Atmospheric effects

1. Basics & Nomenclature

Ground-based astronomers must reckon with the effect of the atmosphere on their observations. The atmosphere imprints wavelength-dependent absorption on the incoming light. It glows with a complex, time-dependent and space-dependent spectrum. It refracts the light as a function of zenith angle and wavelength. Finally, turbulence in the atmosphere distorts the incoming light's wave fronts, leading to image motion and blur.

When calculating the effects of the atmosphere, the zenith angle z is a critical factor. In the plane-parallel approximation, which virtually always holds, the column density of atmosphere at z scales as the *airmass*, $a = 1/\cos z$.

Figure 1 shows the atmospheric transmission at zenith $t(z = 0°)$ as a function of wavelength at sea level. The transmission at other airmasses is:

$$t(z) = [t(z = 0°)]^a, \tag{1}$$

where a is the airmass. It also depends on height above sea level. The sharp absorption features are known as *telluric lines*; the strongest of these are the Fraunhofer A and B bands around 7000–7500 Å, due to O_2.

The ultraviolet and higher energy photons are essentially entirely absorbed below 3500 $Å$, mostly due to ozone. Starting in the near-infrared and continuing to about mm wavelengths, the atmosphere has strong absorption bands associated with water vapor and carbon dioxide. The exact level of absorption depends on the humidity, pressure, and temperature. This means the transmission spectra depends on time and the average conditions vary considerably between different locations. Favorable locations include but are not limited to the high deserts of Chile and the South Pole.

Figure 2 shows the atmospheric emission as a function of wavelength. The components of this emission include a scattered light component. This scattered light comes primarily from ground sources and the Moon. When the Moon is out it tends to dominate the continuum regions of the sky spectra; this spectrum then resembles the solar spectrum. Other scattered light yields a spectrum that reflects the light source, often from mercury or sodium lines due to artificial lighting (with the sodium lines occasionally containing a broad component due to high pressure sodium lamps; Osterbrock et al. 1976). The scattered light emission is dependent on Moon phase and angle to the Moon (or to other sources) and is fairly smoothly varying in time and angle.

Emission also originates from the atmosphere itself. In the optical and near-infrared, this emission is dominated by fluorescence due to excitation of atoms and molecules, known as *airglow*. Neutral oxygen has several important lines, and OH exhibits a suite of rotation-vibrational modes

(Osterbrock et al. 1996, 1997). The airglow varies rapidly in time (over tens of minutes) and in angle (on scales of tens of arcminutes). Past 2–3 microns, the spectrum starts to be dominated by thermal emission (though at these wavelengths the telescope itself becomes the more important background).

An important source of background emission is also the *zodiacal light*, which originates in the Solar System and concentrated to the ecliptic plane, with a complex dependence on angle.

The light that is transmitted from outside the atmosphere to the telescope is also refracted by the atmosphere. At reasonable zenith angles and almost all conditions, the atmosphere can be treated as plane parallel, and all that matters for the refraction effects is the index of refraction at the telescope. This index depends primarily on pressure (and thus altitude) and to a lesser extent on temperature and relative humidity. Snell's Law is a strong enough function of zenith angle that for fields of view above a few arcminutes, usually one needs to worry about differential refraction across the field inducing both a monopole and a quadrupole distortion.

Because the index of refraction is a function of wavelength, the refraction means that the images of different wavelengths will appear in different locations. In this way, the atmosphere acts as a weak prism, dispersing the light along the direction to and from zenith, called the *parallactic angle*. This effect can be up to a couple of arcseconds and so be very significant.

Finally, the light being transmitted usually arrives at the atmosphere from infinity in plane waves, except in the case of radio waves which experience interstellar scintillation. These plane waves are distorted when passing through the atmosphere. These distortions occur because of turbulent mixing between atmospheric layers with different indices of refraction, which cause fluctuations in the wave fronts. These distortions are known generically as *seeing*.

Under good conditions, the seeing is dominated by a turbulent surface layer near the telescope and a handful of thin turbulent layers within a few kilometers of the surface. The index of refraction varies over short length scales in these turbulent layers. The variation of this index leads the electromagnetic plane waves to become wrinkled in a time-dependent fashion. The coherence length of the waves r_0 depends on conditions, but under reasonably good conditions is about 20 cm and because of the variation of the index of refraction with wavelength scales as $\lambda^{6/5}$.

