10. Spectroscopy

IR spectroscopy has advanced tremendously in recent years. In this section I will discuss the basic ideas in taking spectra in the near-IR (1-5 μm), data reduction, and spectral classification.

The main difference between IR spectroscopy and optical spectroscopy is the higher and more variable background emission in the IR. Therefore techniques are necessary to remove the background as much as possible.

I will show spectra from the SpeX instrument on the NASA IRTF to illustrate data taking.

Notes:

SpeX: 0.7-5.3 μm medium-resolution spectrograph and imager

SpeX is a medium-resolution 0.7-5.3 μm spectrograph for the NASA Infrared Telescope Facility (IRTF) on Mauna Kea.

Specifications:

- Spectrograph pixel size 0.10"
- Slit widths: 0.3", 0.5", 0.8", 1.6" and 3.0"
- PRISM 0.7-2.52 μm, R~200 matched to 0.3x15" slit or 0.3x60" slit
- Short wavelength cross-dispersed (SXD) 0.7-2.55 micron, R~2000 matched to 0.3x15" slit
- Long wavelength cross-dispersed (LXD)
- LXD_short 1.67-4.2 micron, R~2500 matched to 0.3x15" slit
- LXD_long 1.98-5.3 micron, R~2500 matched to 0.3x15" slit

Slit viewer: 60x60" FOV at 0.12" per pixel, with selection of filters

For optically visible objects a dichroic guiding with a CCD camera. This camera is also used as a scientific CCD imager for simultaneous optical and IR observations.

Notes: IRTF web page: http://irtfweb.ifa.hawaii.edu/~spex/

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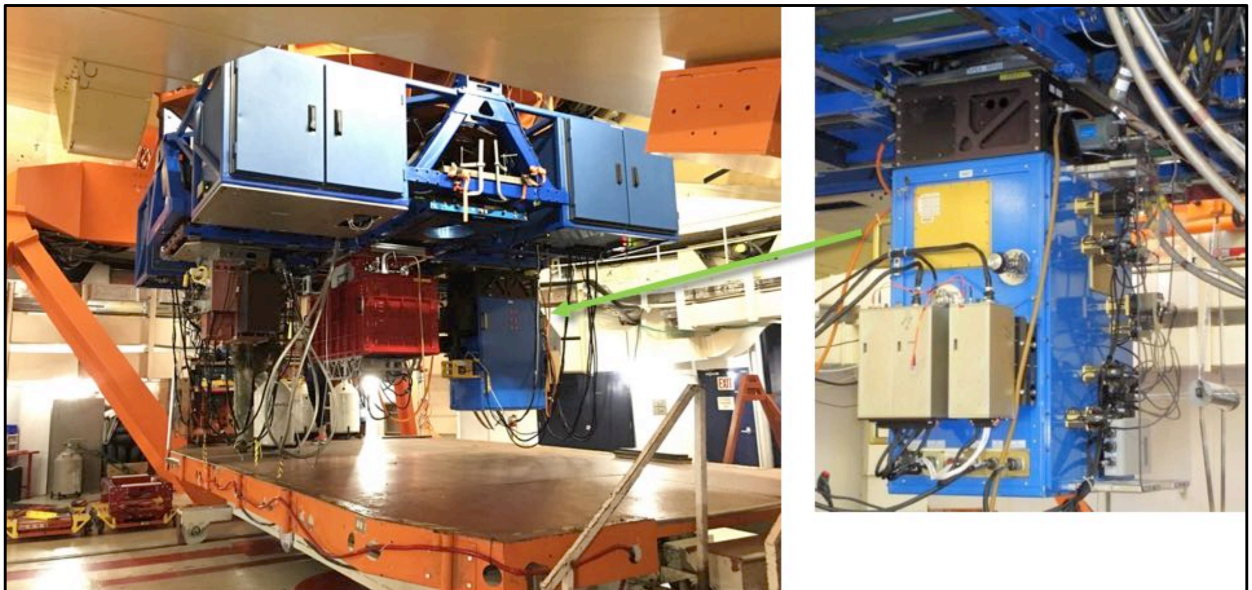
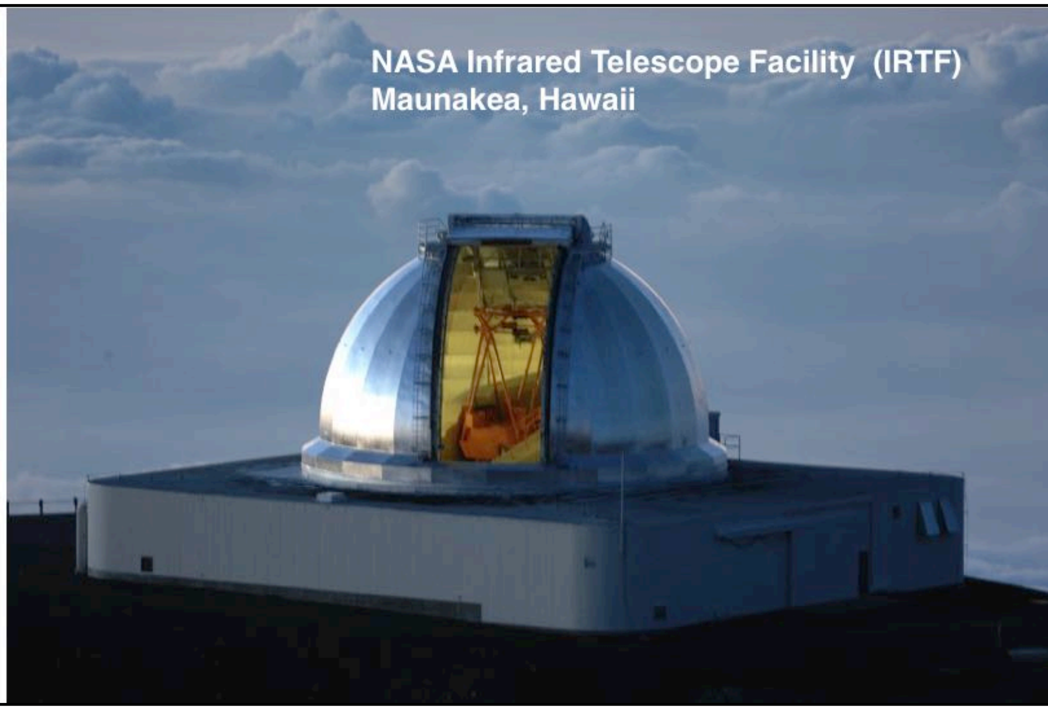


