# *Astronomical Imaging and Photometry*

## *The Atmosphere*

# What does the atmosphere do?

1. The refractive index of the atmosphere is nonunity and varies with wavelength. This gives rise to color- and zenith-angle dependent shifts in the positions of stars. This is one of the major problems with ground-based astrometry. We will not discuss this very much here.

2. Turbulence in the atmosphere gives rise to spatial and time-dependent refractive index variations which yield image sizes of order one arcsecond and associated variability in the image size, shape, and total flux. this is SEEING.

3. Molecules and aerosols in the atmosphere absorb and scatter the light from astronomical objects causing less than perfect TRANSMISSION

4. Those same agents emit radiation, giving rise to backgrounds in all observable wavelength regions. This is the airglow BACKGROUND.

I will discuss points 2-4, beginning with 2.

# Seeing

***The troposphere is convectively unstable from the surface to the tropopause at 8-18 km altitude. The associated turbulence is reasonably well described by Kolmogorov theory, in which the turbulence is a scale-free gaussian random process in which power cascades from large convective eddies to smaller scales, finally to be dissipated as heat on very small scales.***

***Except on very small scales, the turbulence is adiabatic, so perturbations in density are accompanied by perturbations in temperature. The motions are very subsonic, so the perturbations are small; generally*** $\Delta\rho/\rho \sim (v/c_s)^2 \sim 1e\text{-}3$.

$n-1 \sim \rho$, ***so density fluctuations give rise to refractive index variations, which give rise to phase variations considered in wave space, or angular variations of the propagation vector if you think about rays. The two are related, again, by***

$$\gamma = \lambda \, d\phi / dx$$

If we project the density distribution down onto the aperture of the telescope, the 2-d distribution is proportional to the phase retardation along the ray which arrives at a given place in the aperture:

$$\lambda(\phi - \phi_{vac}) = \int (n-1)\, dl \sim \int 2e\text{-}4\, \Delta\rho/\rho\, dl$$

at typical observatory altitudes.

The turbulence in the Kolmogorov approximation is a gaussian random process and so is completely characterized by its autocovariance,

$$\xi(r) = <[\phi\,(x)\phi(x+r)\,]^2>,$$

but is usually described by the equivalent statistic, the **STRUCTURE FUNCTION:**

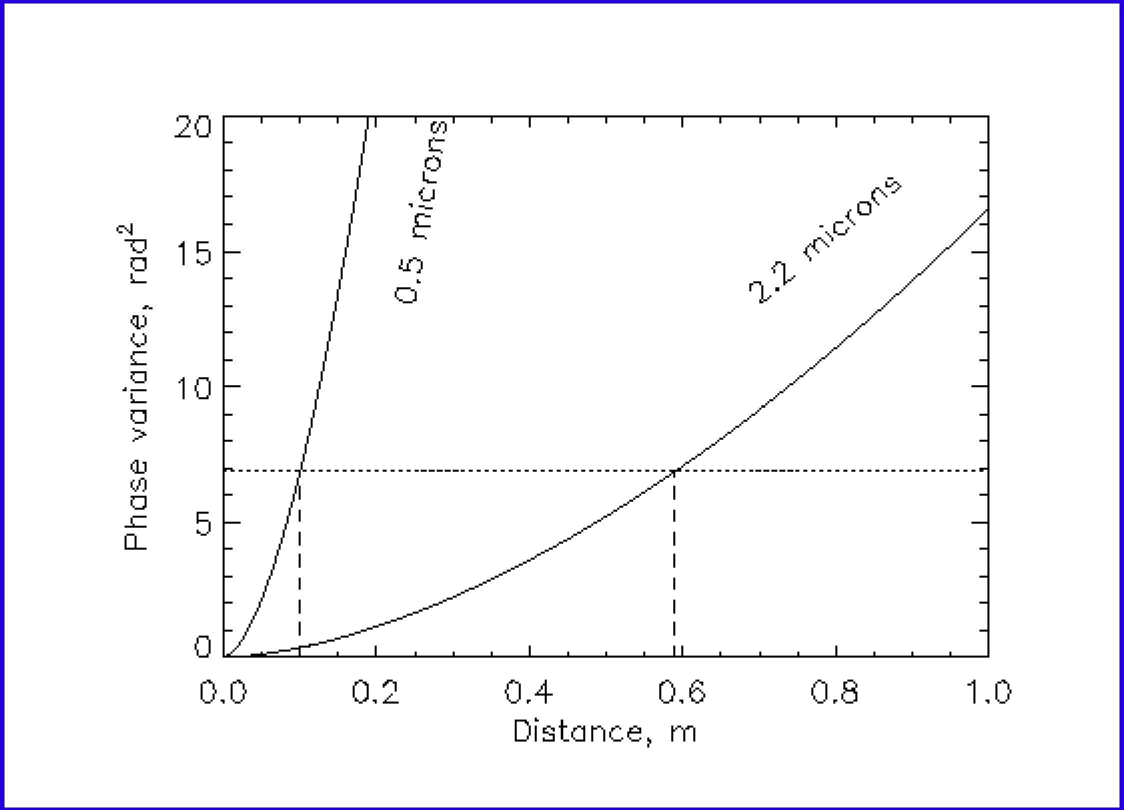
$$D(r) = <[\phi\,(x) - \phi(x+r)\,]^2> = 2[\xi(0) - \xi(r)]$$

***Kolmogorov turbulence theory predicts the FORM of D(r):***

$$D(r) = 6.88\,(r/r_0)^{5/3}$$

***The AMPLITUDE depends on the energy input and is not predictable; it is incorporated in the single parameter $r_0$, the FRIED parameter or Fried radius, which is the value of r for which the average of D over the disk of radius r is about one radian. This average value clearly also goes like $r^{5/3}$. The refractive index of air varies but little with wavelength, so for given conditions, the physical optical path in cm is almost wavelength-independent. But D is a variance in PHASE, so $\lambda^2 D$ is constant, and so***

$$r_0 \sim \lambda^{6/5}$$



*Physically, $r_0$ is the ray separation for which the standard deviation of the phase difference becomes large (~2.5 radians) One can think of the atmosphere as consisting of roughly coherent patches of size ~ $r_0$.*

*The DIFFRACTION LIMIT of a telescope is set by the angle at which the phase of an incoming plane wave differs by +/- $\pi$ radians across its aperture, and is thus*

$$\gamma_d = \lambda / D$$

*If the telescope is larger than r0, the atmosphere already results in phase differences this large long before one reaches the edge of the aperture from the center, and the resolution thus becomes, roughly,*

$$\gamma_s = \lambda / r_0 .$$

*Since $r_0 \sim \lambda^{6/5}$, the seeing limit improves at longer wavelengths as $\lambda^{-1/5}$*

# The Modulation Transfer function and the PSF

*If the pattern of illumination on the sky is a plane wave of angular frequency $\omega$, the ratio of the imaged amplitude to the amplitude at the source is called the MODULATION TRANSFER FUNCTION or MTF. Telescopes have finite resolution, and so the MTF drops to of order ½ at angular frequencies which are of order $1/\gamma_s$, and typically falls very rapidly for larger frequencies. Indeed, if $D(r) \sim r^{5/3}$ the MTF can be shown to be*

$$MTF = \exp(-\omega/\omega_c)^{-5/3}$$ *(also true for any other exponent)*

*$\omega_c$ is the critical angular frequency set by the seeing angular resolution limit,*

