Observational Astrophysics
3. Earth's Atmosphere

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Autumn/Winter 2021/2022

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1 Read this other text

Sometimes I will not write the whole reading material from scratch, but point out a text that you should read. This is one of those times.

For the topic of atmospheric effects on astronomical observations, you should please read pages 25-46 of the book "Astronomical Measurement – A Concise Guide" (Lawrence 2013)[1]. The text discusses atmospheric absorption, scattering, refraction, emission, and turbulence (and a few other things that are good to know) in detail.

Below, I just try to make a quick summary of important topics, suggest additional resources for those that are interested, and show a few additional plots and tables with useful illustrations and information.

2 Introduction

A large fraction of astronomical observations are performed from the ground. Remember that only in the last century it became possible to go to outer space and perform observations "outside" the atmosphere (first attempts to beat down atmospheric effects were made with balloon experiments[2], some 140-150 years ago, followed by the use of souding rockets[3] and then finally with satellites).

[1] `https://link.springer.com/book/10.1007/978-3-642-39835-3`

[2] For the history of scientific experiments in balloons see Pfotzer (1972) in `https://ui.adsabs.harvard.edu/abs/1972SSRv...13..199P/abstract` and Gaskin et al. (2014) in `https://www.worldscientific.com/doi/pdf/10.1142/S2251171714030019`. As they describe, it seems the first astronomical experiment in a balloon was made by Crocé-Spinelli & Sivel (1874). They used a spectroscope to investigate the origin of the water vapor lines detected in ground-based spectroscopic observations of the Sun. The experiment showed that the water vapor was from the Earth's atmosphere, see page 152 of this document for the original report in French. Both Crocé-Spinelli and Sivel ended up dying asphyxiated in another balloon flight in 1875 (see `https://www.atlasobscura.com/articles/the-balloonists-of-pere-lachaise-cemetery`).

[3] The first UV solar spectrum taken using a V-2 rocket was reported by Baum et al. (1946). These and additional data were analyzed in Durand et al. (1949). The early days of science with sounding rockets in the USA are summarized in the book "Beyond the Atmosphere: Early Years of Space Science" by Homer E. Newell Jr. (see page 75, Newell 2011). For a historical account of European activity with sounding rockets see Seibert (2006) in `https://www.esa.int/esapub/hsr/HSR_38.pdf`.

For the proper use and interpretation of ground-based observations, we need to understand the impact and limitations caused by the Earth's atmosphere. Such knowledge is also important for choosing the best sites on where to build new observing facilities.

The atmosphere of course does not have a well defined external boundary, but gets progressively less dense with altitude. For legal purposes, one usually adopts a line of 100 km above sea level as the division between the Earth's atmosphere and outer space. This is the so-called Kármán line (or von Kármán line) named after the Hungarian engineer and physicist Theodore von Kármán[4]. A drawing indicating the different atmospheric layers is shown in Fig. 1 and a table with height levels is shown in Fig. 2. Figure 3 gives information about the average composition of the atmospheric gases, which is important to understand the atmospheric effects on astronomical light.

The uppermost atmospheric layer is the exosphere. It starts at the so-called exobase, a level above which the density is low enough that the material is essentially collisionless. The exosphere extends at least to about 10 000 km, where the solar wind becomes the dominant component. In this region, a faint glow of UV radiation scattered by hydrogen has been detected by satellites and photographed from the moon. This UV glow is called the geocorona and might actually extend to farther distances (Baliukin et al. 2019)[5].

The atmosphere affects astronomical observations in several ways: i) through absorption and scattering of the radiation; ii) through refraction, which alters the apparent position of the object in a wavelength-dependent way; iii) through emission (line and thermal continuum), which affects spectra and creates a flux background; iv) through turbulence, which degrades the image; v) and through the ionosphere which affects radio observations at the lowest frequencies. All these phenomena cause effects that are not constant but vary with time and can also depend on geographical location.

3 Atmospheric extinction and emission

Some of the main concepts about atmospheric extinction to keep in mind:

- The atmosphere is opaque below ∼300 nm because of the ozone (O_3) layer. Ozone reaches a maximum concentration between altitudes of 15 to 30 km. Dioxygen (O_2) blocks radiation below ∼200 nm and N_2 below ∼100 nm.
- In the visible, atmospheric extinction reaches about 10 to 15%. Ozone also has absorption bands in the optical: the so-called Huggins band[6] between 310-370nm (Huggins & Huggins

[4] Apparently, the value of 100 km was never formally calculated by von Kármán. It just appeared as an order of magnitude estimation during discussions in a conference. The idea was to define the boundary where forces due to orbital dynamics exceed aerodynamic forces, but such boundary would not even define a fixed altitude, see McDowell (2018) in `https://ui.adsabs.harvard.edu/abs/2018AcAau.151..668M/abstract`.

