VIII. The (Negative) Effects of Earth's Atmosphere [v1.3.2]

A. Overview

- The majority of astronomy, especially historically, has been performed from the surface of the Earth
  - *Much* cheaper to build telescopes on Earth
  - *Much* easier to maintain them
  - And to communicate with them
- Downside to this approach: Atmosphere
  - Absorption
  - Scattering
  - Emission
  - Turbulence
- References
  - Léna, "Observational Astrophysics"

B. Basics

- To first approximation, the atmosphere is a big wet blanket!
- Constituents: Molecules and aerosols (a.k.a. particulates)
  - O_2, N_2
  - H_2O
  - CO_2, O_3
- Pressure and Density (Inner atmosphere)
  - At low altitude ($Z < 100\,\mathrm{km}$), the pressure at a given height Z above the Earth's surface is defined by balancing the weight of the mass above it (i.e. hydrostatic equilibrium)
  - Simple derivation: Consider the change in pressure over an interval dZ.
    - ▲ Balance change in forces
    - ▲ Appreciate that the change in acceleration $g(r) = GM_\oplus/r^2$ is negligible because $Z \ll R_\oplus$.

$$dPA = -dmg \tag{1}$$
$$dP(4\pi r^2) = -\rho(4\pi r^2)dZg \tag{2}$$
$$dP = -\rho g dZ \tag{3}$$

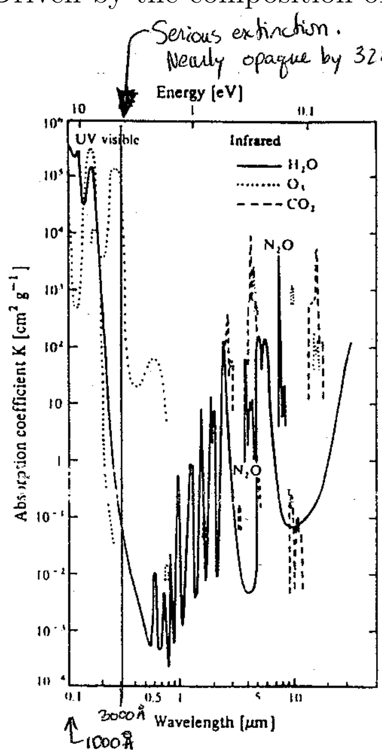
    - ▲ Simple exponential (+ Ideal gas law [$PV = nRT$])
      - ∘ Replace ρ with PM_0/RT

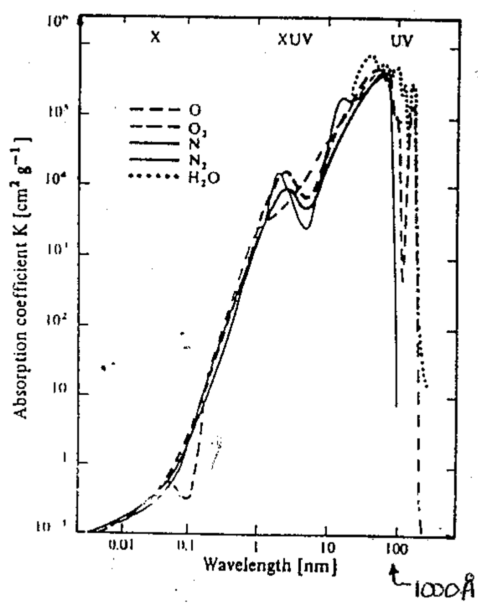
$$P(Z) = P_0 \exp\left(\frac{-Z}{H}\right) \quad \text{with } H = \frac{R}{M_0}\frac{T}{g} \tag{4}$$

  - ◦ $R = 8.32\,\mathrm{J/K/mole}$
  - ◦ $M_0 = 0.029\,\mathrm{kg}$ [mean molecular mass of air]
  - ◦ $H = 7998\,\mathrm{m}$ ($\sim 8\,\mathrm{km}$) near the surface
- ◇ Density profile (inner atmosphere) – Trivial
  - ▲ Assume T is nearly constant
  - ▲ $n = P/T$
  - ▲ i.e., the density has an exponential profile too
- Upper atmosphere ($Z > 100\,\mathrm{km}$) – To be explored by you!

