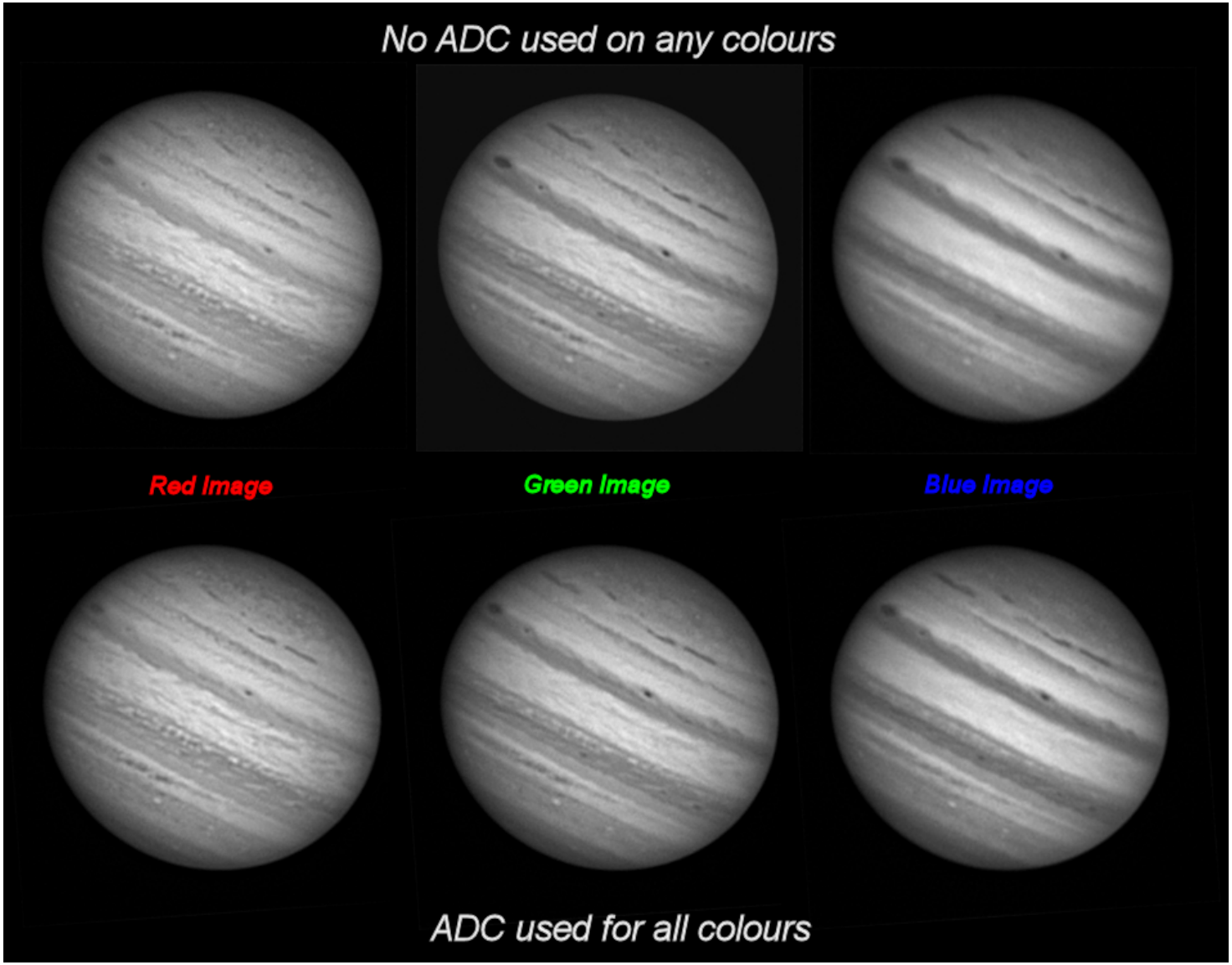
Atmospheric Dispersion: Corrector

Does opposite of atmospheric dispersion:

1. refractive element (e.g., prism)
2. second prism (different material with different dispersion) to keep beam straight
3. second (identical) double prism assembly to adjust strength of correction for different zenith angles.

