ASTR469 Lecture 5: Effects of the Atmosphere and Dust (Ch. 7)

1 Airmass

In an earlier lecture we mentioned that some wavelengths must be observed from space, because the atmosphere blocks that light. In radio bands, the sky is pretty transparent (low optical depth). The atmospheric optical depth the optical and near-infrared is low, but non-zero, so we must determine how the atmosphere changes our observations.

Atmospheric effects depend on how much air you're looking through, and we can define the amount of atmosphere using a parameter called **"airmass."** We want to normalize this parameter by the smallest amount of atmosphere a sight line can traverse, which is when looking straight up (zenith). All other sight lines will pass through more atmosphere. We define the "zenith angle," z as how far from straight up you're looking. The horizon is by definition at $z = \pi/2\,\mathrm{rad}$ (90 degrees from straight up). See Fig. 1 for a visual of this.

If we model the atmosphere as "plane parallel" (no curvature) then the amount of atmosphere that the light coming to the telescope passes through is proportional to the secant of z (as you can infer from Fig. 1). We define the **airmass** X as a scaling based on what factor *more* atmosphere you're looking through than straight up:

$$X = \sec(z)\,. \tag{1}$$

You probably don't have much experience with secant; it just means $1/\cos(z)$.

Of course, this is only approximate because the Earth is not flat, and neither is the atmosphere. More accurately accounting for curvature:

$$X = \sec(z)[1 - 0.0012(\sec^2(z) - 1)] \tag{2}$$

Looking straight up ($z = 0$), we see that we recover $X = 1$. If $z = 30\,^\circ$, $\sec 30\,^\circ = \frac{2}{3^{0.5}} = 1.1547$, and the exact expression gives 1.1542. It's generally a small correction, but becomes large with $z > 60\,^\circ$.

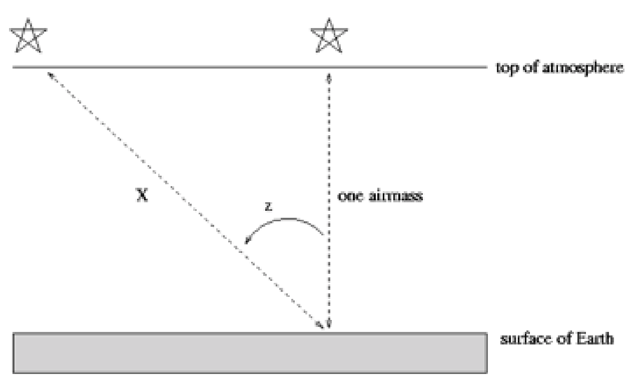

Figure 1: Visual for zenith angle and (simplified) airmass.

2 Absorption and Scattering

The airmass is not just a theoretical construct. We can plot the airmass versus the apparent magnitude to chart the amount of "extinction" caused by the atmosphere, as shown in the plot on question 2 of these lecture notes. "Extinction" refers to a decrease in intensity due to an intervening medium. This may be caused by both **absorption** and **scattering**, which are closely-related but distinct phenomena. In absorption, a photon excites a dust particle. This dust particle can then re-emit at a different wavelength. In scattering, the photon is immediately re-emitted at a different direction but with the same frequency (and therefore energy). In both cases, the photon is removed from the line of sight, and so the net effect is the same. In fact, we often combine both into the term *attenuation* or *extinction*.

In space "dust" does much of the absorption and scattering at many wavelengths (it is frequently dust in our atmosphere that causes the extinction as well). Dust are macroscopic particles that are either carbon- or silicate-based. Unlike atmospheric extinction, we can't create a general model for cosmic extinction; it depends on the distribution and properties of dust along the sight line.

Our atmosphere absorbs some light and scatters some light (think of a red sunset/red moon). The setting Sun actually tells us that this effect is dependent on how much atmosphere you're looking through (more atmosphere when Sun is close to horizon=red), and is thus dependent on your zenith angle.

One can calculate the relationship between airmass and extinction both theoretically and empirically. Let's consider theory briefly. The equation of radiative transfer was in the Lecture 3 notes. If we're looking through the atmosphere, some light might be lost due to atmospheric attenuation. The second term (with $B_\nu(T)$ in it) is close to zero if the atmosphere is mostly transparent; that is, the atmosphere itself does not contribute any light. So, we're just stuck with some absorption of the background (star) signal, I_0:

$$I_\nu(\tau_\nu) = I_0 e^{-\tau_\nu} = I_0 e^{-\int \kappa_\nu ds}, \tag{3}$$

Where τ_ν is the amount of opacity we're seeing in the atmosphere and I_ν is the amount of light we actually observe. Or, in terms of airmass:

$$I_{\rm obs}(X) = I_0 e^{-qX} \,. \tag{4}$$

Here, q is some factor that depends on the properties of the atmosphere.

We can also use this to show that the change in a star's brightness in magnitudes as it goes through different airmass X is approximately:

$$m(X) = m_0 + kX \tag{5}$$

where m_0 is the magnitude outside the atmosphere, and k is again some constant which depends upon properties of the local atmosphere and the wavelength of light. What a convenient equation! It's just a linear function.

We call the coefficient k the "first order extinction coefficient." If one observes through the standard Johnson-Cousins UBVRI filters, one finds typical values

filter	k
U	0.6
B	0.4
V	0.2
R	0.1
I	0.08

Although these are average values, k depends on the conditions at the time of observation, and so changes every night (e.g. haze, temperature, smog), and changes between locations (e.g. altitude, climate). The better the observing site, and the clearer the night, the smaller the extinction coefficient. If one is trying to correct for extinction, one must determine the first-order coefficient since the air changes from one night to the next; in fact, some astronomers observe multiple times to solve for variations in extinction over the course of a night (e.g. example on self-quiz).