C. Extinction

- Scattering (mostly) + Absorption (very little)
- Define: Mean absorption coefficient κ_λ, a.k.a. opacity
  - ◇ Function of wavelength
  - ◇ Defined per unit mass: units of $\mathrm{cm^2/gm}$
  - ◇ Driven by the composition of the material

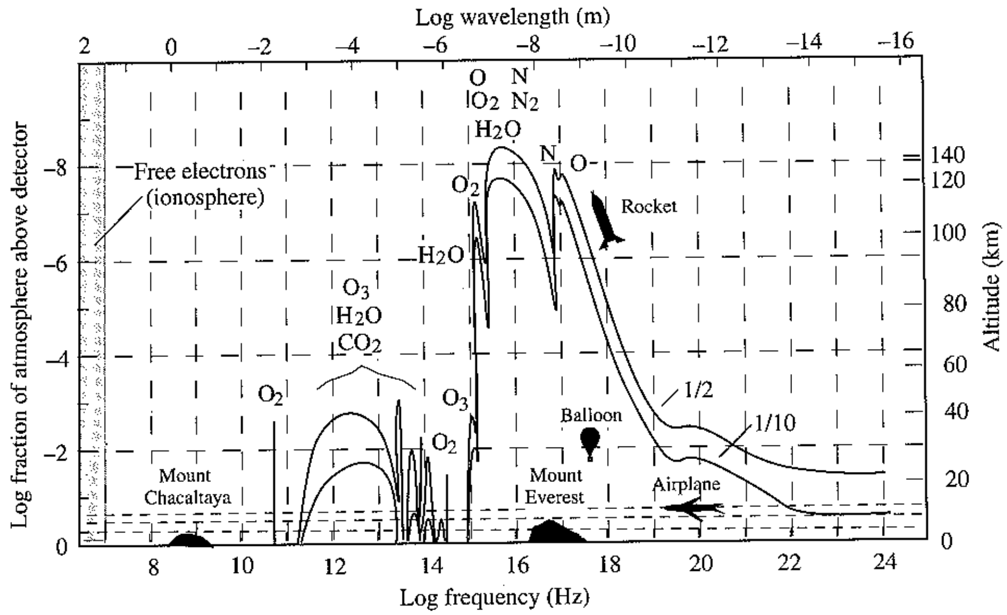




- Optical depth τ_λ
  - ◇ Integrated opacity over a given path (unitless)
  - ◇ Consider straight up from the Earth's surface

$$\tau_\lambda(R_\oplus) = \int_{R_\oplus}^{\infty} \rho(Z)\kappa_\lambda\, dZ \tag{5}$$

- ◇ A careful calculation would account for the variations in composition with height
- ◇ In practice, the extinction is measured empirically
  - ▲ Composition changes in time (e.g. humidity)
  - ▲ Composition changes with location
  - ▲ Following curves show the altitude where only ≈ 1/10 of the radiation will survive passage through the atmosphere above that point



- Extinction
  - ◇ Simple Radiative transfer

$$\frac{dI_\lambda}{ds} = -\kappa_\lambda I_\lambda + j_\lambda \tag{6}$$

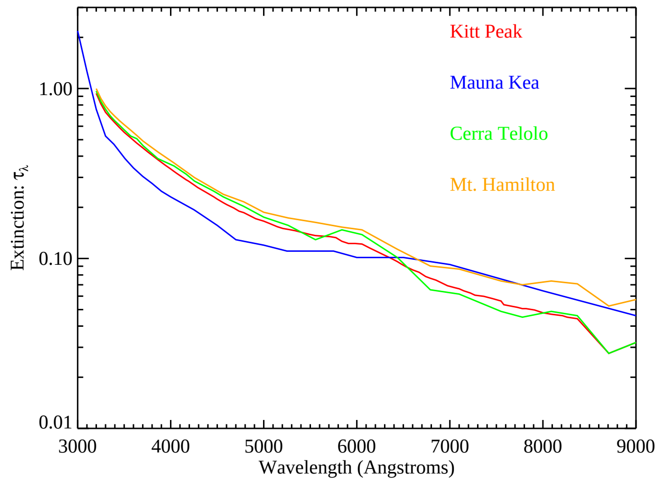
  - ▲ I_λ is the measured intensity of our source [$I_{\lambda,0}$ at the source]
  - ▲ j_λ is a term for emission (to be ignored here)
  - ▲ s is the path travelled
  - ◇ Integrating