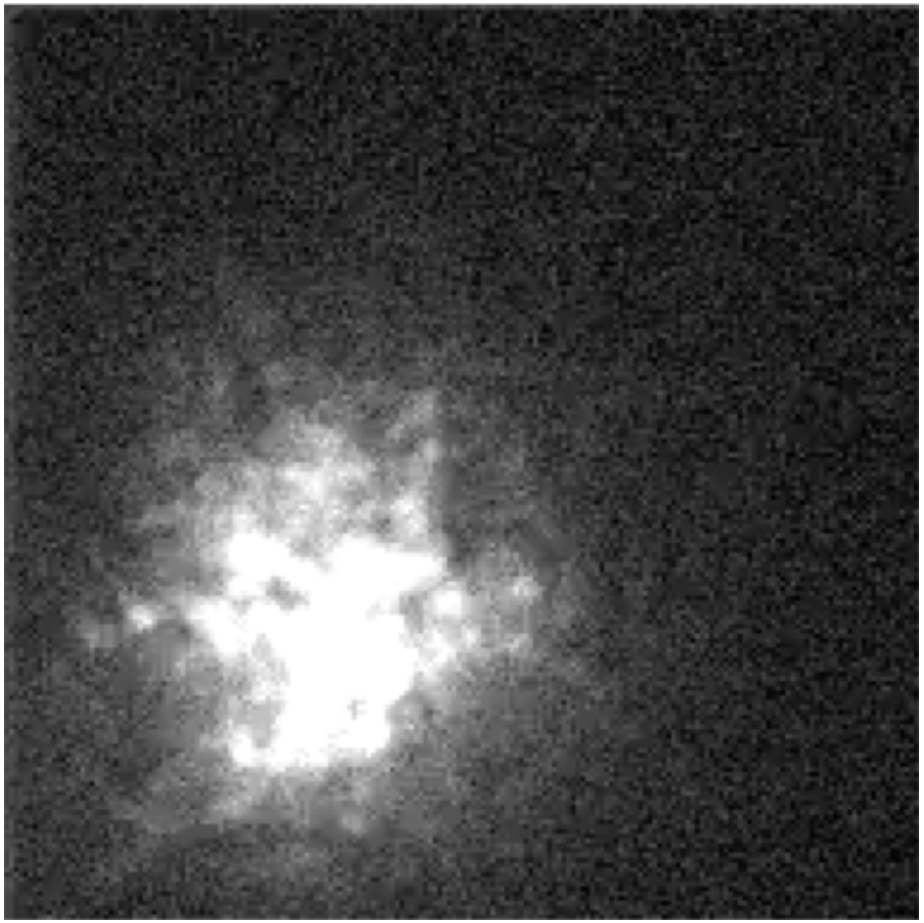


Benefits of ADC



www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm

Atmospheric Turbulence: Seeing



