

5 Looking through the Earth's Atmosphere

5.1 Atmospheric Transmission, Emission, and Scattering

All observations using ground-based instruments suffer the effects of having to look through the Earth's atmosphere. Turbulence and temperature variations in the atmosphere can blur any incident astronomical signal, and the transparency of the atmosphere is a function of wavelength — in some wavelength regimes a strong one. Below ~ 310 nm, the atmosphere is essentially opaque, due to the combined effects of ozone (O_3) and Rayleigh scattering ($\propto \lambda^{-4}$). Above ~ 800 nm there are only discrete windows where observations are possible (see Fig. 1). Atoms and molecules in the atmosphere are also emitting light at specific wavelengths (see Fig. 2). And lastly we have to contend with light from our Moon that is scattered by the atmosphere.

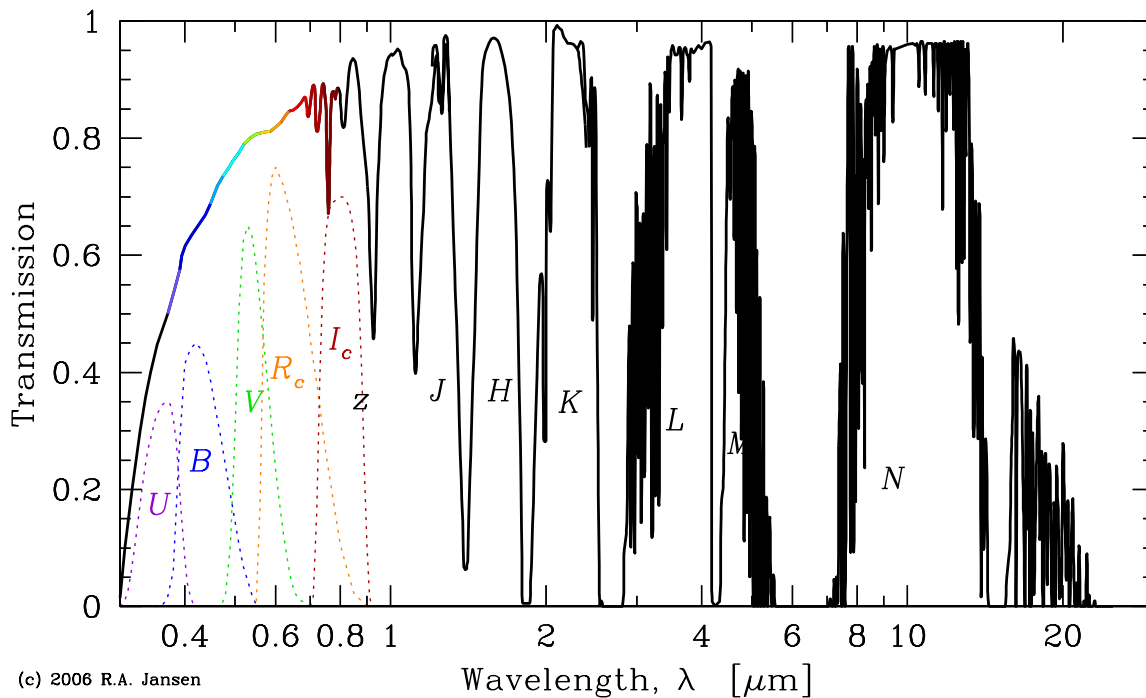


Figure 1: Atmospheric transmission from the atmospheric cut-off in the near-UV (~ 310 nm) to the cut-off redward of the N window in the mid-IR (After: *RCA Electro-Optics Handbook*). The shape of several classical filter passbands ($UBVR_cI_c$) is indicated, and the atmospheric windows in the near- and mid-IR are labeled. Most of the atmospheric absorption is due to molecules: O_3 in the near-UV and visible, and O_2 , H_2O , CO_2 , and N_2O in the infrared. The transmission of the atmosphere is strongly dependent on the amount of precipitable water vapor in the atmosphere above the telescope. The effects of atmospheric *emission*, which limits the usable wavelength intervals even further, is not included in this plot (but see Fig. 2).