Notes:

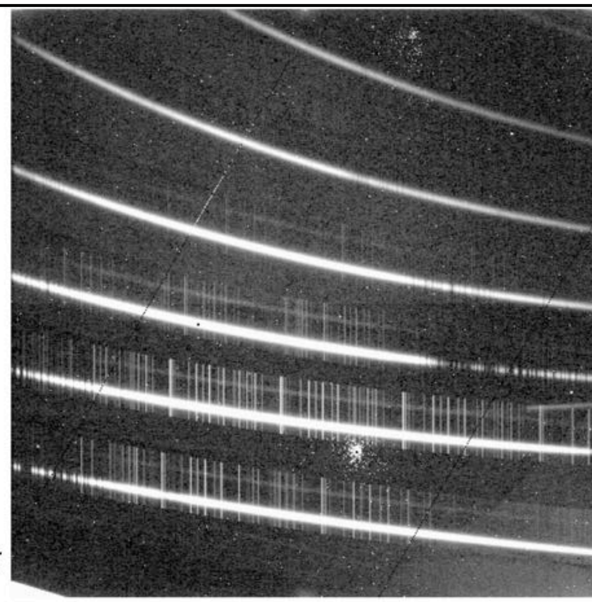


Notes: website: http://irtfweb.ifa.hawaii.edu/

8.1 Taking near-IR spectra

Acquisition and reduction of near-IR spectra employ techniques similar to near-IR imaging observations. Sequential observations are obtained with the object located on one of two positions on the slit (A and B). The A and B exposures are subtracted to remove the dark current and thermal background from the sky as well as the telescope.

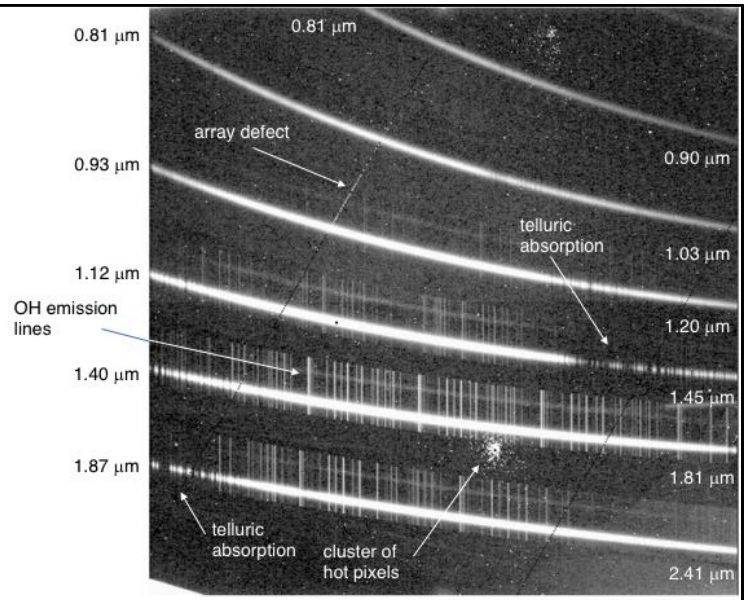
The figure to the right shows shows a raw exposure taken with a 0.8-2.4-µm spectrum of an M6 V star obtained with the SpeX spectrograph on the NASA IRTF (Rayner et al. 2003) at the IRTF. The wavelength range is covered in six orders with 2048x2048 pixel InSb array. The width of the stellar spectrum is determined by the seeing. The length of the slit is 15 arcsec.



Notes:

Rayner, J.T. et al. (2003). "SpeX: A Medium-Resolution 0.8-5.5 Micron Spectrograph and Imager for the NASA Infrared Telescope Facility." Publications of the Astronomical Society of the Pacific 115: 362-382.

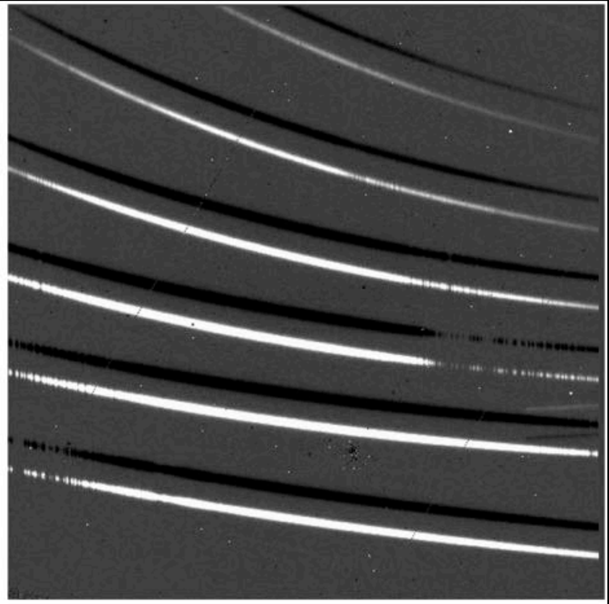
Bad (insensitive) and hot (high dark current) pixels can be seen. Bad and hot pixels areas are ~1% of the array. These are entered into a bad pixel mask and either are ignored in the reduction process or are replaced by interpolation.



Notes:

The usual observing technique involves moving the object between two positions (named A and B) on the slit. The A and B exposures can be subtracted to remove the background emission and dark current. For this technique to be successful, the integration times at the two positions must be equal.