$$\frac{dI}{I} = -\kappa ds \tag{7}$$

$$\ln I = -\tau \tag{8}$$

$$I_\lambda = I_{\lambda,0}\, \mathrm{e}^{-\tau_\lambda} \tag{9}$$

  - ◇ Empirical estimations



- ▲ These curves ignore line absorption
- ▲ e.g. molecular band-heads (A-band, B-band)

- Airmass (AM)
  - ◇ We have defined the extinction for an observation performed at Zenith (i.e. straight up)
    - ▲ But, for observations away from Zenith, we observe through a longer pathlength of the atmosphere
  - ◇ Define Airmass:
    - ▲ Length through the atmosphere relative to that at Zenith
    - ▲ AM=1 if at the Zenith
  - ◇ Off Zenith
    - ▲ Assume a plane-parallel model for the atmosphere
    - ▲ Define ZA=Zenith Angle (ZA=0° at Zenith)

$$\mathrm{AM} = \frac{1}{\cos(\mathrm{ZA})} \tag{10}$$

    - ▲ New Extinction

$$I_\lambda = I_{\lambda,0} \exp(-\tau_\lambda * \mathrm{AM}) \tag{11}$$

D. Scattering

- Rayleigh scattering
  - ◇ Driven by the molecules
    - ▲ Not small angle scattering
    - ▲ $\sim 30\%$ of light scatters away from its original trajectory
  - ◇ Cross-section

$$\sigma_R(\lambda) = \frac{32\pi^3}{3} \frac{(n-1)^2}{N^2\lambda^4} \tag{12}$$

- ▲ Note the λ^{-4} dependence!!
- ▲ N = Number of molecules per unit volume
- ▲ n is the index of refraction

$$n - 1 \approx 80 \times 10^{-6} \, \frac{P(mb)}{T(K)} \tag{13}$$

- ▲ Because $n-1$ is proportional to density N, σ_R is independent of it

◇ Intensity

$$I = I_0 \frac{8\pi^4 N \alpha^2}{\lambda^4 r^2} (1 + \cos\theta)^2 \tag{14}$$

- ▲ r is the distance to the particles
- ▲ θ is the angle of scattering
- ▲ α describes the polarizability (related to index of refraction)

- Mie scattering
  - ◇ Forward scattering (and diffracted)
  - ◇ Dominated by the particulates

E. Atmospheric Dispersion

- Earth's atmosphere acts a low dispersion prism!
  - ◇ Bends the light rays (refraction)
  - ◇ Wavelength dependent index of refraction
  - ◇ See Fillipenko 1982
- Index of refraction (Barrell 1951)
  - ◇ Sea level ($P = 760\,\mathrm{mm\,Hg}$; $T = 15°\mathrm{C}$)

$$(n_\lambda - 1)_{\mathrm{Sea}} \, 10^6 \approx 64.328 + \frac{29498.1}{146 - (1/\lambda)^2} + \frac{255.4}{41 - (1/\lambda)^2} \tag{15}$$

  - ◇ At higher altitudes (i.e. observatories)

$$(n_\lambda - 1)_{P,T} \approx (n_\lambda - 1)_{\mathrm{Sea}} \frac{P[1 + (1.049 - 0.0157T)\, 10^{-6}\, P]}{720.883(1 + 0.003661\, T)} \tag{16}$$

  - ◇ Water vapor reduces the refraction by a factor (f is the water vapor pressure in mm of Hg):

$$\frac{0.0624 - 0.000680/\lambda^2}{1 + 0.003661\, T} \, f \tag{17}$$

- Atmospheric Differential Refraction
  - ◇ Smart 1931
  - ◇ Light rays of a given wavelength arrive offset from those at another wavelength
  - ◇ i.e., the Earth's atmosphere behaves like a prism

