Intro to High Spectral Resolution Infrared Satellite Measurements

Part 1:
Understanding the Spectra

Hampton University
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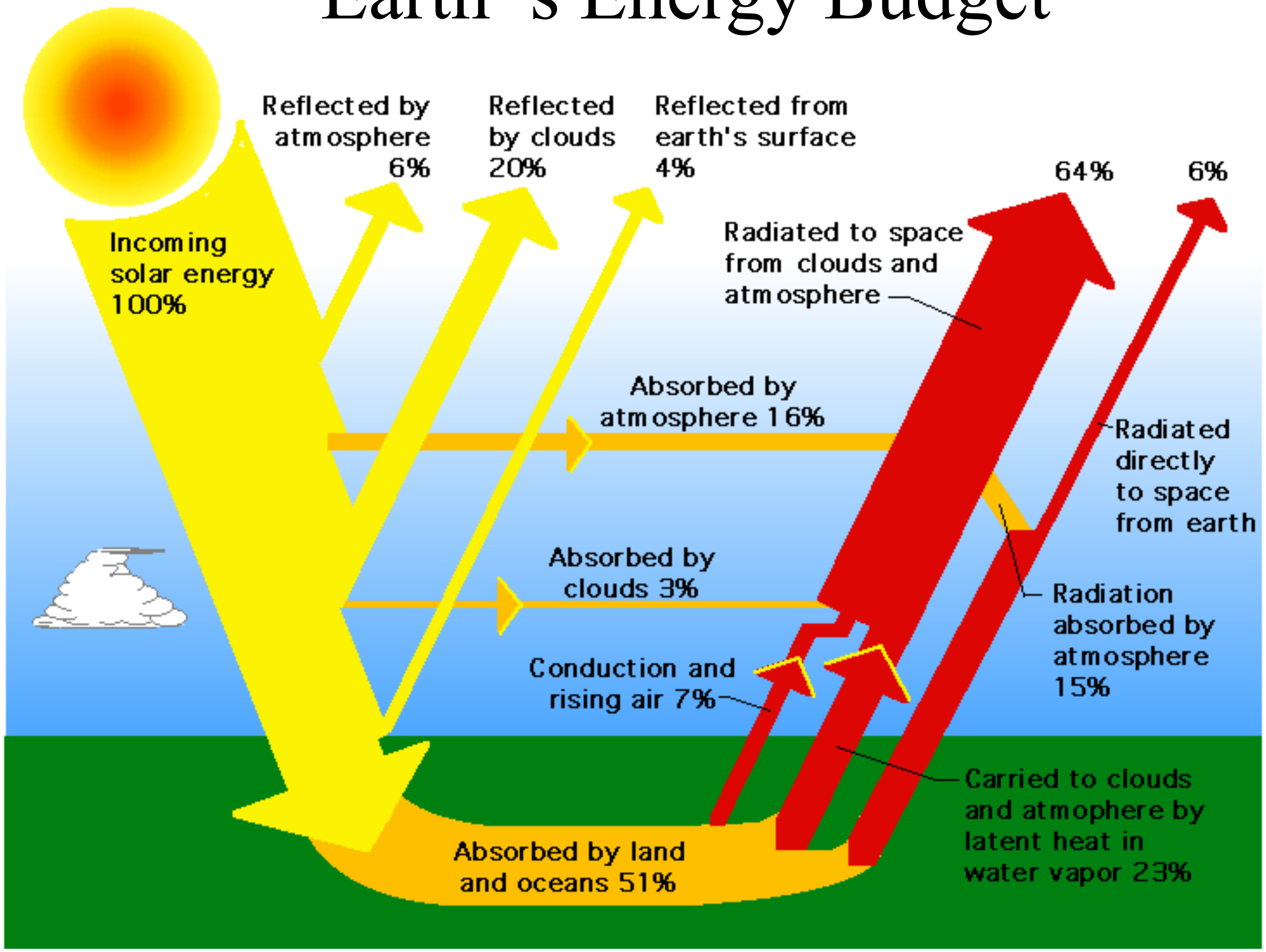
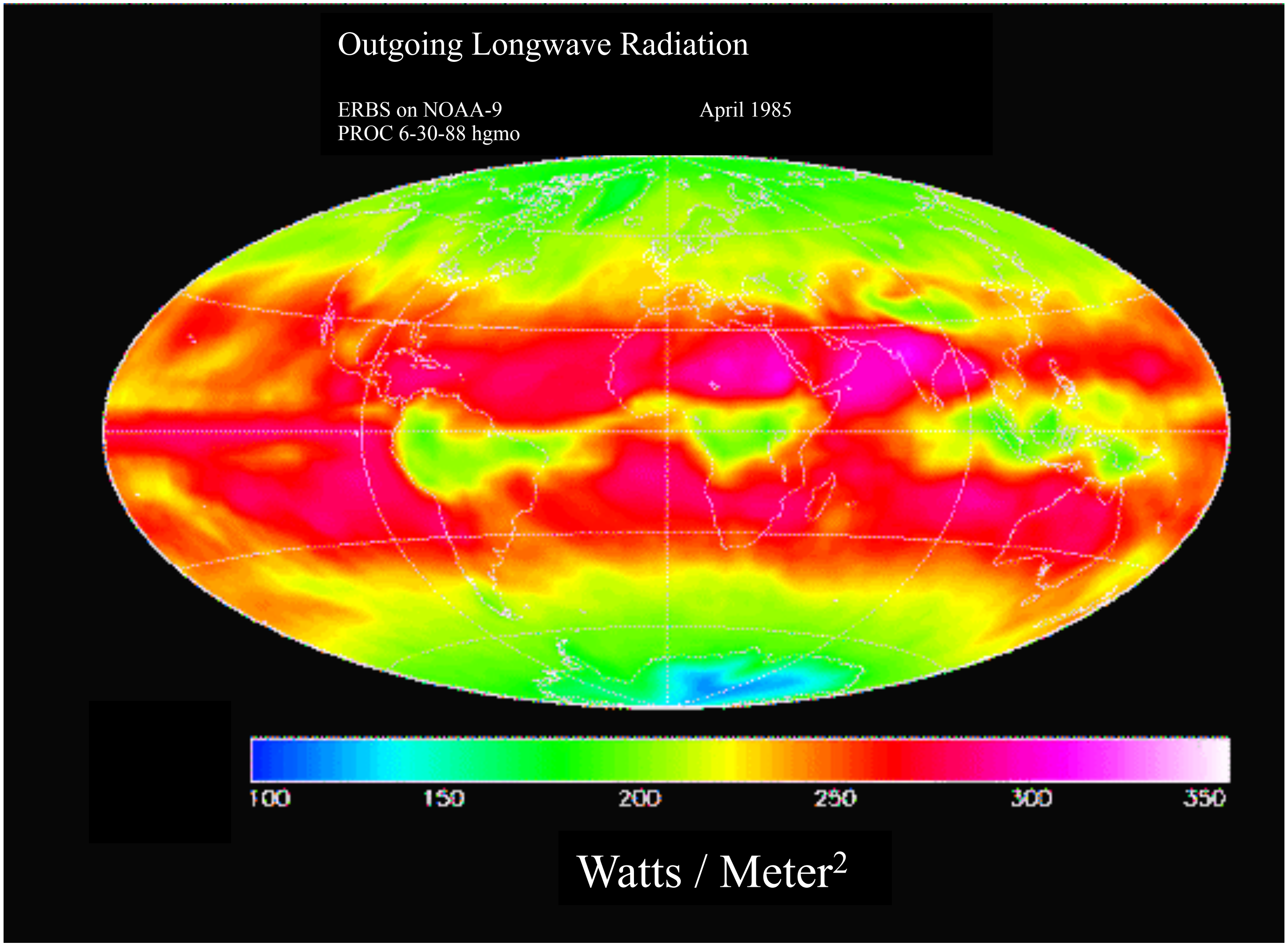
Earth’s Energy Budget