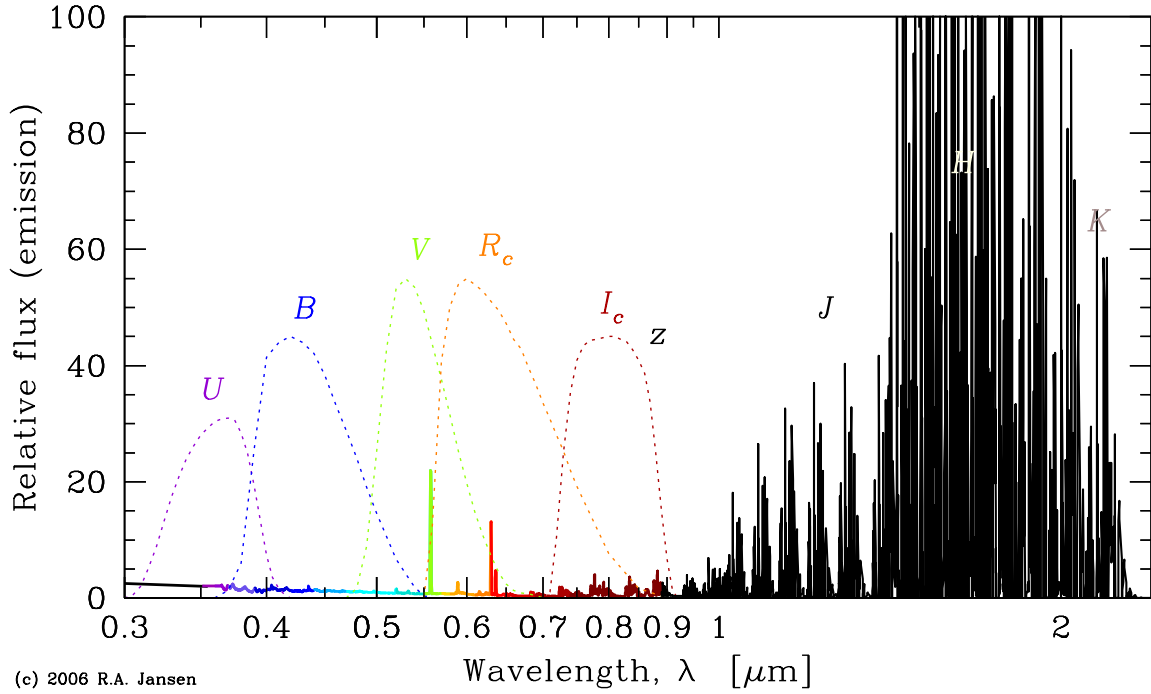


Figure 2: Atmospheric emission from the atmospheric cut-off in the near-UV through the near-IR *K* band (Source: *0.3–0.9 μm*: based on *VLT/UT3+FORIS1* spectra obtained by R. Jansen & P. Jakobsen; *0.9–2.5 μm*: theoretical *OH* night-sky lines from Rousselot et al. 2000). Again, shapes of several classical filter passbands or their effective wavelengths are indicated. Although the optical night-sky spectrum — but for the very strong *O I* lines at 557.7, 630.0 and 636.3 nm — is relatively clean, the sky spectrum beyond ~ 750 nm is dominated by strong series of *OH* lines. The strengths of night-sky emission lines tend to vary throughout a night and from night to night. Beyond $\sim 4 \mu\text{m}$, the sky becomes exceedingly bright.

Table 1: Sky brightness for different lunar ages at CTIO

Lunar age (days)	Sky surface brightness (mag/arcsec ²)				
	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Source: Alistair Walker, NOAO Newsletter #10

Table 1 tabulates the average surface brightness of the sky background and its dependence on lunar phase for five filters (*UBVRI*) and lunar ages of 0 (New Moon) through 14 (Full Moon). This dependence is due to scattering of moonlight in the Earth’s atmosphere. The actual brightness also depends on how close to the moon you look and, for partial phases, whether the Moon is above the horizon. (Remember, that for partial phases, the Moon is up only part of the night, while at Full Moon it is up *all* night). The main trends are, that:

- The Moon’s effect is strongest in the bluest bandpasses: in *U*, the sky is 5 mag (i.e., a factor 100!) brighter at full moon than at new Moon or when the Moon is well below the horizon. In *B*, the difference is ~ 3.2 mag. In the redder *I* filter, the difference is reduced to a factor ~ 2 . This dependence on wavelength is partly because the moonless sky is fainter in the bluer bandpasses than it is in redder passbands — in the mid-IR the sky is so bright that there is little difference between day and night!
- Taylor, Jansen & Windhorst (2004) show that the darkest skies at the summit of Mt. Graham, AZ, where the 2×8.4 m Large Binocular Telescope (LBT) is being built, have a sky surface brightness that is comparable to the darkest nights at Cerro Tollelo Inter-american Observatory (CTIO) in Chili.