[5] `https://ui.adsabs.harvard.edu/abs/2019JGRA..124..861B/abstract`

[6] Named after the English astronomer William Huggins, see `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_660`.

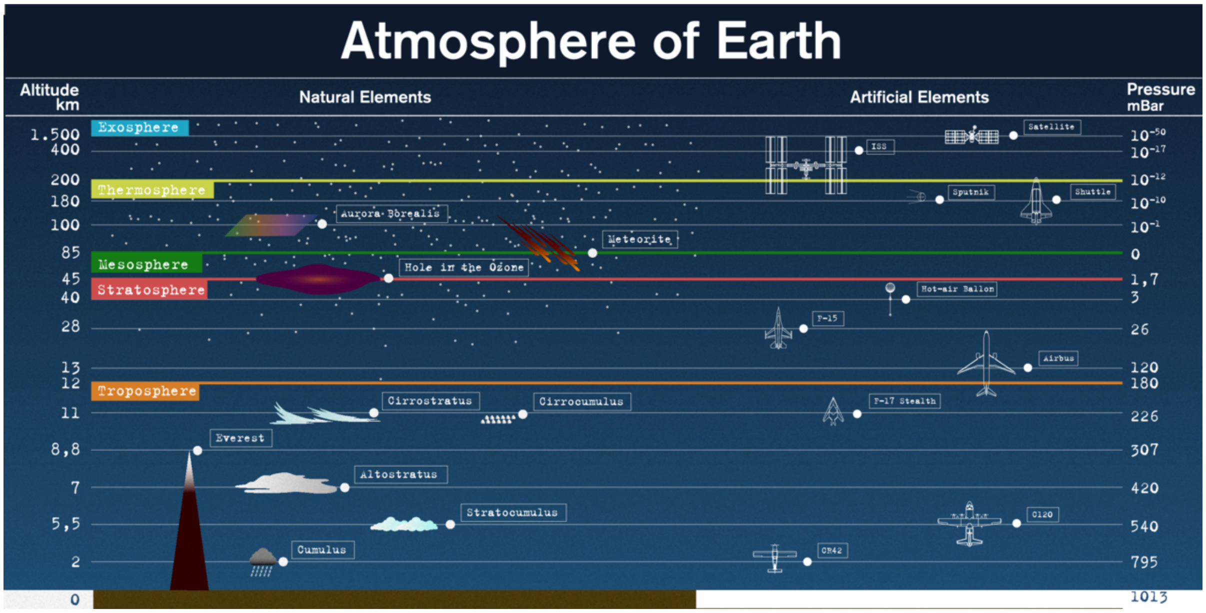

Figure 1: Atmospheric layers in comparison to several natural and artificial elements. Credit: Marco Saporiti, DensityDesign Research Lab. The image was released under CC-BY-SA licence, see here.

1891)[7] and the Chappuis bands[8] between 400 and 700 nm (Chappuis 1880)[9].

- Between 800-1350 nm (the near infrared; near-IR), there are absorption bands of water vapor and molecular oxygen. The atmosphere is never completely opaque. Vibration-rotation bands of O_2 and H_2O are relevant sources of absorption above ~600 nm. Entering the infrared, CO_2 and other gases become important, but the main source of absorption bands is still water vapor.

- Such absorption lines/bands are called telluric lines or telluric bands (telluric derives from the Latin *tellus* which means Earth). There are modern tools for simulating such bands for the correction of stellar data (e.g. Molecfit, see Smette et al. 2015)[10].

- Beyond 1300 nm, there are regions where the atmosphere is completely opaque and regions (called windows) where some light reaches the surface. These windows are the infrared bands shown in Fig. 4.

- Beyond ~2500 nm, the atmosphere is again totally opaque down to about 1 mm.

- After the radio wavelength band, the ionosphere becomes an issue, blocking radiation of wavelength longer than about 10m.

[7] `https://royalsocietypublishing.org/doi/10.1098/rspl.1890.0029` and for a more recent discussion see Qu et al. (2004) in `https://www.researchgate.net/publication/8097382_The_Huggins_band_of_ozone_A_theoretical_analysis`

[8] Named after the French chemist and physicist James Chappuis.

[9] See `https://gallica.bnf.fr/ark:/12148/bpt6k30485/f987.item` for the original in French or see Grebenshchikov et al. (2007) for a more recent discussion (in `https://www.iup.uni-bremen.de/~weber/ozone_papers/yu_PCCP2007_o3photodissociation.pdf`).