The figure to the right shows the result of one A-B image pair (with the A exposure positive). Exposure times at each nod position are typically on the order of a few minutes, short enough that the sky emission level does not change substantially and the OH emission lines do not saturate. Then the differences in the mean level of the sky emission between the two exposures should be small.The subtraction also removes any diffuse scattered light.



Notes:

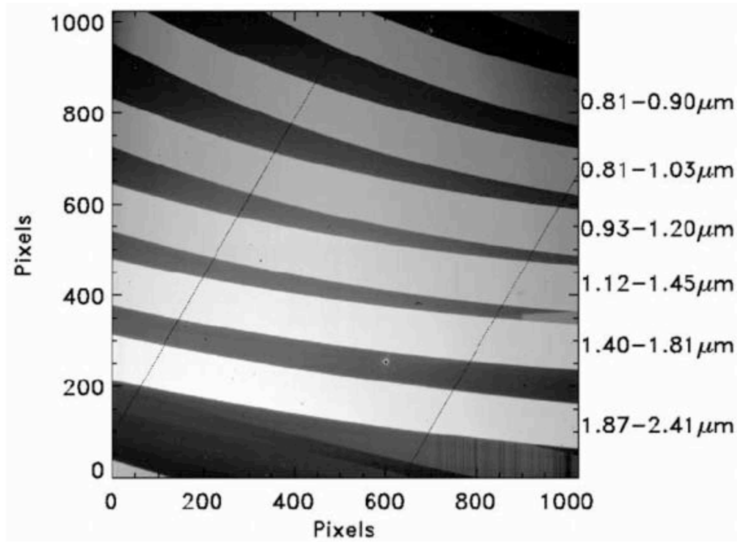
In this example the slit is long enough that the spatial extent of a point source at the two positions do not overlap and the sky residuals can be subtracted from the spectrum of the object. As many AB pairs are obtained as necessary to build up the desired signal-to-noise ratio.

Flat fields for near-IR spectra are usually generated from internal lamps, by subtracting a lamp-off frame from a lamp-on frame and median combining several of these pairs. To reduce the effects of flexure, the flat-field exposures should be taken at the same telescope elevation angle as that for the object observations.

Notes:

What the flat field image looks like. The full length of the slit is illuminated by the flat field source.

From Cushing et al. (2004).



Notes:

Cushing, M. C., W. D. Vacca and J. T. Rayner (2004). "Spextool: A Spectral Extraction Package for SpeX, a 0.8-5.5 Micron Cross-Dispersed Spectrograph." Publications of the Astronomical Society of the Pacific **116**: 362-376.

A full description of the general data reduction procedures for SpeX is given by Cushing et al. (2004). The steps in the data reduction:

- After pair subtraction, the image is divided by the flat field, the positions of the object spectra are determined at each position on the array (traced), the extraction apertures for the object and the background are determined, and residual background levels at each wavelength are subtracted.

- The spectra are extracted at each wavelength point by either summing the background-subtracted signal in the spatial direction (along the slit) at each wavelength. The result of this procedure is a one-dimensional spectrum of each order.

- Wavelength calibration is achieved by observing internal arc lamps or from the wavelengths of the observed telluric emission and absorption features.

- Telluric absorption and the instrument response is achieved by observing a spectral standard star whose intrinsic spectrum (in physical units) is known.

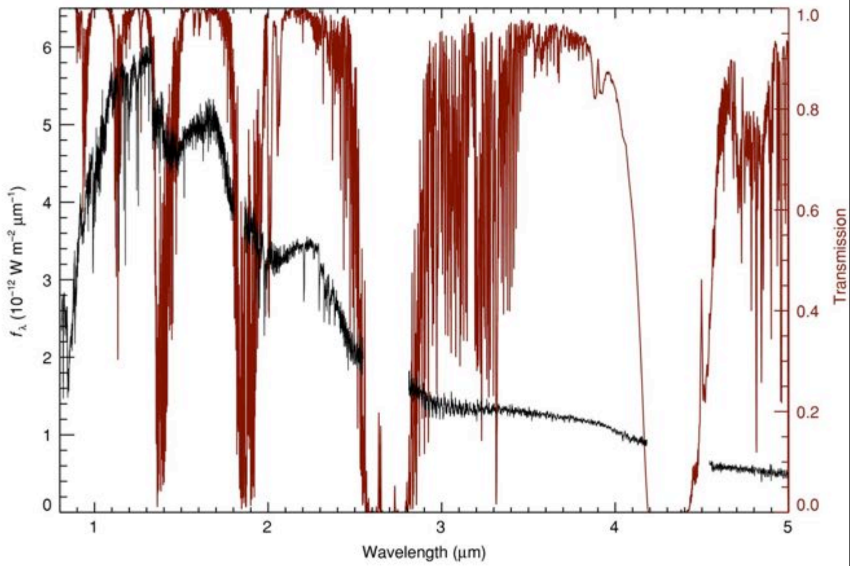
- The standard star is observed and reduced in the same manner as the science object. The ratio of the reduced and wavelength calibrated spectrum of the standard star to the known spectrum yields a correction spectrum that can then be applied to a science object.

Notes:

Black line: a SpeX spectrum of Gl 406 (M6V; black line). The spectrum is extracted from the different spectral orders shown in slide 8-5.

Red line: Atmospheric transmission for Mauna Kea (4,200 m, airmass 1.15, precipitable water vapor 2 mm).