$$\omega_c = (2\pi/2.099)\,(r_0/\lambda)$$

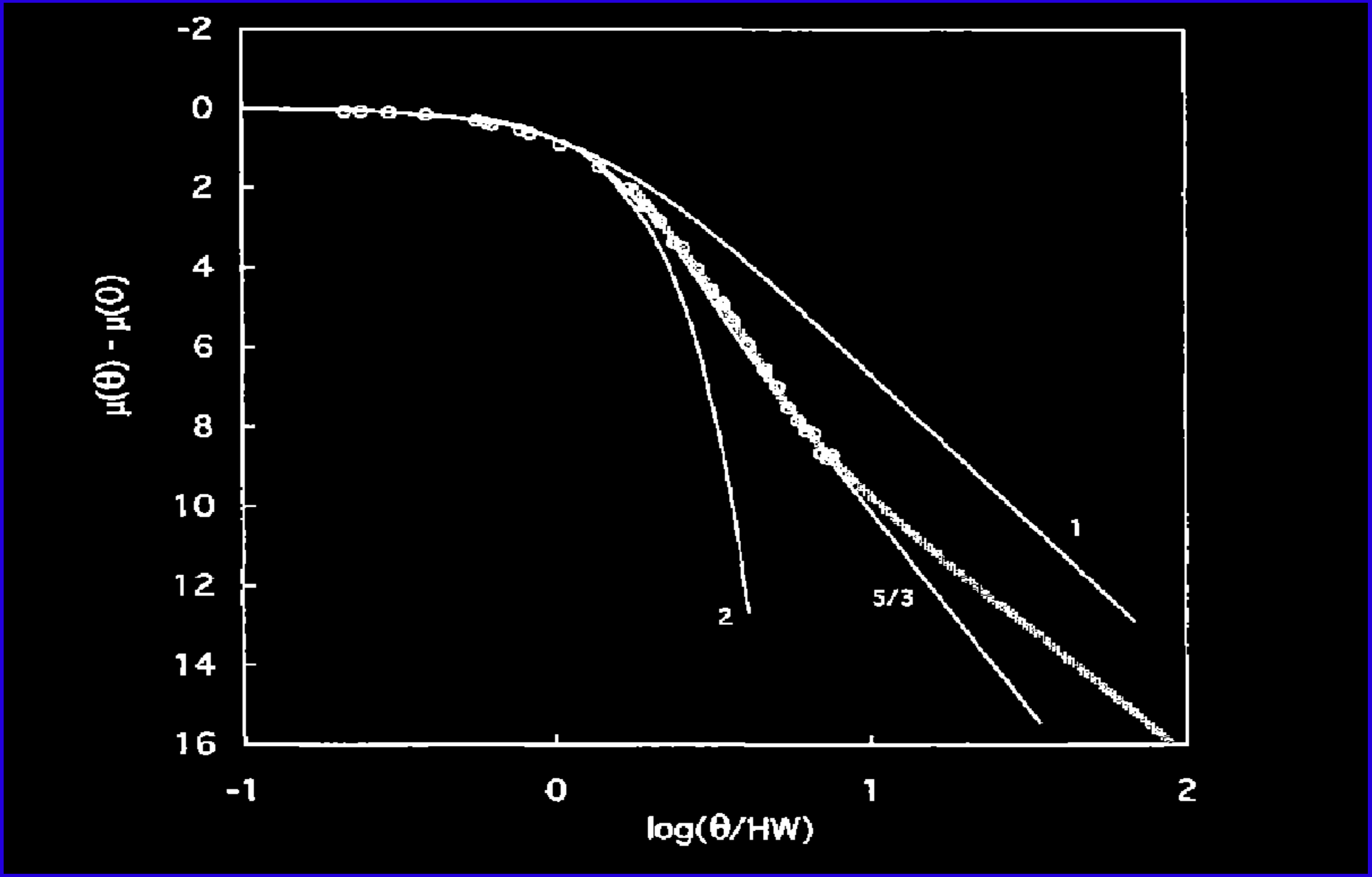
*The physical scale associated with a wave is usually taken to be half a wavelength, $\pi/\omega$; in our case*

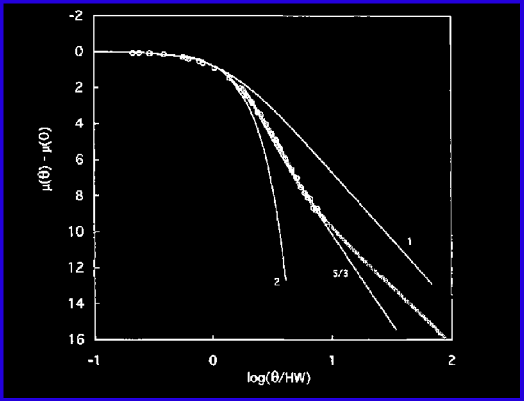
$$\gamma_c \sim 1.05\, r_0/\lambda$$

*$r_0$ is typically of the order of 10-20 cm in the visible (5500, say) at moderate to good sites under moderate to good conditions. This corresponds to $\gamma_c$ of order 0.5 – 1 arcsecond. Under exceptional conditions, $r_0$ can be as large as 40 cm, corresponding to FWHM resolution of order 0.25 arcsecond.*

*We will not be discussing adaptive optics, but note that the number of independent phase patches across a telescope aperture is of order $(D/r_0)^2$, which is huge in the optical, of order 1600 for an 8-meter telescope with half-arcsecond seeing, but drops to of order 60 at K (2.2 microns). This means that adaptive optics is merely difficult in the IR, but is well-nigh impossible in the visible.*

*Since the MTF($\omega$) is the response to a sine wave image, the form in the focal plane from a delta function at the source, which is the Fourier transform of a function which is constant; ie, is the superposition of waves of constant amplitude at all angular frequencies, is simply the Fourier transform of the MTF. It looks like the `5/3' curve here:*





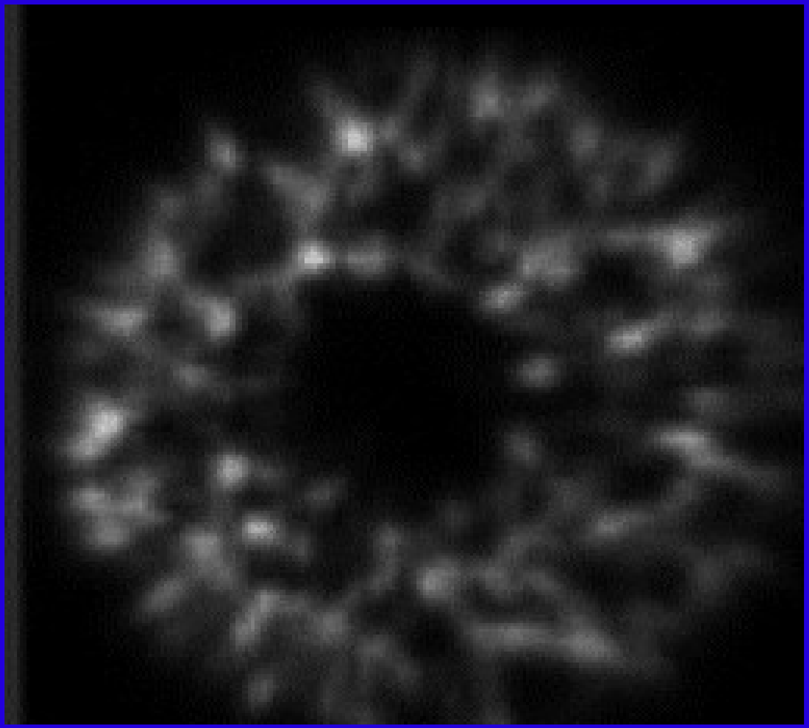

*The straight portion of the curve just outside the core has a logarithmic slope of about -4.7, so the form of the PSF is roughly*

$$PSF(\gamma) \sim a^2/(a^2 + \gamma^2)^{2.35},\ a \sim 1.7\ HWHM$$

*At about 10 half-power radii the theoretical slope flattens slightly, to about -3.8, but the observed PSF, represented by the heavy curve, is even MUCH flatter, and deviates at about the same point. The logarithmic slope of this AUREOLE is about -2.5. Its origin is not completely understood, but probably arises from diffraction associated with dust on the optics, in the atmosphere, and small-scale imperfections in optics and coatings. It is, however, remarkably stable. It contains 2-3 percent of the light.*

*The curve labelled `2' is a gaussian with the same core radius; it is not a very good fit outside about 2 core radii, but the approximation is often used anyway. A better one is a DOUBLE gaussian, the sum of a central one with amplitude 0.9 to represent the core, and a wider one with twice the width of the small one and amplitude 0.1*

*If one takes an out-of-focus image of a star, one gets basically an image of the pupil of the telescope. It looks like this:*



*The structures have a characteristic scale, referred to the pupil, of r0. This is a 2.5-meter telescope (I think) under seeing conditions of about 1 arcsecond, so the spots are ~ 10 cm across.*

*The pattern changes on a timescale t ~ $r_0$/V, where V is the wind velocity. For V~10m/s, $r_0$ ~ 10cm, t ~ 10 ms. D/V is also relevant; this is about 1 s for large telescopes, and is the time for the whole pattern to move across the aperture.*

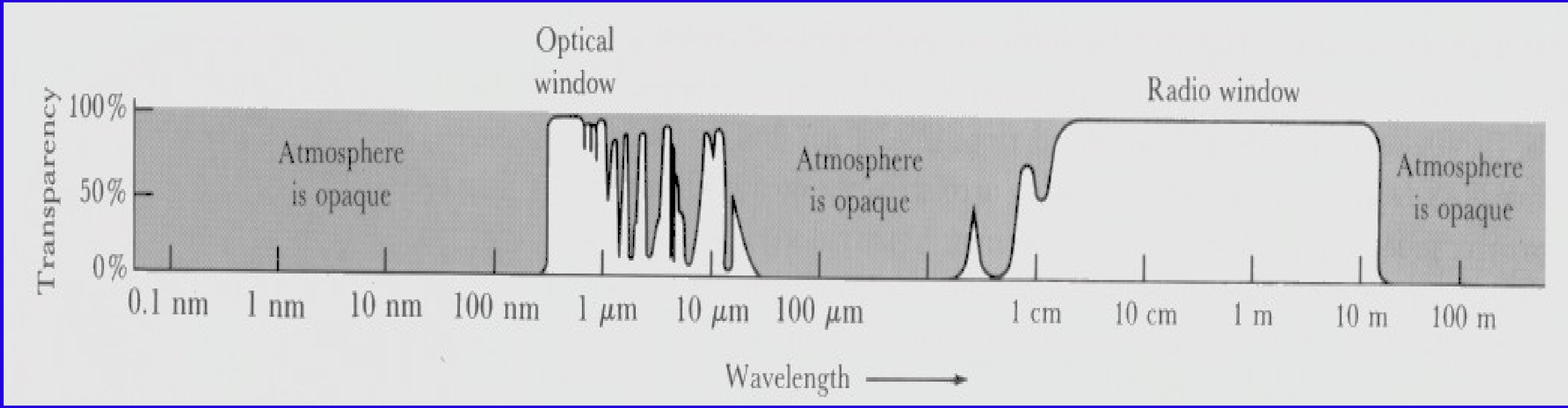
*All of the previous discussion is for so-called FREE-AIR SEEING, which is typically much better than the actual image quality delivered by real telescopes. Part of the difference arises in optical imperfections in the telescopes and instruments themselves, but unfortunately much of it often arises from thermal convection driven by the enclosure and the telescope and its associated machinery and electronics, and from low-altitude (“ground layer”) turbulence associated with the wind interacting with local topography and the telescope/enclosure structure.*

