Application Notes

Keywords

- Ozone
- Lunar eclipse
- Atmosphere

Techniques

- Relative irradiance
- Absorption

Applications

- Environmental monitoring

The Visible Signature of Ozone at Twilight

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During the last 15 years, astronomers have discovered over 450 exoplanets (planets outside our own solar system). Due to the nature of the discovery techniques, most of these planets are large -- more like Jupiter than Earth -- and orbit close to their parent star. While a small number of smaller, rocky planets ("super-Earths") have been found, the discovery of a true "exoearth" in the habitable zone around its parent star is still beyond the capabilities of our technology. However, in preparation for such a discovery, which is likely within the next decade or so, there is considerable interest in how to characterize such planets and their atmospheres.

Introduction

It took thousands of years, following the first questioning gaze at the sky, to understand why the clear daytime sky is blue [1]. However, the theory that answers that question -- Rayleigh scattering -- does not explain the entire palette of sky colors that delight us at dawn or dusk. It was only realized in the middle of the last century [2] that the unstable oxygen molecule ozone (O3) has a profound impact on twilight colors.

The ozone layer protects the surface of our planet from the damaging effects of ultraviolet radiation. But few people appreciate that, without ozone, the color of the zenith (overhead) sky at twilight would be a pale green or straw yellow rather than the deep, steely blue that we observe. The electronic Chappuis absorption band of ozone – extending from 450-850 nm -- is intrinsically weak and has little effect on the color of the daytime sky. This band only becomes significant when the pathlength of sunlight through the atmosphere is dramatically increased around sunrise and sunset. At these times, the Chappuis band becomes by far the strongest feature in the visible spectrum of the sky or the setting sun.

Experiment Details

In preparation for future "transit spectroscopy" (analysis of the light transmitted by the atmosphere of a planet transiting its parent star), researchers have performed relative spectrophotometry of the sky during twilight. This can be compared with the observations of the eclipsed Moon [3], which examine light that has grazed the Earth's atmosphere during a lunar eclipse. The eclipse geometry results in a much stronger influence of Rayleigh and aerosol extinction in the light reflected from the eclipsed Moon than in scattered light from the horizon sky at twilight, resulting in strong suppression of the blue end of the spectrum.

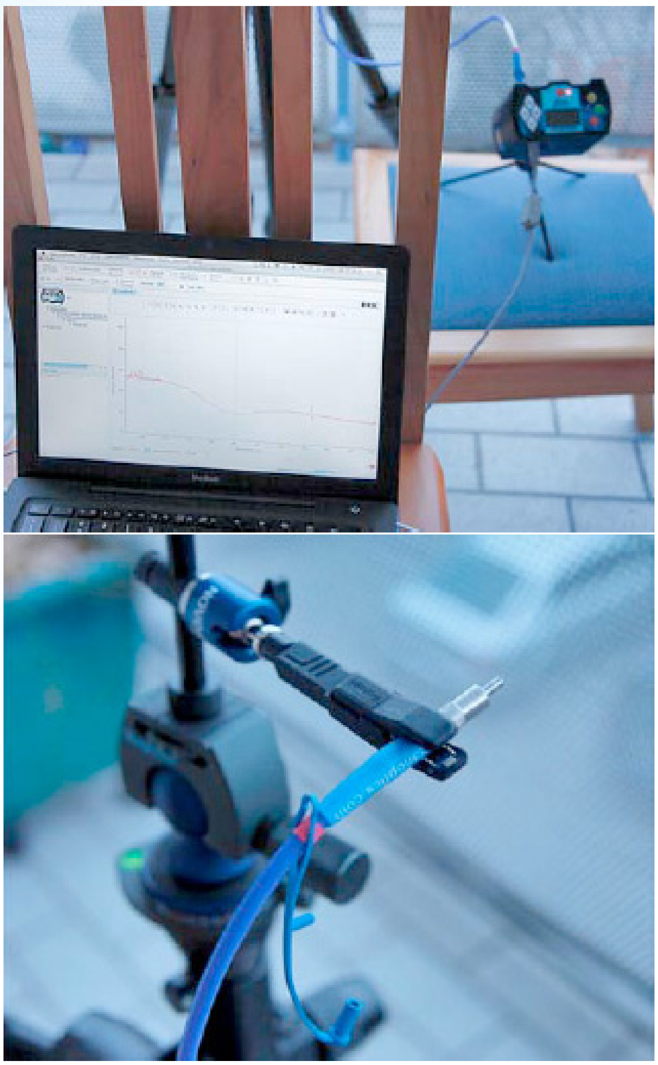

Figure 1. The experimental setup for the twilight observations comprises the Jaz spectrometer, the fiber feed and the data-taking laptop. These photographs, taken around the time of sunset with a "daylight" white balance setting on a Canon 5D Mark II, illustrate the high color temperature of the ambient light at sunset, which is caused predominantly by the ozone absorption (Figure 2).

The twilight spectra appearing in this report were obtained with an Ocean Optics Jaz spectrometer covering 350–1000 nm and using a single optical fiber input pointed about 10° above the western sky in overcast conditions (Figure 1). The altitude of the observing site was 560 m at latitude of +47.8°.