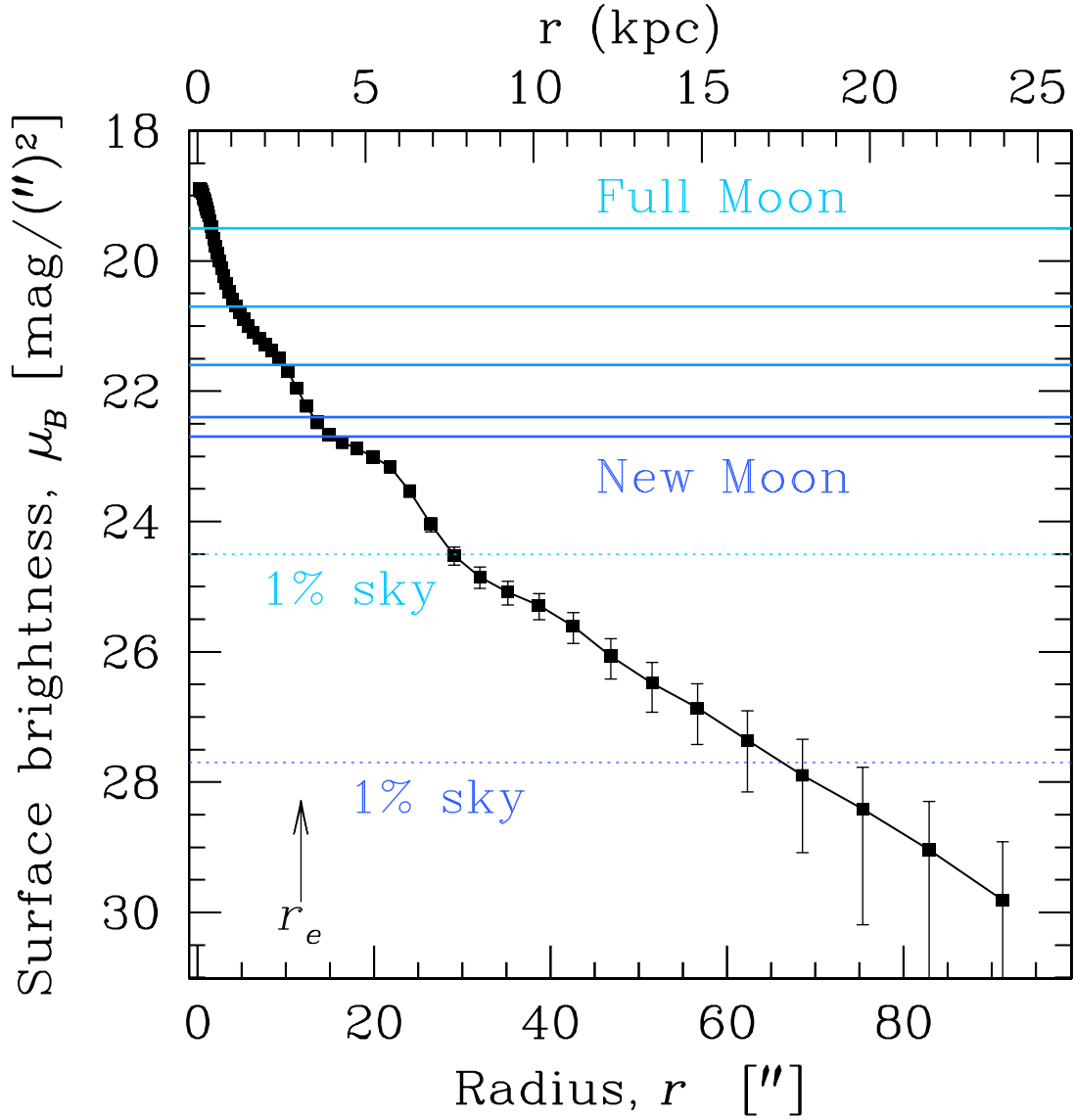


Figure 3: Comparison of the B -filter surface brightness profile of a nearby galaxy (A00389–0159; Jansen et al. 2000a) with the surface brightness of the sky, for the moon phases of Table 1. Note that, even at New Moon, most of the galaxy is fainter than the sky. With a central surface brightness, $\mu_0^B \simeq 19 \text{ mag arcsec}^{-2}$ and a profile that declines exponentially with radius in the outer disk, this galaxy is quite typical of nearby spiral galaxies. Generally, with sufficiently long exposures, one can confidently detect signals to $\sim 1\%$ of the sky background. The difference between observing during *dark* and *bright* sky conditions, corresponds to a factor of more than 2 in radius within most spiral galaxies.

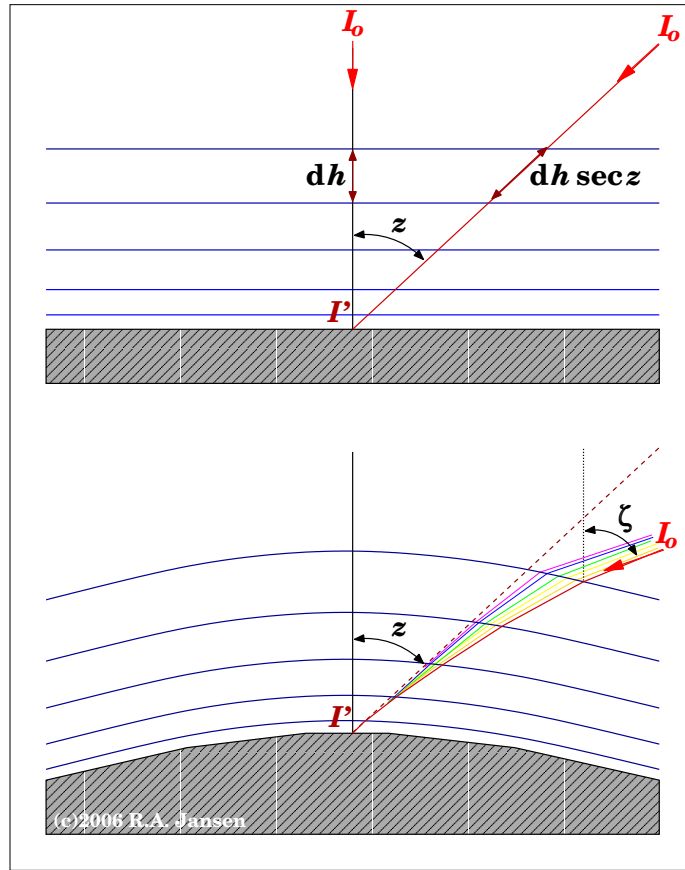


Figure 4: Schematic representation of the geometry of the Earth's atmosphere (a) in the approximation of plane parallel layers; (b) when the curvature of the atmosphere and refraction are taken into account.

Loss of intensity during the passage of light through the atmosphere results from *extinction* — the combined effects of *absorption* and *scattering*. For plane parallel layers and for monochromatic light we have at zenith (see Fig. 4):

$$dI = -I \cdot \kappa dh \quad \text{or:} \quad \frac{dI}{I} = -\kappa dh$$

$$\implies \ln I = -\int_0^\infty \kappa(h) dh + \text{const.}$$

where κ is the extinction coefficient per cm — which will depend on the density of the atmosphere and, hence, on h —, and $\text{const.} = \ln(I_0)$. If we denote the extinction coefficient for one *air mass* (i.e., a full thickness of the Earth's atmosphere) by K , then the *transmission* through the atmosphere will be given by $I/I_0 = e^{-K}$.