[10] https://ui.adsabs.harvard.edu/abs/2015A%26A...576A..77S/abstract

Table 11.20. *Atmospheric layers and transition levels.*

Layer	Height, h (km)	Characteristics
Troposphere	0–11	Weather, T decreases with h, radiative-convective equilibrium
Tropopause	11	Temperature minimum, limit of upward mixing of heat
Stratosphere	11–48	T increases with h due to absorption of solar UV by O_3, dry
Stratopause	48	Maximum heating due to absorption of solar UV by O_3
Mesosphere	48–85	T decreases with h
Mesopause	85	Coldest part of atmosphere, noctilucent clouds
Thermosphere	85–exobase	T increases with h, solar cycle and geomagnetic variations
Exobase	500–1000 km	
Exosphere	> exobase	Region of Rayleigh–Jeans escape
Ozonosphere	15–35 km	Ozone layer (full width at e^{-1} of maximum)
Ionosphere	> 70 km	Ionized layers
Homosphere	< 85 km	Major constituents well-mixed
Heterosphere	> 85 km	Constituents diffusively separate

Figure 2: Height of atmospheric layers and transition levels. Credit: Table 11.20 of Cox (2015), see `https://link.springer.com/book/10.1007/978-1-4612-1186-0`.

- Water vapor is the main absorber in the IR. The scale height of water vapor is about 2-3 km. Hence the advantage of telescopes at high altitudes, of flying IR instrumentation in balloons or airplanes, and of placing observing facilities in Antarctica where the amount of water vapor is considerably smaller.

- The amount of water vapor is usually expressed as the precipitable water vapor (PWV). This is the depth of liquid water (in mm) that would result if all the water vapor in an atmospheric column would get condensed and precipitate. The amount of water vapor in a site is highly variable.

- Scattering of radiation in the atmosphere is caused both by molecules and by aerosols suspended in the air.

- The so-called Rayleigh scattering[11] is the case when the scattering particles are much smaller than the wavelength of the radiation. The theory was originally worked out in a series of works by Rayleigh starting in Strutt (1871)[12]. A quantum version can be found in Vinogradov et al. (2021)[13]. See also Fig. 2.2 of the Lawrence (2013) book mentioned in Section 1 above.

- The Rayleigh scattering cross section is given by $\sigma_{\rm Rayleigh} = \frac{8\pi^3}{3}\frac{(n-1)^2}{\lambda^4 N^2}$, where n is the refraction index and N the number density of molecules.

- The so-called Mie scattering[14] (or sometimes called aerosol particle scattering) is the case of

[11] Named after Lord Rayleigh (John William Strutt), the same of the Rayleigh-Jeans law that we discussed earlier.

[12] `https://www.tandfonline.com/doi/abs/10.1080/14786447108640452?journalCode=tphm15`

[13] `https://ui.adsabs.harvard.edu/abs/2021OExpr..29.2501V/abstract`

[14] Named after the German physicist Gustav Mie. The theory is presented in Mie (1908), which you can find in `https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/andp.19083300302` (in German). Alternatively, have a look at this 2009 special edition of the Journal of Quantitative Spectroscopy and Radiative Transfer commemorating 100 years of Mie's 1908 publication. And you can read a short biography of Mie in Stout & Bonod (2020), see

Table 11.18. *Gases in the well-mixed atmosphere.*

Gas	Molecular weight	Fraction of dry air at surface: volume percent	Fraction of dry air at surface: weight percent	Column amount (atm-cm)[a]
N_2[b]	28.013	78.08	75.52	6.24×10^5
O_2[c]	31.999	20.95	23.14	1.67×10^5
H_2O[def]	18.015	$2 \times 10^{-6} - 3 \times 10^{-2}$	$3 \times 10^{-6} - 5 \times 10^{-2}$	1760
Ar[g]	39.948	9.34×10^{-3}	12.9×10^{-3}	7470
CO_2[c]	44.010	3.45×10^{-4}	5.24×10^{-4}	276
Ne[g]	20.183	18.2×10^{-6}	12.7×10^{-6}	14.6
He[g]	4.003	5.24×10^{-6}	0.724×10^{-6}	4.2
CH_4[h]	16.043	1.72×10^{-6}	0.95×10^{-6}	1.3
Kr[g]	83.80	1.14×10^{-6}	3.30×10^{-6}	0.91
CO[de]	28.010	1.5×10^{-7}	1.5×10^{-7}	0.089
SO_2[de]	64.06	3×10^{-10}	7×10^{-10}	1.1×10^{-4}
H_2[i]	2.016	5.0×10^{-7}	0.35×10^{-7}	0.4
N_2O[j]	44.012	3.1×10^{-7}	4.7×10^{-7}	0.25
O_3[dek]	47.998	$3.0\text{–}6.5 \times 10^{-8}$	$5.0\text{–}11 \times 10^{-8}$	0.343
Xe[g]	131.30	8.7×10^{-8}	39.4×10^{-8}	0.07
NO_2[d]	46.006	2.3×10^{-11}	3.9×10^{-11}	2.0×10^{-4}
HNO_3[d]	63.02	5×10^{-11}	11×10^{-11}	3.6×10^{-4}
NO[de]	30.006	3×10^{-10}	3×10^{-10}	3.1×10^{-4}
$CFCl_3$[l]	137.37	2.8×10^{-10}	13×10^{-10}	2.2×10^{-4}
CF_2Cl_2[l]	120.91	4.8×10^{-10}	20×10^{-10}	3.8×10^{-4}