The power of this relationship is that if the constant k can be determined through observations, we can estimate the true magnitude by inferring the magnitude at $X = 0$ by linear extrapolation (i. e. m_0 is the intercept of the line).

If we wanted to be really precise, the actual correction is not a simple linear fit, there are higher order terms. But, first order is ok for most purposes.

Refraction

Some time in your physics education you should have seen Snell's law:

$$\mu_1 \sin(\theta_{\rm I}) = \mu_2 \sin(\theta_{\rm R}) \ , \tag{6}$$

Where a ray of light coming from medium 1 into medium 2 will start off coming in at angle $\theta_{\rm I}$ and be redirected with a new angle $\theta_{\rm R}$.

Refraction changes the apparent position of stars when their light passes into our atmosphere! Since the index of refraction is larger for the atmosphere than for space, Snell's Law requires that light is bent towards the normal, so stars should be higher in the sky than they otherwise would. Like refraction, this effect is more prevalent at low elevations.

You have seen refraction when you notice the setting Sun turn into an oval. The Sun is actually below the horizon at sunset by around $35'$ (approximately one Solar diameter).

The problem with treating refraction theoretically is that the atmosphere has different layers of varying density and temperature. The amount of refraction is pressure dependent, and so is complicated by the various layers.

Birney says that it can be shown that the only layer that matters is the final one. We can therefore define an angle of refraction

$$R \simeq C \tan z' \tag{7}$$

Where C is a constant and z' is the *observed* zenith angle (not the real one of the source). For z' less than 45°, C may be assigned a value of $1'$. Things again get much more complicated at larger values of the zenith angle.

Empirically there's a good formula called Comstock's formula that gives you the value w.r.t. local atmospheric conditions: barometric pressure b in mmHg and temperature T in Kelvin:

$$\theta_\mathrm{R} \simeq 60.4 \left(\frac{b/760}{T/273} \right) \tan(z') \,\mathrm{arcseconds} \tag{8}$$

This works accurately to angles $z \lesssim 75°$.

Seeing

The atmosphere also distorts astronomical observations in other ways:

1. Stars twinkle (scintillation)
2. Images are blurred
3. The locations of stars in images changes with time

These three effects can be called collectively "seeing," although often scintillation is addressed separately.

Seeing is caused by the non-uniformity of the Earth's atmosphere. The atmosphere is composed of "cells" that have similar temperatures and densities. Adjacent light rays will encounter different cells. This means that adjacent light rays will be diffracted by different amounts.

This leads to image blurring. The diffraction limit discussed earlier is the theoretical best performance you can expect. Real telescopes on Earth almost never reach the diffraction limit due to seeing. "Seeing" is always measured as an angle θ_s: how much a star is blurred or jiggled. As you may expect, seeing gets worse towards the horizon:

$$\theta_\mathrm{s} = \theta_\mathrm{s0} X^{\frac{3}{5}} , \tag{9}$$

where $\theta_s 0$ is the seeing at zenith ($X = 1$).

Seeing ranges from around $1''$ (very good) to $10''$ (very bad), and is caused by cells of air in the atmosphere, most of which are $\sim 7\,\mathrm{km}$ up. If you want to quantify seeing, you can measure the size of a star. This size is the seeing plus the telescope diffraction, added in quadrature. We can correct for seeing using adaptive optics. In adaptive optics, the telescope mirrors are deformed in real time to correct for seeing. Of course, building your telescope at high altitudes in a site without much air turbulence will lessen this effect!

Assess yourself/study guide after lecture & reading (without peeking at notes)...

1. Describe how the atmosphere changes the appearance of the Sun (and moon) as it sets. In your answer, also describe the physical mechanism.

2. For the plot shown below, what is the star's unattenuated magnitude (magnitude before it enters the atmosphere), and what is the value of k?

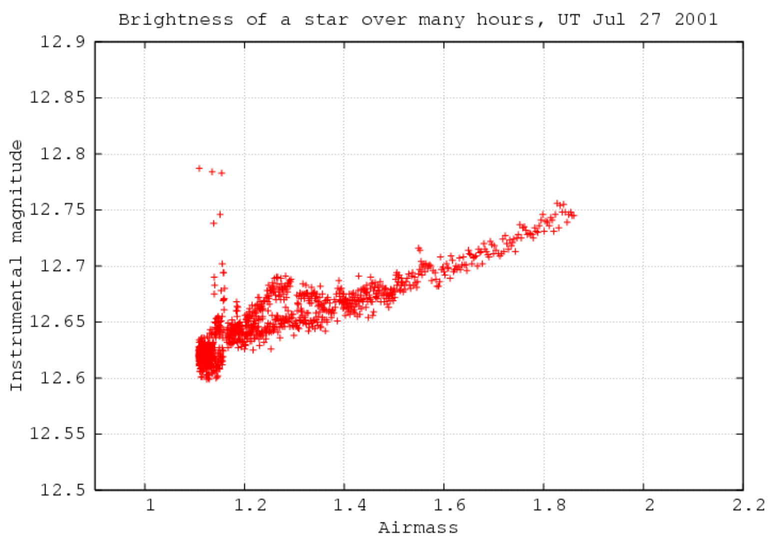

Figure 2: Apparent magnitude of a star as a function of airmass. Each cross is one observation of the same star.