This coherence length sets the diffraction limit for ground-based telescopes. This means that optical observations are typically limited to ~ 1 arcsec FWHM resolution, and that telescopes above a diameter of about 20 cm do not continue to benefit from better diffraction limits.

Because the distortion of the wavefronts on larger scales than the telescope diameter varies over time, it contributes to image motion over time; that is, the diffraction limited spot changes location. For long enough exposures this effect will also contribute to the effective resolution of the image. This effect is more severe the smaller the telescope.

The shape of the atmospheric point spread function within a few times the FWHM can be predicted from a study of turbulence. The power spectrum of effect of Kolmogorov turbulence on the atmospheric wavefront can be translated into the PSF, as described by Fried (1966) and Johnson (1973). The resulting shape of the PSF within a few FWHM is well-approximated by a Moffat function:

$$I(\theta) = \frac{I_0}{\left[1 + (\theta/R)^2\right]^\beta} \tag{2}$$

with $\beta \approx 4$. This region of the PSF is often also approximated by a double Gaussian. Beyond 5–10 FWHM, the profile flattens and is proportional to θ^{-2} and is called the *aureole*; its source is unclear, and may not be due to the atmosphere and instead due to small-scale variations in the mirror around its ideal shape.

Adaptive optics systems seek to mitigate the atmospheric diffraction effects by correcting the wavefront of the incoming light to make it coherent across the pupil and restore the full aperture's diffraction limit. These systems monitor one or more bright stars in the field of view, or artificial stars creating by using a laser to excite sodium atoms in a sodium-rich atmospheric layer about 90 km height, above most of the atmospheric turbulence.

2. Key References

- *Design and Construction of Large Telescopes*, Bely (2003)
- *SkyCorr model of sky emission*, Noll et al. (2014)

3. Order-of-magnitude Exercises

1. A typical specific intensity for the sky continuum in the optical is $f_\nu \sim 10$ μJy arcsec^{-2}. Convert this to AB magnitudes per square arcsecond. In 1 arcsec FWHM seeing, for a point source, at what magnitude is there as much light within the FWHM from the sky as from the source?

4. Analytic Exercises

1. Derive the dependence of the parallactic angle for a field on its altitude, azimuth, and the latitude of the observatory.

5. Numerics and Data Exercises

1. Use the equations for refraction published by Stone (1996) to calculate the angular difference due to chromatic atmospheric differential refraction of the image center location as a function

of wavelength. For airmass of 1.2, what is the difference in image location between wavelength 4000 Åand wavelength 9000 Å?

2. The SDSS imaging camera worked by taking long continuous drift scans, often hours in length. These drift scans were broken up artificially in fields. In the SDSS CasJobs database, you can find all the information for each field, including the estimate of its sky brightness, in the Field table. Find one of the runs which has at least 200 fields, and retrieve the information for one of its `camcols` (say, number 3). Plot the g-band sky brightness as a function of field number and as a function of airmass for these observations. Plot the i-band sky brightness.

3. Take ten random plates from the BOSS spectroscopic survey in SDSS. Determine the phase and altitude of the Moon for the time of each observation, and sort by the Moon illumination. If the Moon altitude is below the horizon, treat the illumination as zero. Plot the mean sky spectrum from the sky fibers for each plate on the same plot, labeled according to Moon illumination, and comment on what you find.

4. Take a single random plate from the BOSS spectroscopic survey. Plot several sky fiber spectra, concentrating on the regions of OH emission, and comment on what you find.