*The goal of modern telescope construction is both to place the telescope at a site at which the free-air seeing is very good, and then not to spoil it by implementing a thermal and aerodynamic design and a tall enough structure to avoid local problems. Real progress is being made in understanding these issues, but the problems are certainly not all solved.*

## *The Atmosphere 2: Transmission*

# The Spectral Transmission of the Atmosphere

***The earth's atmosphere is quite transparent in the visible part of the electromagnetic spectrum, but quite opaque in many others. Schematically, the transmission looks like this:***



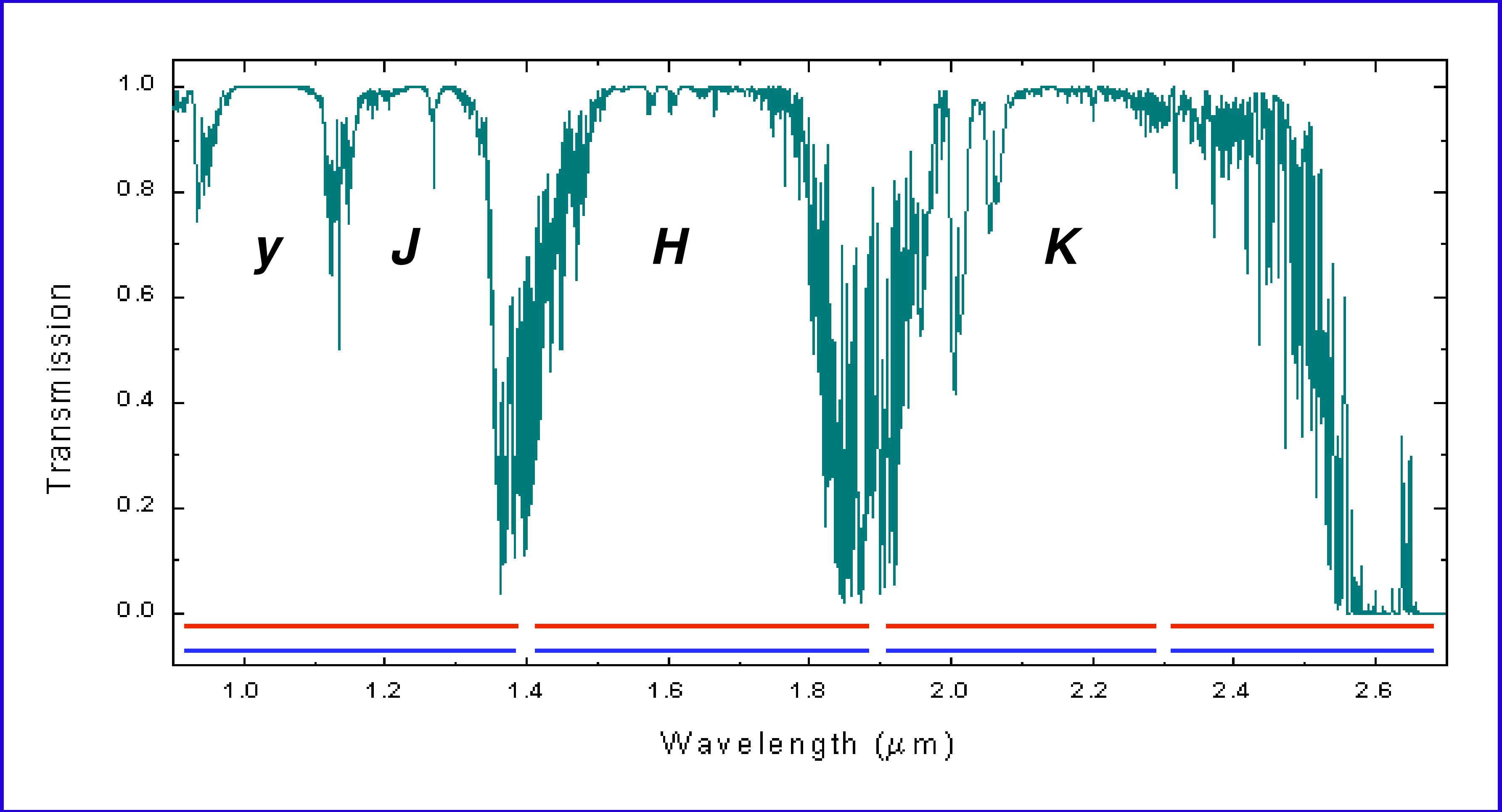
## *What are the absorbants/scatterers?*

***In the near UV, ozone limits observations to about 3100A; Farther to the UV, continuum levels in essentially all the atmospheric gases contribute; the atmosphere is completely opaque to photons of all energies shortward of this.***

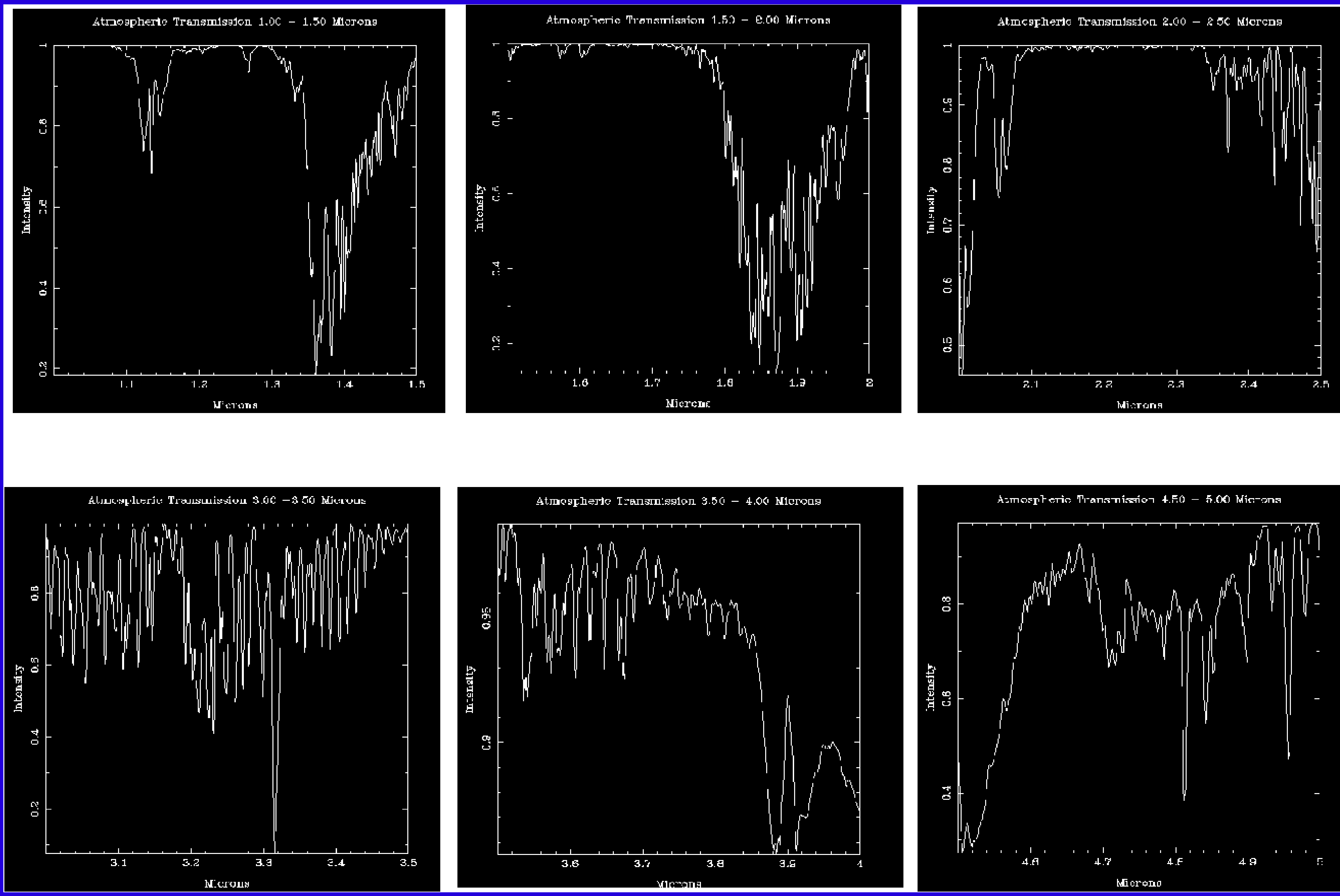
***In the infrared, the primary opacity is water vapor, so high, dry sites are greatly sought for IR observations. The water vapor content is highly dependent on temperature, and several very high sites have less than 1mm of precipitable water, which is the standard way the quantity is expressed.***