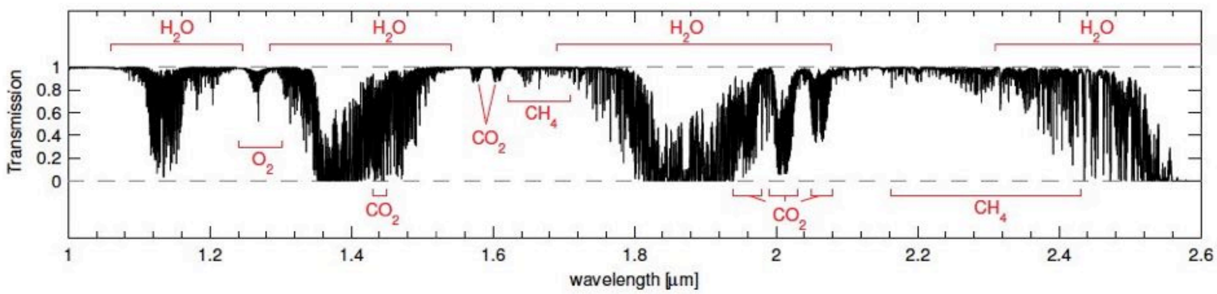
From Rayner et al. (2009).



Notes:

8.2 Telluric correction of spectra

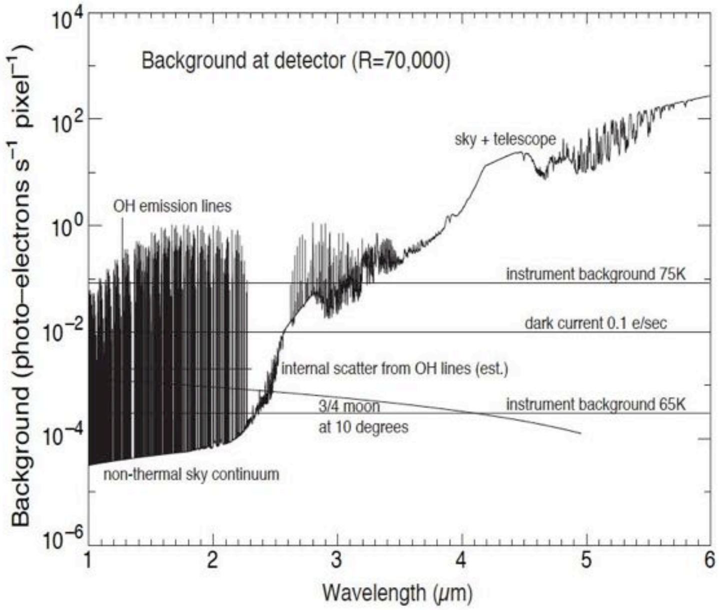
As described in Sections 2 and 3, spectroscopy from the ground must contend with atmospheric absorption and emission. Care is required in how spectra are taken in order to be able to remove the atmospheric effects so long as the absorption and emission features are not saturated.



Atmospheric absorption. From slide 2-3.

Notes:

Sky background in the IR.
From slide 3-18.



Notes:

First method of removing atmospheric lines. An object (a "telluric standard") with a known spectrum is observed. This spectrum is divided by the known spectrum (usually a model atmosphere) to get the telluric absorption. Given the variability of the atmospheric conditions, the success of this method depends on how close in time and airmass the telluric standard and the object are observed.

Vacca et al. (2003) describe a software package, originally developed for the SpeX, that relies on a theoretical spectrum of an A0 V star to generate a telluric correction spectrum from an observation of a star with a similar spectral classification. This software package incorporates all of the aforementioned effects and has been adapted for use with other near-infrared spectrographs.

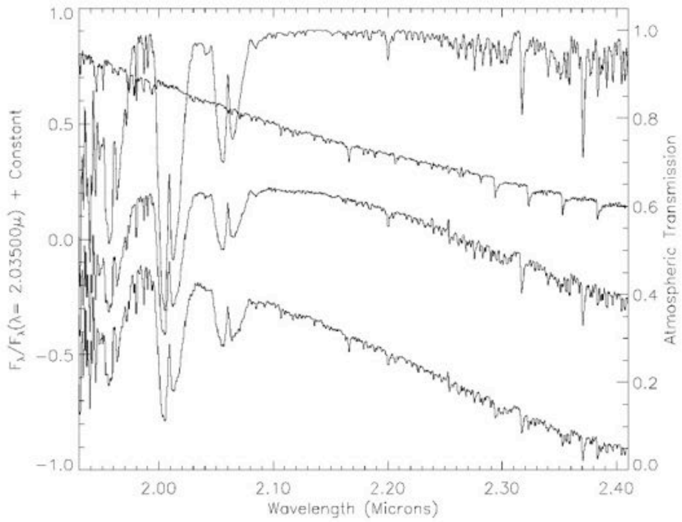
This atmospheric correction method is used in a data reduction tool for SpeX, named SpexTool (Cushing et al. 2004). See also http://irtfweb.ifa.hawaii.edu/~spex/index.html .

Notes:

Vacca, W. D., M. C. Cushing and J. T. Rayner (2003). "A Method of Correcting Near-Infrared Spectra for Telluric Absorption." Publications of the Astronomical Society of the Pacific **115**: 389-409.

Cushing, M. C., W. D. Vacca and J. T. Rayner (2004). "Spextool: A Spectral Extraction Package for SpeX, a 0.8-5.5 Micron Cross-Dispersed Spectrograph." Publications of the Astronomical Society of the Pacific **116**: 362-376.

Final telluric-corrected spectra of a G8 IIIa star generated by the method described by Vacca et al. (2003). The spectra are ordered from bottom to top as follows: the observed stellar G8 IIIa spectrum, the response curve constructed by xtellcor from the A0 V telluric standard, the telluric-corrected G8 IIIa spectrum, and the representative theoretical atmospheric transmission spectrum.



Notes:

Second method of removing atmospheric lines. The atmospheric transmission can be modelled very precisely. Then the object spectrum can be divided by the calculated atmospheric transmission to get the corrected spectrum. This method is described in detail by Smette et al. (2015) and Kausch et al. (2015).