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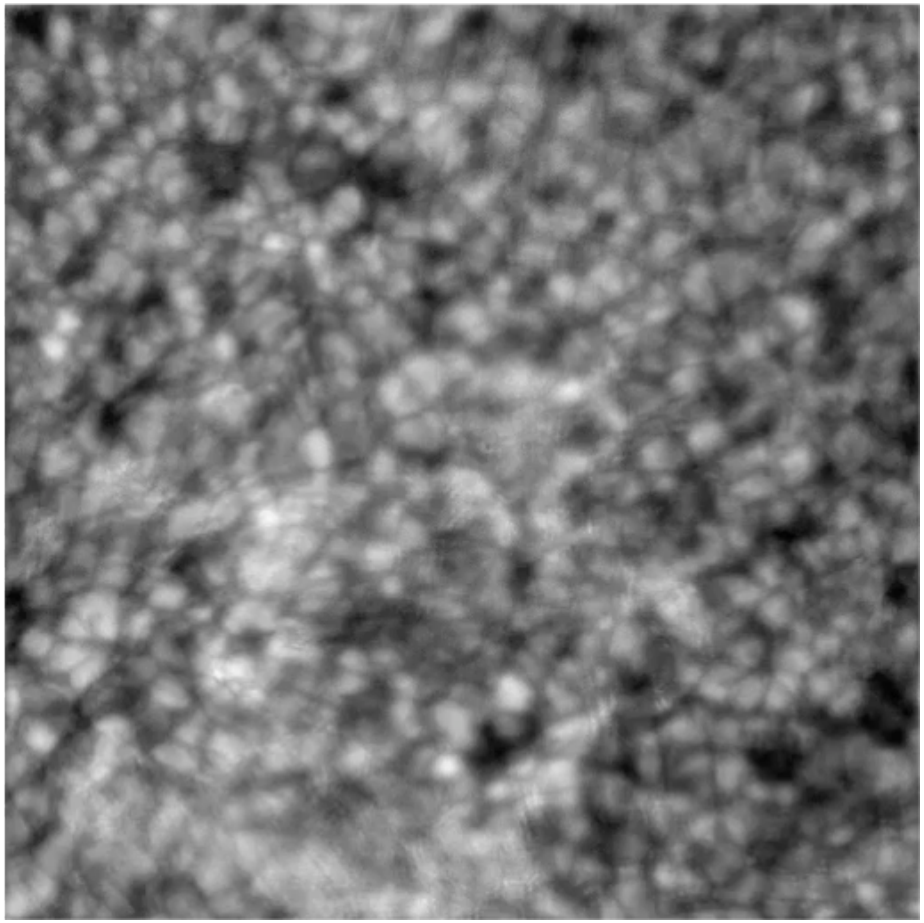
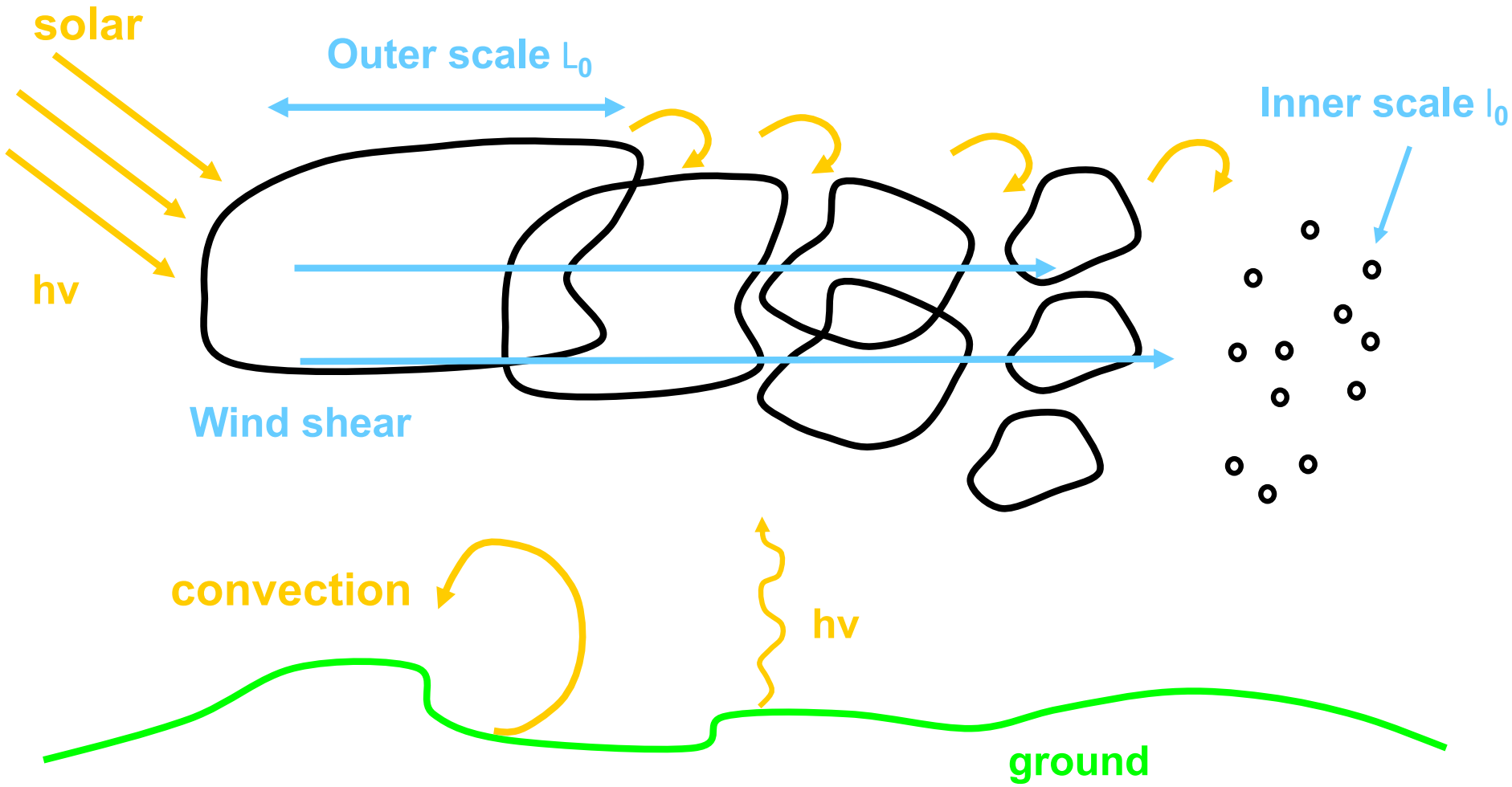