# The Near Infrared

**The near and mid-infrared (1 – 5 microns) is heavily cut up by water vapor bands. The region of the Johnson J (center ~ 1.2μ), H (center ~1.6μ) and K (center ~2.2μ) is shown below.**



# *The near and mid-infrared at higher resolution*



# The Visible and Very Near Infrared (3000-10000A)

The primary absorbants and scatterers (and the processes are strongly dominated by scattering until the ozone absorption sets in at ~3400A) are:

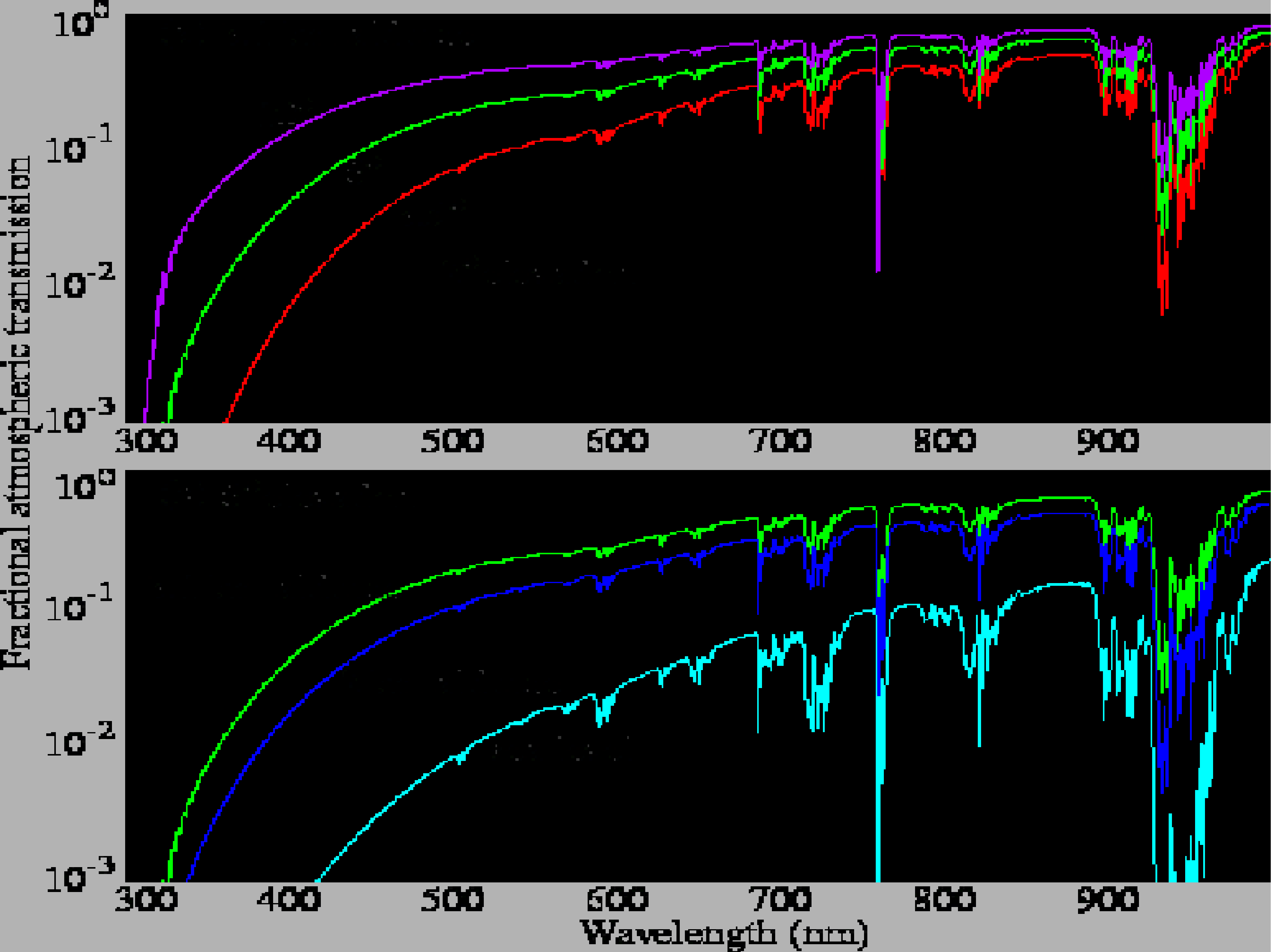
1. Rayleigh scattering from molecular oxygen and nitrogen
   This depends only on atmospheric pressure, and is calculable. The scattering cross section is proportional to $\lambda^{-4}$, so it changes rapidly with wavelength. It is quite coincidental that it is serious and comparable to the ozone absorption just as the ozone is getting strong.

2. Mie scattering from aerosols (dust, smog, both as nuclei for water droplet condensation at high relative humidity). HIGHLY variable with geography and wind conditions. The wavelength dependence depends on the size distribution of the particles; the amplitude, clearly, on their column density.

3. Water. Both as droplets in the last category and a number of discrete electronic bands with vibrational fine structure in the red. Very strong feature at ~9400A, which adversely affects z photometry. Very variable with local and mid-level water vapor levels.

4. Molecular bands. Electronic transitions in $O_2$, in particular. Strong feature at ~6880A (B band) and very strong feature at ~7600A (A band). These are serious but stable. In the near UV, there is very strong absorption by ozone in the Hartley-Huggins bands, which is almost continuous. Below ~3000A, the atmosphere is essentially opaque.

The following slide shows absorption at several altitudes at very low elevations, to make the features more obvious. The very strong $O_2$ A band at 7600 and the enormously strong water feature at 9400 are clear. The B band is not nearly as strong, but the band extends nearly 100 A to the red of the strong head. The strong features at 7200 and 8200 are mostly water, with some contribution from OH in the upper atmosphere; We will learn more about OH in another context later.



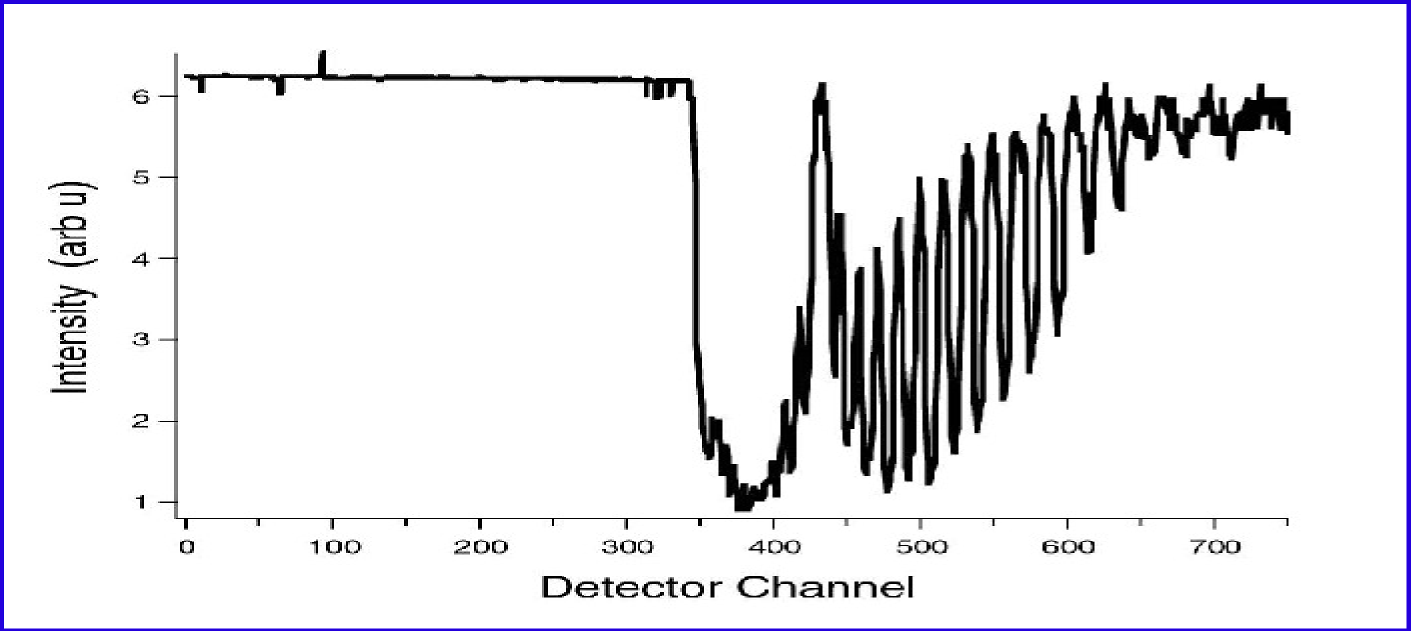
Fractional atmospheric transmission
10^0
10^-1
10^-2
10^-3
300
400
500
600
700
800
900
Wavelength (nm)