A very precise model of the atmospheric pressure, temperature, and composition is made. Then the atmospheric model is adjusted to match the atmospheric absorption features in the spectrum. Care is taken to avoid features that are affected by the stellar absorption lines. The observed spectrum is then divided by the calculated atmospheric transmission to get the corrected spectrum free of the telluric absorption.

This method was also developed independently by Villanueva et al. (2012) to correct very high signal-to-noise IR spectra of planetary atmospheres. This method is much superior for high signal-to-noise spectra than division by a standard star since one can never find a solar type telluric standard that is exactly like the sun and to have the same airmass.

Notes:

Smette, A. et al. (2015). "Molecfit: A general tool for telluric absorption correction. I. Method and application to ESO instruments." Astronomy and Astrophysics **576**: A77.

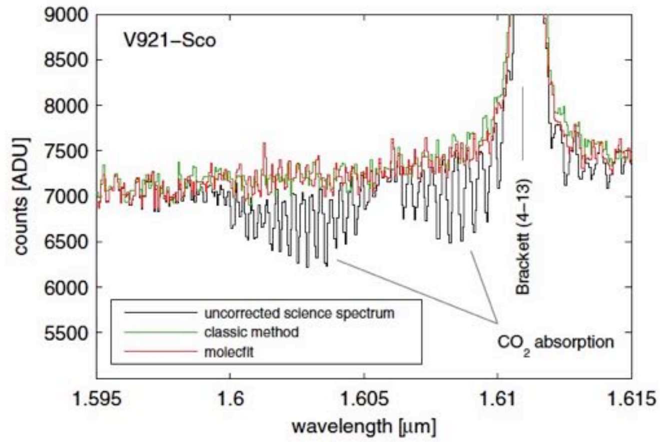
Kausch, W. et al. (2015). "Molecfit: A general tool for telluric absorption correction. II. Quantitative evaluation on ESO-VLT/X-Shooterspectra." Astronomy and Astrophysics **576**.

Villanueva, G. L. et al. (2012). "Water in planetary and cometary atmospheres: H2O/HDO transmittance and fluorescence models." Journal of Quantitative Spectroscopy and Radiative Transfer **113**: 202-220.

Villanueva, G. L. et al. (2013). "A sensitive search for organics (CH4, CH3OH, H2CO, C2H6, C2H2, C2H4), hydroperoxyl (HO2), nitrogen compounds (N2O, NH3, HCN) and chlorine species (HCl, CH3Cl) on Mars using ground-based high-resolution infrared spectroscopy." Icarus **223**: 11-27.

Uncorrected object spectrum (black), molecfit corrected spectrum (redline), and the spectrum corrected with the classical method (green). The classical method is a division by a telluric standard star to remove the atmospheric absorption features.

From Kausch et al. (2015).

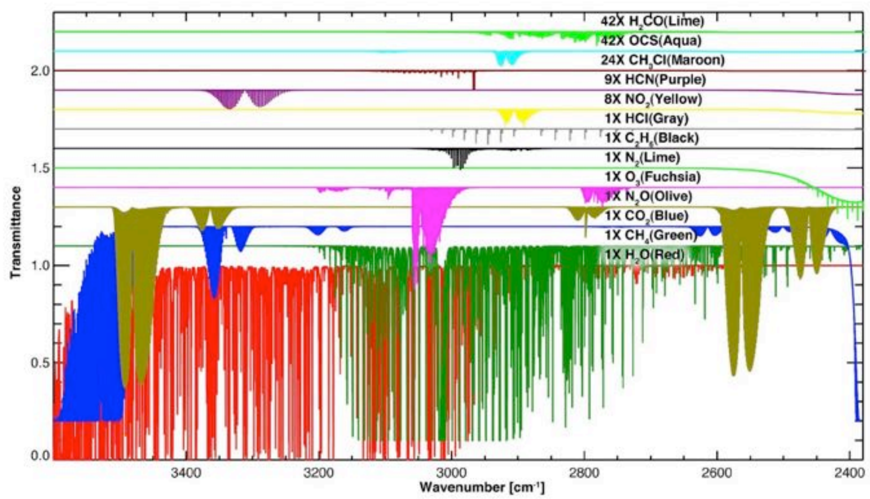


Notes:

Another example of method 2.

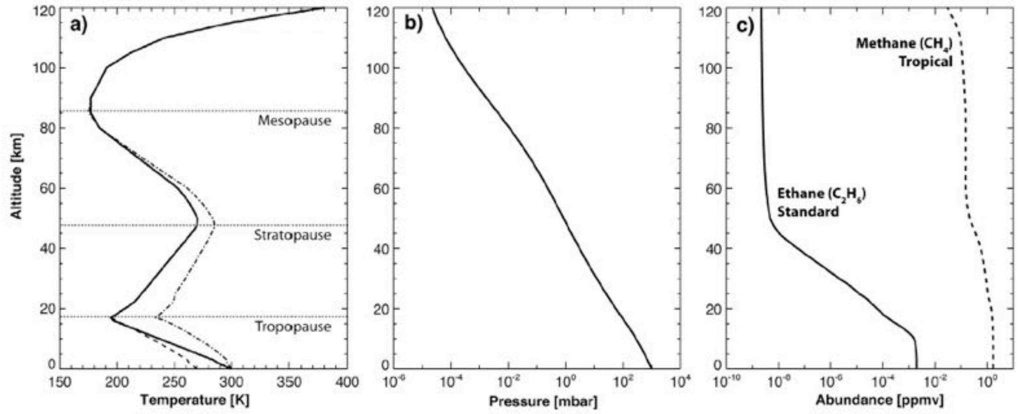
Telluric absorption spectra synthesized with a line-by-line and layer-by-layer radiative transfer model (LBLRTM) for an air mass of 1.0 (zenith), and adopting typical molecular abundances, temperatures, and pressures for Mauna Kea at 4200 m altitude.

From Villanueva et al. (2011).



