Why was the sky so red during the solar eclipse?

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Introduction

[For the protocol due on 17 November 2017, there's no need for a formal Introduction. However, you've already written a brief description of what you're planning to do and why, so I suggest including some of that text here. It'll help me as I'm reviewing your protocol, and it'll help you when you come back to finish your project summary later find you already have a rough draft.]

I saw the 21 August 2017 solar eclipse from the Homestead National Monument in Beatrice, NE. During totality, the horizon surrounding us in all directions had the yellowish, orangish hue I normally associate with sunrise or sunset (Figure 1). I want to use a quantitative model to explore why.

Figure 1: Two photographs looking toward the northeast, from the south edge of the prairie at the Homestead National Monument, showing the sky long before (*left*) and during (*right*) the eclipse totality on 21 August 2017. The exposure time was longer for the in-eclipse image, which is why it appears to have a similar overall brightness to the out-of-eclipse image.

Intuitively, I feel comfortable with why the disk of the Sun itself looks red at sunrise or sunset. When the Sun is low on the horizon, its light has to pass through a much longer path length of Earth's atmosphere, and the λ^{-4} proportionality of Rayleigh scattering ensures less blue light will be transmitted all the way along that slant path. White clouds that are directly illuminated by this already reddened light will also appear red or pink, contributing (in my opinion) to prettier sunsets.

I also have a general instinct for why the daytime sky is blue. When I look at a clear patch of the sky, away from the exact direction of the Sun, the light I see is dominated by solar photons that have scattered off the atmosphere and into my line-of-sight. With red light experiencing a smaller cross section for scattering and tending to continue straight on its original path, less red light is scattered towards us and the diffuse light from the sky appears relatively blue.

So, when the Sun was high overhead during the solar eclipse, why was the light coming from the horizon so red? It must have been scattered, but it also had to be transmitted through a lot of atmosphere. The balance of these effects will influence the color we see; to understand the color of the horizon during a solar eclipse, I plan to look at radiative transfer through an Earth-like scattering atmosphere, with conditions that approximate those present during a solar eclipse.

I will later fill in a smidge more background here, about how spectroscopy is our primary tool for remote sensing conditions and composition in planetary atmospheres and about how our eyes are useful tools, as very coarse spectrometers.

Method

[Below is an example of what an outline of your methodology, or your "protocol", might look like for a project. Many of you are interacting with more complicated datasets than I am here – in those cases I very strongly recommend making a very basic plot of some aspect of your dataset, to convince yourself (and me) that you understand how to start working with it.]

Set up the radiative transfer problem. My goal is to come up with an estimate for the wavelength-dependent intensity $I_\lambda(\tau_\lambda = 0, \phi, \theta)$ I receive, as an observer located at $\tau_\lambda = 0$ and from a direction denoted by the angles ϕ and θ. This is exactly the setup we used for the Week 9/10 project, where we wrote

$$I_\lambda(0, \phi, \theta) = I_\lambda(\tau_\lambda, \phi, \theta) e^{-\tau_\lambda} + \int_0^{\tau_\lambda} S_\lambda(\tau_\lambda) e^{-\tau'} d\tau' \quad (1)$$

with the source function contributing new radiation into the beam written as

$$S_\lambda = (1 - \omega_\lambda) B_\lambda + \omega_\lambda J_\lambda \quad (2)$$

for isotropic scattering and a given single-scattering albedo of ω_λ. As before, we will assume $B_\lambda \approx 0$ because Earth's atmosphere is cool and we're talking about visible light. Before, we assumed the mean intensity field J_λ was constant everywhere in space because the Sun was shining down equally on all parts of the the landscape. Here, we will allow J_λ to vary with distance away from us, thus simulating a situation where the distant atmosphere is sunlit but our nearby surroundings are in shadow.

Identify an appropriate functional form for J_λ. I need to write down an expression for J_λ as a function spatial location, which I can then relate to τ_λ. I'll do this assuming I'm standing in the center of the Moon's shadow, so that J_λ is a function only of the radial distance away from me. The simplest option would be a step function, with $J_\lambda = 0$ nearby and $J_\lambda > 0$ beyond some distance away from me. I will need to calculate an appropriate size to use for the Moon's shadow.

Identify appropriate extinction (=absorption + scattering) coefficients. One option is to assume pure Rayleigh scattering off N_2 in the atmosphere, taking expressions for this expression from Pierrehumbert (2010) as we did for the Week 9/10 project. If I want to also include scattering off larger particles or gaseous absorption, I will pull calculations from the transmission models associated with the ESO SkyCalc Model Calculator (Moehler et al., 2014).

Solve the radiative transfer equation for multiple wavelengths λ. To understand the color of the light I would see from any patch of the sky, I need to calculate $I_\lambda(0, \phi, \theta)$ for a range of wavelengths spanning $0.3 < \lambda < 0.8\ \mu m$, for fixed values of ϕ and θ. I will assume a plane-parallel atmosphere in hydrostatic equilibrium, with constant composition everywhere. One choice to make will be identifying what to adopt for my distant intensity field $I_\lambda(\tau_\lambda, \phi, \theta)$: do I set it to 0, or do I include some illuminated layer of clouds somewhere in the distance?

Convert spectra into RGB colors. Finally, once I have calculated spectra for the light we will see along a given path, I will use our spectrum-to-RGB code to determine the color we would perceive for them (Figure 2). I'll play around with the parameters I put into my model (scattering coefficients, size of the Moon's shadow, θ) and see what effects they have on the color!

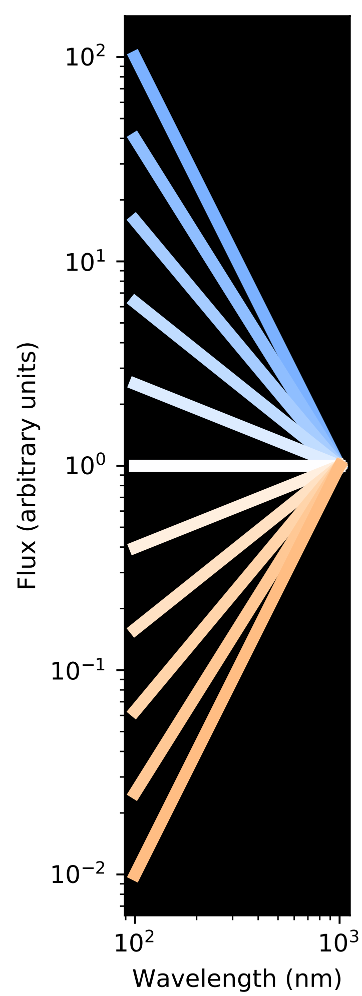

Figure 2: Our code from earlier in the semester can be used to convert from arbitrary spectra to an RGB color for plotting. Here, I tested power law spectra ($I \propto \lambda^x$) for a range of power law indices x. Once I have wavelength-dependent intensities from my scattering model, I can calculate what color they should be!

Results

When I plot some plots and find some findings, I'll put them here!

Discussion

Here, I will discuss the implications of the results in Section . I will try to put them in a broader context among the concepts we covered in class.

References

Moehler, S., Modigliani, A., Freudling, W., et al. 2014, A&A, 568, A9

Pierrehumbert, R. T. 2010, Principles of Planetary Climate