Figure 3: Composition of the atmospheric gases. Credit: Table 11.18 of Cox (2015), see `https://link.springer.com/book/10.1007/978-1-4612-1186-0`.

scattering by small particles with sizes close to the wavelength of the radiation. The expression for this scattering is more complicated and depends on the abundance, composition, and size distribution of the particles. For things like water droplets or dust grains (such as silicates) the cross section is proportional to $\propto \lambda^{-1}$. An example is shown in Fig. 5.

- The contribution of aerosols (dust, pollen, smoke, water droplets in clouds) is very variable and depends on weather, pollution, volcanic events, etc.
- The total effect of atmospheric extinction depends also on the zenith angle (z), i.e. on the amount of atmosphere the light is crossing. To quantify this, usually the concept of "airmass" is introduced. Airmass is the ratio between the size of the atmosphere in the direction of observation and the size in the zenith direction. If you can approximate the atmosphere as a series of parallel layers, then the change in magnitude can be expressed as a function of z, actually $\sec z$, which is what we call airmass. At large zenith angles, however, the approximation as a function of $\sec z$ breaks down as one has to take into account Earth's curvature (See Section 3 of Chapter 3 of Rozenberg 1966)[15].

If you are interested to read an investigation about the atmospheric extinction over the Cerro Paranal Observatory, have a look at Patat et al. (2011)[16]. If you want to know how the atmosphere

`https://www.photoniques.com/articles/photon/pdf/2020/02/photon2020101p22.pdf`.

[15] `https://link.springer.com/book/10.1007/978-1-4899-6353-6`

[16] `https://ui.adsabs.harvard.edu/abs/2011A%26A...527A..91P/abstract`

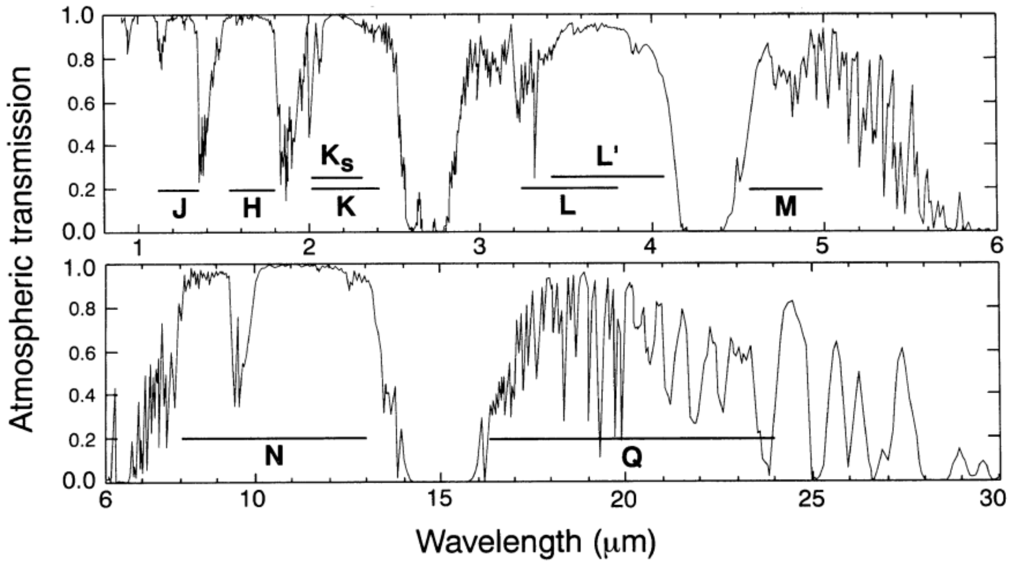

Figure 4: Atmospheric transmission and windows in the infrared. Credit: Figure 7.1 of Cox (2015).