solar photosphere

Atmospheric Turbulence: Origin



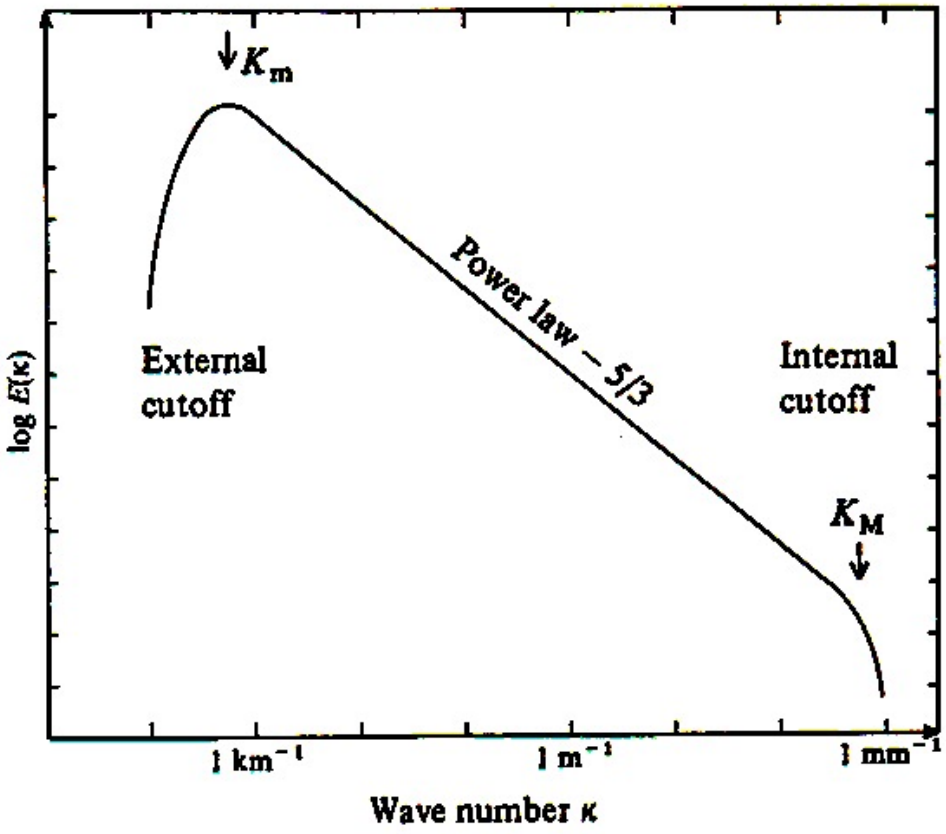
Komogorov Turbulence

- kinetic energy of large scale (~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 considered length scale
- mean spectrum of kinetic energy (Kolmogorov spectrum)