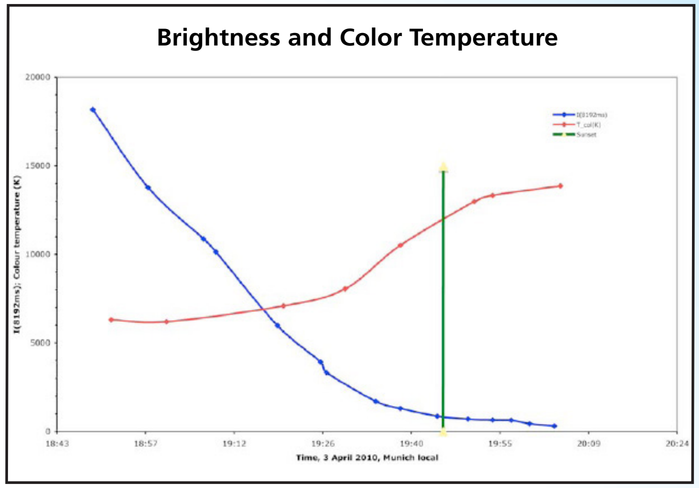

Figure 2. These spectra reveal variation of sky brightness at 700 nm, in units of counts per 8192 ms, and color temperature measured with a Gossen Colormaster 2F color meter.

Results

This simple experiment clearly illustrates the profound influence of the ozone Chappuis absorption on the color of the twilight sky (the color temperature of the western sky varied from 6,000 K to14,000 K during the course of the observations) and the very strong visible spectral signature that could be expected in transit spectroscopy of an oxygen-rich exoearth atmosphere (Figure 3).

The absence of strong signatures of O2 and H2O in the spectral ratios probably indicates that most of the light entering the spectrometer has passed above the cloud layer, in the stratosphere (~25 km), where ozone dominates the absorption.

An interesting exercise with these data is to invert the results to derive the ozone Chappuis absorption cross-section times the column density of the atmospheric pathlength that is characteristic of these twilight observations.

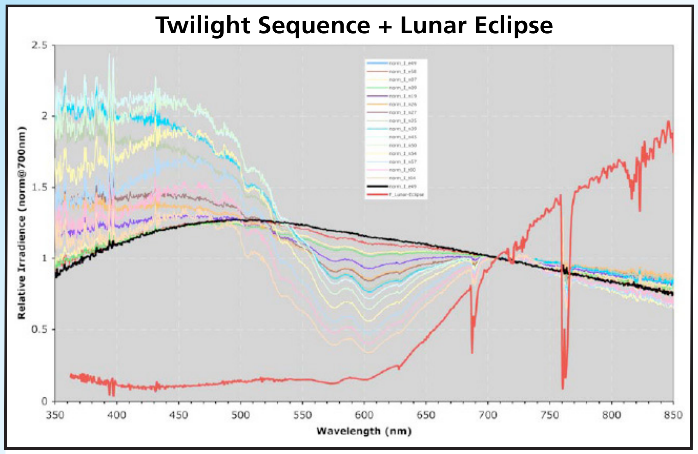

Figure 3. A sequence of relative irradiance spectra is captured under a cloudy western sky at approximately 10-minute intervals from an hour before, to 15 minutes after, sunset. Also plotted is the lunar eclipse spectrum from [3]. The rapid development of the ozone Chappuis absorption, centered at 600 nm, is apparent together with the dramatic bluish tint of the sky color during this period. The somewhat irregular behavior of the blue end of the spectrum is due to the variable cloud thickness during these measurements. The reference spectrum is taken with a solar altitude of +13° and the final spectrum of the sequence is with an altitude of -3°.

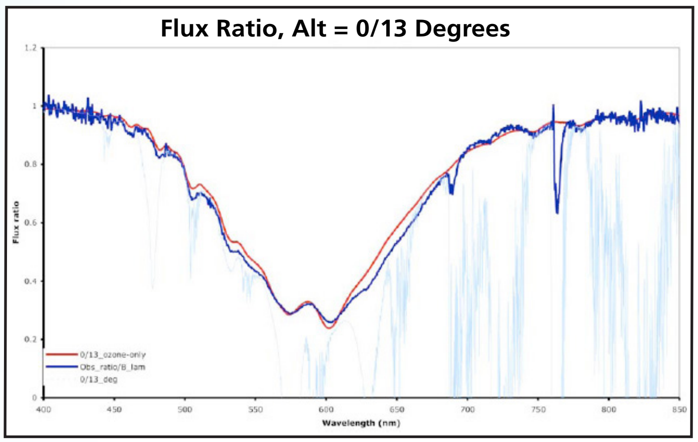

Figure 4. The observed ratio (dark blue), with a normalized continuum, of a spectrum taken with a solar altitude of-3° is compared to one at +13°. Atmospheric models [4] using the HITRAN database (cfa.harvard.edu/hitran) [5], with similar but pure transmission geometry, are over plotted (red: pure ozone absorption; light blue: ozone + O2 + H2O). The models have been scaled in intensity by a factor of 1.7 as a way of accounting for the simplification of the model geometry.

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