Telluric Line Removal in Astrophysical Spectroscopy

By: Erin Wood
ASEN/ATOC 5235
April 25, 2003
Introduction

Although some astronomical spectroscopy today is done using space-based telescopes, much is still done in ground-based observatories using CCD cameras due, in part, to the limited time available on space-based instruments. Ground-based astronomical spectroscopy is plagued by extinction and absorption within the atmosphere. Absorption features that originate in the Earth’s atmosphere are referred to as telluric features and are prevalent in the IR and visible regions of the spectrum. Removing these features proves to be a difficult task which requires either modeling the atmosphere using an atmospheric line database such as HITRAN, or by taking a reference spectrum to create a telluric template. This paper will address these methods and their flaws, and will also discuss the need for spectroscopic data in the IR region in astronomical applications.

Telluric Features

Telluric features are atmospheric absorption lines inherent in the Earth’s atmosphere. When an astronomer observes something from the Earth, such as a star, the starlight passes through the atmosphere and these telluric absorption features appear superimposed with the stellar spectrum. Telluric features in the IR region of the spectrum are mainly the result of absorption by ozone (O₃), gaseous oxygen (O₂), and water vapor (H₂O) (Adelman, Bikmaev et al., 2002). Other lines include the sodium-D lines (Lundstrom, Ardeberg et al., 1991) and Carbon dioxide (CO₂) (Kingdon, Ferland, 1991). Of these lines, H₂O proves the most problematic, varying not only with air mass but with humidity levels within the atmosphere as well. Water vapor lines are also abundant within the IR region of the spectrum. When the
spectrum of the object is taken in several different exposures, the telluric features will not be identical in each spectrum (Lallement, Bertin et al., 1993).

Atmospheric lines may be modeled by Doppler or Lorentz profiles or with a combination of the two, called a Voigt profile. A Lorentz profile is used to characterize pressure broadening which is caused by collisions between molecules. Pressure broadening is dominant in the lower atmosphere where pressures are high. A Doppler profile is used to model molecular motions in the atmosphere which broaden the lines. In the upper atmosphere where the pressure is much lower, Doppler broadening becomes dominant, and a Doppler profile is used to model the absorption lines. Most observatories are at high altitudes to avoid looking through so much atmosphere. At these altitudes (20-50 km), a Voigt profile is used, which is an amalgamation of the Doppler and Lorentz profiles. The Voigt profile is given by the equations:

\[
\int_{-\infty}^{\infty} \frac{1}{\alpha_D \pi^{3/2}} \exp \left[ -\left( \frac{\nu - \nu'}{\alpha_D} \right)^2 \right] d\nu'
\]

where \( \alpha_D \) is the Doppler line width defined by:

\[
\alpha_D = \frac{V_0}{c} \left( \frac{2k_B T}{m} \right)^{1/2}
\]

where \( c \) is the speed of light, \( k_B \) is Boltzmann’s constant, and \( m \) is the mass of the molecule. \( \alpha_L \) is the half-width of the Lorentz line shape defined by:

\[
\alpha_L(P,T) = \alpha_0 \left( \frac{P}{P_0} \right) \left( \frac{T}{T_0} \right)^n
\]
where $P$ is the pressure and $T$ is temperature. $\alpha_o$ is the reference half-width at $T_o = 273$ K, $P_o = 1013$ mb. $n=1/2$ for most gases (lecture 7 of the class notes).

Line widths are subject to change due to varying wind speeds, and pressure and temperature changes. The central wavelength of the lines may also shift due to high winds as a result of the Doppler Effect. Water lines are affected by altitude at which the observations are made, air mass related to the secant of the zenith angle, and humidity at the time of the observations. Seasonal variations also occur. All of these things must be taken into account before removal of the lines can take place.