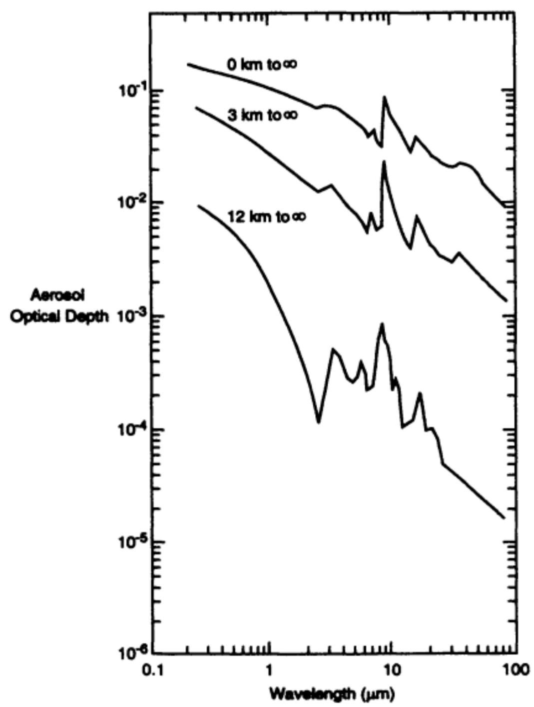

Figure 5: Integrated aerosol optical depth from the study of Toon et al. (1976) involving ammonium sulfate, aluminum oxide, and sodium chloride. Credit: Figure 11.1 of Cox (2015).

is taken into account when planning observations with ESO telescopes, see the document called The Cerro Paranal Advanced Sky Model.

Now, a short list of some of the main concepts about atmospheric emission and background light to keep in mind:

- In optical and infrared, the main sources of atmospheric emission are scattered light and airglow. In the mid-IR, thermal emission becomes important (of Earth, but also of everything around including the telescope, the instrument, etc). And in radio you can have interference from terrestrial radio signals.
- The Moon is an important source of scattered light during the night. For faint sources, you will want to observe in dark time, when the Moon is not visible. Even for brighter sources, you will want to take care and point your telescope keeping a certain Moon distance. See Fig. 6 for an illustration of the Moon effect in visible wavelengths.
- Light pollution from human activity can be a problem, but most large professional observatories are built in isolated places.
- Although not an atmospheric source of background, satellite constellations are becoming a concern as an important source of contamination, see Williams et al. (2021)[17].
- Airglow at night is dominated by emission from the recombination of atoms and molecules, that were affected by solar radiation during the day, at heights between 100 and 300 km.
- Although not an atmospheric source, zodiacal light contributes with a certain fraction of night sky brightness. Zodiacal light is caused by emission from small dust grains in the inner solar system[18]. See Fig. 7 for a comparison of all contributions in the case of Paranal when the Moon is above the horizon.

For a short discussion concerning airglow over ESO observatories see Christensen et al. (2016)[19]. To read more about zodiacal light over ESO observatories see Horálek et al. (2016)[20] and you can follow the references in there to dig deeper in the subject. For additional discussions on the night sky of Paranal, see Patat (2003, 2004, 2008)[21] and also Noll et al. (2012)[22] for a model of atmospheric radiation in Paranal. For curiosity, Fig. 8 displays a Table with the sky brightness during dark time in Paranal in visible bands.

For a more general (i.e., not limited to Paranal or ESO facilities), but older discussion see "The Light of the Night Sky" by Roach & Gordon (1973)[23] and for a more recent reference (although still old...) see Leinert et al. (1998)[24].

[17] https://arxiv.org/abs/2108.04005

[18] The PhD thesis of Brian May, guitar player of Queen, was on the topic of zodiacal light, see May (2008) in https://spiral.imperial.ac.uk/bitstream/10044/1/1333/1/May-BH-2007-PhD-Thesis.pdf.

[19] https://ui.adsabs.harvard.edu/abs/2016Msngr.163...40C/abstract

[20] https://ui.adsabs.harvard.edu/abs/2016Msngr.164...45H/abstract

[21] See https://ui.adsabs.harvard.edu/abs/2003A%26A...400.1183P/abstract, https://ui.adsabs.harvard.edu/abs/2004Msngr.118...11P/abstract, and https://ui.adsabs.harvard.edu/abs/2008A%26A...481..575P/abstract

[22] https://ui.adsabs.harvard.edu/abs/2012A%26A...543A..92N/abstract

[23] https://link.springer.com/book/10.1007/978-94-010-2553-9

[24] https://ui.adsabs.harvard.edu/abs/1998A%26AS..127....1L/abstract

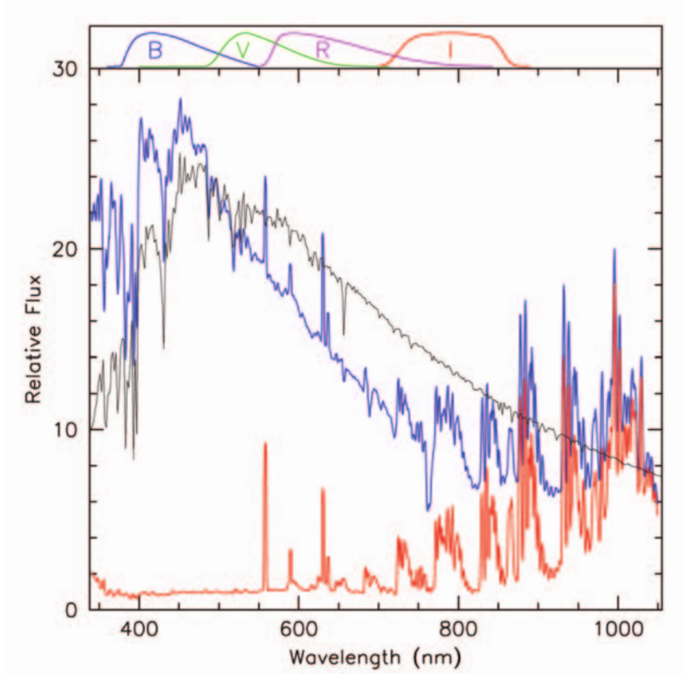

Figure 6: Comparison between a spectrum taken at dark time in Paranal (red line) with one taken at bright time (i.e., with the Moon shinning on the sky, blue line). Credit: Figure 2 of Patat (2004).

You can also have a look at the report[25] that originated from work for the "Dark and Quiet Skies Workshop", co-sponsored by the IAU, the Instituto de Astrofisica de Canarias (IAC), and the United Nations Office of Outer Space Affairs (UN-OOSA), whose aim was to prepare a set of policy recommendations[26] for the United Nations on dark and quiet sky protection.

3.1 Refraction

- Atmospheric refraction changes the apparent position of the object being observed, so that it appears to have a smaller zenith angle. The change itself is a function of zenith angle (or of airmass), being larger the farther away from the zenith we observe.
- The amount of water vapor can cause (small) changes in the refractive index of the air and thus affects the amount of refraction.
- The refractive index also depends on wavelength. Blue light is refracted to a larger angle than red light. This effect is usually called atmospheric dispersion. At the zenith, this differential effect is very small and can be ignored, but at larger zenith angles the effect can amount to several arcseconds (so the blue image of your source does not coincide with the red image of the same source).
- One way to counteract this chromatic effect is by inserting an optical element called atmospheric dispersion corrector (ADC) in the light path between the telescope and the instrument.

[25] `https://www.iau.org/static/publications/dqskies-book-29-12-20.pdf`
[26] `https://www.iau.org/static/publications/uncopuos-stsc-crp-8jan2021.pdf`

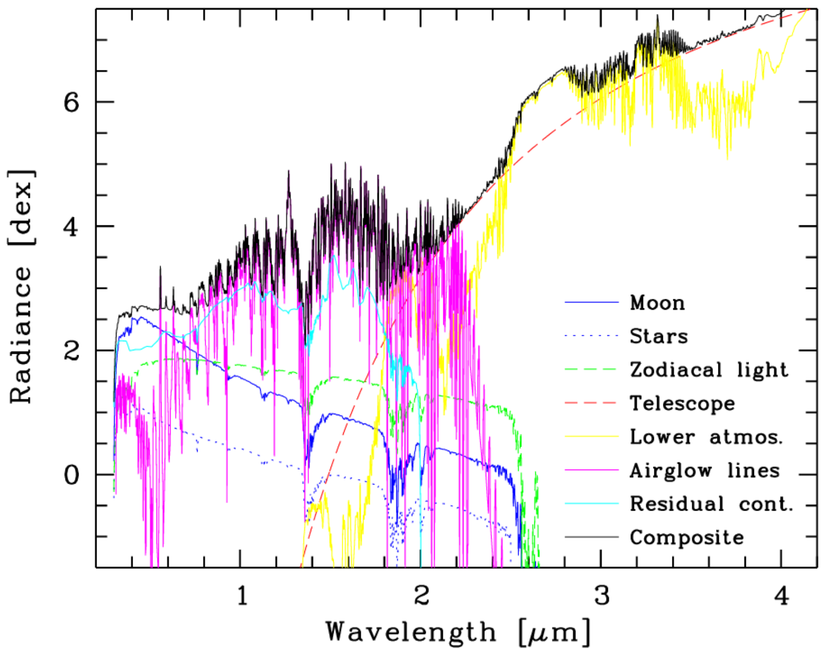

Figure 7: Components of the sky emission model over Paranal. Credit: Figure 1 of Noll et al. (2012).