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

- l_0 = inner scale, L_0 = outer scale

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

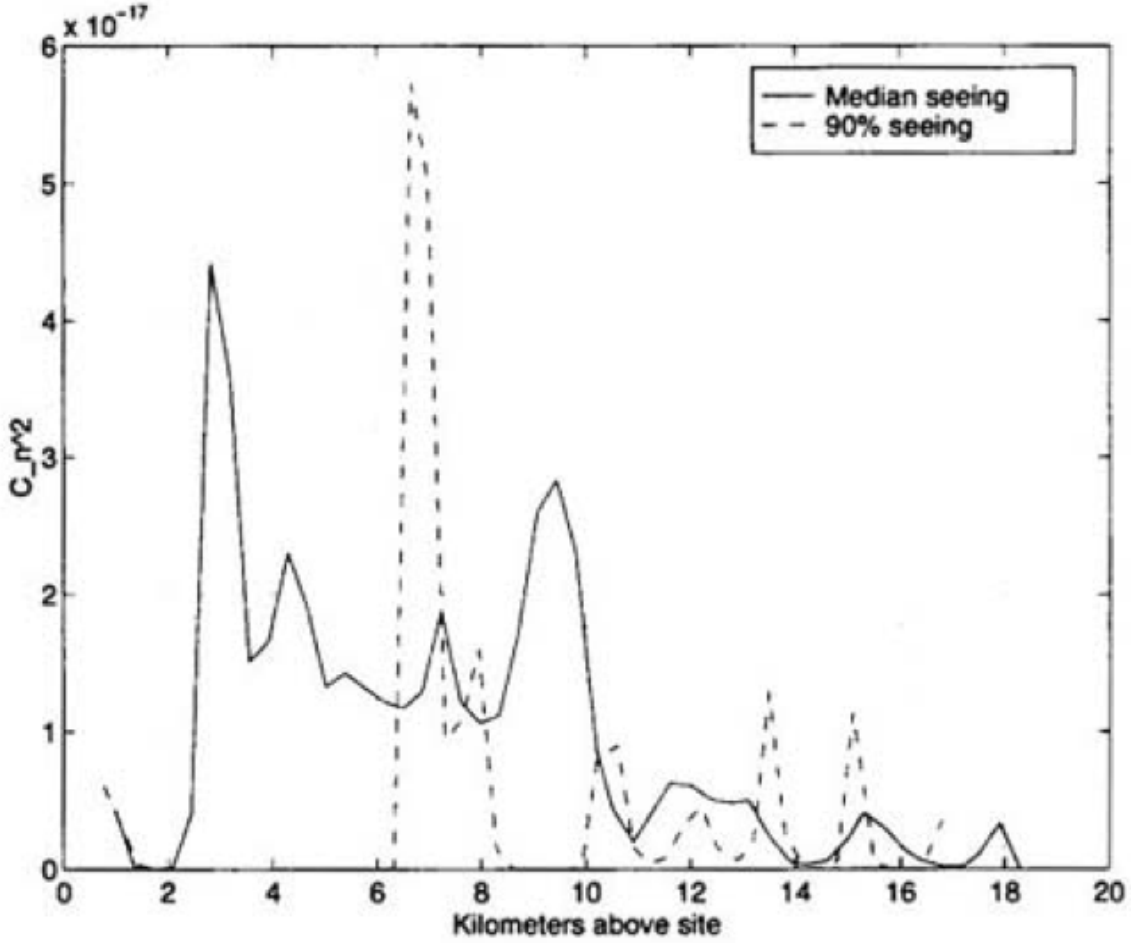


Air Refractive Index Fluctuations

- 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 m × 10^{-8} = 10^{-4} m = 100 waves at 1µm
- refractive index of water vapour is less than that of air → moist air has smaller refractive index