**Heliocentric Velocity and Wavelength Calibration**

When any observation is made, the reference frame must be taken into account. The Earth is moving relative to the Sun, and the object being observed is moving as well. When objects are first observed, the coordinate frame is Earth-centered, or geocentric. A correction to this reference frame is made so that the object velocity can be determined more accurately, making the observations Sun-centered, or heliocentric. If these data are kept in a geocentric coordinate frame the velocity of the object relative to Earth would be changing constantly due to the Earth’s motion around the Sun (see figure 1).
An object’s lines will appear to shift against the telluric features since telluric lines are not affected by the motion of the Earth around the Sun. The object’s lines will shift according to the Doppler Effect, being blue shifted slightly when the Earth moves toward the object, and red shifted when the Earth moves away. Since the telluric lines do not shift wavelengths, this motion around the Sun provides yet another problem with data analysis of the object. During some points in the year, an absorption feature that lies close to a telluric line may blend with that line, and any line that lies within +/- 30 km/s of the telluric feature may be affected (Pepe, Mayor et al., 2002). Any feature of interest that lies within this distance from the telluric feature may be affected by blending. Any attempt to remove the telluric feature out of the spectrum will also affect the line of interest, possibly rendering the data around the telluric feature useless.
Recall that the Doppler shift is defined by the equation:

\[ \Delta V = \left( \frac{\Delta \lambda}{\lambda} \right) c \]

where \( \Delta V \) is the change in velocity, \( c \) is the speed of light, \( \Delta \lambda \) is the rest wavelength subtracted from the observed wavelength, and \( \lambda \) is the rest wavelength.

There is also a positive side to having telluric features within spectra. Raw spectroscopic data from CCDs comes without wavelength calibration. Spectroscopic data comes in a series of orders which are basically chunks of the spectrum. CCDs do not have continuous coverage of all wavelengths, but have missing wavelengths between the orders. Sometimes several orders will even overlap each other depending on the how the CCD was constructed. Normally, an astronomer uses a known calibration lamp to determine the wavelengths of the different orders of the spectrum taken. The CCD detectors are usually curved, and if the calibration lamp is positioned such that the light follows a different optical path than the object, there will be a displacement between the data and the calibration spectrum. Since the telluric lines and the observed lines are taken simultaneously they provide a useful wavelength reference without the possibility of error resulting from a misplaced calibration lamp (Caccin, Cavallini et al., 1985).

Wavelength ranges of the orders with telluric features can be established easily if the rest wavelength of the feature is known. One disadvantage of this method is that telluric lines may not be present in every order. Another problem results from the Doppler Effect. The telluric feature may be shifted slightly due to winds, which may result in an error between 10-30 m/s. The telluric line may also be asymmetric due to pressure broadening which makes it difficult to establish a central wavelength (Caccin, Cavallini et al., 1985). The method of wavelength
calibration of spectral orders using telluric lines is only useful if the lines are sharp and well defined.

**Using a Database to Remove Telluric Features**

A database such as HITRAN may be used to remove telluric lines from spectra. HITRAN, or high-resolution transmission molecular absorption database, contains data which may be used to simulate the spectrum of the Earth’s atmosphere. Using this database, for example, code has been written which incorporates temperature variations and water vapor content as a function of altitude. A Voigt profile may be used to model the lines, and subtle changes to the water vapor content in the layers of the atmosphere can be made to match local observing conditions at the correct elevation of the observation site (Stevenson, 1993).

Essentially, changes are made to the atmospheric lines until the profile of the lines matches with the atmospheric lines seen in the observer’s spectrum, creating an atmospheric template. This template is divided out of the observer’s spectrum, producing a clean spectrum devoid of telluric features.

Immediate problems may be seen with this approach. One problem lies in the resolution of the HITRAN template. The template will show the lines individually resolved. Generally, data for astrophysical observations rarely has this high of a resolution. Atmospheric lines are usually not distinct, but appear as bands in the spectrum. Matching the line profiles proves impossible using this approach for low resolution data.

Another issue that arises is that water vapor, although most abundant in the IR, is not the only constituent of the atmosphere which changes with time and altitude. Ozone, for example,
may change with altitude and concentrations have been known to vary within a few hours’ time
(Adelman, Bikmaev et al., 2002). If water vapor is the only constituent that is corrected
appropriately in the template, the other constituents’ features will not align properly in strength
and width with the observer’s spectrum, producing an inaccurately divided spectrum.

A-type Stars as Telluric Standards

A popular method of telluric line removal is to use A-type stars as the telluric template
(Vacca, Cushing et al., 2002). A-type stars do not contain many spectral features because of the
temperature of the photosphere. They are referred to as having few “metal lines” by
astrophysicists. A “metal line” is any spectral feature other than hydrogen. The idea behind this
method is that an A-type star is observed at the same air mass as the observation, and this is used
as the telluric template.