For a *zenith distance* (angle from zenith) z this becomes:

$$I/I_0 = e^{-K \sec z} \quad , \quad \text{with:} \quad \sec z \equiv \frac{1}{\cos z} \quad (1)$$

And expressed in magnitudes:

$$\begin{aligned} m - m_0 &\equiv -2.5 \cdot \log(I/I_0) = -2.5 \cdot \log(e^{-K \sec z}) \\ &= -2.5 \cdot (-K \sec z) \cdot \log e \simeq 1.0857 \cdot K \sec z \end{aligned} \quad (2)$$

5.2 Atmospheric Refraction and Dispersion

In reality, however, the Earth's atmosphere is curved, not plane parallel, and the path followed by a beam of light will be curved due to *atmospheric refraction*. This is illustrated in the bottom panel of Fig. 4. Generally, it may be necessary to use the actual air mass, $M(z)$, instead of $\sec z$.

To evaluate the importance of the difference between $\sec z$ and $M(z)$ and of atmospheric refraction, in Table 2 we compare the relative intensity losses I/I_0 for each at two different wavelengths. The correct form of Eq. (1) is:

$$I/I_0 = e^{-K \cdot M(z)} \quad \text{with:} \quad M(0) \equiv \sec 0 \equiv 1 \quad (3)$$

It is important to note that the values for $M(z)$ listed in Table 2 are valid for standard temperature and pressure *at sealevel*; $M(z)$ varies with altitude and temperature. Nonetheless, we find that the intensity losses do not differ significantly for zenith distances $\lesssim 80^\circ$. The extinction coefficient $K(\lambda)$, however, is — as we already found from Fig. 1 — a strong function of wavelength, as evidenced here by the large difference in losses at 5500\AA and 3200\AA .

The zenith distance z of an astronomical object as observed at the ground is always *smaller* than the true zenith distance ζ that one would measure outside of the Earth's atmosphere. For a precise calculation of the refraction one would need to know the geometry of the atmosphere and the change in refractive index as a function of density (height) along the curved(!) light path. And the refractive index itself is also a function of wavelength. The relation between refractive index and wavelength is called *atmospheric dispersion*.

- Due to atmospheric dispersion, any object that isn't exactly at zenith will appear to the observer as a small spectra. Since the refraction will be stronger for bluer wavelengths than for redder wavelengths, the blue side of that spectrum will point to zenith and the red side away from it (i.e., the blue side points *up*).

A good approximation for the difference between true and apparent zenith distance to $\zeta \simeq 75^\circ$ (for $\lambda = 5500\text{\AA}$, 750 mbar, 0°C) is given by the expression:

$$(\zeta - z) = 60''4 \tan \zeta - 0''064 \tan^3 \zeta \quad (4)$$

In view of Snell's law, the wavelength dependence of this difference between true and apparent zenith distance with respect to the dispersion at 5500\AA is given by:

$$(\zeta - z)_\lambda = (\zeta - z)_{5500\text{\AA}} \cdot \frac{(n_\lambda - n_{\text{vac}})}{(n_{5500\text{\AA}} - n_{\text{vac}})} \quad , \quad \text{where} \quad n_{\text{vac}} \equiv 1 \quad (5)$$

Table 3 tabulates the atmospheric dispersion coefficient with respect to that at 5500Å for five wavelengths from the atmospheric cut-off in the near-UV to the near-IR (800 nm). From this table we can then evaluate how severe the distortion of the image of that astronomical object into a little spectrum will be, for a moderate zenith distance of, say, 45°:

$$\left. \begin{aligned} (\zeta - z)_{3000} &= 1.047 \cdot (60''4 \tan 45^\circ - 0''064 \tan^3 45^\circ) \\ (\zeta - z)_{8000} &= 0.989 \cdot (60''4 \tan 45^\circ - 0''064 \tan^3 45^\circ) \\ \tan 45^\circ &\equiv 1 \end{aligned} \right\} \implies$$

$$(\zeta - z)_{3000-8000} = (1.047 - 0.989) \cdot (60''4 - 0''064) \simeq 3''50$$

And at an air mass of 2 (zenith angle of 60°), the length of the same spectrum would have grown to $\sim 6''0$.