- ◇ Define relative to 5000Å and at a zenith angle (ZA)

$$\Delta R(\lambda) \equiv R(\lambda) - R(5000\text{Å}) \tag{18}$$
$$\approx 206265\,[\,n_\lambda - n_{5000}\,]\ \tan(ZA)\ \ \text{arcsec} \tag{19}$$

- ◇ The light is dispersed perpendicular to the horizon

- Observational effects
  - ◇ Size of the object is 'extended' (morphology)
  - ◇ Centroid of the object is offset (astrometry)
  - ◇ Spectrophotometry (slit losses)

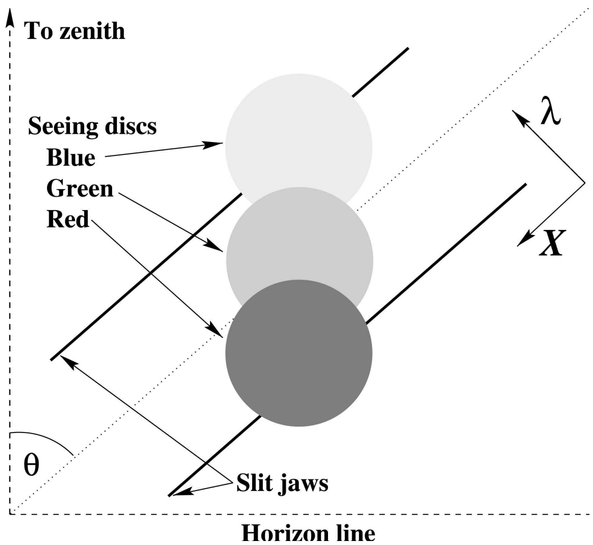
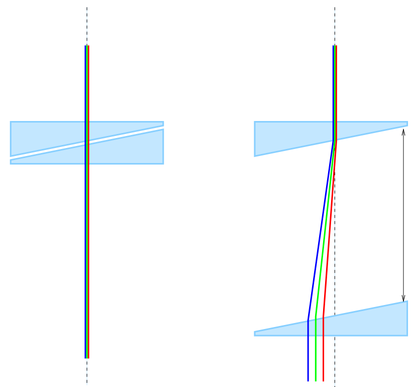
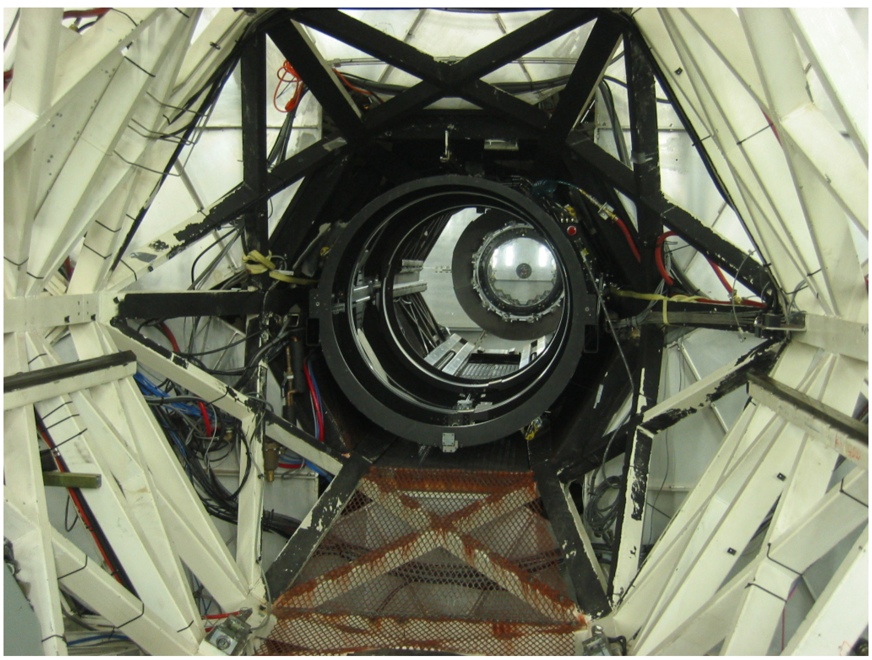


Figure 5. Schematic diagram showing the effects of atmospheric dispersion. The HIRES slit is projected on to the sky so that we see the seeing discs of blue, red and green light from a point source dispersed with some component along the spectral direction of the slit. The spectral direction is indicated by λ and the spatial direction by *X*. Note that the refraction is worse in the blue.