There are many advantages to this method. If done properly, the air mass, water vapor
content, and any atmospheric effects, such as Doppler and Lorentz broadening, will already be
taken into account without the need to model the atmosphere above the site. The elevation of the
site has also been automatically included and the resolution of the template will be identical to
the observation since they have been taken with the same instrument. If, however, the
observation of the A-type star has been taken with a large time delay from the original
observation, the atmospheric spectrum may have changed in that time. Water vapor content,
wind, pressure, and temperature all change with time, so any large delay may affect the resulting
spectrum. Poor tracking, poor seeing, and changes in focus will also change the resolution,
causing a mismatch in resolution between the object and the template (Thorburn, 2003).
A misclassification of the standard star would prove problematic since the method relies on the assumption that the standard star is essentially featureless. If the standard star has been classified incorrectly it may have lines inherent to the star within the template spectrum (see plot 3). Any division with a misclassified star may create unwanted features within the divided spectrum (Vacca, Cushing et al., 2002). Another related problem has to do with an effect called interstellar reddening. The area between stars is not devoid of material, but contains gas and dust. Starlight passing through this material will be scattered according to Raleigh scattering, and will produce absorption features within the stellar spectrum. An A-type star may be chosen that is not reddened significantly to avoid this problem.

Although the spectrum of an A-type star is essentially featureless, it still contains hydrogen absorption features. These features are particularly broad owing to the fact that A-type stars are fast rotators. This fast rotation creates Doppler broadening of the lines. If the observer is intent on studying anything around the hydrogen absorption features, this method of division is not ideal (Vacca, Cushing et al., 2002).

An A-type star that is not heavily reddened may not be available with the same air mass as the observation, so this method may not always be used. An alternative method uses A-type stellar spectra and combines these with some atmospheric modeling to produce a template. The program IRAF, widely used for data reduction in astrophysics, contains a task called ‘telluric’ which uses Beer’s law to approximate extinction due to telluric lines. This task uses hot A-type stars as templates, and then shifts and scales the spectrum (IRAF Newsletter, 1998). Although this is not the same method as described previously, it employs a similar use of a standard star. This method contains all of the problems stated previously in this section, and there is a greater chance of a mismatch in resolution because of differences in instrumentation. A Beer’s law
approximation may be too simplistic to model the effects of the atmosphere, and line strengths and widths may not be accurately represented by the template since the observation and the template were not taken at the same time. Plots 1-3 show examples of telluric line removal using the task ‘telluric.’ Plot 1 shows a successful removal of telluric water vapor lines. In plot 2, the telluric template has lines that are stronger than the observation, creating false features on the quotient due to overcorrection. In plot 3, an absorption feature in the template is stellar in origin, which results in removing the feature from the observation and actually creating a false feature in that area. All plots are of O and B type (very hot, high flux) stars.

Plot 1: An example of successful removal of H$_2$O
Plot 2: Template lines are too strong
Conclusion

The use of infrared wavelengths is essential to many areas of research in astrophysics. Cool objects such as K and M type stars emit primarily in the IR wavelength region. White dwarf remnants, or the dying embers of an average sized star at the end of its life cycle, emit primarily in the IR. Many lines in interstellar gas and dust are studied using IR as well. Gas
and dust is of particular interest to those studying the origin of elements within the Universe and is also crucial to the study of stellar life cycles. Distant galaxies are also shifted into the red due to the Doppler shift, so the study of distant galaxies is often done in the IR.

It becomes clear that the presence of telluric lines in the IR is a problematic issue for astrophysicists trying to study these topics. Since access to space-based telescopes is limited, ground-based observations are the norm and not the exception. A dependable method of telluric line removal is needed for IR study. Of the methods mentioned previously, the use of A-type stars as a template is the most desirable, but still has many problems since hydrogen lines and the lines around them cannot be studied using this method. It is inadvisable to divide the entire spectrum with the template at once, but rather used order by order when telluric line removal seems feasible, and should be avoided in areas around hydrogen lines.

References:


http://iraf.noao.edu/irafnews/apr98/irafnews.1c.html

Thorburn, Julie, U. Chicago, private communication, 2003