Index Fluctuations with Altitude

- $C_n^2(z)\cdot\Delta z$ indicates index fluctuation contributions from layer Δz
- typical value: $C_n^2\cdot\Delta z \sim 4\cdot10^{-13}$ cm$^{1/3}$ for a 3 km altitude layer
- turbulence often occurs in layers



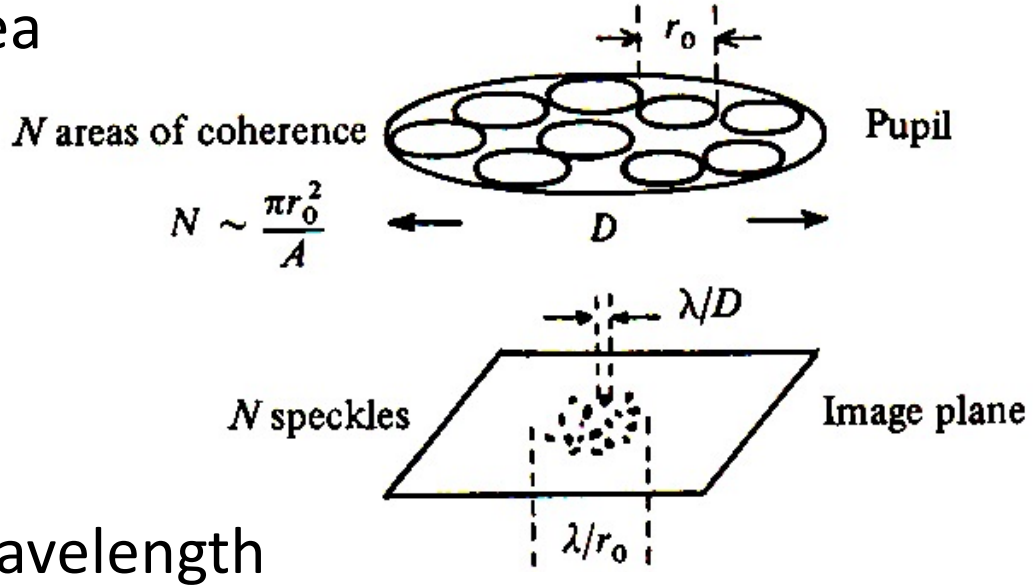
Median seeing conditions on Mauna Kea $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are $r_o \sim 0.40$ m.

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

Fried Parameter r_0

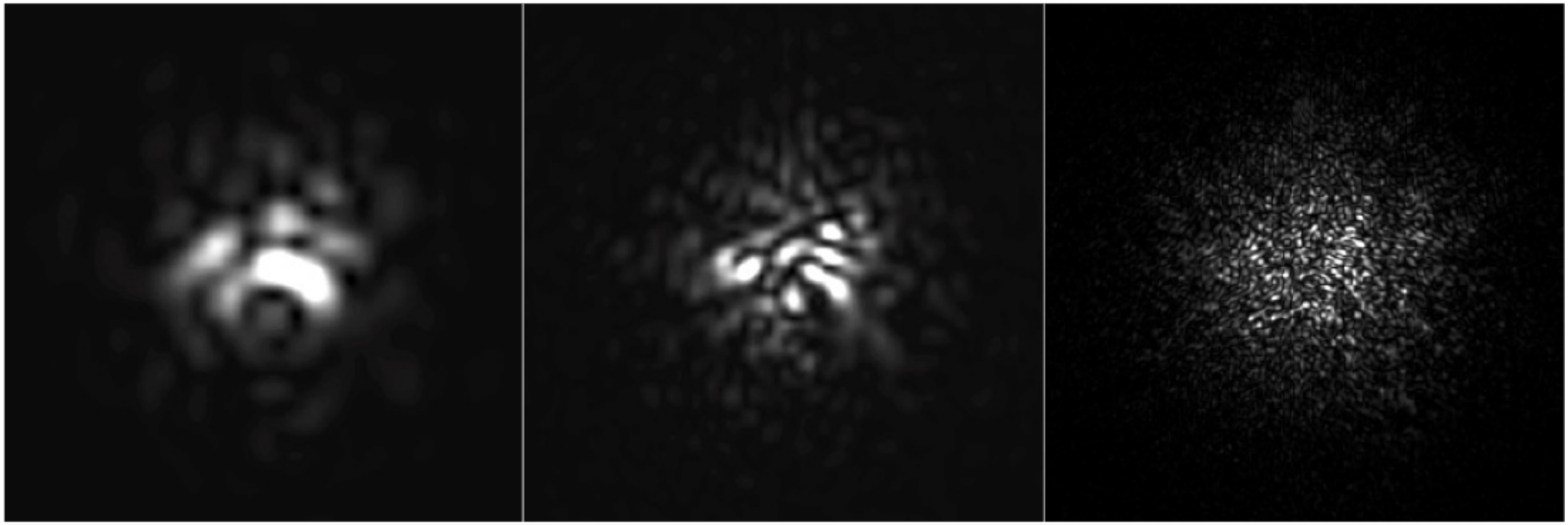
- radius of spatial coherence area (of wavefront) given by Fried parameter r_0 :