*The Rayleigh, Ozone, and aerosol contributions are continuous, and in the approximation that the atmosphere is plane-parallel, the optical depth of these goes simply as*

$\tau_\lambda (z) = \tau_\lambda (0) \sec z$

*This is fine for Rayleigh and ozone, but can fail for aerosols if there is a local source, such as a nearby dusty desert or industrial sources.*

*The molecular bands, however, are another matter altogether. The A band looks like this at moderate resolution (~0.2A):*



*This is typical; at higher resolution, the lines in the band are narrower and all essentially black in the center. Thus the band removes light as its column density increases by increasing the opacity in the WINGS of the lines; the center is already completely saturated. In all atmospheric cases, the wings of the lines are determined by pressure broadening, the effect of molecular collisions on the energy levels and their lifetimes. The profiles are Lorenzian; the cross sections look like*

$$\sigma_\lambda = \sigma_0 / [(\lambda - \lambda_0)^2 + a^2]$$

*and the core width a is very small. The optical depth is just*

$$\tau_\lambda = \int n\sigma_\lambda \, dl \sim N/\Delta\lambda^2$$

*and at a given optical depth (say 1) the width of the line clearly goes as the SQUARE ROOT of the column density, so the absorption seen at low resolution goes as (sec z)$^{1/2}$, NOT sec z.*

*This subject is enormously complicated in detail, and this is the primary reason photometry is so very hard. You can get at moderate cost from a US Air Force lab a wonderful program called MODTRAN4, which will calculate all of these things to very high accuracy, IF you know in detail the nature of the particulates which are responsible for the aerosol scattering (and, of course, their column density), the accurate distribution of water with height, etc, etc.... things we do not and probably cannot with any reasonable expenditure of effort, know. We CAN measure these things with an accurate relatively low-dispersion spectroscopic system with a well-understood network of standard stars, but this approach has not been tried on any reasonable scale yet; PanSTARRS I and LSST are planning to do this---wait and see.*

# *The Atmosphere 3: Background Emission*

# Astronomical Backgrounds in the OIR

*As already noted in the introduction, and as we all know, the sky at night is not dark, This lecture will investigate the sources of this background light, its levels, and its spectrum.*

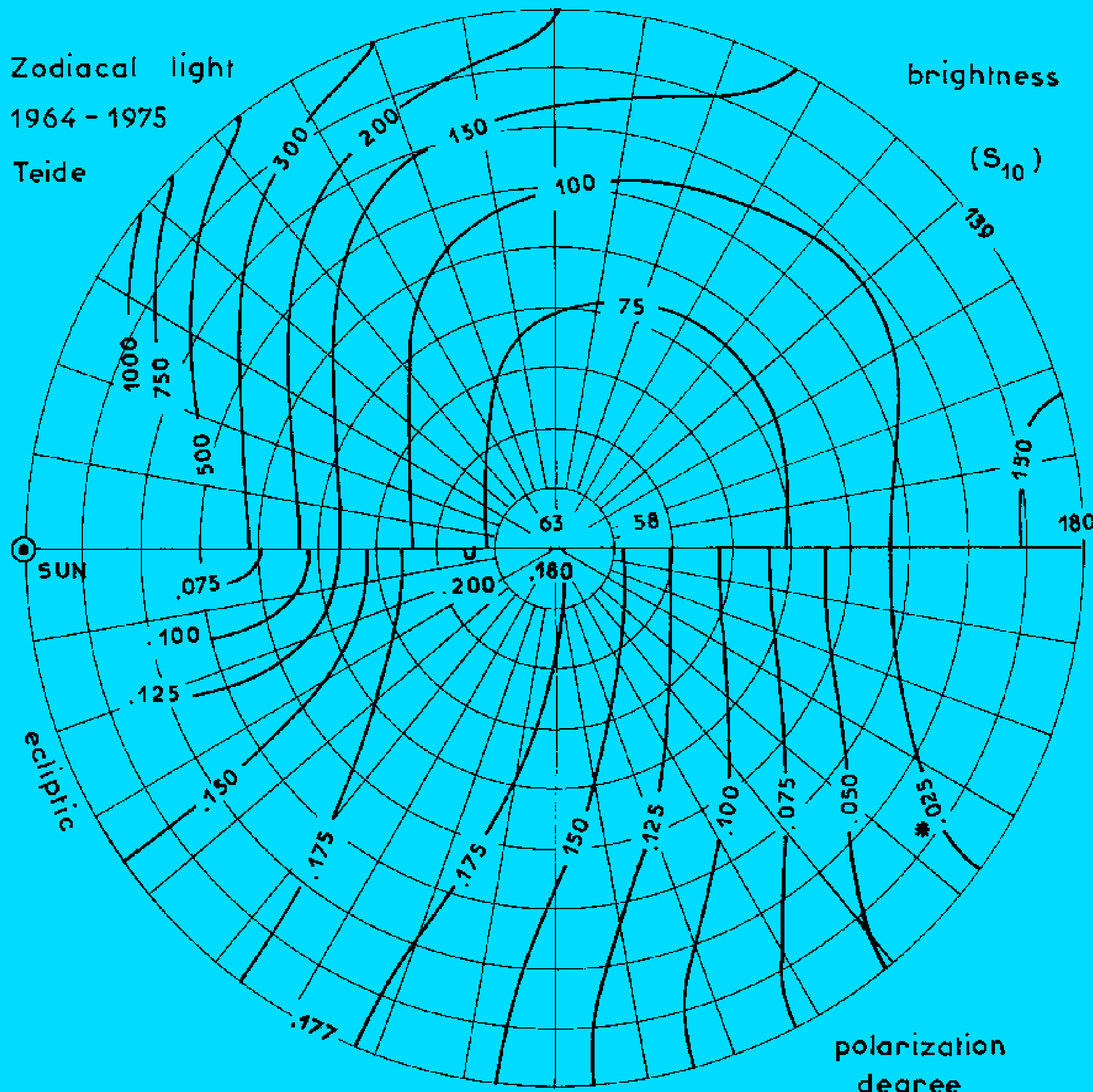
*The sources are only a few; they are*

*1. The Zodiacal light; sunlight which in the visible, near, and mid-IR is simply reflected sunlight from zodiacal dust, generated by the mutual destruction of small asteroids. the average particles are large enough that the spectrum reasonably (to within 15 percent or so from B to K) is that of the sun, There are serious deviations longward of 1 micron, the causes for which are not well understood. The brightness of the zody is highly variable; very bright in the ecliptic plane, especially in the sunward hemisphere. Faintest slightly antisunward of the ecliptic poles. It varies stochastically at the 20% level (why?) with timescales of months. The mean level in the antisun hemisphere is about 22.5 V magnitudes per square arcsec, so a little fainter than the airglow in the visible; in the visible (blue and green) the sky is not much fainter from space than from the ground!*

*The following slide provides a map of the time-averaged zodiacal light. It is assumed symmetric about the ecliptic plane and about the plane containing the sun, observer, and ecliptic pole. The map is a projection of the celestial sphere on the ecliptic plane. The ecliptic pole is in the center, and the circles are parallels of ecliptic latitude, plotted every 10 degrees.*

*The upper half is intensity, in S10V units, ie, number of 10$^{th}$ magntitude (V) stars per square degree. 100 S10V is 22.78 V magnitudes per square arcsecond, so you see that the zodiacal light at high ecliptic latitudes is comparable to the airglow in the visible (and also in the blue). The airglow rises precipitously in the red, as we shall see, so the sky from space, while only a factor of two or so fainter than from the ground in the visible, is hundreds of times fainter than the airglow in the near infrared.*

*The lower half plots polarization, which you can see rises to almost 20 percent at ecliptic longitudes near 90 degrees.*


Zodiacal light
1964 - 1975
Teide
brightness
(S10)
300
200
150
100
75
63
58
139
150
180
1000
750
500
SUN
ecliptic
.075
.100
.125
.150
.175
.177
.200
.180
.175
.150
.125
.100
.075
.050
.025
polarization
degree

*2. Continuum airglow. Shortward of about 7000A, this is the largest source outside the strong emission lines. Its origin is not completely understood, but is almost certainly photochemical and probably related to OH and $O_3$.*