- Mitigations for Atmospheric Differential Refraction
  - ◇ Atmospheric Dispersion Corrector (imaging)
    - ▲ Optical elements added to the system to counteract the Earth's refraction
    - ▲ Often a pair of prisms whose separation varies as the telescope moves about



Linear ADC, conceptual. Prism separation controls image offset.



◇ Parallactic Angle (PA)

- ▲ Orient the spectroscopic slit *parallel* to the atmospheric dispersion
- ▲ When observing along the meridian (up), PA=0° or 180°
- ▲ Off the meridian, it is a function of the hour angle (HA), latitude (ϕ) and declination (δ)

$$\sin(PA) = \frac{\sin(HA)\cos(\phi)}{\sqrt{1 - [\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(HA)]^2}} \tag{20}$$

F. Seeing

- Combined effects of the Earth's atmosphere on image quality

- ◇ For perfect optics, a mirror with diameter D will produce an image with angular size

$$\theta = \frac{\lambda}{D} \tag{21}$$

  - ▲ In practice, trade-offs in camera design degrade the image
  - ▲ Still, the image quality for large aperture telescopes may be $\theta < 0.1''$
- ◇ Turbulence in the atmosphere scintillates the light
  - ▲ Dominated by merging streams of warm/cold air
  - ▲ Degrade the image quality to $\sim 1''$ or worse
- ◇ Turbulence near the telescope is also very important

- Upper atmosphere
  - ◇ Higher than ~ 10 miles
  - ◇ Not especially turbulent (jet stream)
  - ◇ Other effects can improve the seeing (cirrus, ice crystals)
- Lower atmosphere
  - ◇ A dominant source of poor seeing
  - ◇ Merging air flows
- Dome seeing
  - ◇ Temperature difference between outside air and telescope
  - ◇ Generates an air flow; right above the mirror!!
- Air pollution
  - ◇ Particulates can heat the air and generate wind currents
    - ▲ Soot
    - ▲ Volcanic emissions
    - ▲ Dust storms
- Micrometerology
  - ◇ Boundary layer seeing
    - ▲ Thin layer just above the Earth's surface (~ 10 m)
    - ▲ Disruptions from physical objects (e.g. trees)
    - ▲ Mitigated by leveling the surface and raising the telescope platform
  - ◇ Geography matters
    - ▲ Air is less turbulent on hill tops than in valleys
- (Semi)-Quantitative Measures of Seeing
  - ◇ FWHM of image quality
    - ▲ Effects of seeing are approximately Gaussian
    - ▲ Characterize the image quality by the FWHM ($\approx 2.35\sigma$)

- ▲ Estimated empirically (in arcseconds)
- ◇ Fried parameter (r_0)
  - ▲ Size of a typical lump of *uniform* air in the turbulent atmosphere
  - ▲ An area over which the RMS wavefront aberration is less than 1 radian
    - ○ Sets the seeing limit of the telescope
    - ○ Typically $5 - 40\,\mathrm{cm}$
    - ○ Bigger means better conditions
  - ▲ Mathematical definitions
    - ○ Aperture diameter d where the variance of the wavefront phase becomes unity

$$\sigma^2 = 1.02999 \left(\frac{d}{r_0} \right)^{5/3} \tag{22}$$

    - ○ Derivation from the C_N^2 profile (γ is the angular distance of the source from zenith)

$$r_0 = \left[16.7 \lambda^{-2} (\cos\gamma)^{-1} \int_0^\infty C_N^2(h) dh \right]^{-3/5} \tag{23}$$

- ◇ t_0: Timescale over which changes in the turbulence become significant
  - ▲ Typically 0.01s !
- Mitigations
  - ◇ Get above the atmosphere! :)
  - ◇ Speckle imaging: Take very short exposures ($1 - 10\,\mathrm{ms}$) and process in software
  - ◇ Lucky imaging: Similar to Speckle, but keep only the good ones
  - ◇ Adaptive Optics: Correct the atmosphere using a "guide" star and deformable mirrors