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



- 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 0.5µm)
- seeing is roughly equivalent to FWHM of long-exposure image of a point source (Point Spread Function)

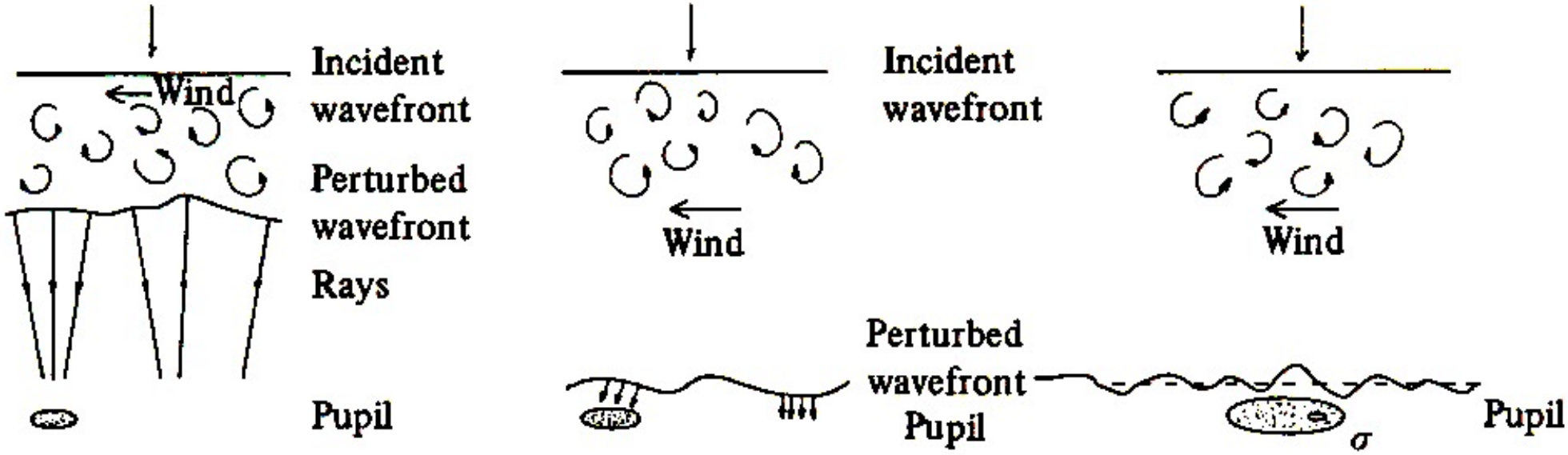
Speckles & Telescope Diameter



1 m 2 m 8 m

Telescope Diameter

Aspects of Image Degradation



Scintillation
energy received by pupil varies in time (stars flicker)