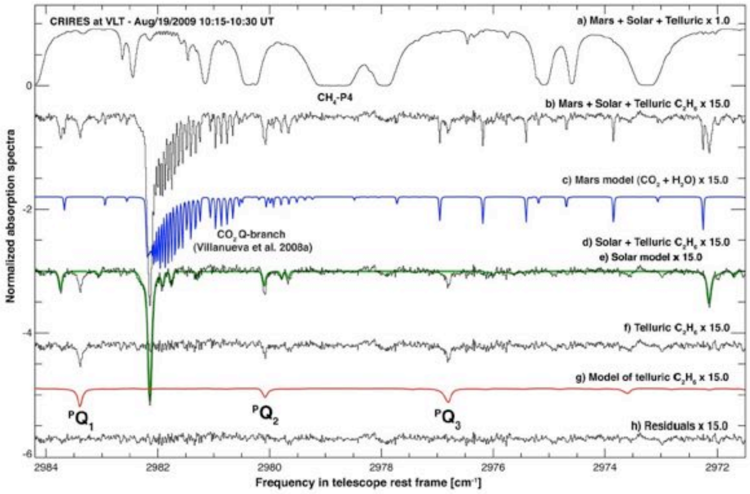
Notes:

Villanueva, G. L., M. J. Mumma and K. Magee-Sauer (2011). "Ethane in planetary and cometary atmospheres: Transmittance and fluorescence models of the ν7 band at 3.3 μm." Journal of Geophysical Research (Planets) **116**: CiteID E08012.



Assumptions for the telluric absorption calculation. The adopted vertical profiles of (a) temperature, (b) pressure, and (c) mixing ratios for CH4 and C2H6 are shown in the figure to the right. Temperatures and pressures are scaled relative to standard tropical value. From Villanueva et al. (2011).

Notes:



Example of spectral analysis. Search for ethane (C_2H_6) in the atmosphere of Mars. (a) Calibrated Mars continuum affected by telluric absorption, (b) Mars residual spectrum after removing the telluric absorption (without telluric C_2H_6). (d) Residual spectrum after removing (c) a Martian absorption spectrum containing CO_2 and H_2O (d) Residual spectrum containing solar Fraunhofer lines and telluric C_2H_6 lines, (e) model of solar spectrum, (f) Residual telluric ethane spectrum and (h) overall residual after removing the telluric C_2H_6 spectrum. From Villanueva et al. (2011).

Notes:

8.3 Spectroscopic Standards

Many spectral libraries of O through M stars exist. See Table 1 of Rayner et al. (2009) for a list up to 2009.

Near-IR spectral features frequently used to classify cool stars include CO, H_2O, FeH, and various atomic metal lines (e.g., Lançon and Rocca-Volmerange 1992; Meyer et al. 1998; Burgasser et al. 2002; Ivanov et al. 2004; Cushing et al. 2005; Rayner et al. 2009).

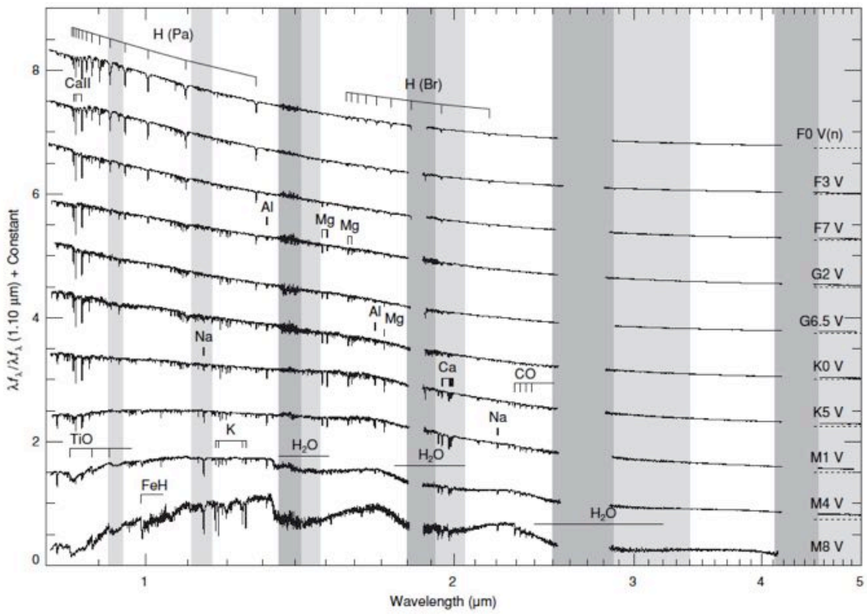
The classification of hot stars typically relies on the relative strengths of H and He lines (Hanson et al. 1996; Blum et al. 1997;Hanson et al. 1998; Lenorzer et al. 2002).

Notes:

Burgasser, A. J., et al. (2002). "The Spectra of T Dwarfs. I. Near-Infrared Data and Spectral Classification." The Astrophysical Journal **564**: 421-451.
Cushing, M. C., J. T. Rayner and W. D. Vacca (2005). "An Infrared Spectroscopic Sequence of M, L, and T Dwarfs." Astrophysical Journal **623**: 1115-1140.
Ivanov, V. D. et al. (2004). "A Medium-Resolution Near-Infrared Spectral Library of Late-Type Stars. I." Astrophysical Journal Supplement Series **151**: 387-397.
Lançon, A. and B. Rocca-Volmerange (1992). "A library of near-IR stellar spectra from 1.328 to 2.5 microns." Astronomy and Astrophysics Supplement Series **96**: 593-612.
Meyer, M. R. et al. (1998). "Near-Infrared Classification Spectroscopy: H-Band Spectra of Fundamental MK Standards." Astrophysical Journal **508**: 397-409.
Rayner, J. T., M. C. Cushing and W. D. Vacca (2009). "The Infrared Telescope Facility (IRTF) Spectral Library: Cool Stars." Astrophysical Journal Supplement **185**: 289.
Hanson, M. M., P. S. Conti and M. J. Rieke (1996). "A Spectral Atlas of Hot, Luminous Stars at 2 Microns." The Astrophysical Journal Supplement Series **107**: 281.
Blum, R. D. et al. (1997). "H-Band Spectroscopic Classification of OB Stars." The Astronomical Journal **113**: 1855-1859.
Lenorzer, A. et al. (2002). "An atlas of 2.4 to 4.1 μιχρον ISO/SWS spectra of early-type stars." Astronomy and Astrophysics **384**: 473-490.
Hanson, M. M., G. H. Rieke and K. L. Luhman (1998). "Near-Infrared H-Band Features in Late O and B Stars." The Astronomical Journal **116**: 1915-1921.
Hanson, M. M. et al. (2005). "A Medium Resolution Near-Infrared Spectral Atlas of O and Early-B Stars." The Astrophysical Journal Supplement Series **161**: 154-170.