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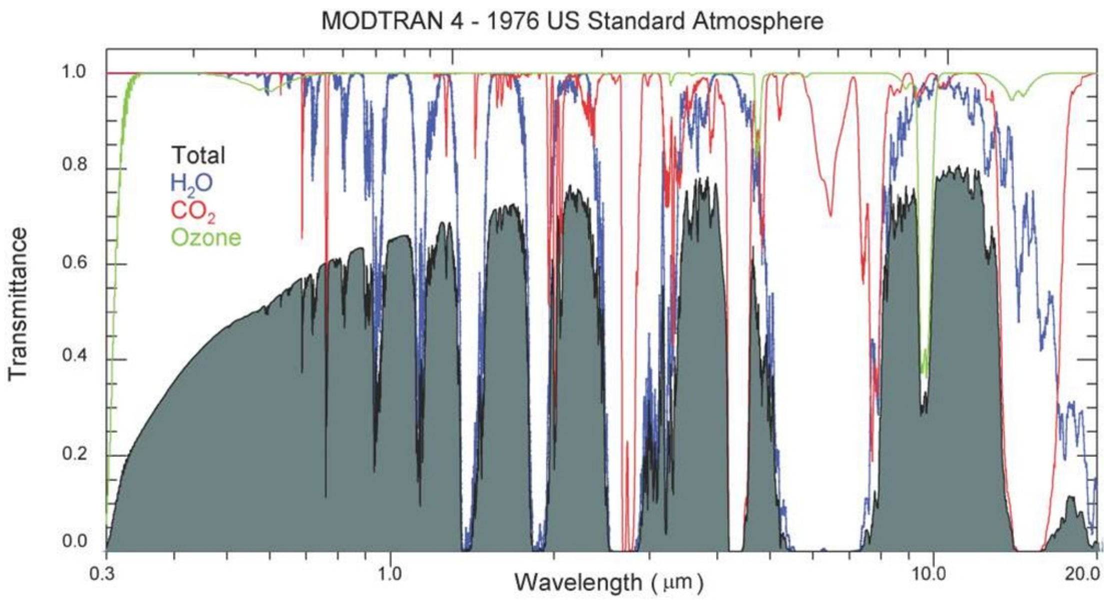

Fig. 1.— Transmittance of atmosphere, as reported at this web site and based on the MODTRAN software. The broad band pattern is due to scattering by molecules and aerosols.

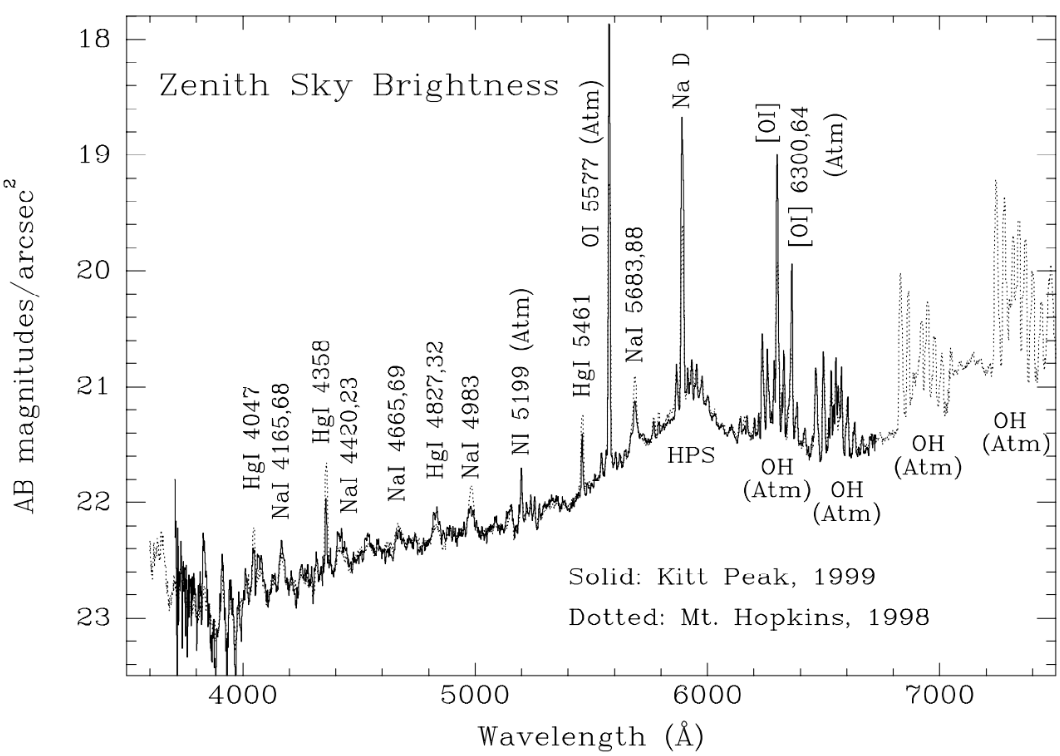

Fig. 2.— Sky spectrum from Massey & Foltz (2000).