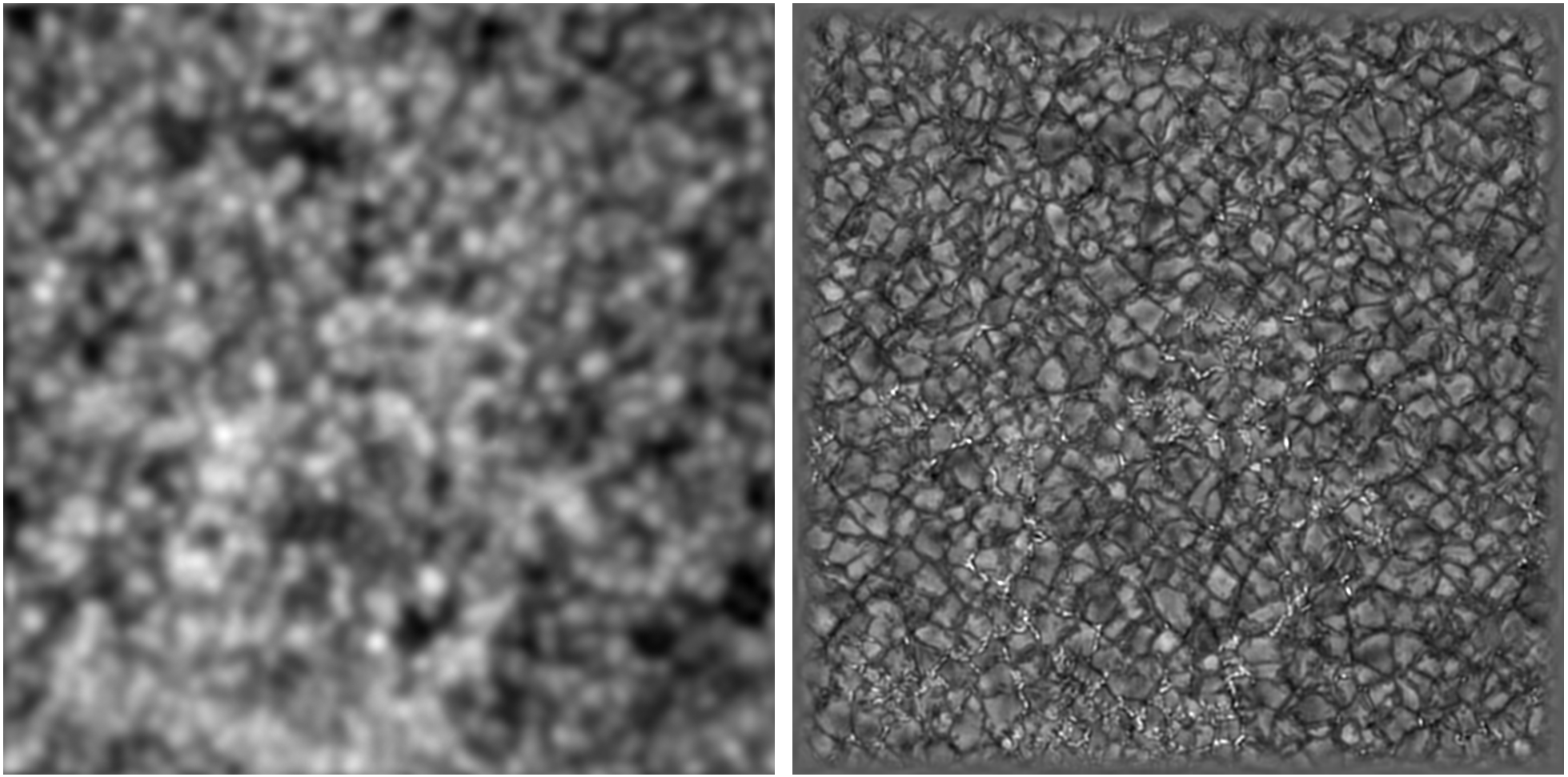
Image Motion
average slope of wavefront at pupil varies ("tip-tilt", stars move around)

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

Long Exposure of Solar Photosphere