When trying to obtain a spectrum of an object through a typical spectrograph slit of $\sim 1''$ width, one might completely lose the blue and red parts of the spectrum when the green light is centered in the slit (Filippenko 1982).

z	$\zeta - z$	sec z	$M(z)$	$(I/I_0)_{\text{sec } z}$		$(I/I_0)_{M(z)}$	
				5500Å	3200Å	5500Å	3200Å
0°	0''	1.000	1.000	0.83	0.40	0.83	0.40
10°	10''	1.015	1.015	0.83	0.39	0.83	0.39
20°	21''	1.064	1.064	0.82	0.38	0.82	0.38
30°	34''	1.155	1.154	0.81	0.35	0.81	0.35
40°	49''	1.305	1.304	0.78	0.30	0.78	0.30
50°	1'10''	1.556	1.553	0.75	0.24	0.75	0.24
60°	1'41''	2.000	1.995	0.69	0.16	0.69	0.16
70°	2'39''	2.924	2.904	0.58	0.069	0.58	0.070
80°	5'19''	5.76	5.60	0.34	0.005	0.35	0.006
85°	9'52''	11.47	10.40	0.12	0.000	0.14	0.000
90°	35'22''	∞	38.	0	0	0.0008	0.000

Table 2: Transmission of the Earth's atmosphere for different zenith distances z and wavelengths λ . The 2nd column lists the angular deviation, $(\zeta - z)$, for $\lambda = 5500\text{Å}$ (as defined in Fig. 4).

λ (Å)	3000	4000	5000	6000	8000
$\left(\frac{n_\lambda - 1}{n_{5500} - 1}\right)$	1.047	1.014	1.001	0.995	0.989

Table 3: Atmospheric dispersion with respect to the dispersion at $\lambda = 5500\text{Å}$

- To avoid this, the spectrograph slit should be aligned with the *parallactic angle*: the angle at which the spectrograph slit is normal to the horizon.

Although in imaging applications one never covers such a large range in wavelength, a stellar image observed in, say, the *B* filter would still be elongated by $\sim 0''.5$ at $z=45^\circ$ and $\sim 1''.0$ at $z=60^\circ$. This is sufficiently noticeable that large telescopes at good sites have implemented *atmospheric dispersion correctors*.



Figure 5: Example of the effects of atmospheric dispersion. The stellar image above was observed in a quick succession of *BVR* exposures at the 6.5 m Magellan ‘*Baade*’ telescope with the IMACS instrument in Dec 2003 (R. Jansen & R. Windhorst) — before the atmospheric dispersion corrector was commissioned. The air mass was 1.33 (i.e., $z \simeq 41^\circ$) and the seeing $0''.75$ (3.38 pixels) FWHM. Atmospheric dispersion caused a noticeable differential shift of the centroids of the *B* and *R* images on the CCD of $\sim 1''.0$.

5.3 Seeing and Scintillation

Along the path of a beam of light through the atmosphere, changes in intensity and direction not only occur due to extinction and refraction, but also due to *atmospheric turbulence*. Turbulence causes fluctuations in density, ρ , of the air — mostly as a result of temperature differences. Pressure fluctuations at small scales are negligible, since these would rapidly (at the sound speed!) smooth out. Temperature differences can be much longer-lived.

Let's estimate the effects due to such fluctuations. For changes in direction of a beam of light, any incremental change in refractive index, $\Delta n \equiv n - n_0$, is important. The refractive index of air is proportional to its density: $(n - 1) \propto \rho$ and $n|_{\rho=0} \equiv n_{\text{vac}} \equiv 1$. For an ideal gas, we have:

$$\frac{n - 1}{n_0 - 1} = \frac{\rho}{\rho_0} = \frac{P/T}{P_0/T_0} = \frac{P T_0}{P_0 T} \quad (6)$$

Because pressure differences can be ignored, $P = P_0$, from which follows (if we take $\Delta n/\Delta T \simeq dn/dT$):

$$\Delta n = -(n_0 - 1) \cdot \frac{T_0}{T^2} \cdot \Delta T \quad (7)$$

At sea level, $T \simeq T_0 \simeq 300$ K and $n_0 = 1.000293$, which gives $\Delta n \simeq -10^{-6} \Delta T$. At altitude h , the pressure and, hence, the density of the air and its refractive index decrease, and they do so roughly exponentially:

$$\frac{n_h - 1}{n_0 - 1} = e^{-h/H} \quad (8)$$

where H is the exponential scale height of the Earth's atmosphere ($H \simeq 8$ km). This then gives us (Eq. 8 \rightarrow Eq. 6 \Rightarrow Eq. 7):

$$\Delta n \simeq -10^{-6} \cdot e^{-h/H} \cdot \Delta T \quad (9)$$

As it turns out, turbulence in the atmosphere results in *two* separate effects:

1. it causes changes in direction of the incident beam of light, which we call *seeing*;
2. it causes fluctuations in intensity, which we call *scintillation*.