G. Night Sky

- Despite the appearance of darkness, the night sky is far from truly dark
  - ◇ Scattered moonlight
  - ◇ Scattered city lights
  - ◇ Excited molecules and atoms
  - ◇ Blackbody radiation
  - ◇ Zodiacal light
  - ◇ Extragalactic background light
- Blackbody radiation
  - ◇ Air shines as a blackbody with $T \approx 300\,\mathrm{K}$

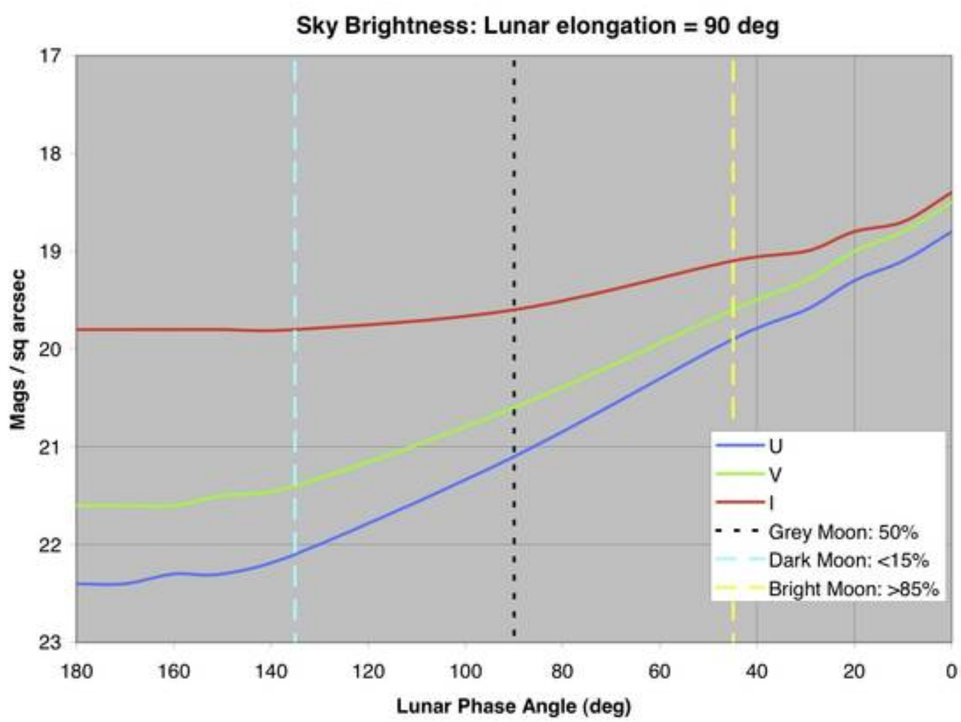
- ◇ Strong emission in the mid-IR (space wins *easily*)
- ◇ Relatively unimportant at optical wavelengths [prove it!]

• Airglow

- ◇ Atoms and molecules are bombarded by UV light during the day
  - ▲ Ionized by this radiation
  - ▲ Recombination time is long: hours
  - ▲ Line emission dominates in optical/IR
- ◇ Examples
  - ▲ OI at 5577Å, 6300Å
  - ▲ NaI at 5893Å
  - ▲ OH radical bands at > 7000Å
- ◇ Line strength is variable and unpredictable!
  - ▲ Difficult background to remove
  - ▲ Need to characterize it simultaneously with the target