*3. Atomic emission lines. The brightest are of [OI], at 5577, 6300, and 6363A; there are much weaker NI features. 5577 has an equivalent width of about 100A against the airglow+zody continuum.*

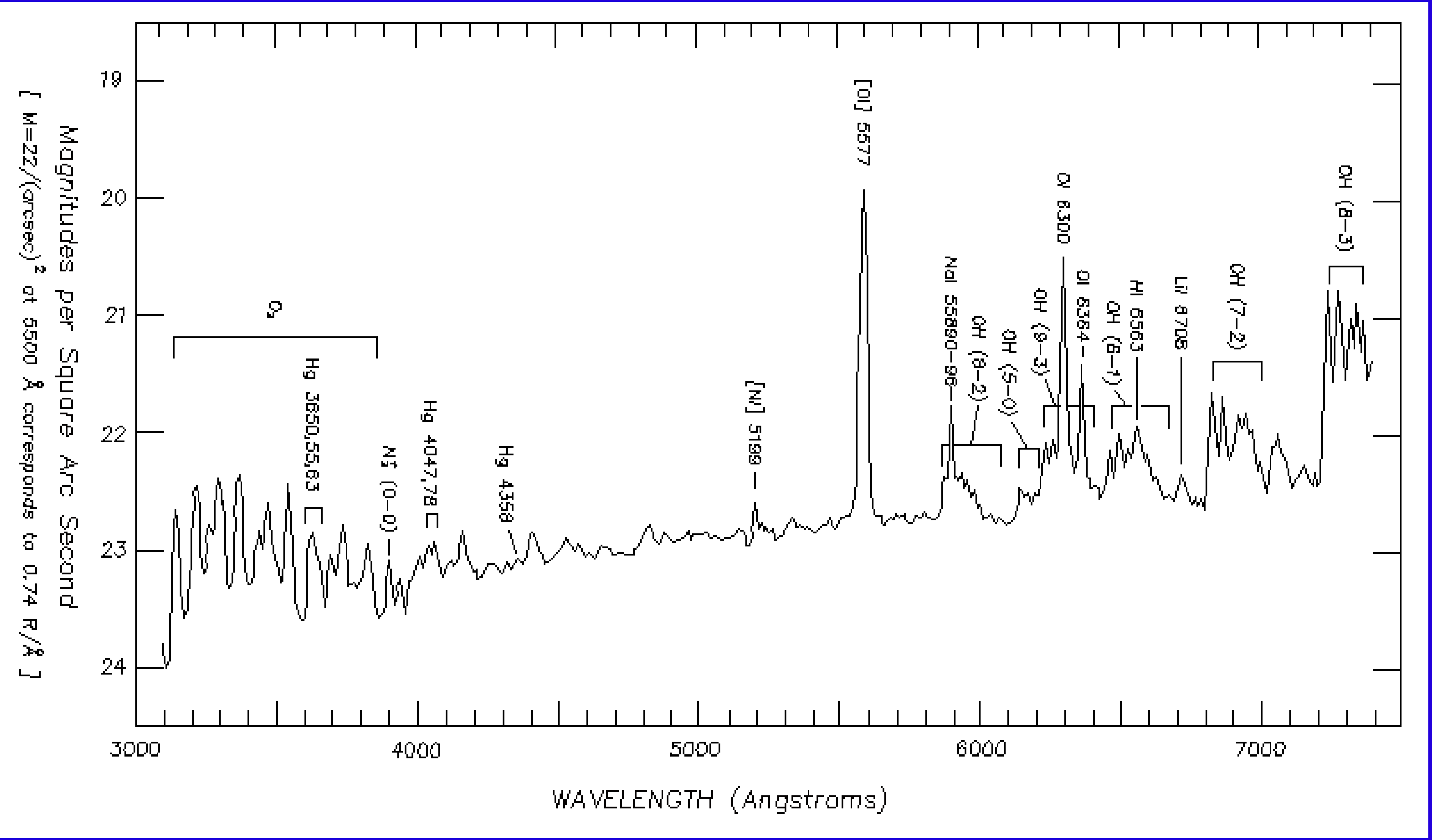
*In sites near western civilization, there are also strong features at the HgI lines 4358, 5460, and the NaI D lines at 5870,90, as well at some locations as a strong broad feature redward of the D lines caused by high-pressure sodium lamps. There is sometimes some strong continuum contribution, and this will steadily worsen.*

*At more northerly sites and sometmes even in New Mexico, one sees strong highly blueshifted Ha from incoming auroral particles This can on occasion dominate the sky brightness in the red.*

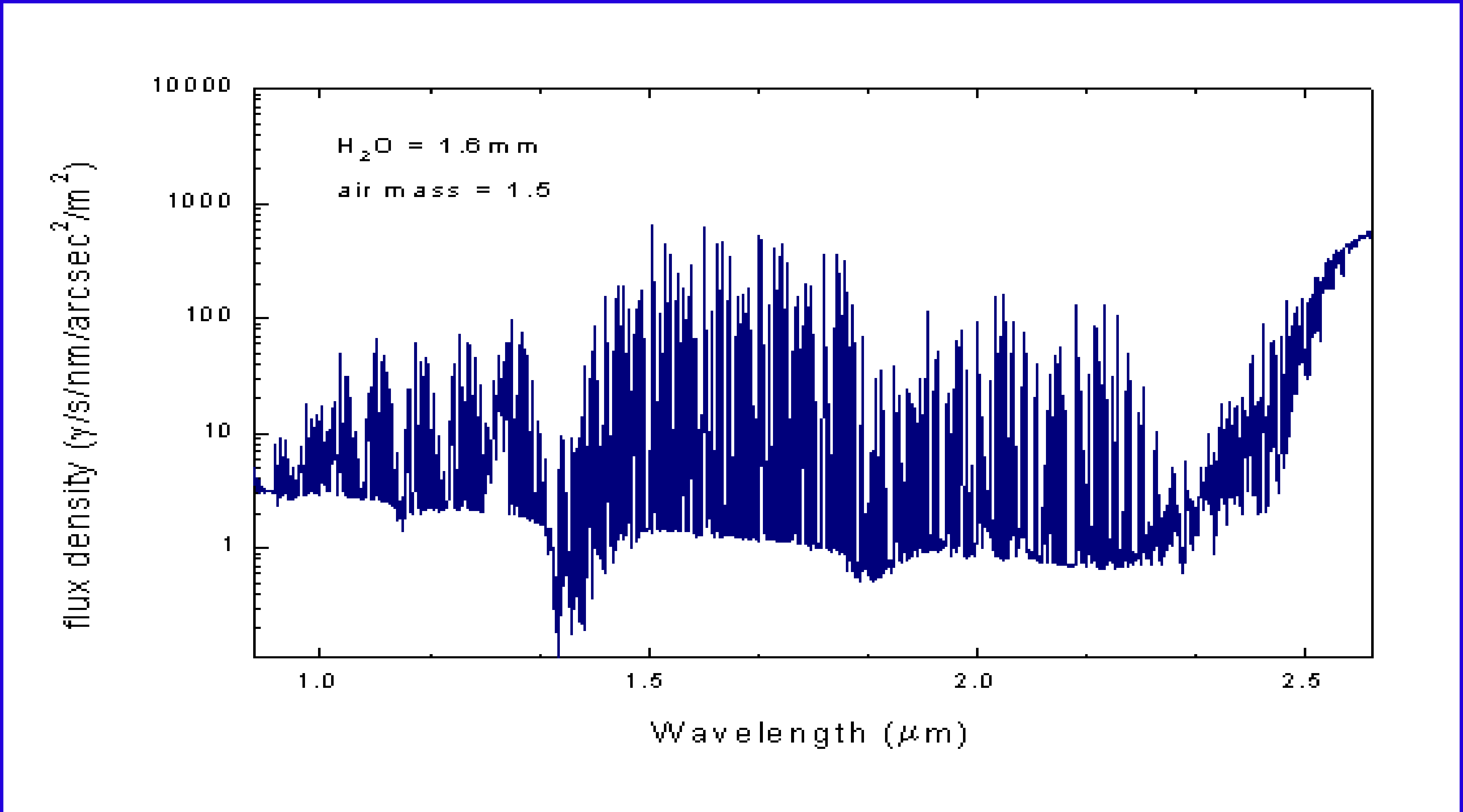
*4. Molecular emission. There is strong $O_3$ emission in the blue, stronger by a little than the continuum. Scattered molecular emission bands of OH appear at about 5800, and longward of 7200 COMPLETELY dominate the emission through the infrared to about 2.2 microns.*

*5. Longward of about 2.4 microns the thermal emission from the atmosphere dominates and remains dominant until the atmosphere becomes quite transparent again at short centimeter wavelengths.*