Dwarf sequence from 0.8–5 µm. The spectra have been normalized to unity at 1.10 µm and offset by constants (dotted lines). Regions of strong (transmission <20%) telluric absorption are shown in dark gray, while regions of moderate (transmission <80%) telluric absorption are shown in light gray.

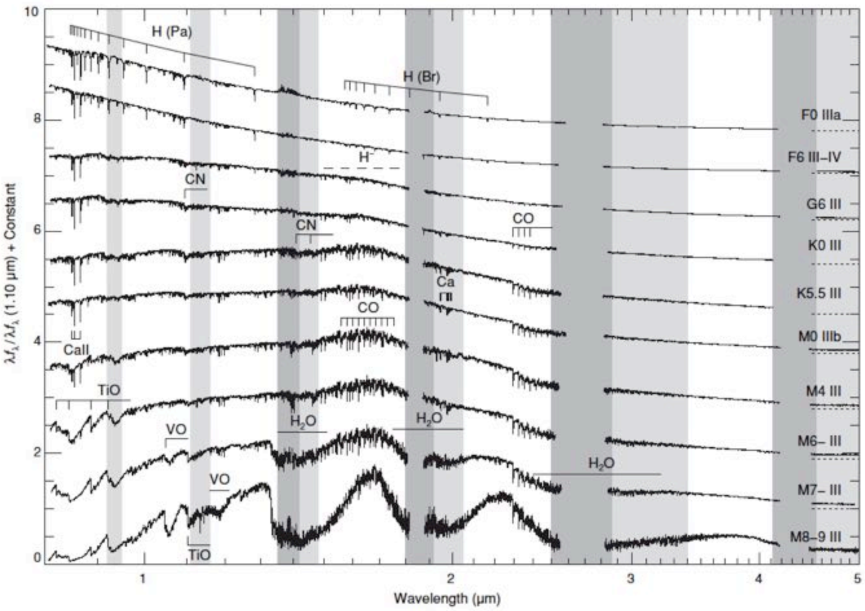
From Rayner et al. (2009).



Notes:

Giant sequence from 0.8–5 µm. The spectra have been normalized to unity at 1.10 µm and offset by constants (dotted lines). Regions of strong (transmission <20%)telluric absorption are shown in dark gray, while regions of moderate (transmission <80%) telluric absorption are shown in light gray.

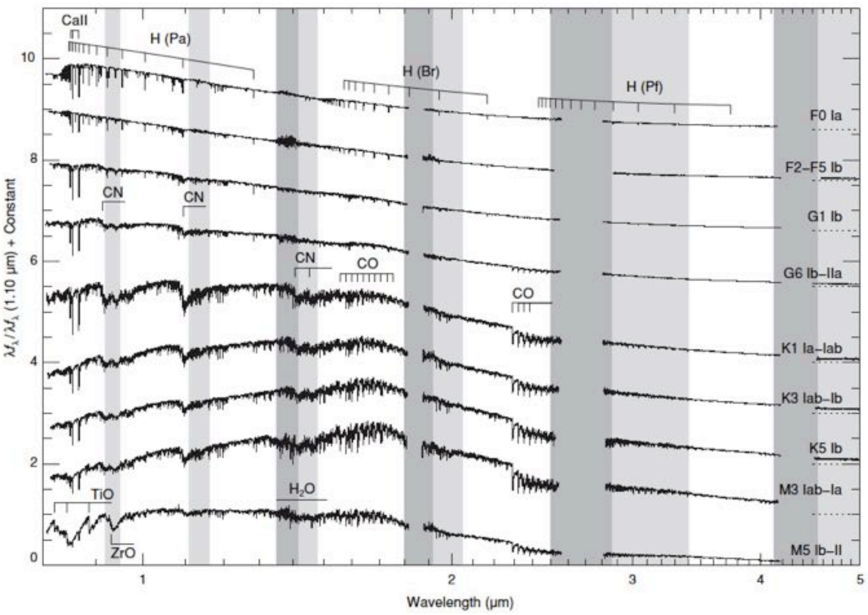
From Rayner et al. (2009).



Notes:

Supergiant sequence from 0.8–5.0 µm. The spectra have been normalized to unity at 1.10 µm and offset by constants (dotted lines). Regions of strong (transmission <20%) telluric absorption are shown in dark gray, while regions of moderate (transmission <80%) telluric absorption are shown in light gray.

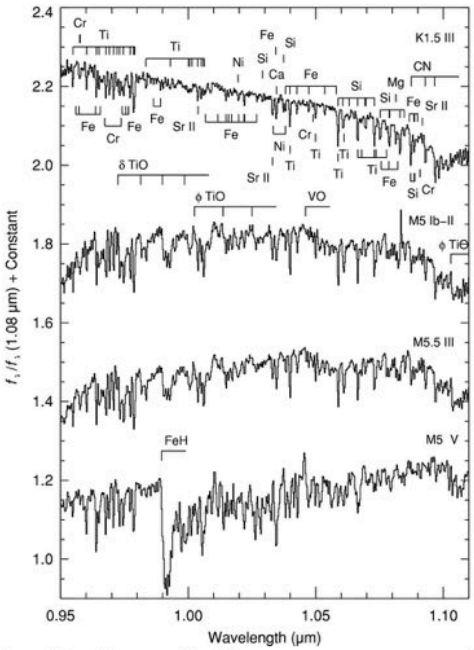
From Rayner et al. (2009).