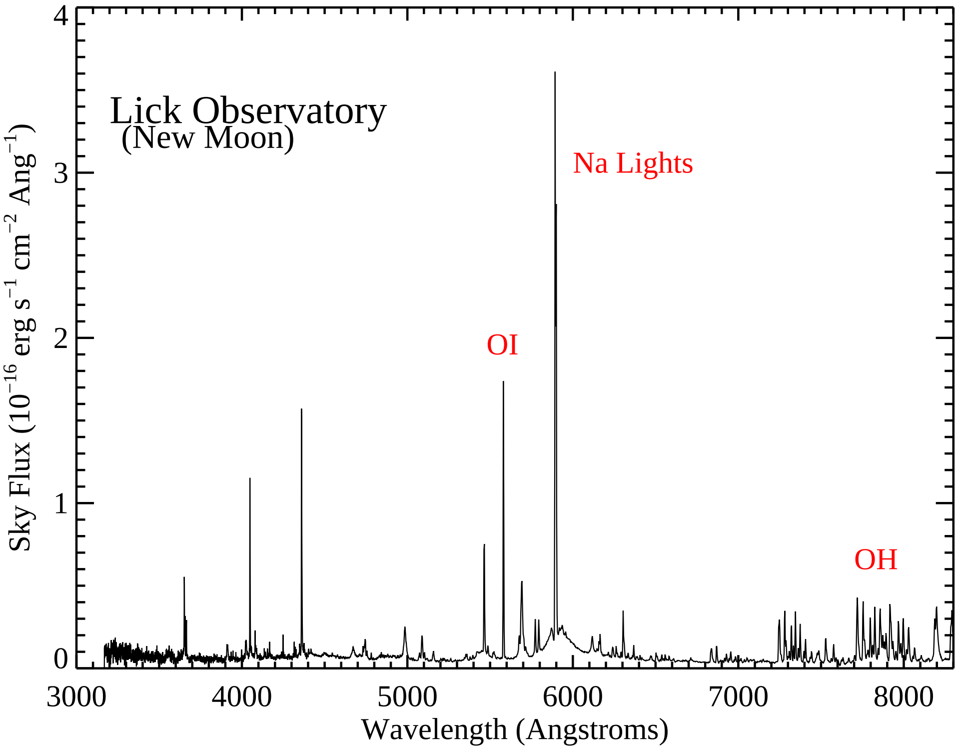
• Scattered light

- ◇ Moon (if present) dominates at $\lambda < 7000$Å

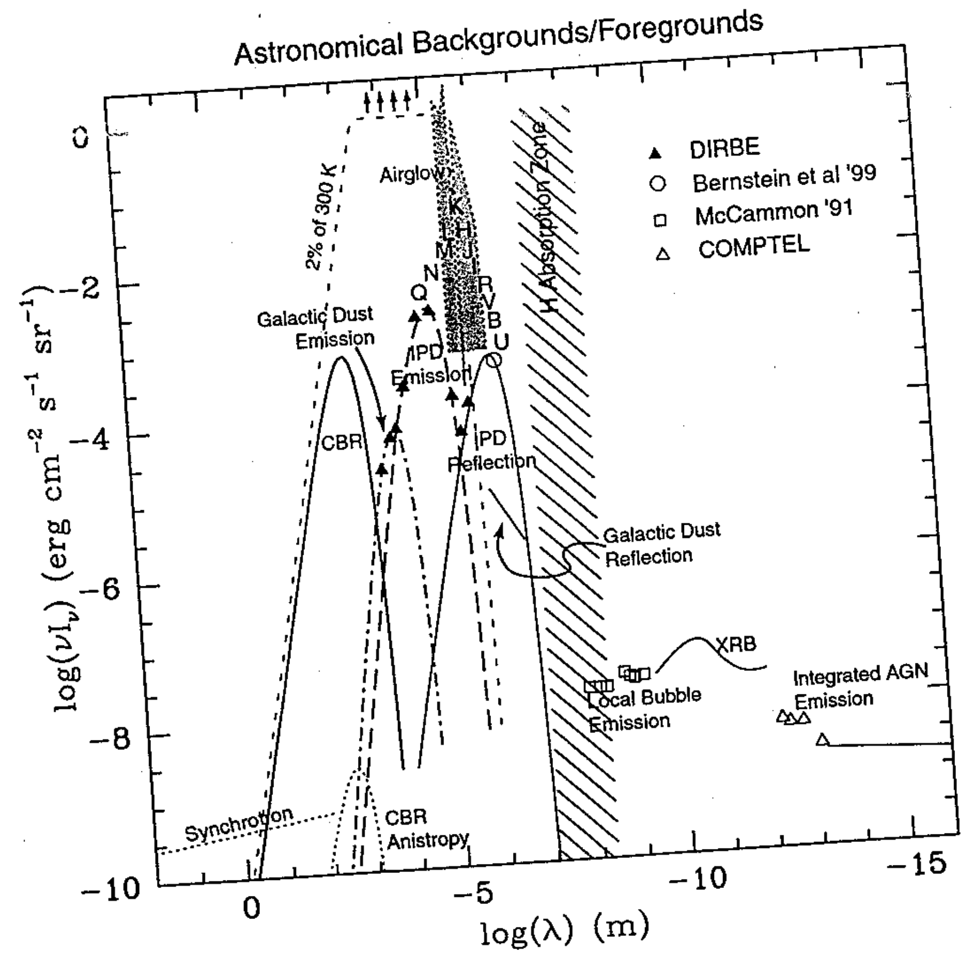


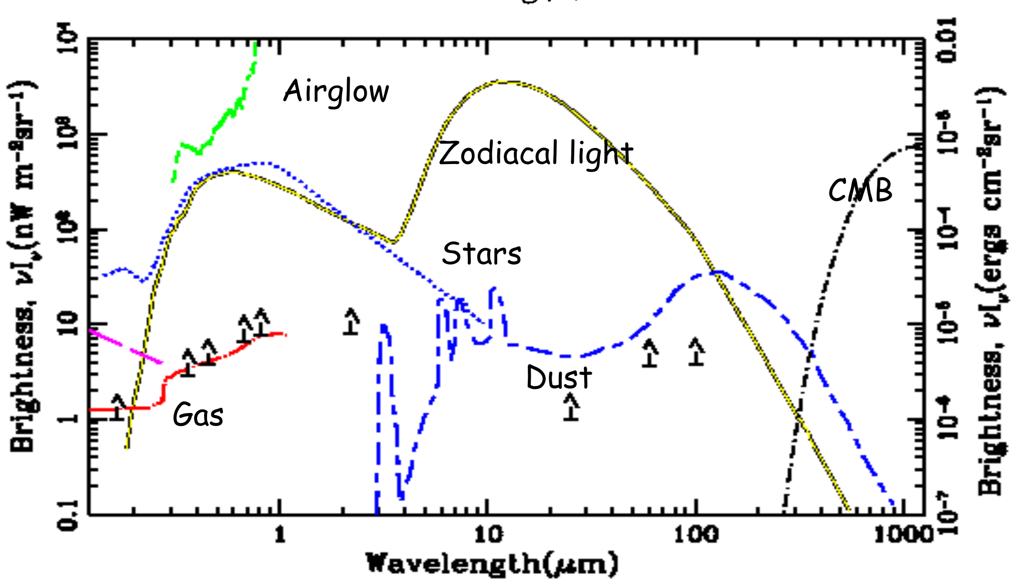
  - ▲ In the U-band, even 4 days from the new moon doubles the background level
- ◇ City lights
  - ▲ View of San Jose from Lick Observatory on a good (i.e. foggy) night!

▲ Lick sky spectrum



- Zodiacal light
  - ◇ Scattered sunlight by dust in the Solar System
  - ◇ Major contribution to the "night sky" at $\lambda < 7000$Å
    - ▲ Also affects space-bourne telescopes
    - ▲ HST/JWST only really win at $\lambda > 7000$Å(or < 3000Å)
- Summary of all backgrounds


Astronomical Backgrounds/Foregrounds
DIRBE
Bernstein et al '99
McCammon '91
COMPTEL
2% of 300 K
Airglow
Galactic Dust Emission
IPD Emission
CBR
IPD Reflection
H Absorption Zone
Galactic Dust Reflection
XRB
Local Bubble Emission
Integrated AGN Emission
Synchrotron
CBR Anistropy
log(νI_ν) (erg cm^-2 s^-1 sr^-1)
log(λ) (m)


Airglow
Zodiacal light
CMB
Stars
Dust
Gas
Brightness, νI_ν(nW m^-2 sr^-1)
Brightness, νI_ν(ergs cm^-2 sr^-1)
Wavelength(μm)