In the following, we will consider a much simplified model of a single turbulence element (*turbulence cell*) of diameter L and refractive index $n_0 + \Delta n$, embedded in the ambient air (with index n_0), and reduce the problem to the two-dimensional geometry illustrated in Fig. 6.

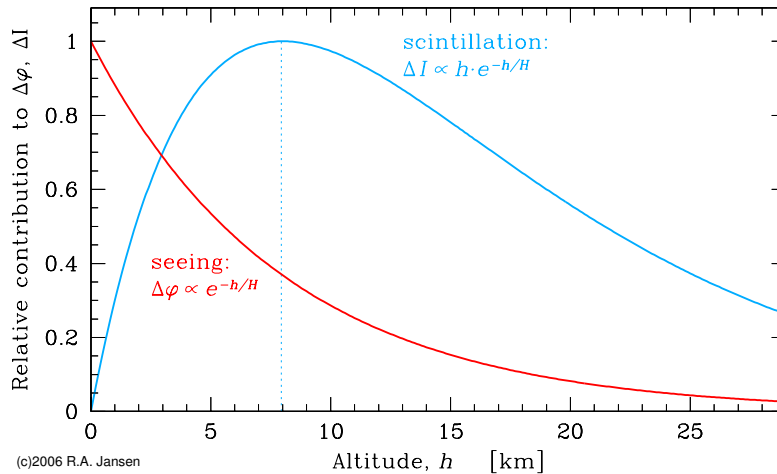


Figure 7: Relative contributions to the seeing and scintillation as a function of the altitude of the turbulence elements. The exponential scale height of the atmosphere is 8 km. The maximum contributions to seeing and scintillation are at quite different altitudes. This means that *seeing and scintillation are uncorrelated*.

b) Scintillation. The intensity fluctuations as observed at ground-level due to the passage through a turbulence element is proportional to the change in beam diameter, hence $\Delta I \propto h \cdot \Delta\phi$. So now we're dealing with $h \cdot e^{-h/H}$ instead of with $e^{-h/H}$. This means that the maximum effect of scintillation occurs higher in the atmosphere. As it turns out, at an altitude of ~ 8 km.

- The difference in dominant altitude implies that *seeing and scintillation are uncorrelated*.

If D denotes the diameter of a telescope, then:

- if $D \lesssim L$: most of the time only one turbulence element will be within the beam \implies the entire (sharp) source image will be displaced but unsmearred at any one time, but that image will show strong fluctuation in intensity (i.e., scintillation);
- if $D \simeq L$: At $h \simeq 0$ and for $\Delta T = 1^\circ \implies \Delta\phi = 2 \times 10^{-6} \text{ rad} = 0''.41$;
- if $D \gg L$: several turbulence cells will be within the beam at any one time: their combined displacements will smear the source image to a seeing-disk, but the net amplitude of scintillation is less severe.

A typical diameter of a turbulence cell of ~ 10 cm at an altitude of 8–10 km subtends an angle of:

$$\tan \theta \simeq \theta = \frac{10}{(8-10) \times 10^5} \cdot \frac{180}{\pi} \cdot 3600 = 2''.58 - 2''.06$$

Because most planets subtend angles larger than $2''.6$ (Mars: 5–15'', Jupiter: 30–40'', Venus: 10–60''), planets do not scintillate. Twinkle, twinkle is a star after all...

Appendix A. Sources, references, and additional reading

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- SITe 2048×4096 Scientific-Grade CCD (ST-002A CCD data sheet) (<http://www.ociw.edu/-instrumentation/ccd/parts/ST-002A.pdf>)
- Outreach and Education site of the Australia Telescope (<http://outreach.atnf.csiro.au/education/-senior/astrophysics/>)
- Frank Lakiere’s web-site on photography (webhost.ua.ac.be/elmc/website_FL/index-eng.htm)
- Various *Wikipedia* pages (beware: information in these may neither be complete nor correct)