Notes:

Spectra of spectroscopic standards in the Y band to illustrate the complexity of the stellar spectra.

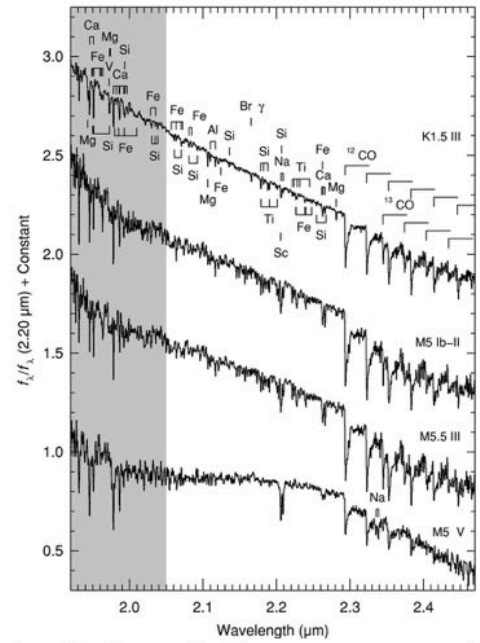
From Rayner et al. (2009).



Notes:

Spectra of standard stars in the K band

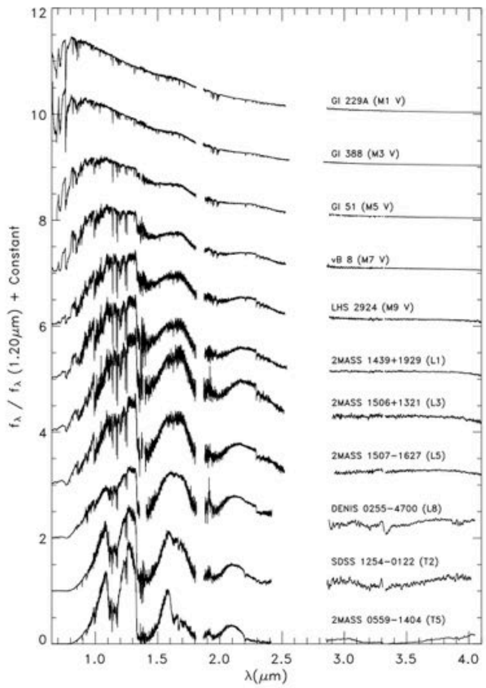
From Rayner et al. (2009).



Notes: DESCRIBE SOME ELEMENTS OF SPECTRAL CLASSIFICATION.

The 0.6–4.1 μm sequence of M, L, and T dwarfs. The gaps in the spectra at 1.85 μm are due to a break in the wavelength coverage of the SXD mode of SpeX. The spectra from 2.5 to 2.9 μm were removed because the atmosphere is opaque at these wavelengths.

From Cushing et al. (2005).

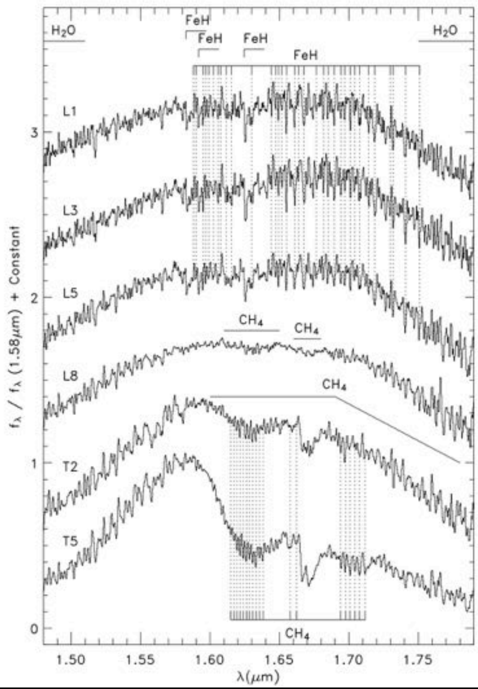


Notes:

Cushing, M. C., J. T. Rayner and W. D. Vacca (2005). "An Infrared Spectroscopic Sequence of M, L, and T Dwarfs." Astrophysical Journal **623**: 1115-1140.

H-band spectra of brown dwarfs. The most prominent molecular and atomic features are indicated.

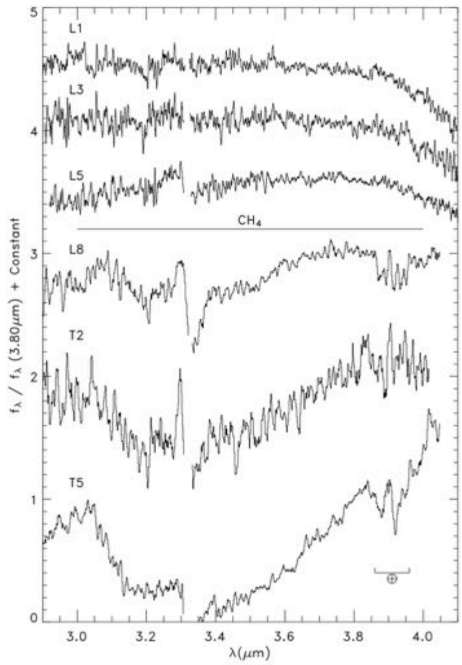
From Cushing et al. (2005).



Notes:

L-band spectra of brown dwarfs. The most prominent molecular and atomic features are indicated. The absorption features centered at 3.9 mm are due to incomplete removal of the N_2O telluric feature.

From Cushing et al. (2005).



Notes: