The Solar Spectrum: an Atmospheric Remote Sensing Perspective

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University of Toronto, Oct 21, 2013

Solar radiation is commonly used for remote sensing of the Earth.

It provides a bright, stable and spectrally continuous source.

Both direct and reflected sunlight are used:

- Direct: MkIV, ATMOS, ACE, SAGE, POAM, NDACC, TCCON, etc.
- Reflected: OCO, GOSAT, SCIA, TOMS, etc.

Abstract

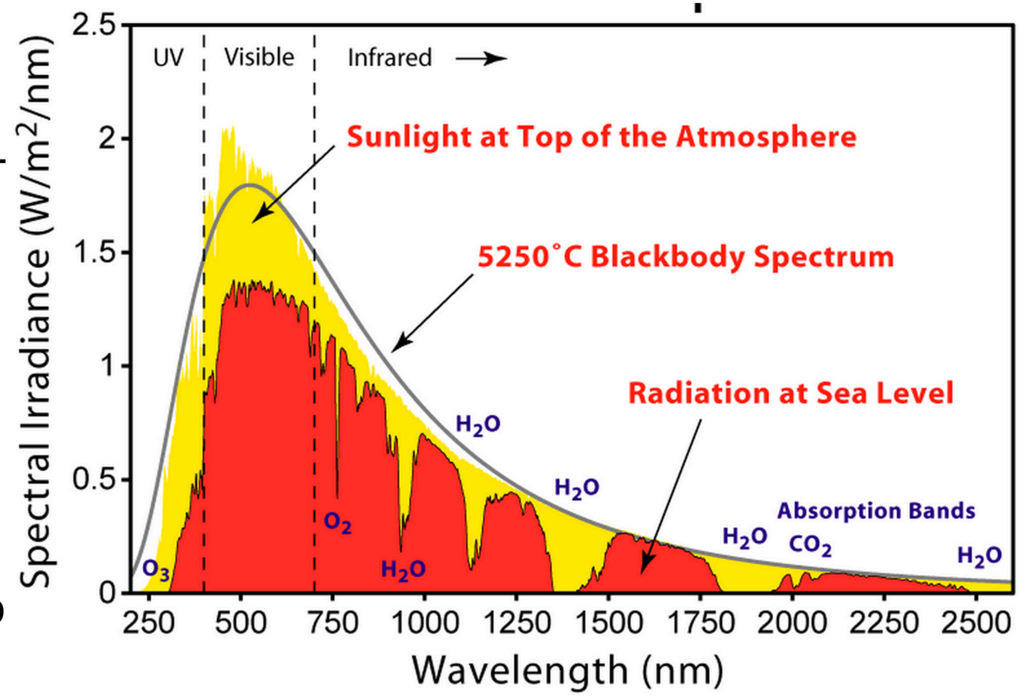
The solar spectrum not only contains information about the composition and structure of the sun, it also provides a bright and stable continuum source for earth remote sensing (atmosphere and surface). Many types of remote sensors use solar radiation. While high-resolution spaceborne sensors (e.g. ACE) can largely remove the effects of the solar spectrum by exo-atmospheric calibration, this isn't an option for sub-orbital sensors, such as the FTIR spectrometers used in the NDACC and TCCON networks. In this case the solar contribution must be explicitly included in the spectral analysis. In this talk the methods used to derive the solar spectrum are presented, and the underlying solar physics are discussed. Implication for remote sensing are described.

Background

Astronomers hate the Earth's atmosphere – it impedes their view of the stars and planets

Atmospheric scientists hate the sun – its spectrum is so complicated:

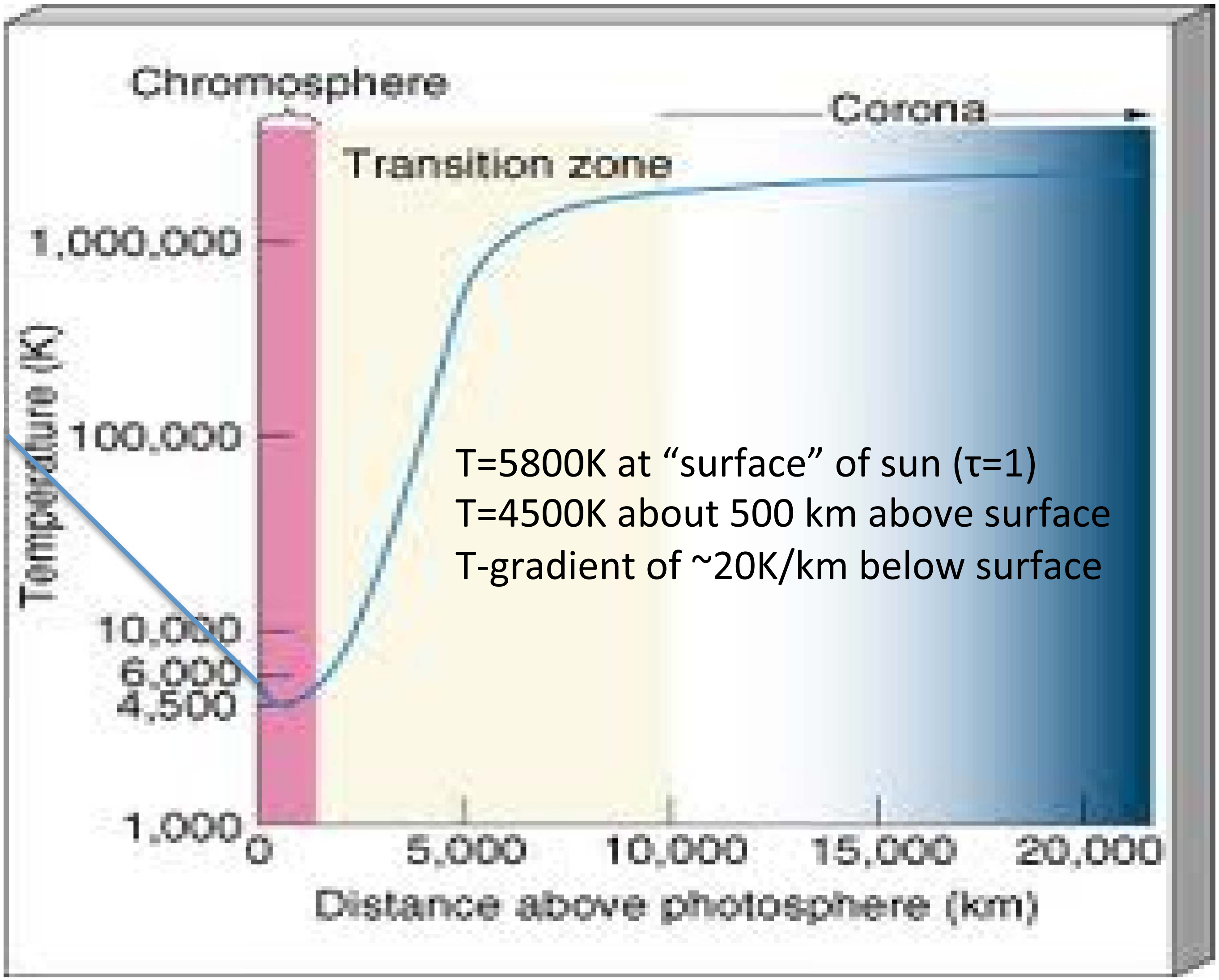
- Fraunhofer absorption lines
- Doppler shifts
- Spatial Non-uniformities (sunspots, limb darkening)
- Temporal variations (transits, solar cycle, rotatio 5-minute oscillation)



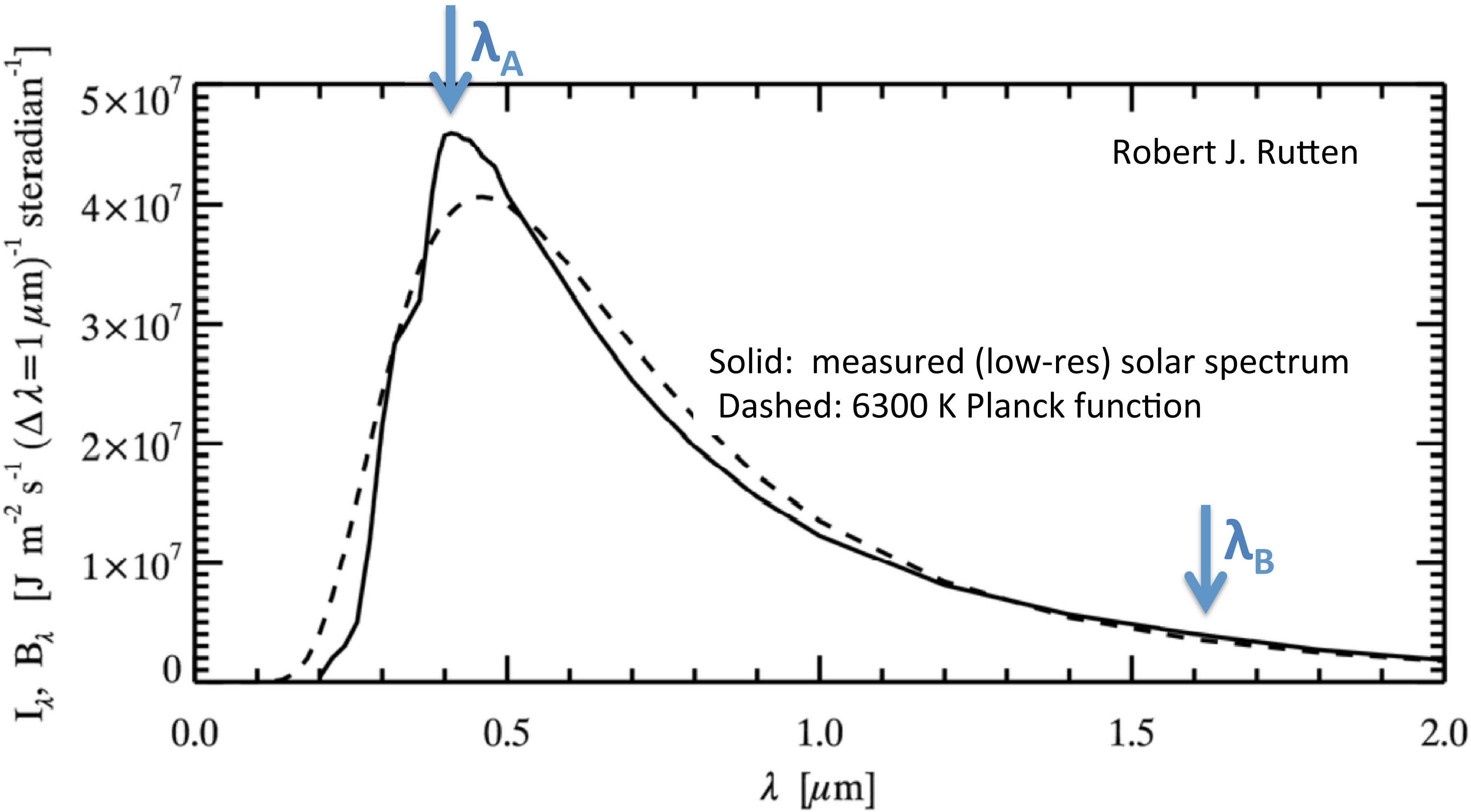
all of which complicate remote sensing of the Earth using sunlight.

To analyze solar absorption spectra, the underlying solar spectrum has to be either accounted for or calibrated out.

The Solar Temperature Profile



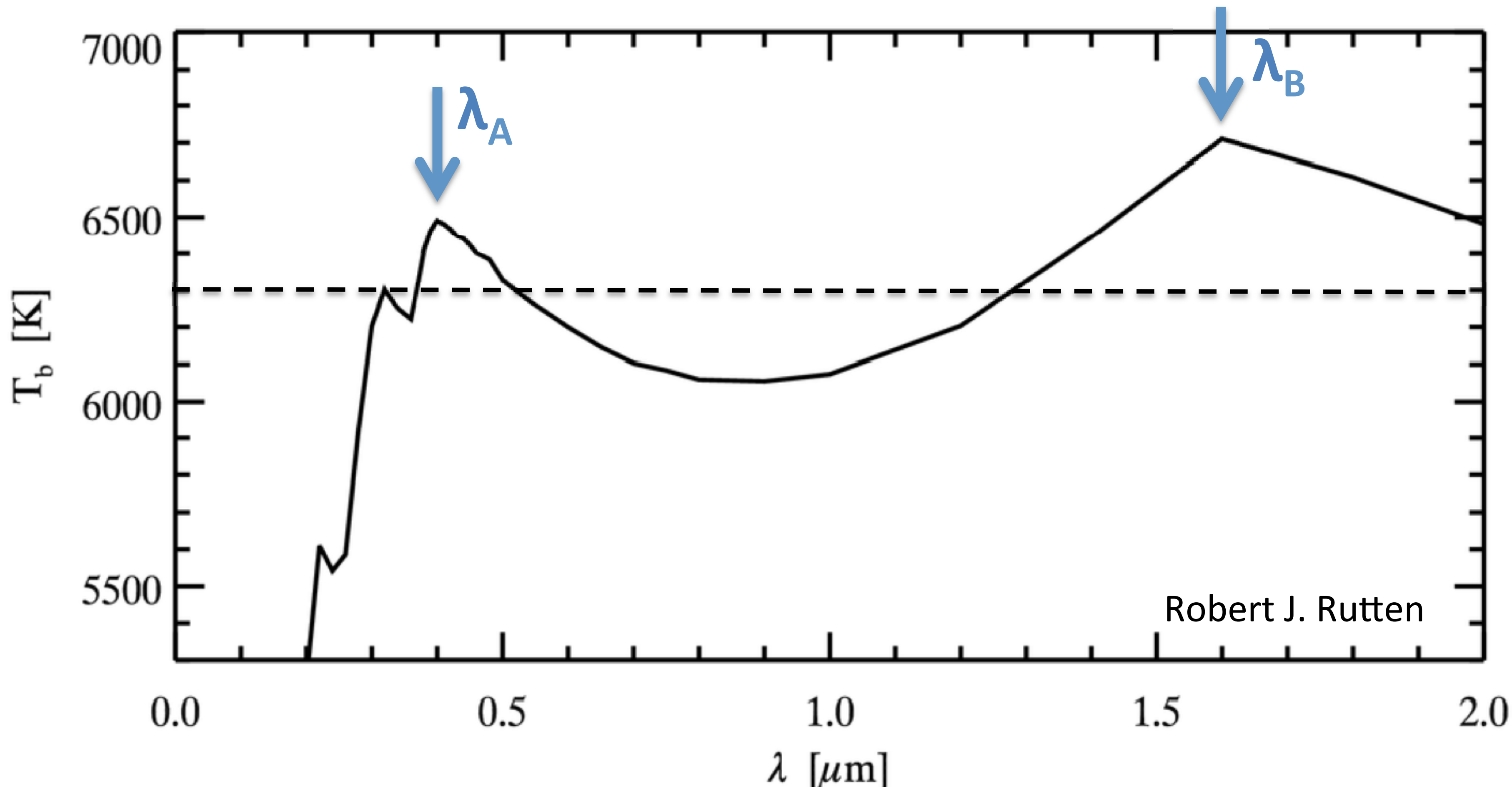
The Low Resolution Solar Spectrum



Can be approximated by a Planck Function

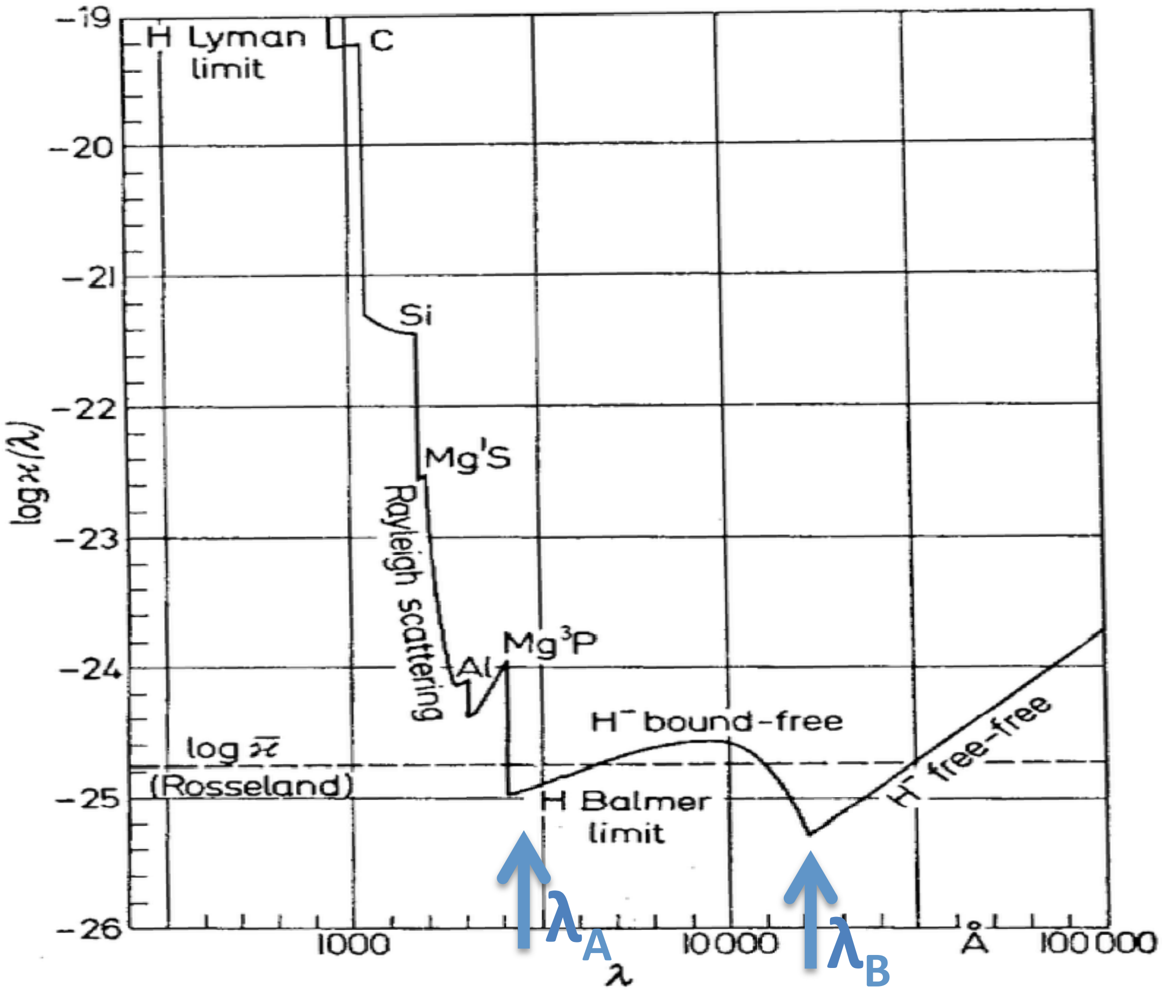
At which wavelength is solar radiation hottest?

Effective Solar Brightness Temperature



Why is sun hottest at 1.6 um ?
Why is the solar spectrum so close to a black body anyway?
Why don't we see deeper the sun? It just a bunch of H & He atoms

Solar Photospheric Opacity

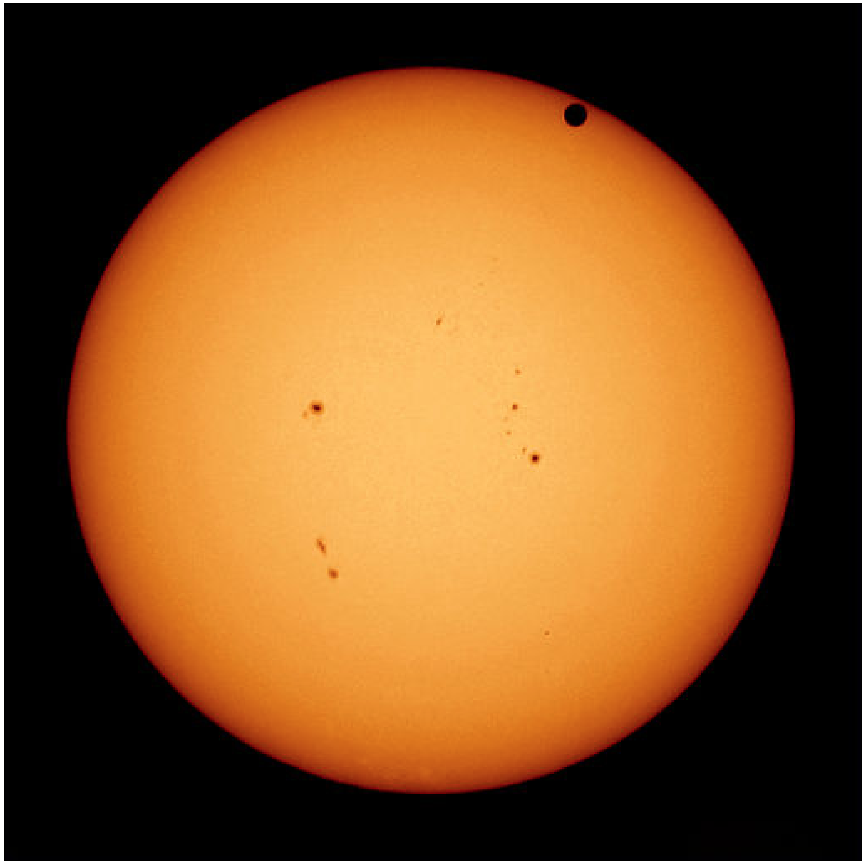


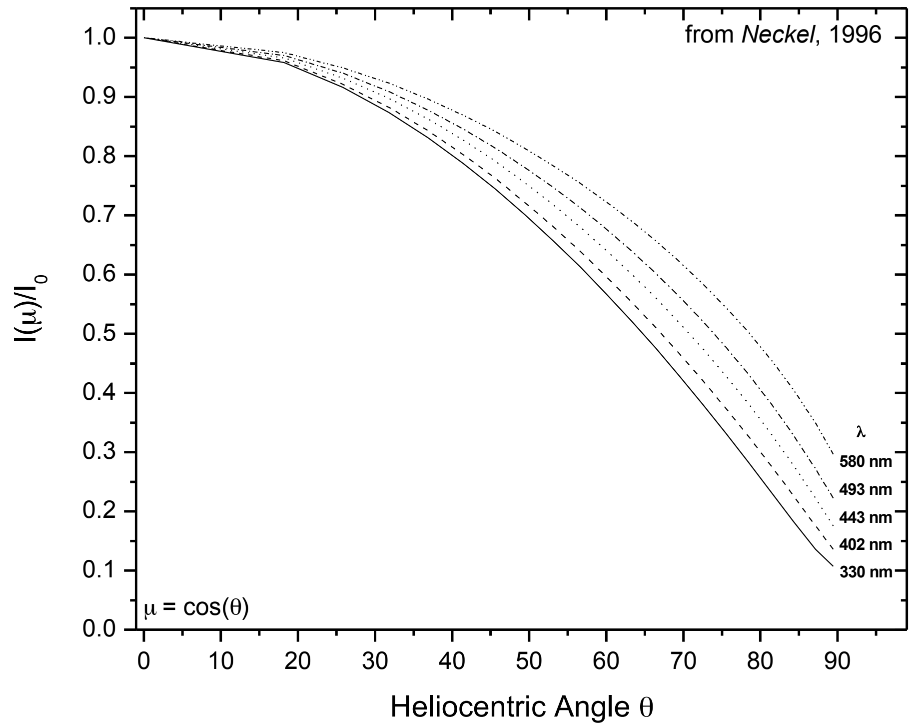
H Lyman limit:
1→ ∞ 91 nm

H Balmer limit:
2→ ∞ 365 nm

In the visible and IR, H^- ions are the dominant source of opacity. So almost every solar photon that we see (Vis) or measure (IR) was emitted by an H^- ion. Without H- ions, the solar spectrum would be much brighter in the Vis/IR

Solar Limb Darkening





Confirms the decrease of temperature with altitude in photosphere.
At normal incidence, we see deeper into the sun (hotter & brighter).
Viewing the limb, unit opacity occurs at a higher latitude, where it's colder.
Limb/Center intensity ratio ≅ Planck(4800K,v)/Planck(5800K,v)

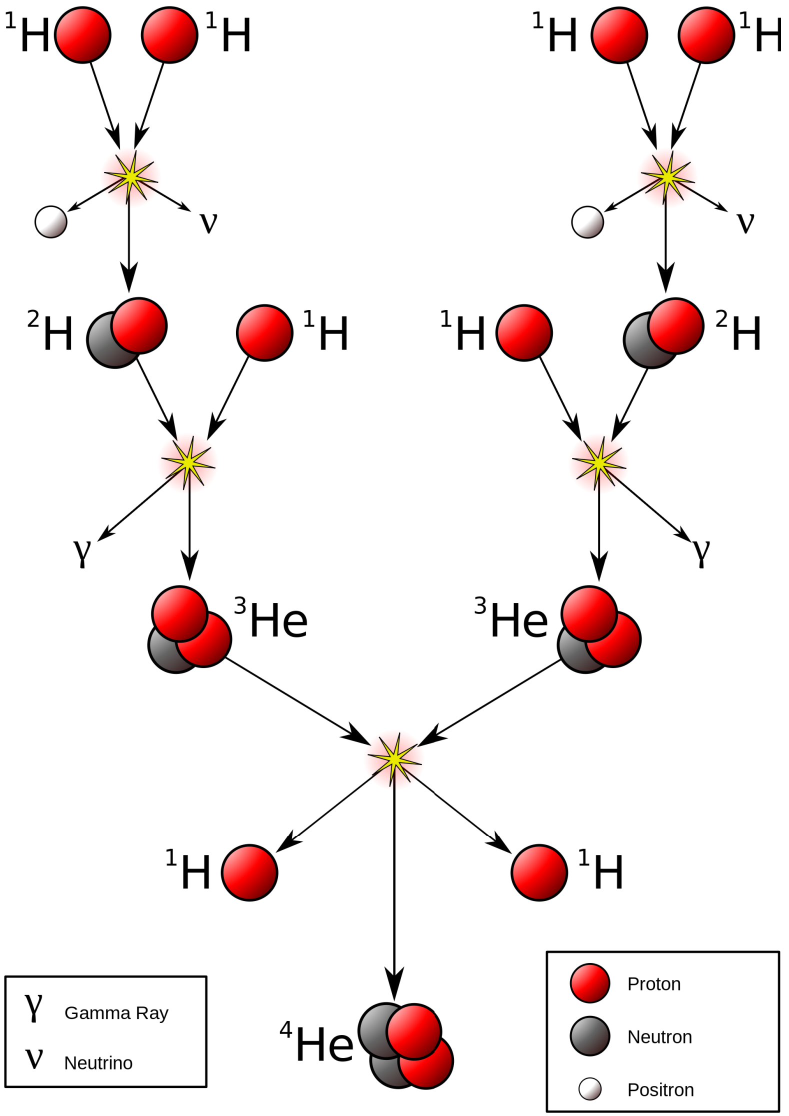
Detour – Nuclear fusion in the sun

Energy production at the sun's core is 275 W/m^3, about the same as a typical compost heap.

So why is the sun so hot? Because it is huge: the energy production varies as r^3, but the energy can escape only through the surface, whose area varies as r^2. So the energy escaping per unit area (and hence T) varies as r.

At temperatures of ~15 MK (with help from quantum tunneling) two protons can occasionally overcome their electrostatic repulsion and fuse together under the strong nuclear force, emitting a positron and a neutrino. This is the rate-limiting step to the proton-proton reaction chain (right), from which the sun generates most of its power.

The net result is to convert 4 protons into a ^{4}He nucleus, two positrons, two neutrinos, and γ-rays, with a loss of 0.7% of the initial mass.



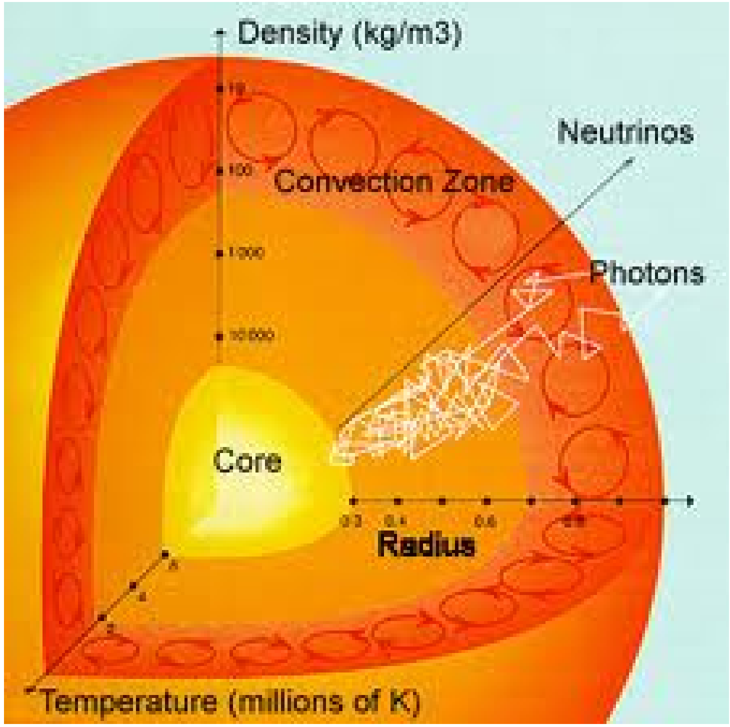
Detour – Nuclear fusion in the sun

Only the innermost 25% of the sun (1.5% by volume) generates energy.

Most of the energy produced in the sun's core is gamma rays. This has a MFP of only a couple of mm, and are absorbed and re-emitted (at slightly lower energies) gazillions of times in a random walk before the radiation reaches the surface.

No gamma rays are emitted by the sun. They are all absorbed and re-emitted as lower energy radiation (e.g., X-ray, UV, Vis, IR).

Radiation starting at the core (as gamma rays) takes ~10M years to reach the surface (as visible radiation), despite travelling at the speed of light the whole time. So the sun's core is extremely well insulated. In fact, diffusion of radiation is so slow that convection is faster.



Neutrinos, on the other hand, take just 2s to escape the sun and 8 min to reach Earth. So if the sun goes out, we'll find out first from the drop in neutrinos.

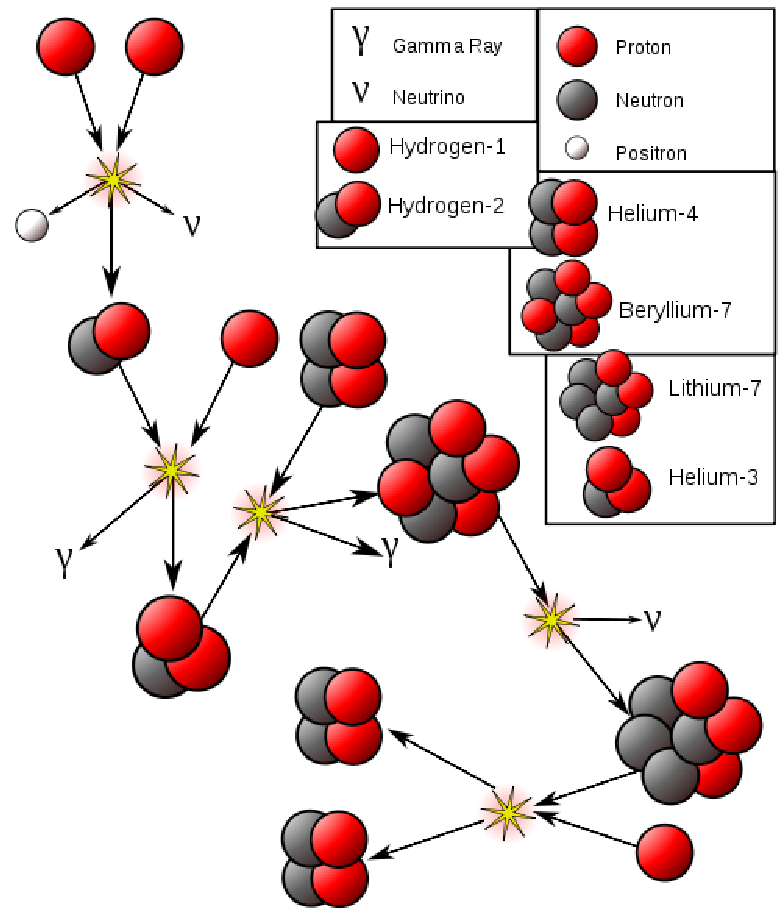
Detour – H-Bomb

Skips the incredibly slow initial Proton-Proton reaction by starting with Lithium Deuteride.

Can achieve energy density of ~2×10^{20} W/m^3

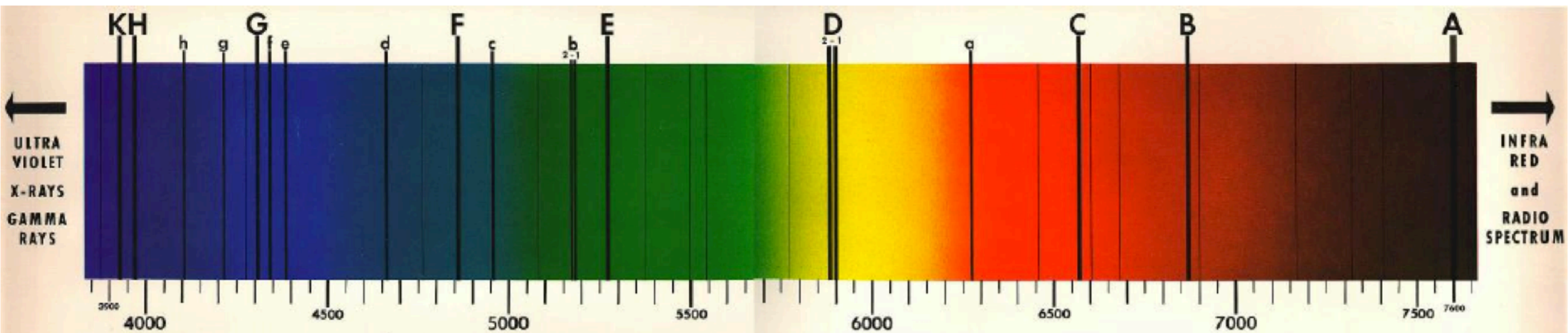
18 orders of magnitude more then Sun.

So fuel is consumed in 0.1s instead of several billion years.



The Solar Spectrum – High Resolution

In 1814, Fraunhofer invented the spectroscope, and discovered 574 dark lines appearing in the solar spectrum. They are still called Fraunhofer lines. Kirchhoff and Bunsen showed in 1859 that they are atomic absorption features providing diagnostics-at-a-distance of the local conditions in the atmospheres of the Sun and other stars.



scale in Ångstrom; 1 Å = 0.1 nm

K & H: resonance lines of calcium ions
G: rotation-vibration band of CH molecules
F: Balmer-β line of hydrogen atoms
b: three lines of magnesium atoms
E: a group of lines of iron atoms
D: two resonance lines of sodium atoms (the same as in street lights)
C: Balmer-α line of hydrogen atoms
B & A: rotation-vibration band of oxygen molecules in the Earth atmosphere

The Solar Spectrum

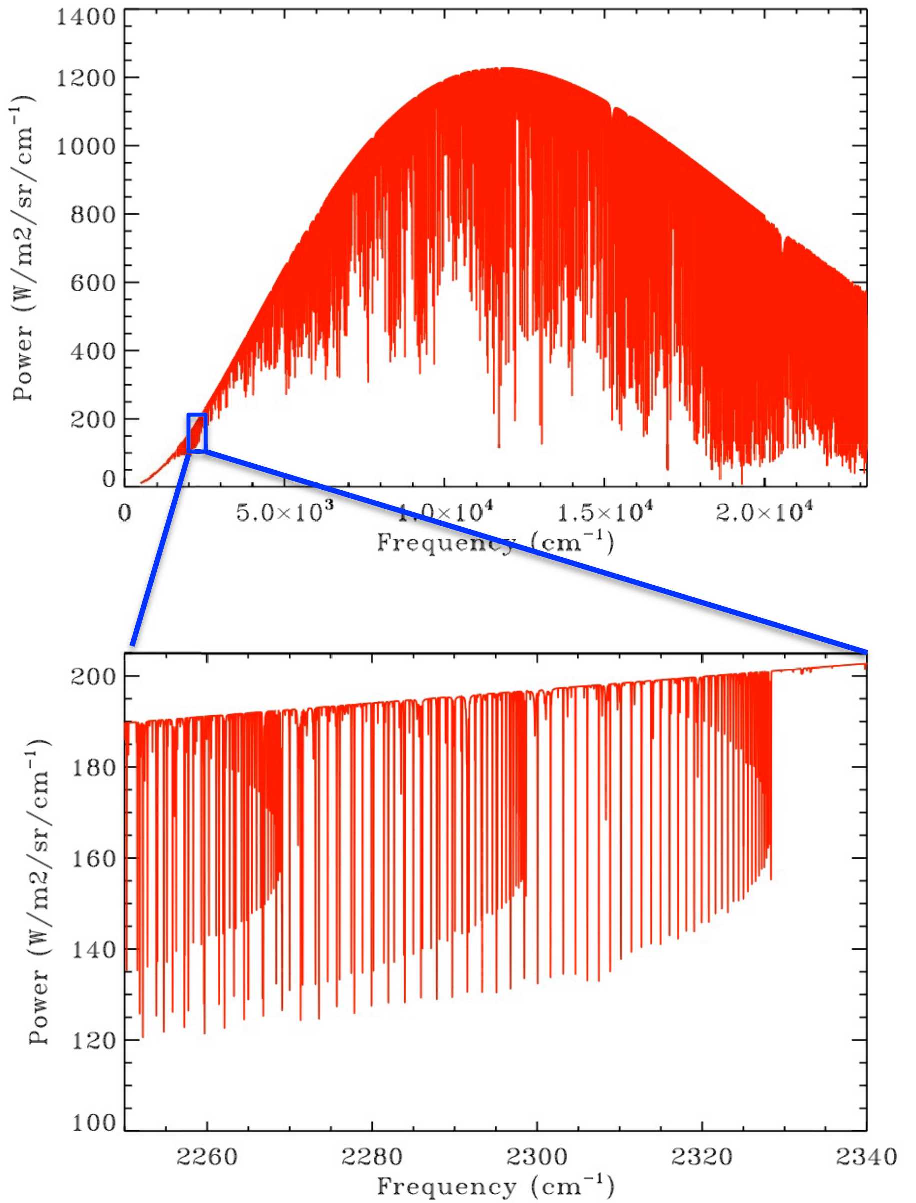
At high spectral resolution, the solar spectrum has over 40,000 documented discrete absorptions.

These represent photons that were absorbed during their passage through the 4500K temperature minimum above the photosphere.

In the IR these are mostly due to CO.

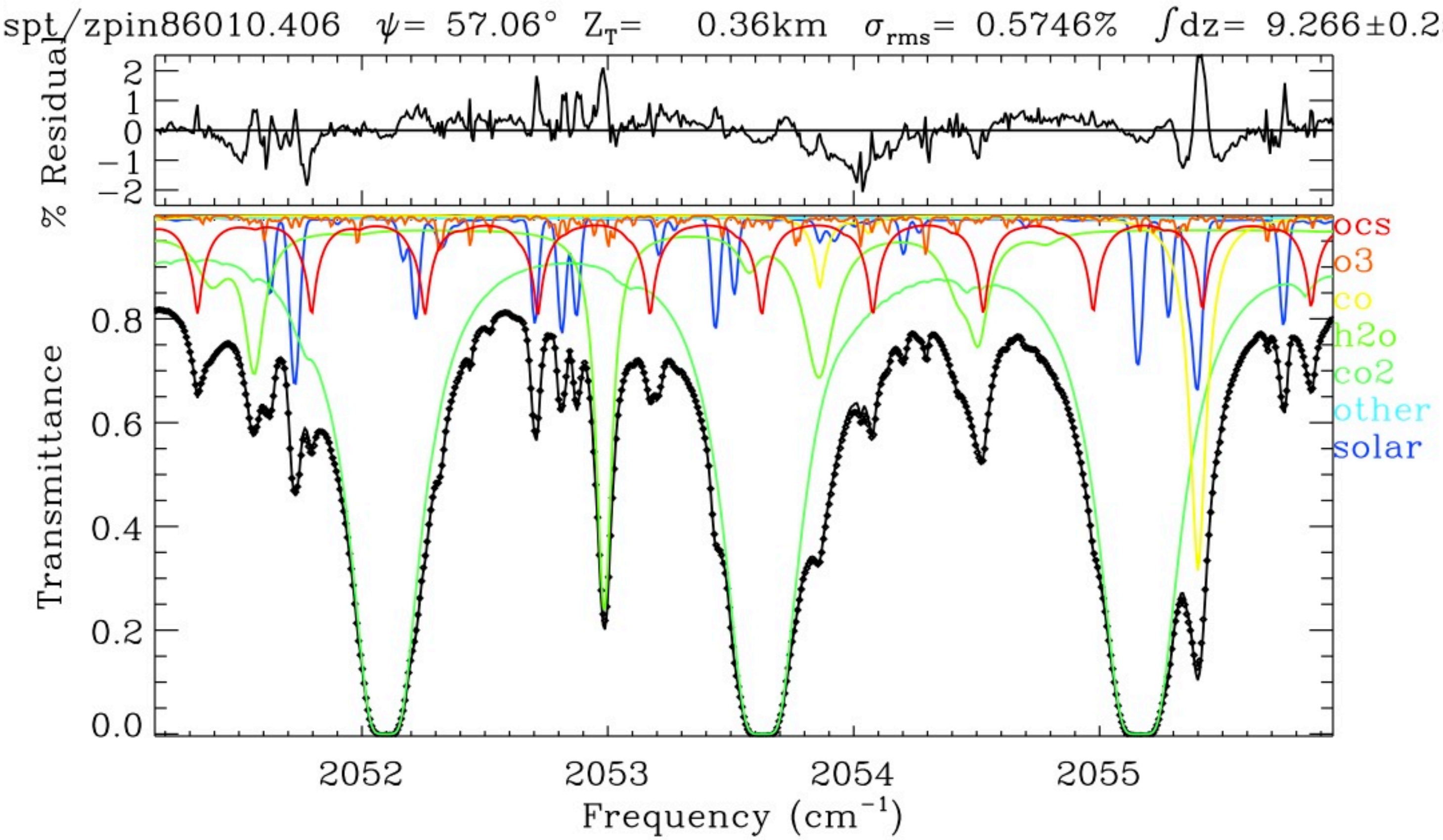
In the NIR and Vis they are mostly due to atomic transitions (Fe, Ni, Si, Mg, Na, K, C, H, He).

He was first discovered on the sun.



Disentangling the Solar Spectrum

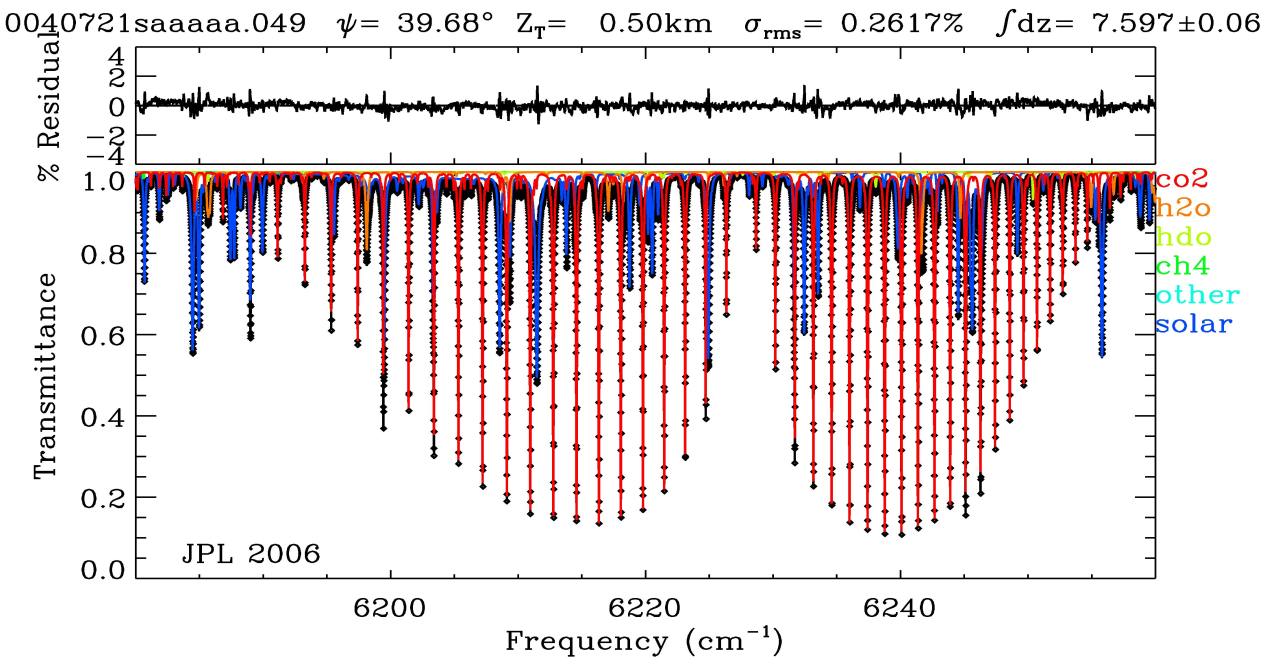
Solar spectrum can be a nuisance – you need to remove it or account for it when fitting atmospheric absorptions. See example below.



Or the solar spectrum itself can be very useful (next page).

Disentangling the Solar Spectrum

Even for satellite instruments that measure a calibration solar spectrum from high above the atmosphere, it is still necessary to know the high-resolution solar spectrum because under-resolved solar features don't cancel perfectly.



Science goal is to measure atmospheric CO_2 to 0.1% precision (Carbon Cycle modeling)

Need to accurately represent solar absorption lines in terms of their position, depth & shape.

How do we know which absorptions are solar versus telluric?

How to derive a TOA solar spectrum?

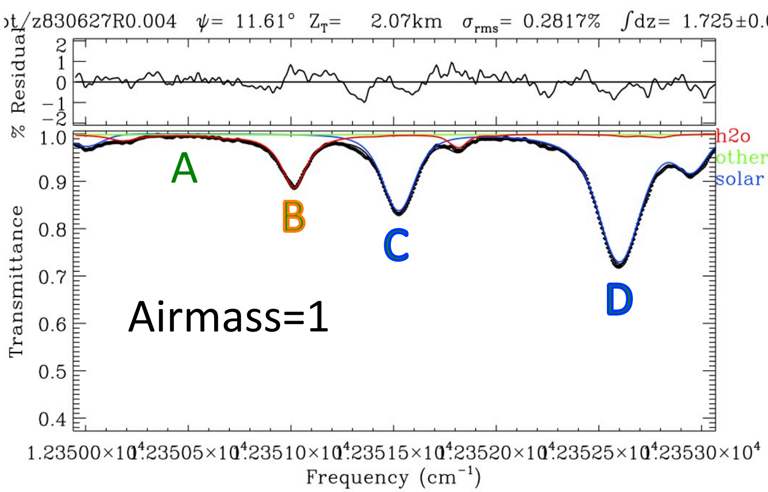
1. Exo-Atmospheric. Measure a solar spectrum from high above the atmosphere (e.g. Farmer & Norton, 1989; Hase et al. 2005, 2010),
    - By far best approach (telluric absorptions are negligible).
    - ATMOS/ACE/GOSAT spectra have limited spectral coverage and/or resolution

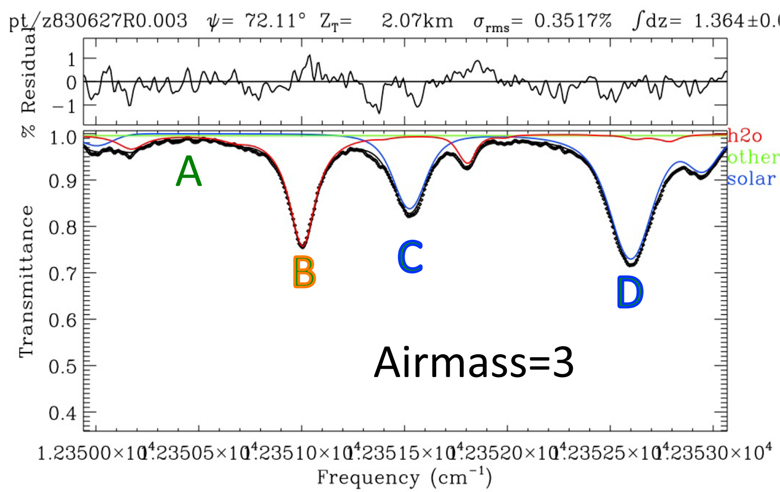
2. Zero Airmass Extrapolation. Measure a series of solar spectra over a range of airmasses and then use the Bouger method (Langley plot) to extrapolate to zero airmass (e.g., Arvesen at al., 1969, Kurucz, 2008, Livingston and Wallace, 1991)
    - Requires unchanging atmospheric conditions (P/T, gas & aerosol)
    - Under-resolved atmospheric absorptions not fully removed if non-linear
    - independent of spectroscopy

3. Telluric Subtraction. Measure low-airmass solar spectra. Fit calculated atmospheric transmittance spectrum. Dividing the ground-based spectrum by the atmospheric transmittance spectrum yields solar/instrument component.
    - Requires good spectroscopic linelist and atmospheric model & fitting software
    - More flexiblity handling different observations and varying atmosphere

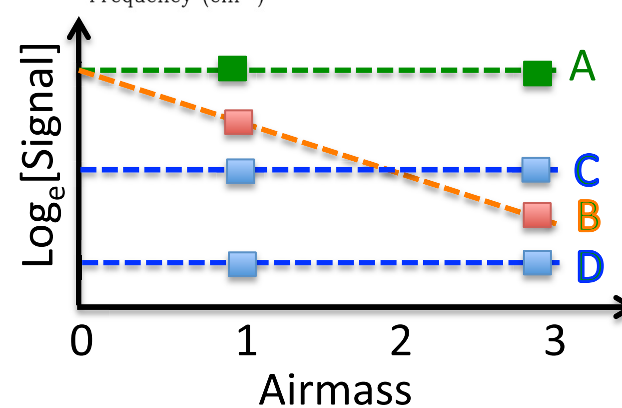
Zero Airmass Extrapolation

Before the satellite era, people derived solar spectra from ground-based and aircraft measurements, by exploiting the fact that telluric absorption lines increase with airmass as Exp[-k_v.a], whereas solar absorptions remain constant in depth.
So plotting $\log_e$(Signal) versus airmass (Langley plot) distinguishes solar from telluric

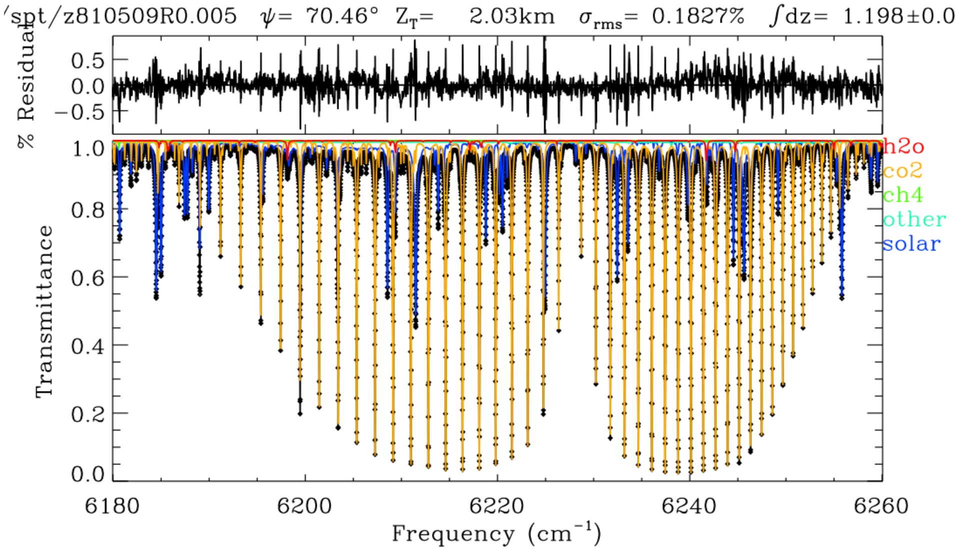




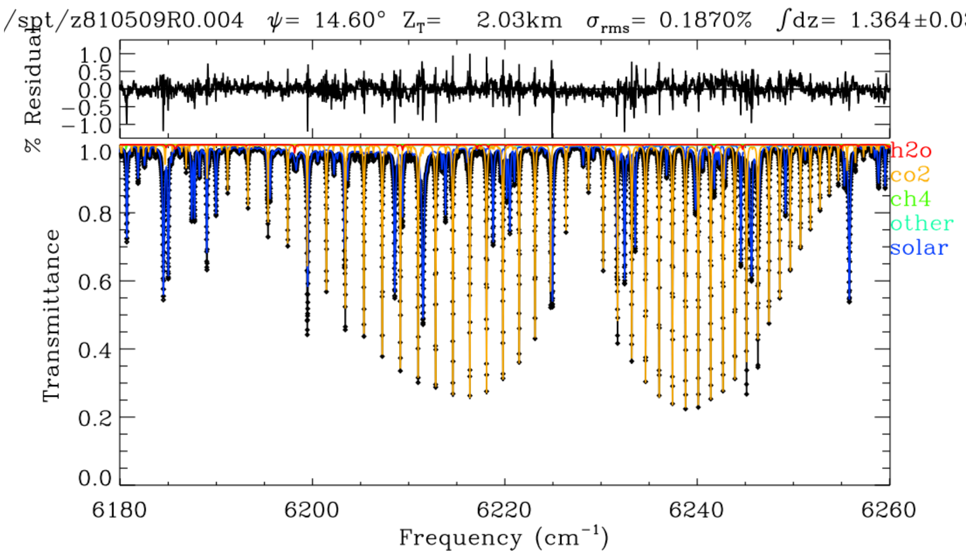
- Atmospheric absorption must remain unchanged between low & high airmass (T/P, gas & aerosol)
- Absorption features must be weak or fully resolved
- Useless in blacked out spectral regions
- Didn't need any spectroscopy knowledge

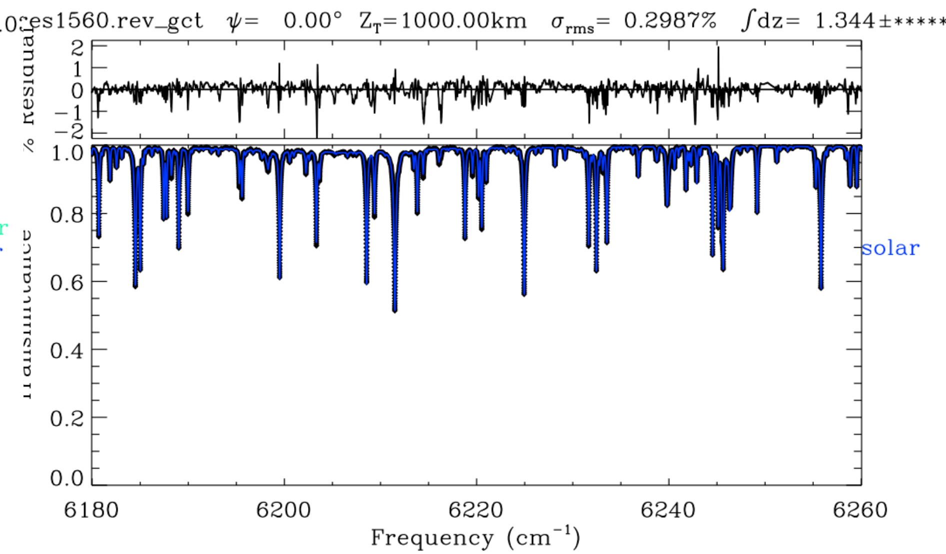


Zero Airmass Extrapolation - Example



Low and high-airmass Kitt Peak spectra and the calculated exo-atmospheric spectrum





Telluric Subtraction Method

3. Telluric Subtraction.
Measure series of low-airmass solar spectra under different conditions (disk center, disk int).
Fit calculated telluric transmittance spectrum.
Divide each measured spectrum by the fitted atmospheric transmittance
Result is pure solar*instrument component.

Improved spectroscopy and telluric modeling/retrieval capabilities make this possible.

Promises greater flexibility

Available FTS Measurements

Instrument	Advantages	Disadvantages
GOSAT (650 km) (2009-present)	Disk-integrated (3 bands)	0.2-0.5 cm^{-1} resolution Disk-integrated only
ATMOS (350 km) 1985-1994	600-4800 cm-1 (3 filters) 0.015 cm-1 resolution	Slight H2O contamination Disk-center only
ACE (650 km) (2003-present)	700-4400 cm-1 simultaneously High SNR. Contamination-free	0.04 cm-1 resolution (apodized) Disk-Center only
MkIV balloon 1989-	650-5650 cm^{-1} simultaneously 0.01 cm-1 resolution	39 km altitude, residual gas absorption. Disk-center only
Denver University 2000 32 km	12930-13250 cm-1 (O2 A-band) 0.02 cm-1 resolution	Telluric O2 absorption
Kitt Peak 1978-2006)	Disk-Center & Disk-Integrated 600-35000 cm-1 @ 0.01 cm-1	2 km altitude Telluric interference.
TCCON	3900-15500 cm-1 Center-to-limb observations	0-2 km altitude H2O contamination

Which instrument provide the best solar spectrum?
They have different strengths and weaknesses.
Can they be combined in such a way that their collective strengths are emphasized?

Empirical Solar Lineshape Model

By making some assumptions about the shape of the solar fraunhofer lines, and their variation from center to limb, develop an empirical solar model.

$$f(\nu-\nu_0)=e^{-\frac{(\nu-\nu_0)^2}{\sqrt{d^4+(\nu-\nu_0)^2 w^2}}}$$

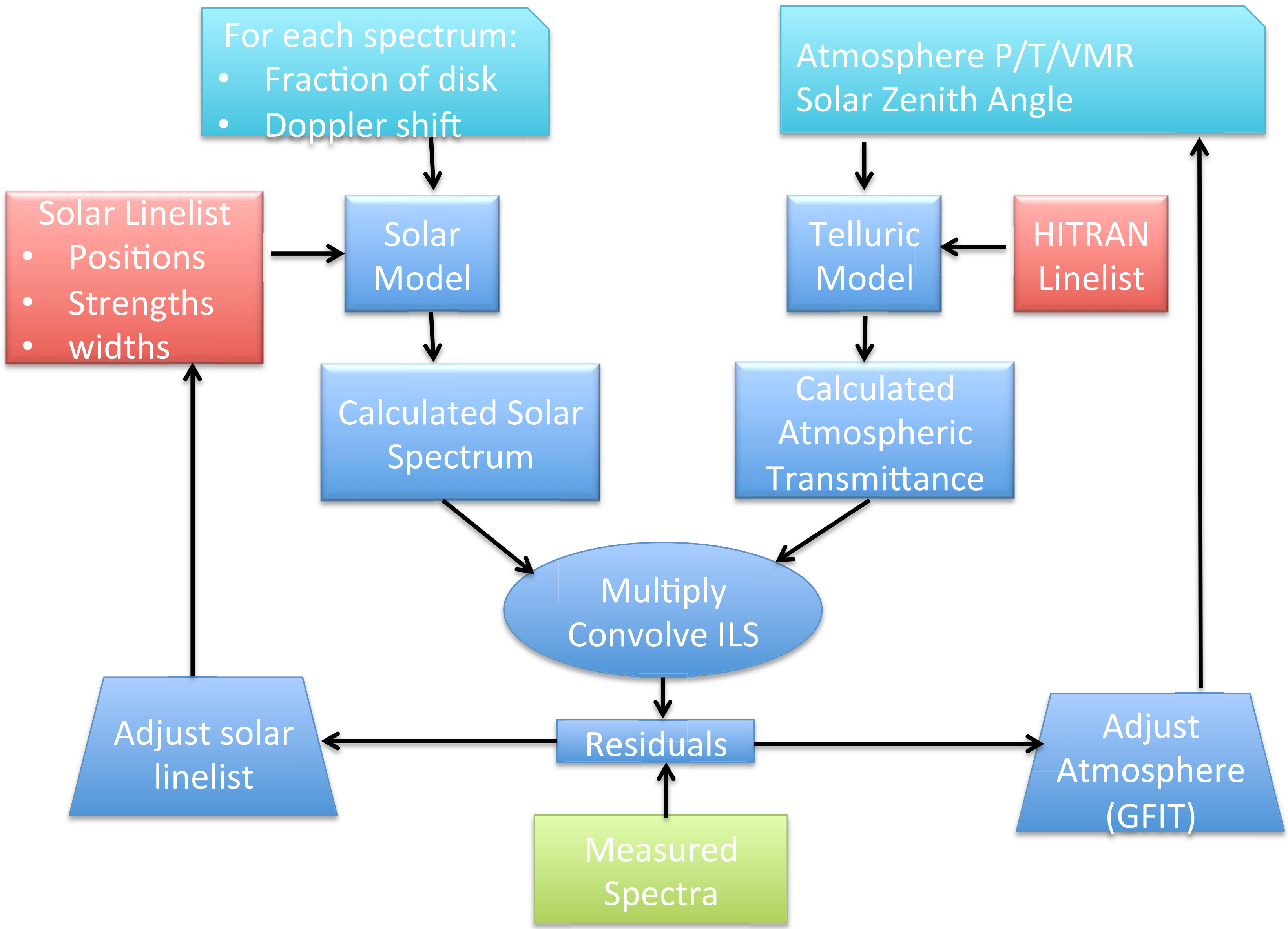
This choice of lineshape has no physical basis, but seems to provide a reasonable representation is nearly all cases.
The various measured solar spectra can then be fitted using the solar model, after accounting for the:

1. Earth atmosphere (observation altitude, Zenith angle, gas vmr profiles)
2. Fraction of solar disk observed (broadening)
3. Time of observation (doppler shift)
4. ILS of the measuring FTS spectrometer

This is a more flexible approach than simply choosing the best spectrum.

Solar line positions, intensities, widths (DC & DI) are determined using ALL spectra.
Using diverse set of measured input spectra helps expose inconsistencies.

Solar Linelist Generation Flowchart



Features of Solar Model/Linelist

A solar linelist has been compiled that, together with a simple subroutine defining the lineshape, allow the computation of a high-res solar spectrum:

- 40000 lines covering 600-15,500 cm-1 range at doppler-limited spectral resolution
- Based on a variety of FTS measurements (Kitt Peak, ATMOS, MkIV)
- Disk-center, disk-integrated or anything in between
- User-defined spectral grid (infinite resolution)

Kitt Peak spectra form the backbone of the new solar spectrum/linelist

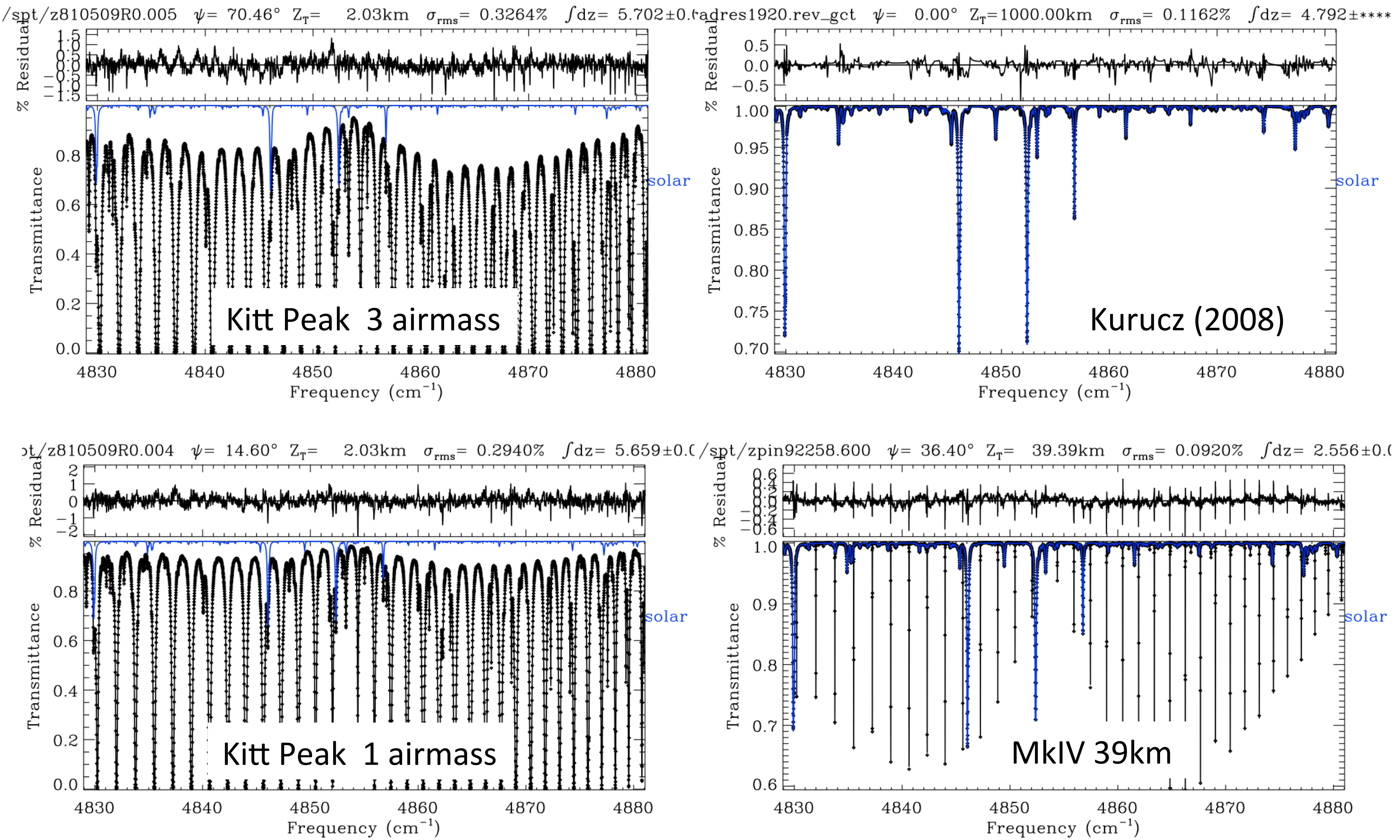
- Available at all frequencies of interest
- Disk-center and disk-integrated
- Solar lines are fully resolved

Supplemented by high-res balloon & spaceborne spectra in available intervals.

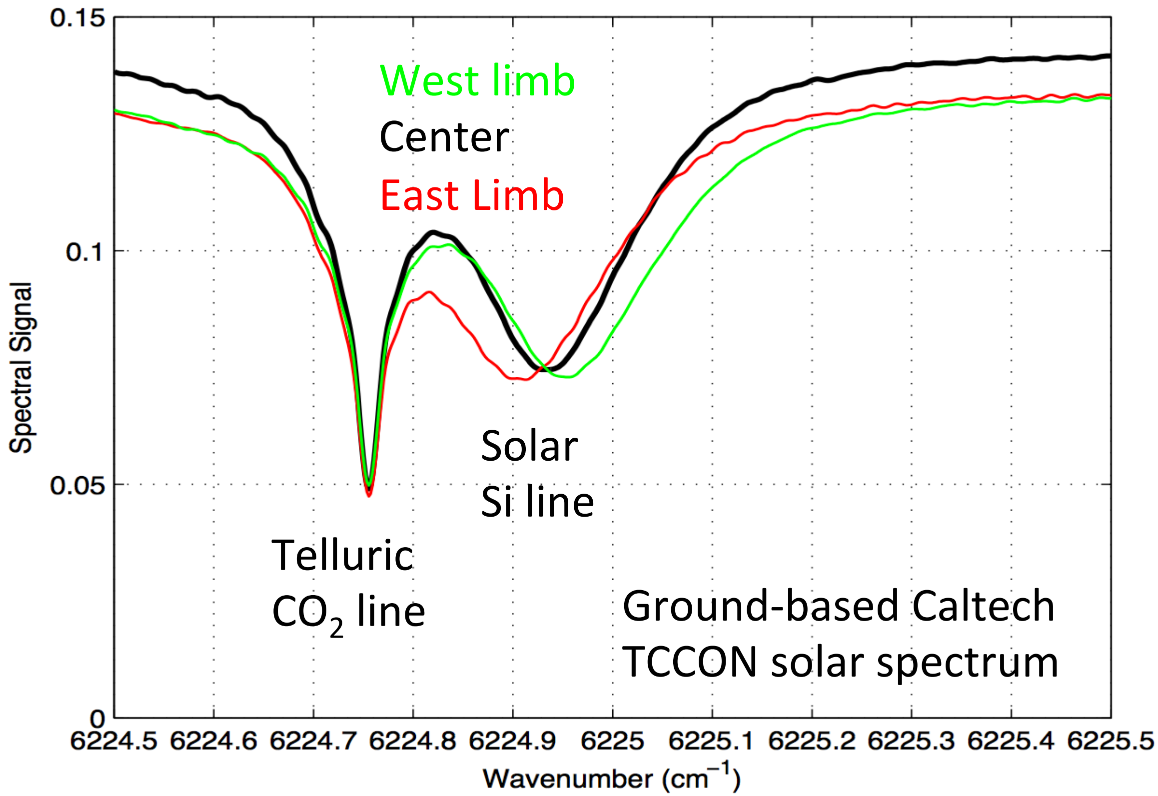
Telluric absorptions are removed by spectral fitting (need good linelist).

Even though space-borne spectrometers can measure an exo-atmospheric solar spectrum for calibration, they still require a high-res solar spectrum if they don't fully resolve solar lines.

Example – strong CO_2 band



Solar spin–induced doppler shifts



East & West limbs of sun doppler shifted relative to disk center.
Continuum level reduced (limb darkening).
Disk-integrated spectrum (average of red/black/green) would therefore have broader, shallower solar lines than disk-center spectra. [0.06/6000 cm-1 = 10^{-5} = 3000 m/s]

Modeling approach caters for disk-center, disk-integrated, and intermediate cases.

Advantages over previous Empirical Solar Reference Spectra/Linelists

- Covers a much broader spectra region (600-15500 cm-1) then previously
- Uses high-resolution spectra measured during high-altitude balloon flights
- Can be calculated on an arbitrary spectral grids
- Calculates disk-center, the integrated solar disk, and intermediate cases

Currently being used for analysis of MkIV, TCCON, GOSAT (and OCO-2) spectra.

Available from: http://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html

Comment: I'm impressed by how good the Kitt Peak solar irradiance spectra are, derived from ground-based spectra only (e.g. Kurucz, 2005, 2008). Balloon-borne spectra from 30+ km altitude (above 99+% of atmosphere) reveal few problems, and only in regions with strong telluric absorption.

Conclusions

Benefitting from:

- Spectroscopic improvements
- Improved atmospheric and solar models
- New high altitude observations

a high-resolution solar "transmittance" spectrum has been derived using a "telluric subtraction" approach. Seems to better represents the high-res structure than was previously possible by zero-airmass extrapolation of ground-based observations.

Uses a mathematical model of the solar lineshape, together with a solar linelist

Can handle multiple measured spectra as input with different:

- Observation geometries and telluric contamination amounts
- Spectral resolutions and coverages
- Solar doppler shifts and fractions of solar disk observed

Fitting to model exposes inconsistencies between measured input spectra.

Artifacts (e.g. ILS, ZLO, CF, gas absorptions) can removed in the fitting process.

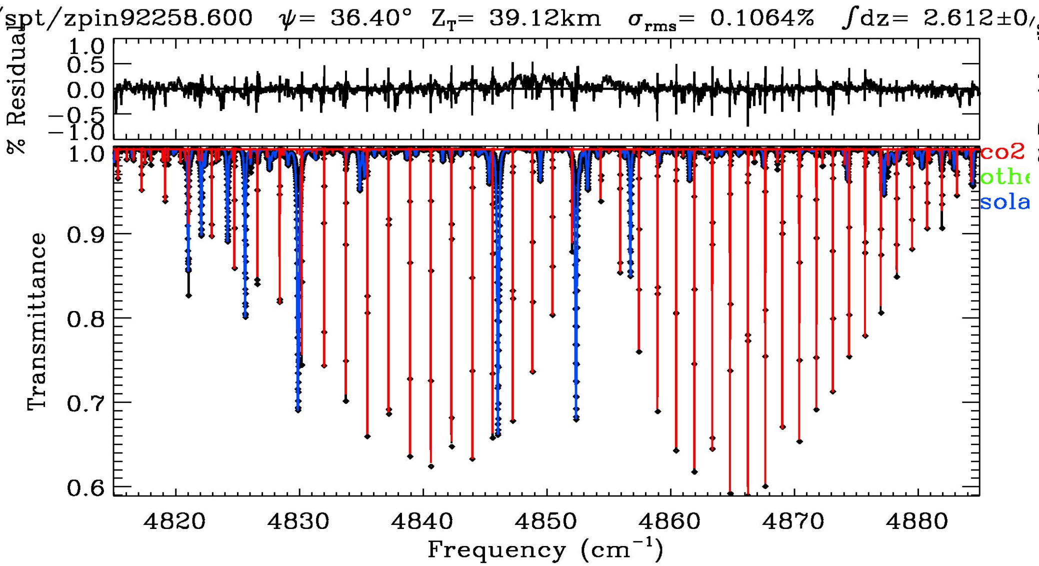
This has improved our ability to represent the solar absorption features, especially in the NIR from 4800 – 15500 cm-1.

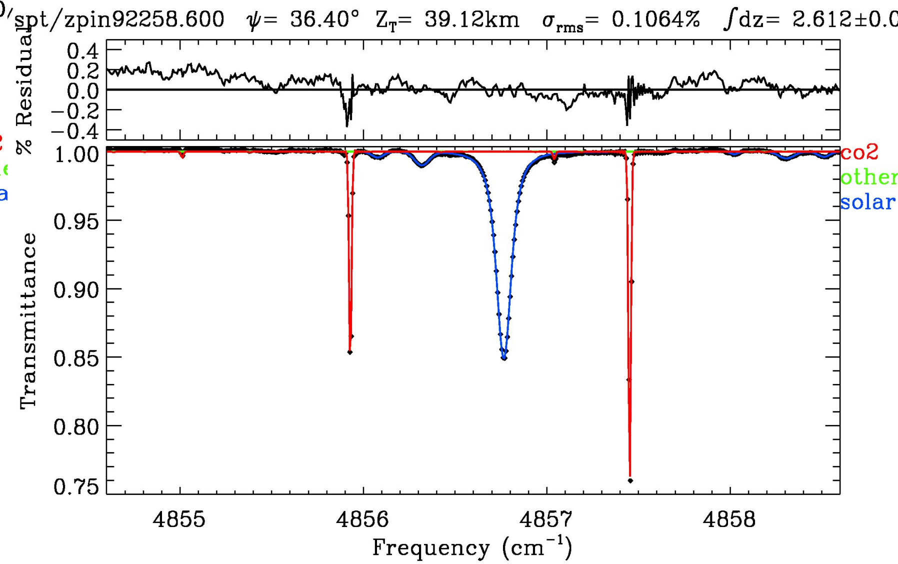
Acknowledgements

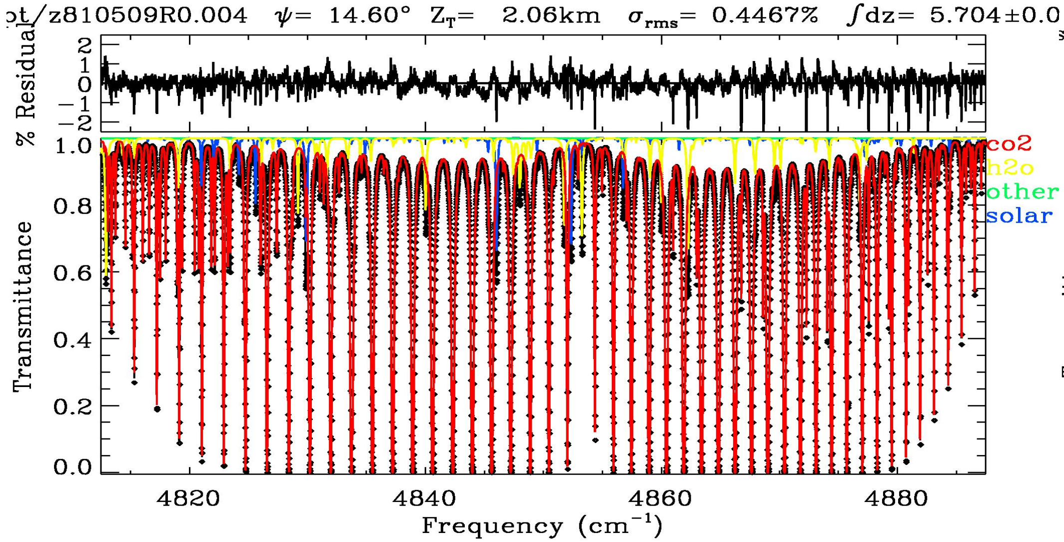
Funding:
- NASA Upper Atmosphere Research Programs
- MASA Carbon Cycle program (TCCON)

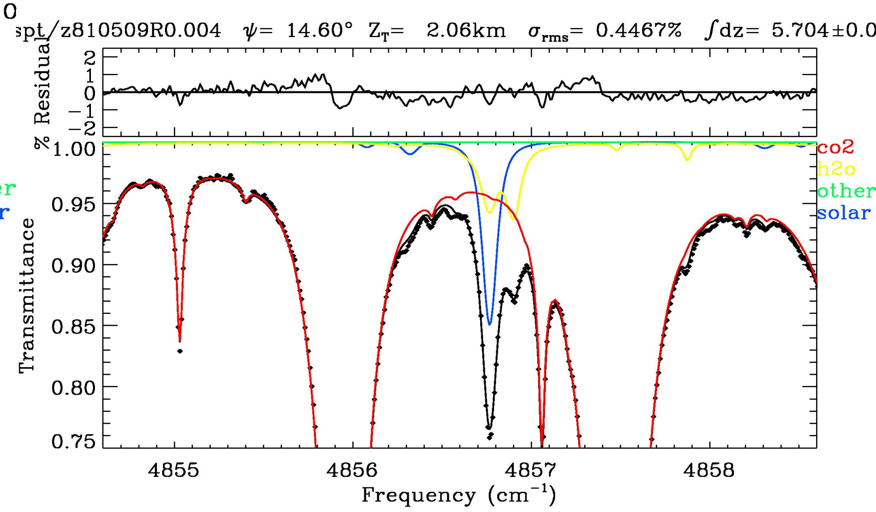
The many people involved in building FTS and acquiring solar spectra
- ATMOS
- ACE
- Kitt Peak
- MkIV
- TCCON
- GOSAT

Example – Comparing Kitt Peak & balloon

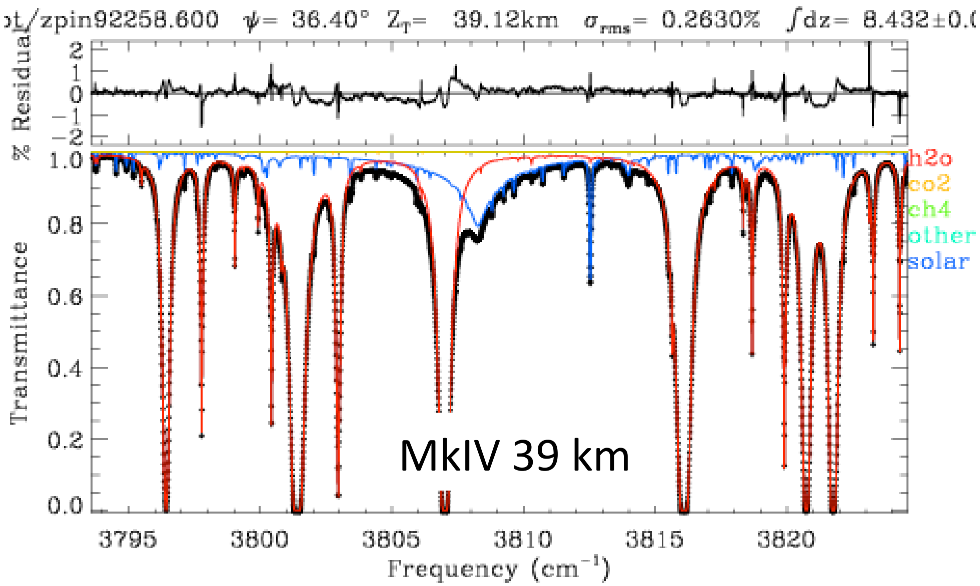




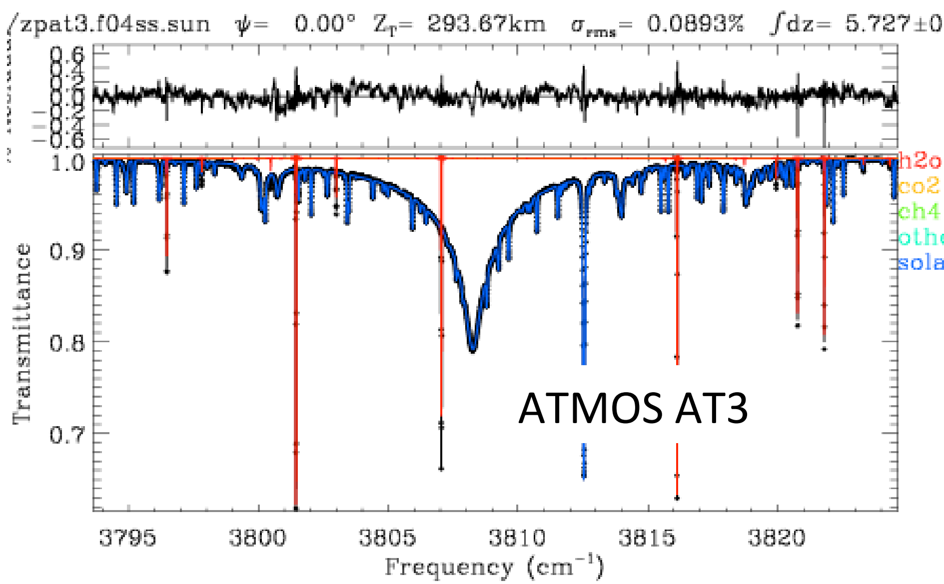


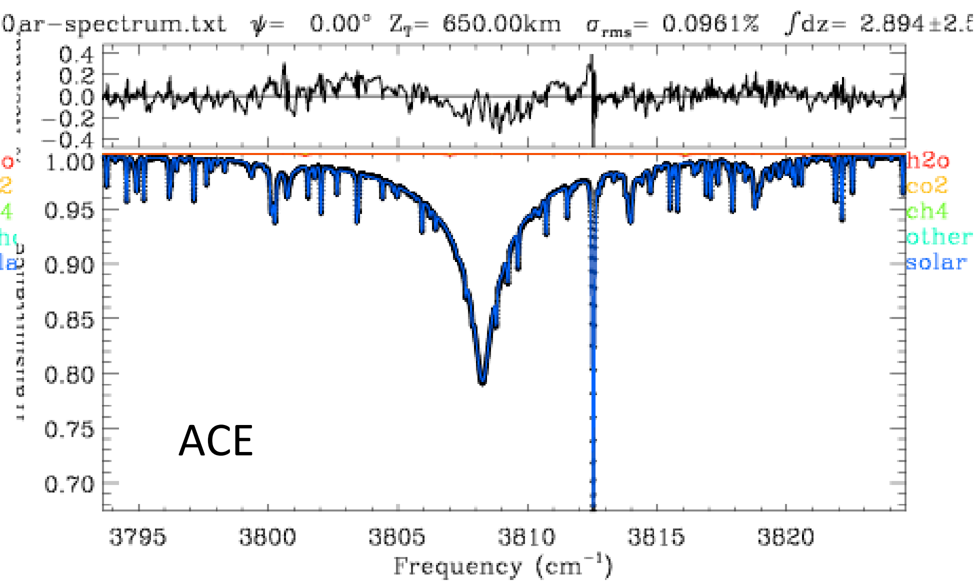


MIR Example

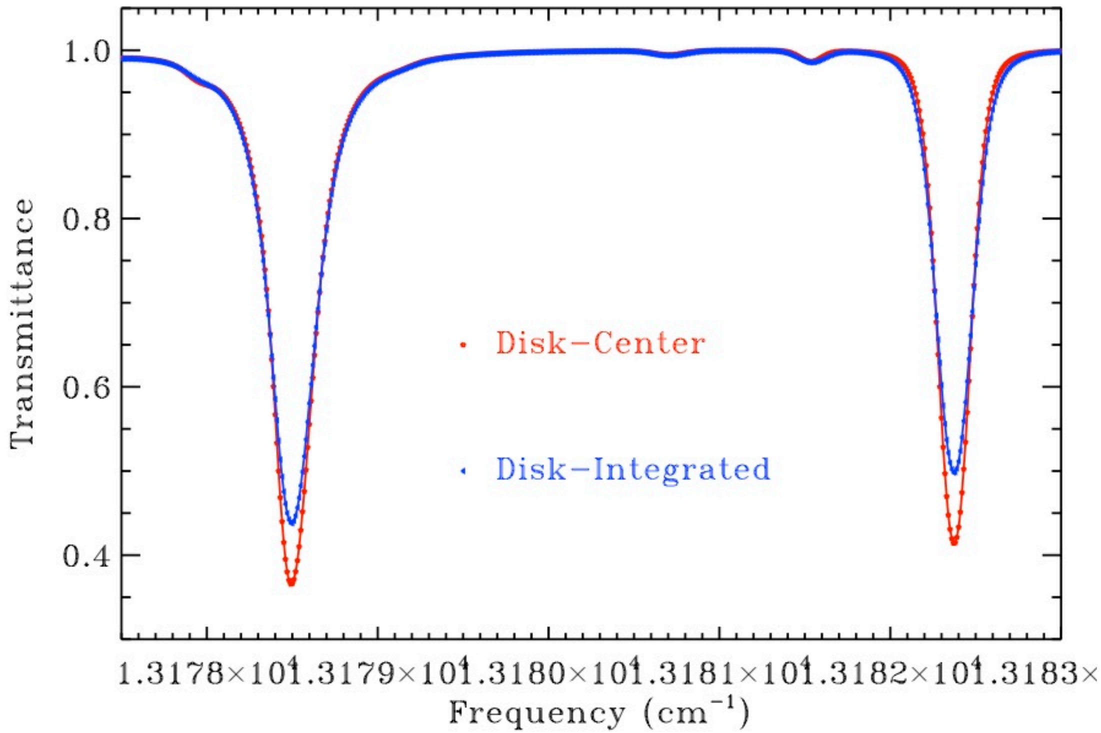


Illustrating the reduced H_2O contamination going from MkIV balloon, to ATMOS, to ACE





Disk-Center versus Disk-Integrated



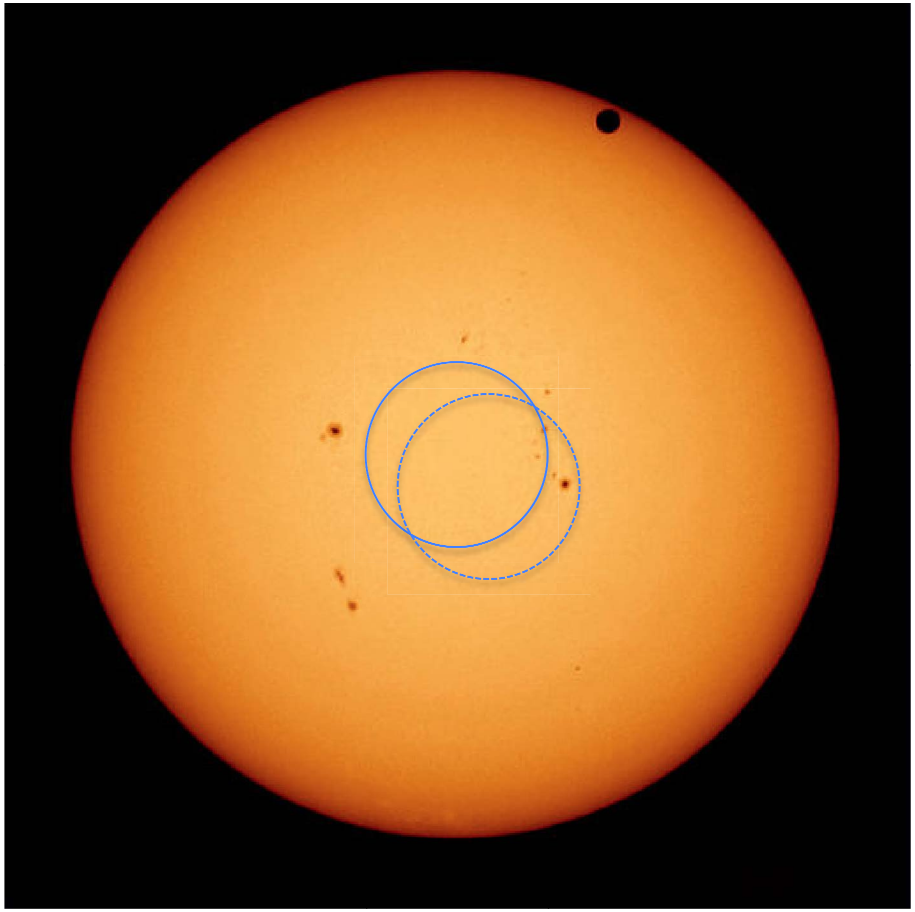
Sensors using direct sunlight (MkIV, ACE) generally use only a small portion of the solar disk near the center, to prevent degradation of spectral/vertical resolution.

Sensors that use reflected sunlight receive photons from the entire solar disk.

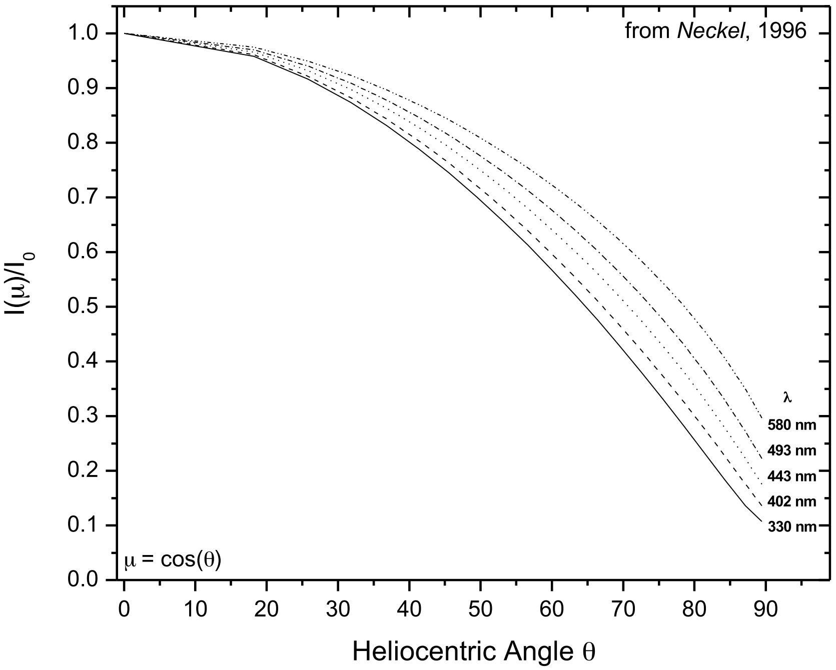
We already know that the center of the solar disk is brighter than the limb because unit optical depth occurs deeper and hence at a higher temperature.

The absorption lines are shallower and broader in the disk-integrated spectrum

Spatial Non-uniformities



- Limb darkening
- Sunspots
- Transit of Venus



Limb darkening caused by the decrease of temperature with altitude in photosphere.
At normal incidence, we see deeper into the sun (hotter & brighter).
Viewing the limb, unit opacity occurs at a higher latitude, where it's colder.

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Disentangling chlorophyll fluorescence from atmospheric scattering effects in O_2 A-band spectra of reflected sun-light

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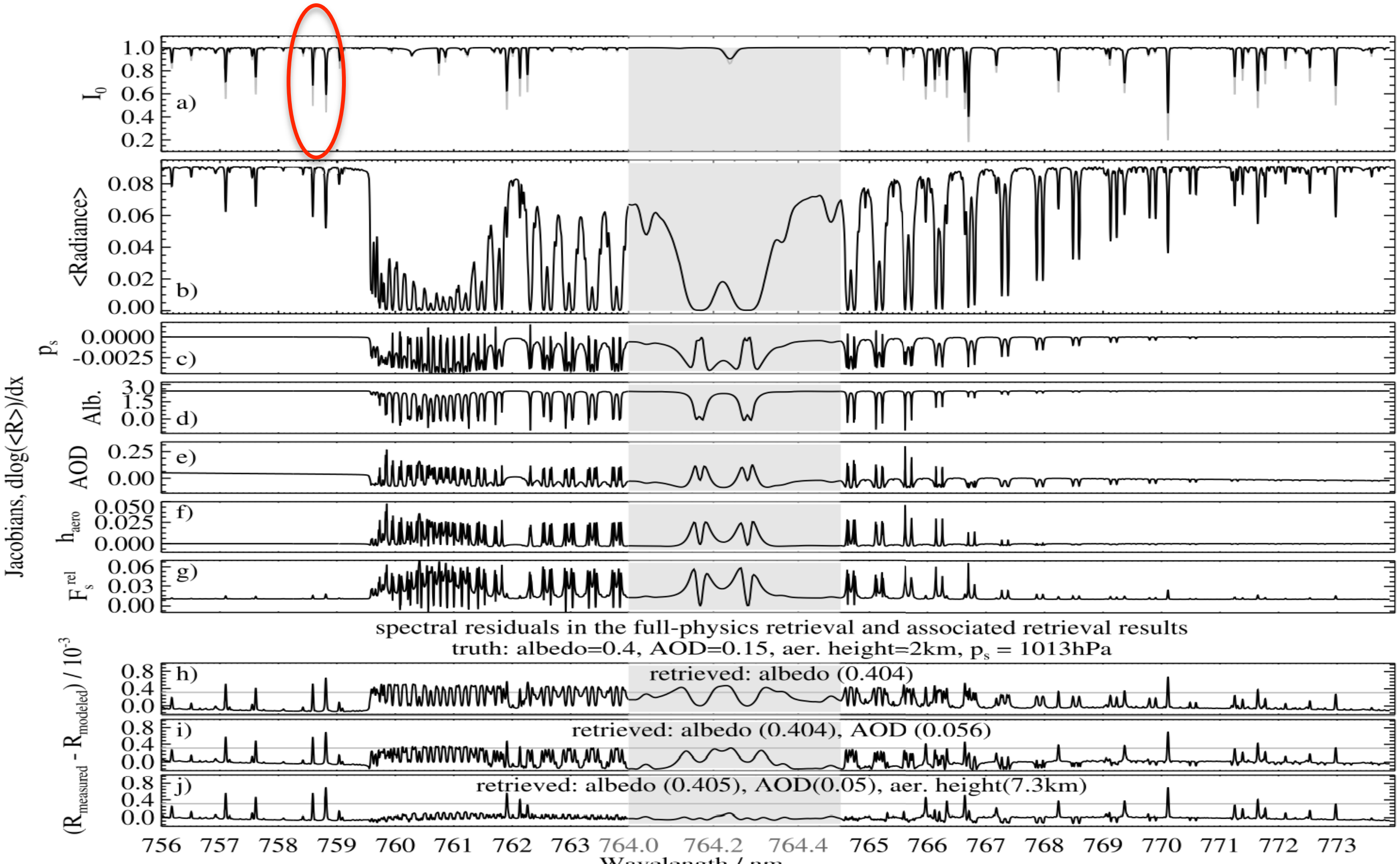
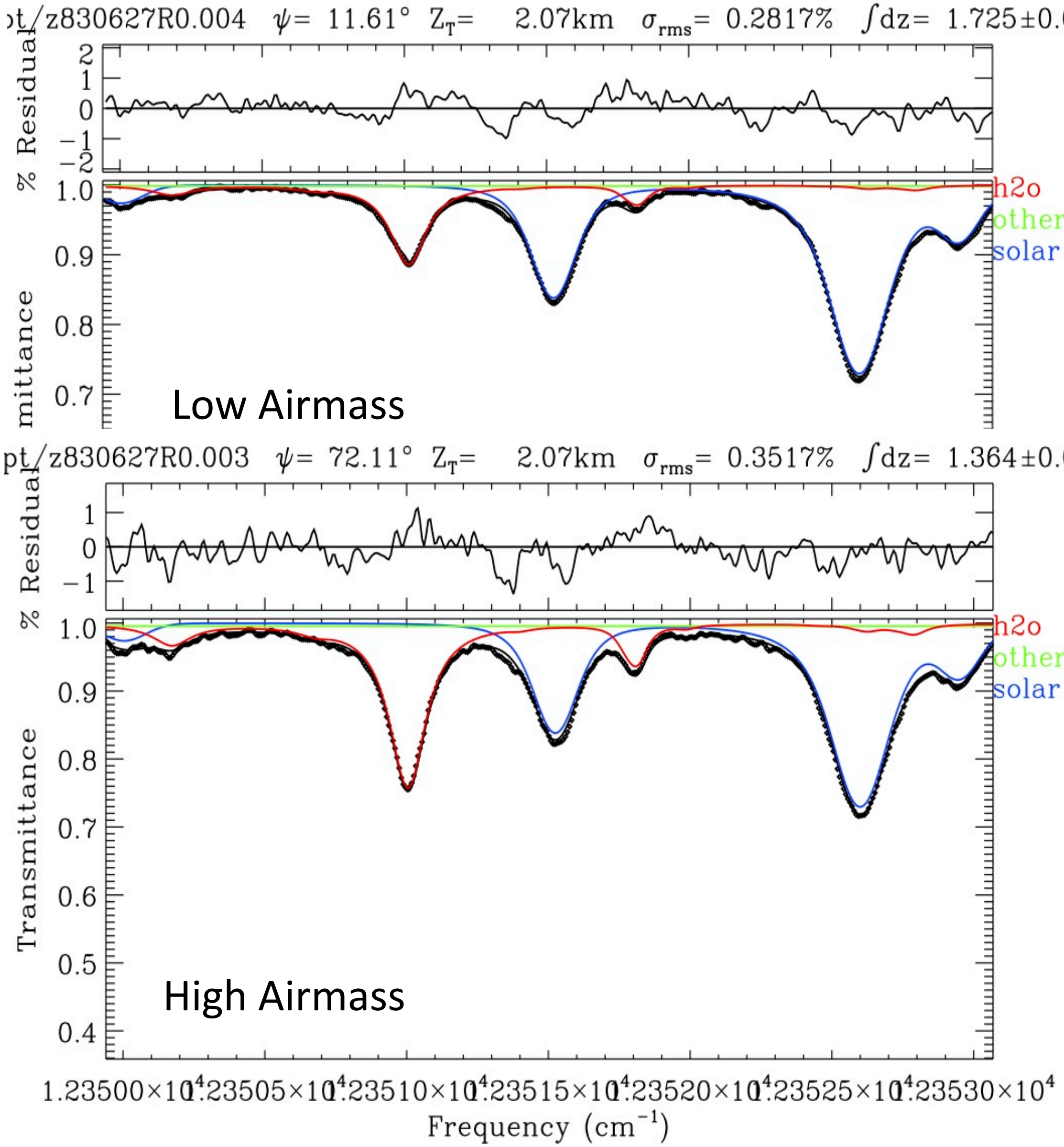


Airmass Independence

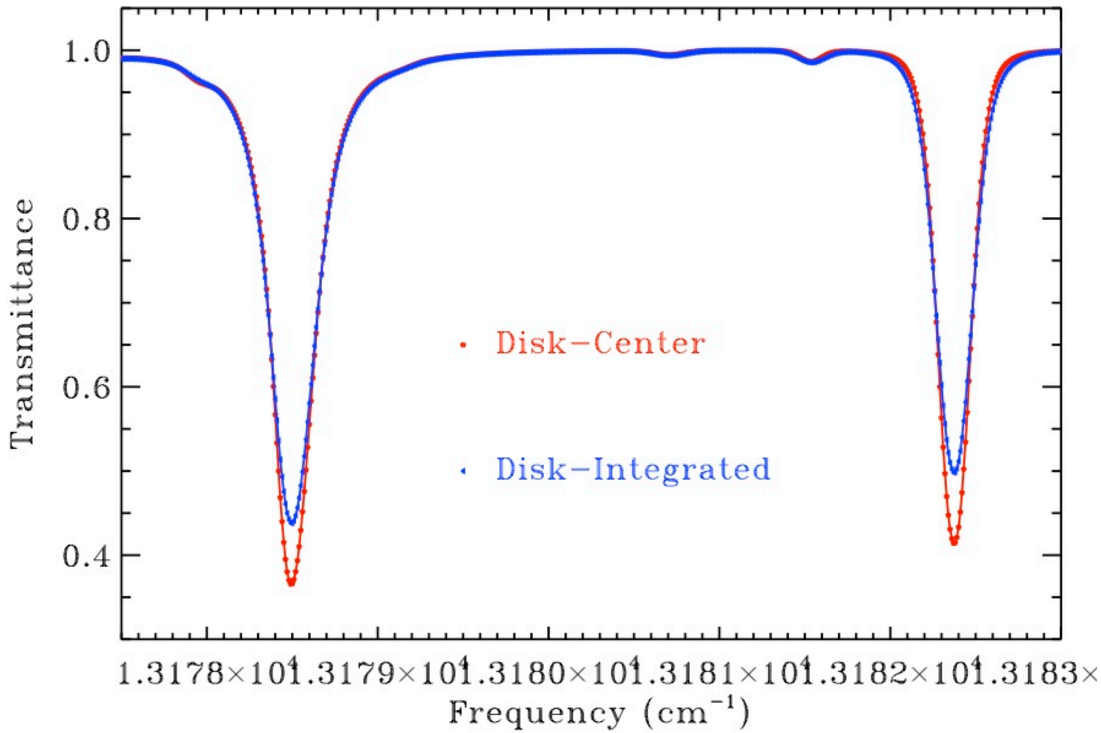


In fits to Kitt Peak spectra, solar lines can be distinguished from telluric lines by their airmass dependence (or lack thereof).

The depth of a solar line is independent of the atmospheric airmass, whereas telluric absorptions grow with airmass.

This made it possible to identify solar absorptions from ground-based spectra years before there were any decent linelists for the atmospheric absorption lines

Disk-Center versus Disk-Integrated



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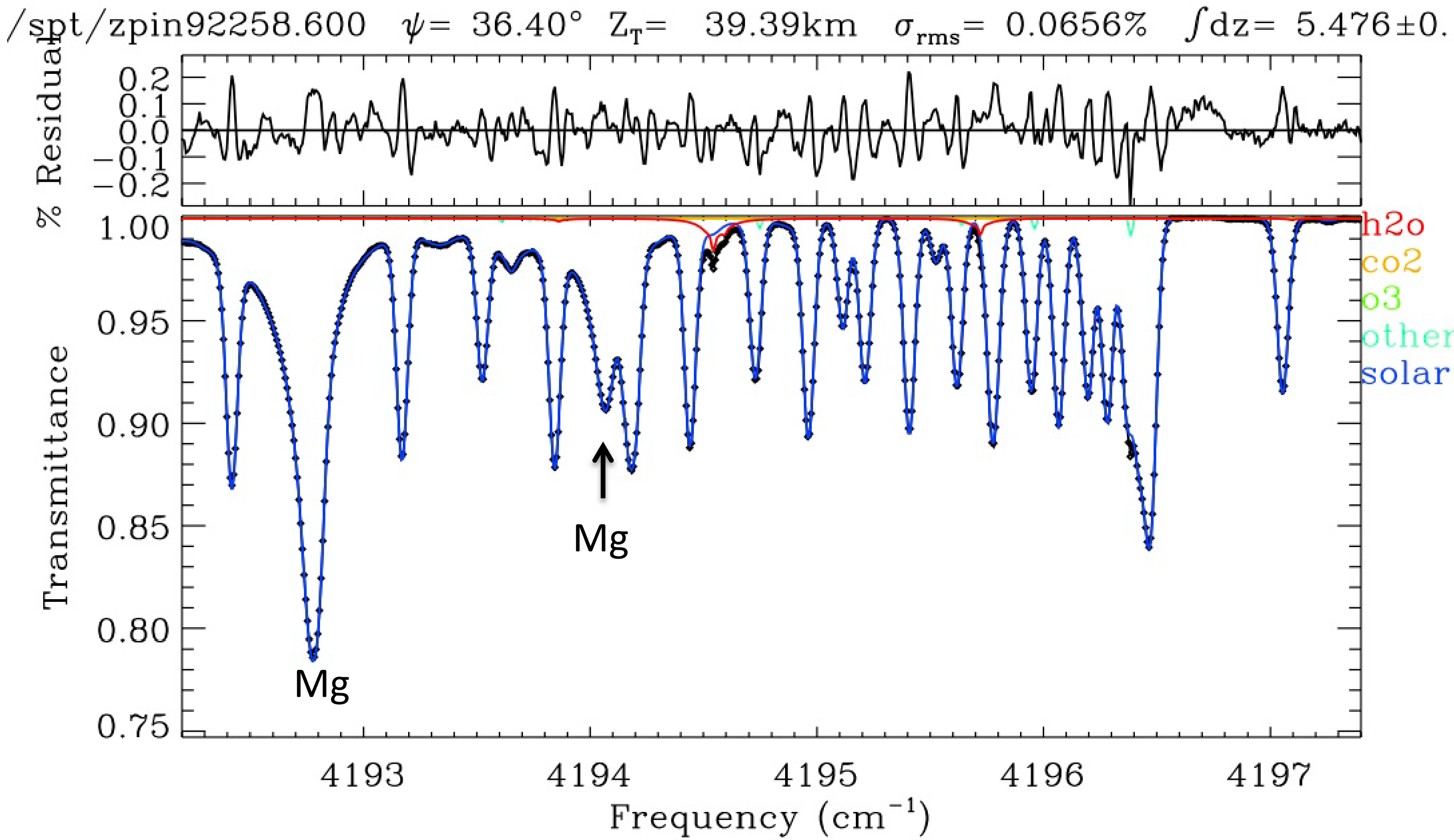
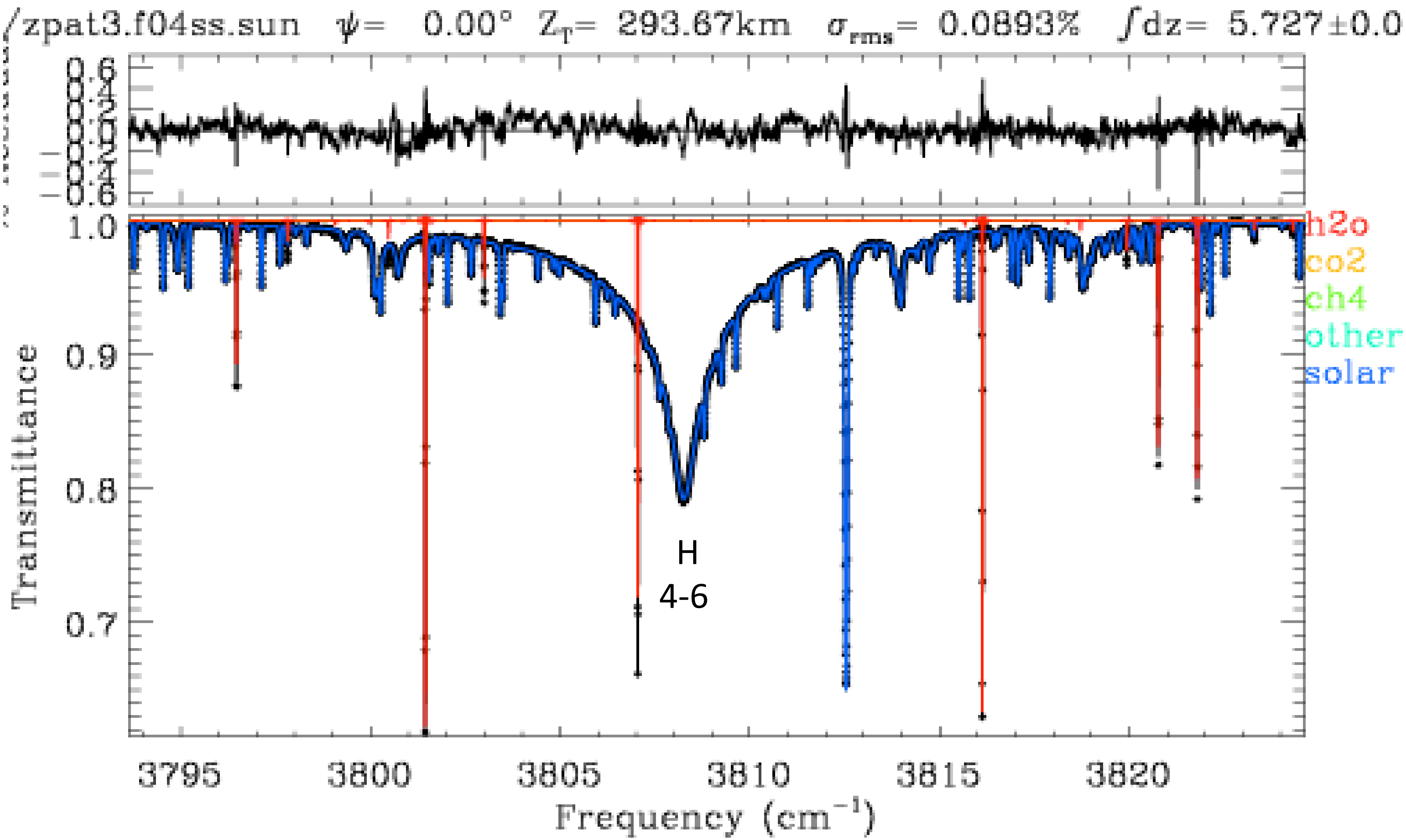
Atomic versus Molecular Absorption



Molecules (e.g. CO, OH, NH, HF) only exist at the coolest temperatures (<4500K) and therefore have narrow lines. Atoms (H, Ca, Mg, Si, Fe, Ni) can exist at cool and hot temperatures and therefore have cusp-shaped absorption lines

H-atom absorption lines



Solar Spectrum - Conclusions

Knowledge of the solar spectrum is important for remote sensing of Earth and planets, and of course for astrosphysicists who want to better understand stars.

Various disparate solar measurements:

- Low-res, high-res
- Disk center, disk-integrated
- UV, Vis, IR
- Ground-based, balloon-borne, satellite

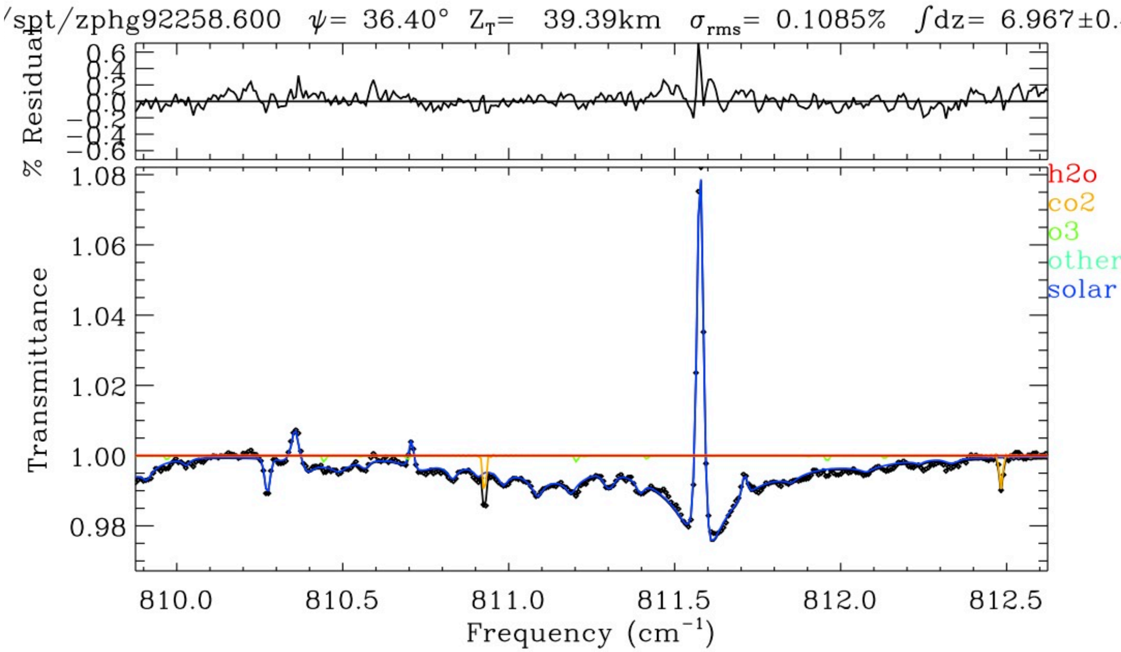
have been assimilated into a model of the solar spectrum.

Low-resolution, disk-integrated, space-borne measurements provide the absolute radiometry.

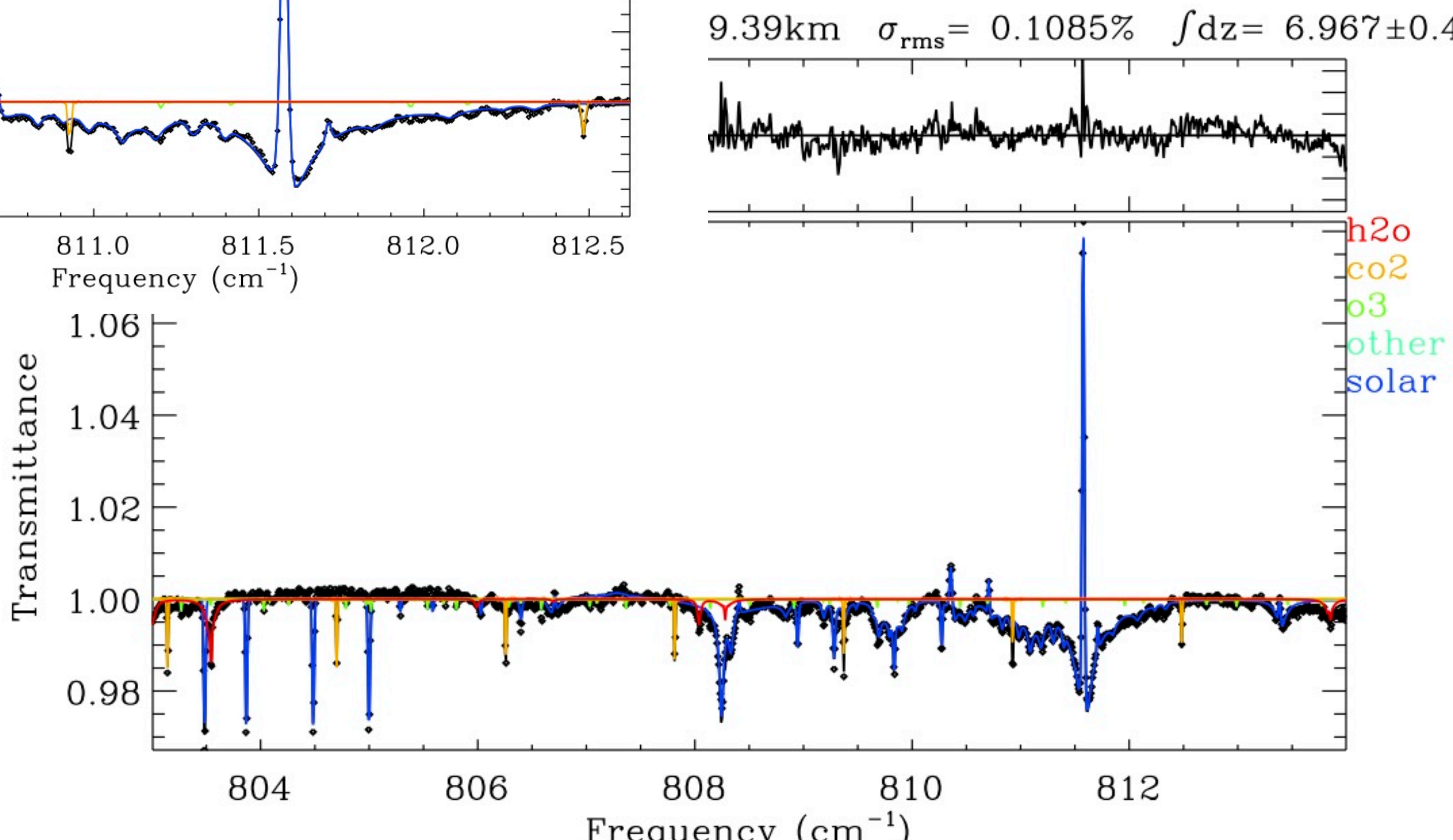
High-resolution ground and balloon measurements provide the spectrometry.

Supplemental Material

Solar Emission Lines



Emission lines (e.g., at 811.6 cm^{-1}) are not well understood



OBSERVATIONS OF SOLAR LIMB DARKENING BETWEEN 0.5 AND 10.2 μ*

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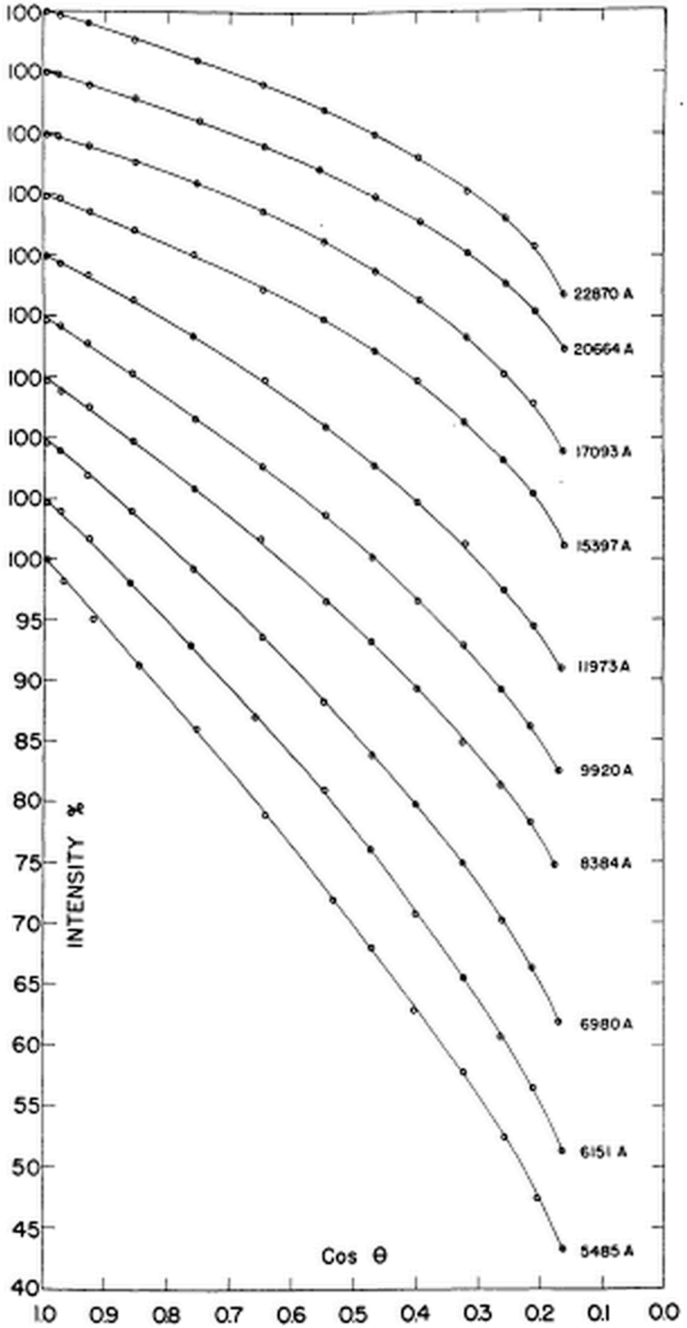

FIG. 5.—Solar limb-darkening-curves for the region 0.5–2.2 μ

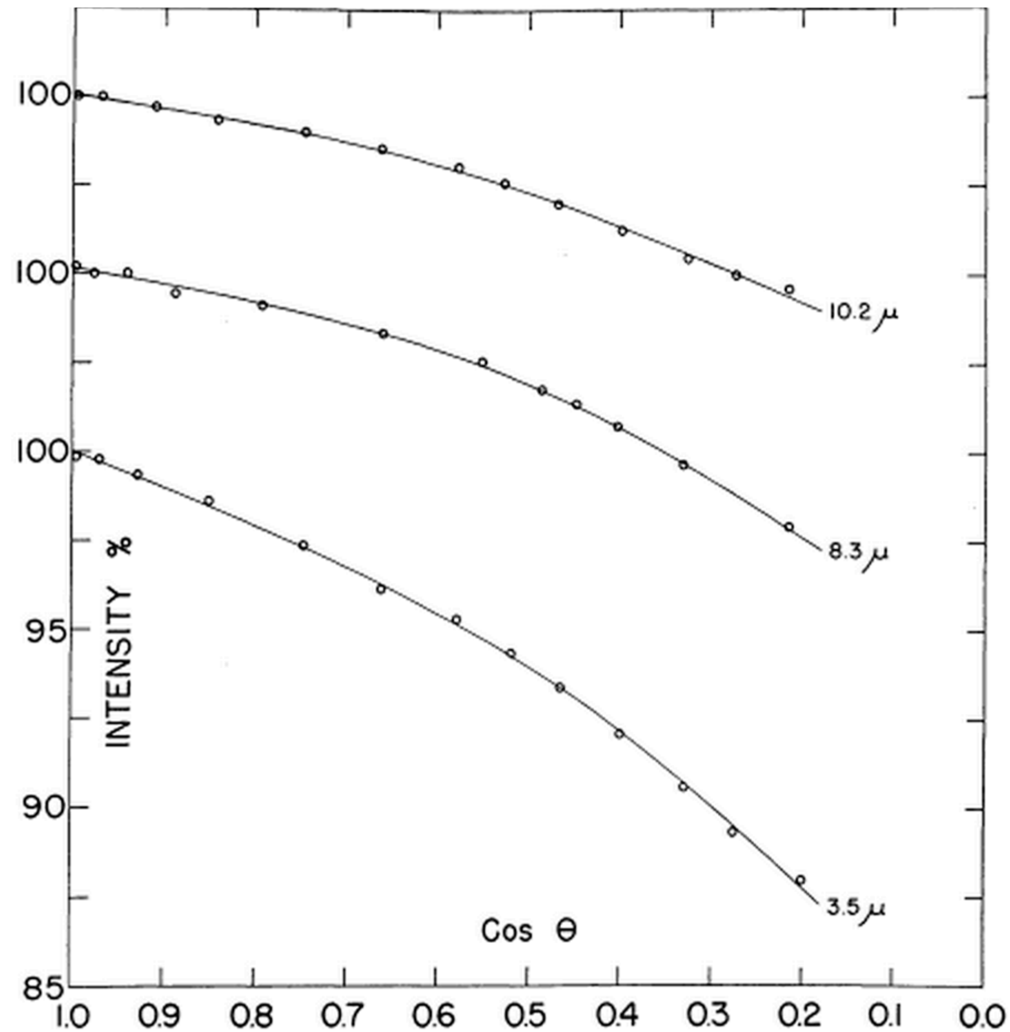

FIG. 4.—Solar limb-darkening-curves for the region 3.5–10.2 μ

Under-Resolved features don't cancel –What does that Mean?

SOLAR SPECTRUM, VARIABILITY and ATMOSPHERIC ABSORPTION