Table 3. Zenith-corrected average sky brightness during dark time at Paranal.

Filter	Sky Br.	σ	Min	Max	$N_{\rm dark}$	$\Delta m_{\rm ZL}$	$N_{\rm tot}$
U	22.35	0.19	21.89	22.78	129	0.20	264
B	22.67	0.16	22.19	23.02	493	0.28	1400
V	21.71	0.24	21.02	22.30	692	0.20	1836
R	20.93	0.24	20.42	21.56	1285	0.16	3931
I	19.65	0.28	18.85	20.56	1137	0.07	3001
Total					3736		10 432

Note: Values are expressed in mag arcsec^{-2}. Columns 3 to 8 show the rms deviation, minimum and maximum brightness, number of dark-time data points, expected average contribution from the zodiacal light, and total number of data points.

Figure 8: Sky brightness during dark time in Paranal. Credit: Table 3 of Patat (2008).

Table 11.24. *Refractive index n and refraction R versus wavelength λ.*[a]

λ(nm)	$(n_d - 1) \times 10^6$	$-(n_w - 1) \times 10^6$	$(n - 1) \times 10^6$	R (arcsec)
200	341.9	0.19	341.7	70.44
220	329.4	0.20	329.2	67.87
240	321.2	0.20	321.0	66.18
260	315.3	0.21	315.1	64.96
280	310.9	0.21	310.7	64.06
300	307.6	0.22	307.2	63.34
320	304.9	0.22	304.7	62.82
340	302.7	0.22	302.5	62.37
360	301.0	0.22	300.8	62.02
380	299.5	0.22	299.3	61.71
400	298.3	0.22	298.1	61.46
450	295.9	0.23	295.7	60.97
500	294.3	0.23	294.1	60.64
550	293.1	0.23	292.9	60.39
600	292.2	0.23	292.0	60.20
650	291.5	0.23	291.3	60.06
700	290.9	0.23	290.7	59.94
800	290.1	0.23	289.9	59.77
900	289.6	0.23	289.4	59.67
1000	289.2	0.23	289.0	59.58
1200	288.7	0.23	288.5	59.48
1400	288.4	0.24	288.2	59.42
1600	288.2	0.24	288.0	59.38
1800	288.1	0.24	287.9	59.36
2000	288.0	0.24	287.8	59.34
3000	287.7	0.24	287.5	59.28
4000	287.7	0.24	287.5	59.28
5000	287.6	0.24	287.4	59.26
7000	287.6	0.24	287.4	59.26
10000	287.6	0.24	287.4	59.26

Note

[a]Refractive index n_d is for dry air at $T_0 = 273.15$ K and $P_0 = 1\,013.25 \times 10^2$ Pa and the correction n_w for water vapor is for $P_w = 550$ Pa. For other temperatures and pressures multiply $n_d - 1$ by PT_0/P_0T and for other vapor pressures multiply $n_w - 1$ by p_w/p_0. Refraction $R = (n^2 - 1)/(2n^2) \cong n - 1$ in arc seconds.

Figure 9: Refraction angle, R, as a function of wavelength. The table also shows the refractive index and the correction needed because of water vapour. Credit: Table 11.24 of Cox (2015)

- For radio waves, there is no dependence of the refractive index with wavelength anymore, but the small effect of water vapour is still present.
- For long-wavelength radio waves, the effect of going through the ionosphere is stronger, and they can be completely reflected.

If you are curious about the equations for the refractive index and the angle of refraction, the place to look is Allen's Astrophysical Quantities book (Cox 2015), Section 11.20, and references therein. For the effects of the ionosphere, you can have a look at the same book, on a few of the Sections just after 11.20. In Fig. 9 you can see how the refraction angle (R, given in arcsec) changes with wavelength. Its not clear for me, however, what zenith angle is assumed there. In any case, you can see for example, that between 300 and 500nm the image of the object can be displaced by something like ∼3 arcsec. Yes, that's small, but think about a spectroscopic observation where the slit has 1 arcsec width. Imagine you want to get the blue part of the spectrum, but your guiding camera is observing in the red, and thus your slit is centered on the red image. You might be missing all of the blue light that you wanted to collect...

3.2 Turbulence

- The atmosphere is not a stable structure. There are three main causes of turbulence that can affect astronomical observations: dome seeing caused by convection inside the telescope dome; ground layer turbulence caused winds colliding with the structures at the observing site; and the atmospheric turbulence proper, happening in different layers of the atmosphere.