# Airglow and zody spectrum, visible, Mauna Kea

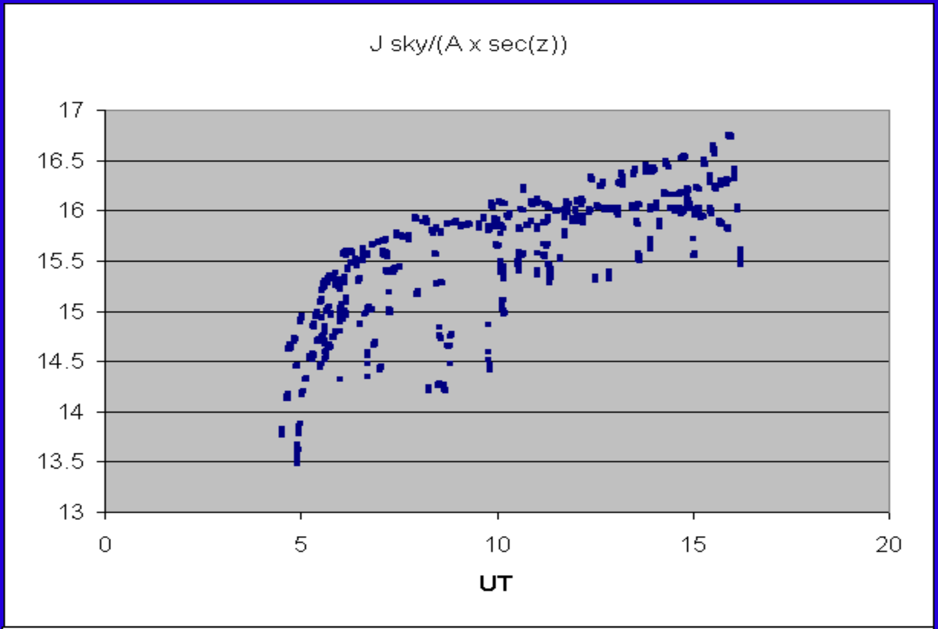


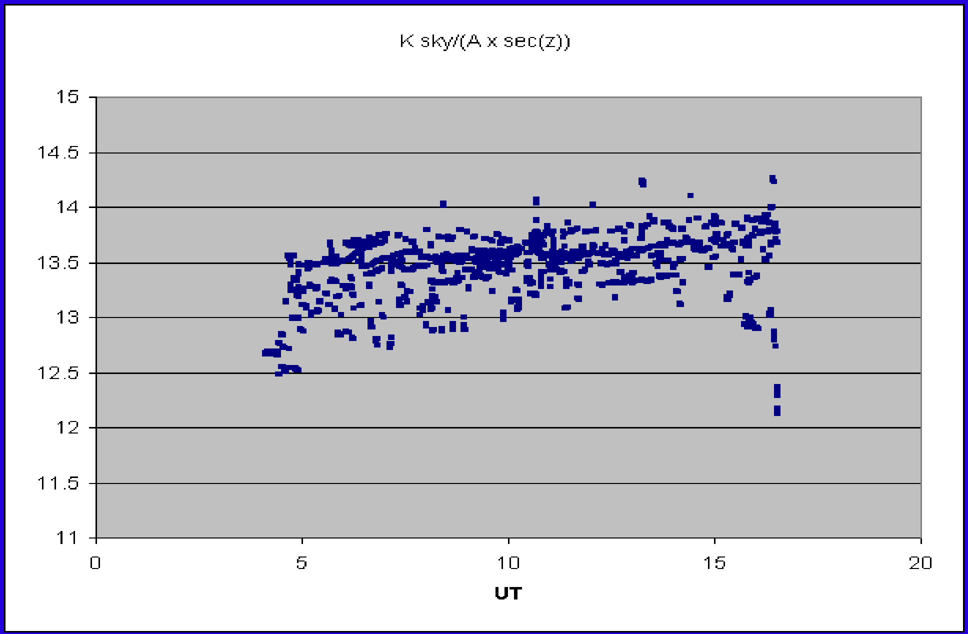
In the near infrared, the OH becomes very, very strong. The sky background spectrum looks like this:

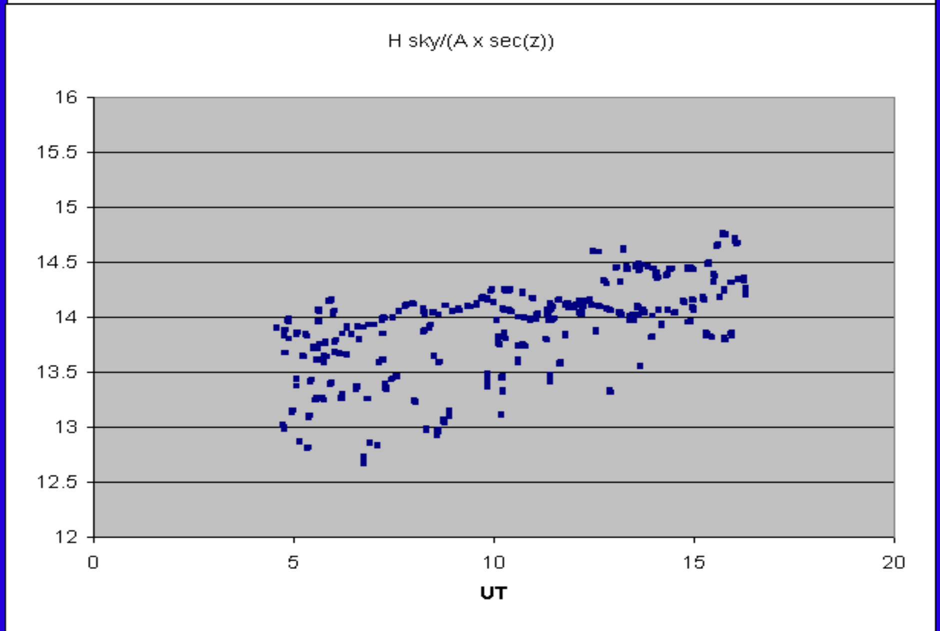



For spectroscopy, a resolving power of at least about 3000 is required to resolve out the individual lines, but the continuum is very faint.

***The sky in the IR changes dramatically through the night, as the photochemical excitation decays. The following plots are in Johnson Vega-scale magnitudes for J,H,K***

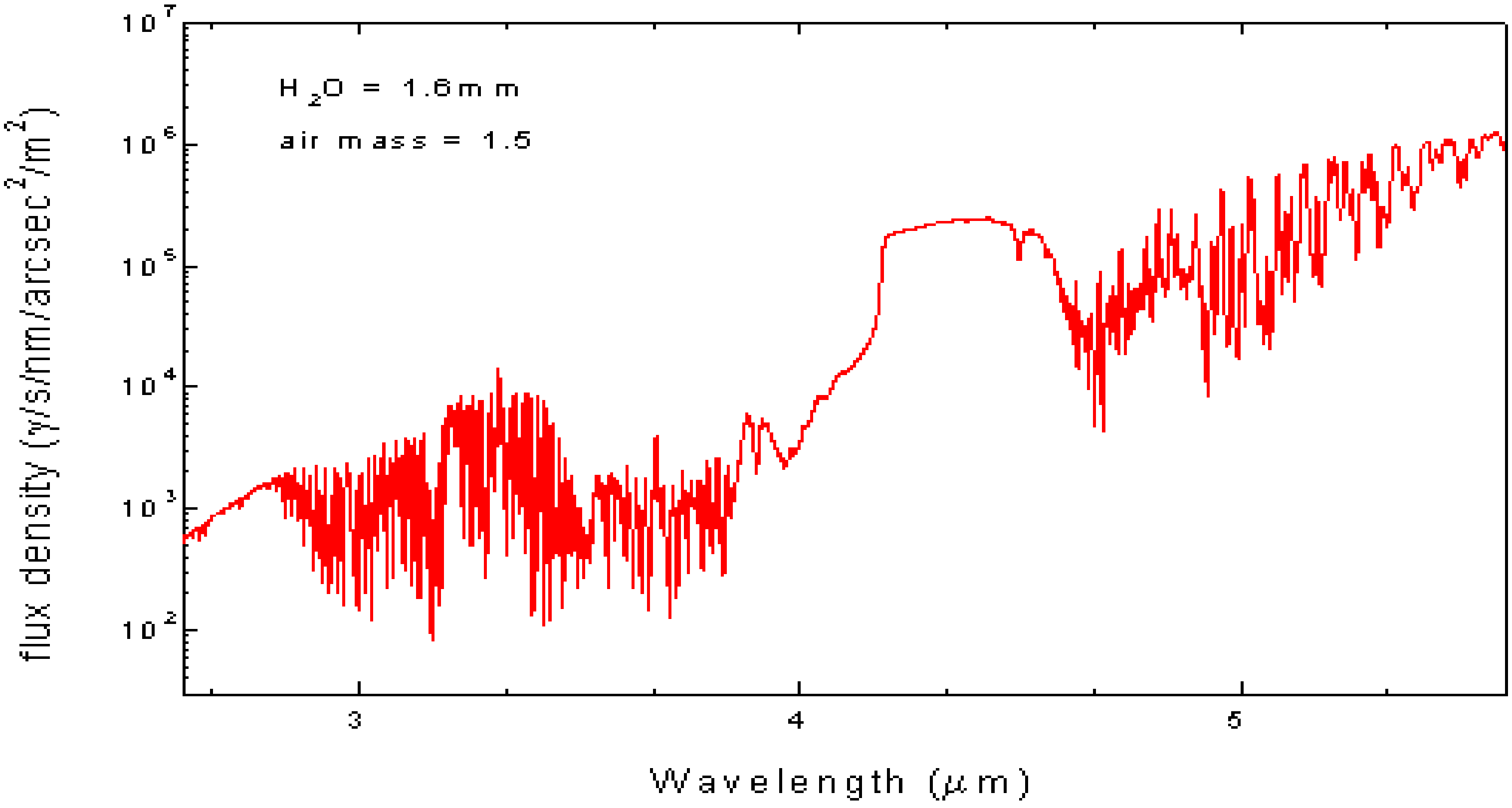



***The mean sky brightness in photons per fractional bandwidth is 150, 350, and 450 times brighter in J,H,and K, respectively, than in V.***