- Modern observing facilities are equipped with technology to decrease the effect of dome seeing and ground layer turbulence.

- Atmospheric turbulence is caused by wind and convection that mixes regions of different temperatures, which have slightly different refractive indexes. This results in constant change in the direction and intensity of the light passing through the atmosphere. The results include the effects known as seeing and scintillation.

- Seeing is the random variation in the direction of light arriving at the telescope, which produces a broadening of the astronomical image.

- Scintillation is the random variation in the intensity of the arriving light; the effect that causes the twinkling of the stars. Scintillation mainly affects systems of small aperture (including the human eye); for large telescopes the effect is averaged and becomes less important. However, there are areas of research that require high-precision photometry (e.g. exoplanets, asteroseismology) where scintillation can be a worry (see a related discussion in Osborn et al. 2015)[27].

- Difraction causes a telescope of diameter D, observing at wavelength λ, to produce an image of size $\theta \sim 1.22(\lambda/D)$. For the VLT (8m), this translates into a disk of 0.016 arcsec. The median seeing at Paranal is 50 times larger, of about 0.8 arcsec.

- Some instruments can do very short exposures of stars, the resulting images show a series of spots, which are the star image dancing around the field. These spots are called "speckles". Speckle imaging is an interesting technique to reveal, for example, companions in multiple stellar systems whose separation is smaller than the typical seeing.

- In turbulence theory, one defines the Fried parameter[28] or Fried length, r_0, which helps to characterize the seeing. You can think about it as the diameter of a bundle of rays that travel through the atmosphere together and still arrive parallel and in phase at the telescope. The Fried parameter is a function of wavelength, $r_0 \propto \lambda^{6/5}$.

- The seeing causes a quasi-Gaussian point spread function (PSF). For a telescope that has a large diameter when compared to r_0, the full width at half maximum (FWHM) of the PSF can be written as FWHM $= 0.98\ \lambda/r_0$. So the seeing varies with $\lambda^{-1/5}$ (a seeig of 1 arcsec at 300nm, at the blue edge, would translate to 0.9 arcsec at 500nm and 0.7 arcsec at 2 μm, in the infrared.).

- Adaptive optics (see e.g. Davies & Kasper 2012; Guyon 2018)[29] has been developed as a way to try to mitigate the effects of seeing. We will come back to this topic at a later opportunity.

[27] `https://ui.adsabs.harvard.edu/abs/2015MNRAS.452.1707O/abstract`

[28] Named after David L. Fried, an American scientist. For the theory, see for example Fried (1966) in here

[29] `https://ui.adsabs.harvard.edu/abs/2012ARA%26A..50..305D/abstract` and `https://ui.adsabs.harvard.edu/abs/2018ARA%26A..56..315G/abstract`

Adaptive optics has allowed basically difraction-limited images in the infrared, with current technology steadily pushing towards obtaining the same at visible wavelengths.

- Large observing facilities are equipped with seeing monitors, small telescopes dedicated to measuring the image quality. These are now usually of the type Differential Image Motion Monitor (DIMM), which uses two apertures to monitor the same star. The differential method[30] cancels out other sources of error, like tracking issues or wind shake. The measurement is then directly related to r_0, which is connected to the seeing. In some places you might read about the DIMM seeing, which is the seeing estimated by such monitor.

- Another effect caused by atmospheric turbulence is the phase delay. A wavefront that is passing through two nearby regions of different refractive index is essentially moving through different optical path lengths. This introduces a phase difference and at a given time different parts of a telescope might not be looking at the same wavefront. This is an important consideration for interferometry.

Atmospheric turbulence can be modelled by the Kolmogorov[31] theory. If you are interested in more details, see Quirrenbach (2000, 2013)[32] and references therein.

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[30] See Fried (1975) in https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/RS010i001p00071 and Roddier (1981) in https://www.sciencedirect.com/science/article/pii/S007966380870204X

[31] Named after the Russian mathematician Andrey Nikolaevich Kolmogorov, who contributed to several different disciplines. In 1941, he published three papers (in Russian) with his version of a turbulence theory. Citation to the original works are given as 1) Dokl. Acad. Nauk. SSSR 30, 9–13, 1941; Dokl. Acad. Nauk. SSSR 31, 538–540, 1941; and Dokl. Acad. Nauk. SSSR 32, 16–18, 1941. An English translation of the two first papers exists in Kolmogorov (1991b,a), see https://www.jstor.org/stable/51980 and https://www.jstor.org/stable/51981.

[32] Page 71 of https://core.ac.uk/download/pdf/79046071.pdf and http://cfao.ucolick.org/aosummer/book/pdf/3.1_quirrenbach.pdf

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