***Farther into the mid-IR, the thermal background is slightly modulated by the atmospheric transparency, but basically continues to rise like a 270 degree black body:***



***The bright OH is not only variable in time, but in space, and responds to wave motions in the atmosphere. This plot shows the OH intensity in the near IR at 30⁰ elevation as a function of azimugh and time through a night in Japan.***

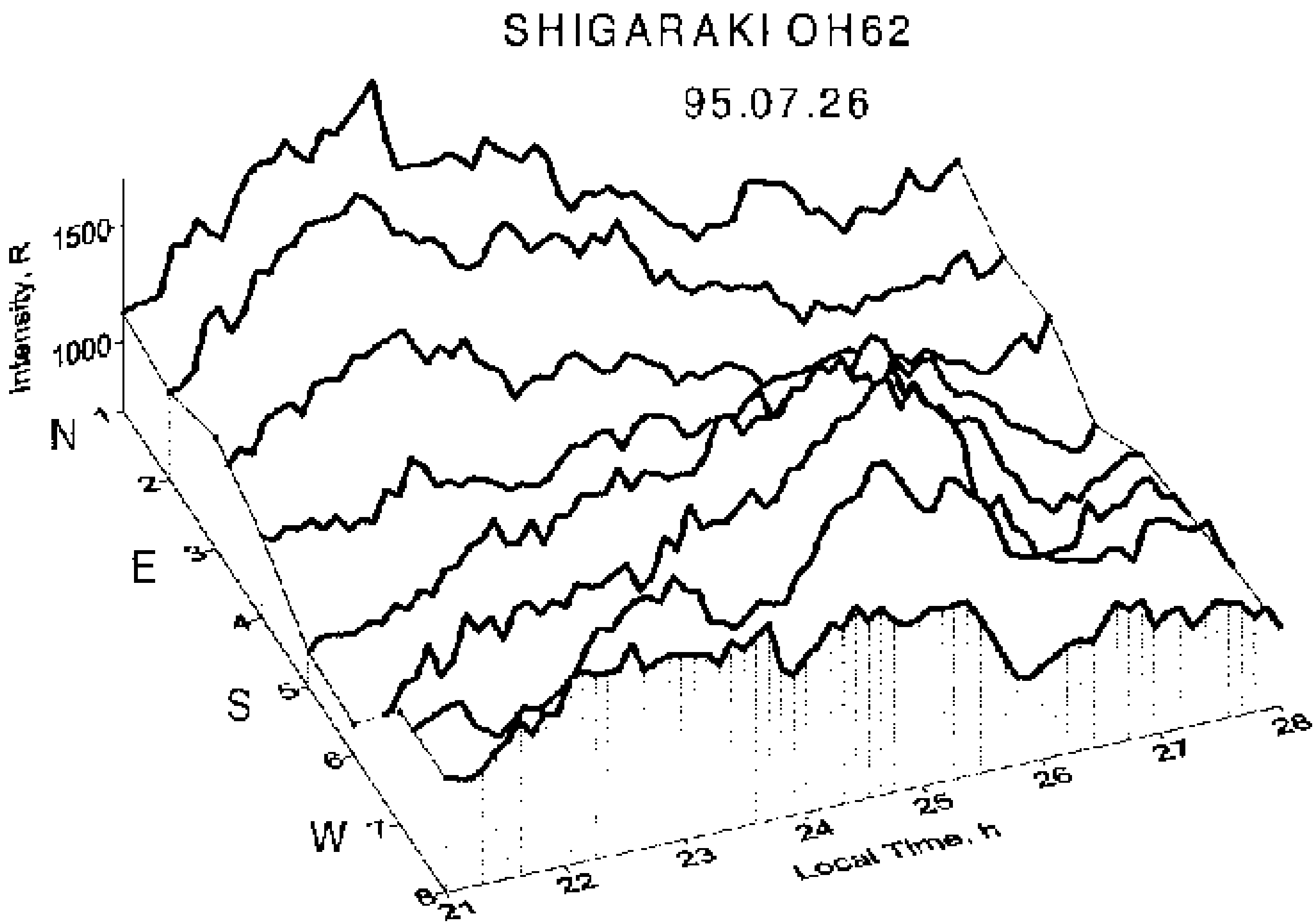



Fig. 6. Same as Fig. 5, except for July 26, 1995.

The 2-dimensional distribution of OH emission on the sky is highly structured and variable on short timescales.

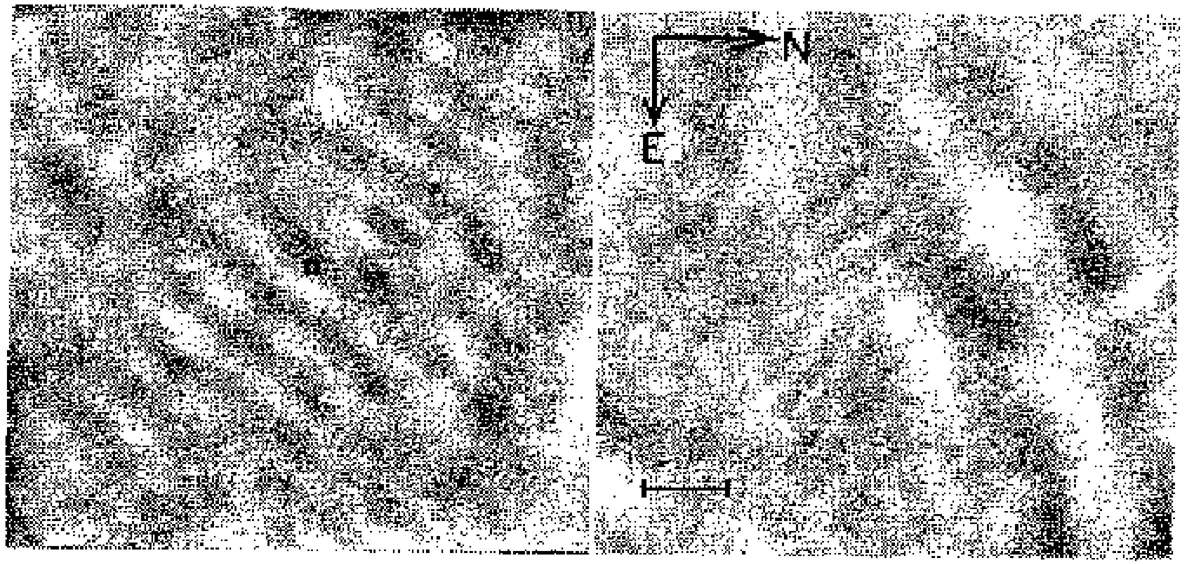



**Figure 1.** Examples for gravity wave modulated OH airglow. The left image shows a regular pattern with 7.5 km horizontal wavelength filling almost the entire field of view. The black square marks the region used for the wavelet analysis. The right image shows two almost perpendicular wave fronts with 3.7 km and 16.5 km horizontal wavelength, respectively. The N-E directions are given. The field of view is 46° x 46°. The scale at the bottom shows 10 km at 87 km altitude.

An easy thing to carry away from this is that it is crazy to try to do IR astronomy from the ground. That may well be true, but we need IR astronomy very badly, and we may or may not be able to do it from space.

*One fact which was not clear from the low-resolution data displayed here is that the OH is not accompanied by a substantial continuum contribution. It is still argued how much continuum there is, but it might be very small indeed. Doing high-resolution spectroscopy of faint objects is possible by working between the OH lines; this requires resolving power (l/Dl) of order 4000, which is relatively easy to achieve. On might imagine incredibly sophisticated interference filters which reject the many hundreds of OH lines in a typical broadband filter, or on a much shorter timescale, integral field spectrographs which are used not to take spectra but to image in the line-free continuum. The filters are under active development, and IFU spectrographs with this capability are coming-- but so is JWST.*

*Also coming on some timescale are coherent fibers tuned by refractive index variations to reject discrete lines. Fascinating technology, but not here yet.*