Balance between the incoming (solar) radiation and the outgoing (reflected solar and emitted infrared) radiation

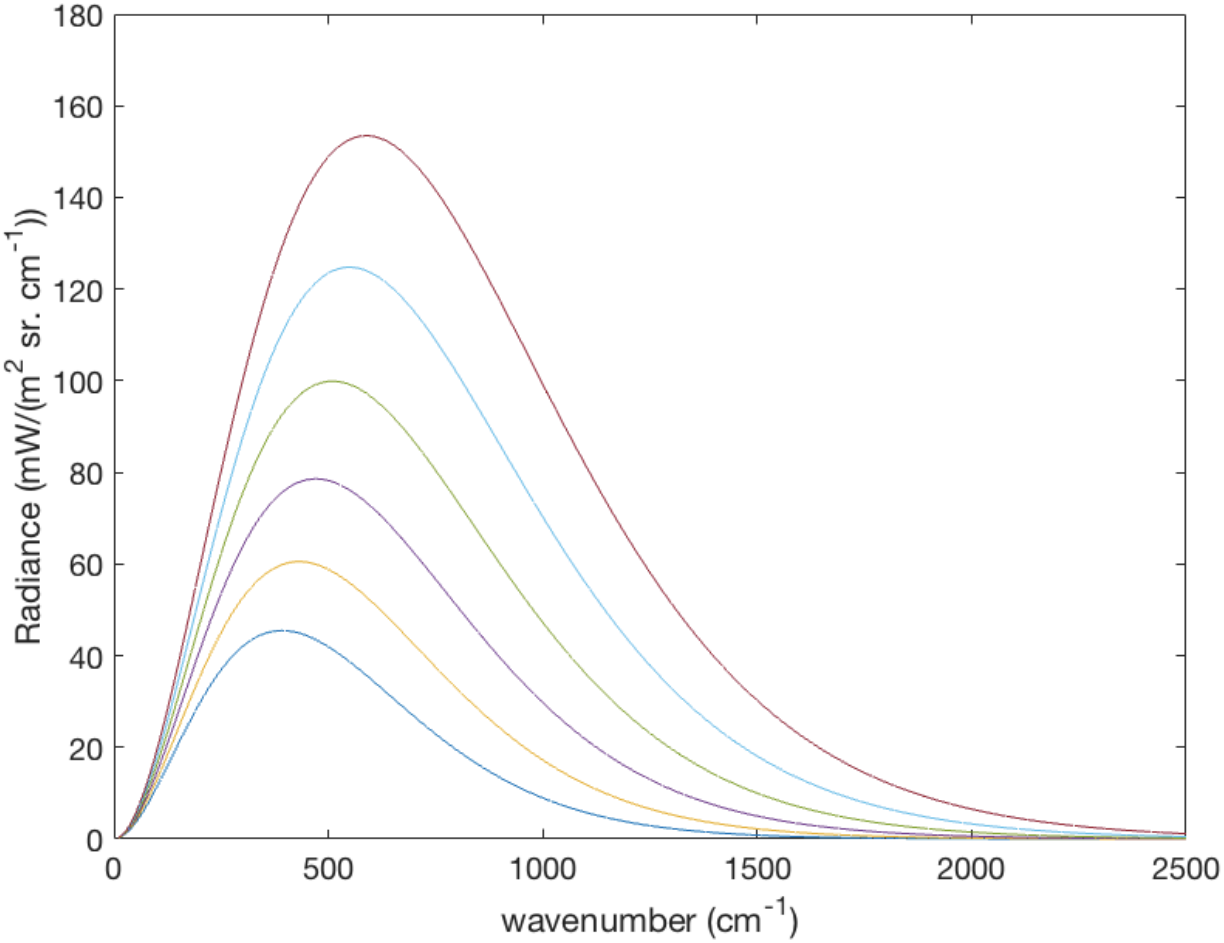
Outgoing Longwave Radiation (OLR) example

Mean OLR observed by the Earth Radiation Budget Satellite (ERBS) for April 1985

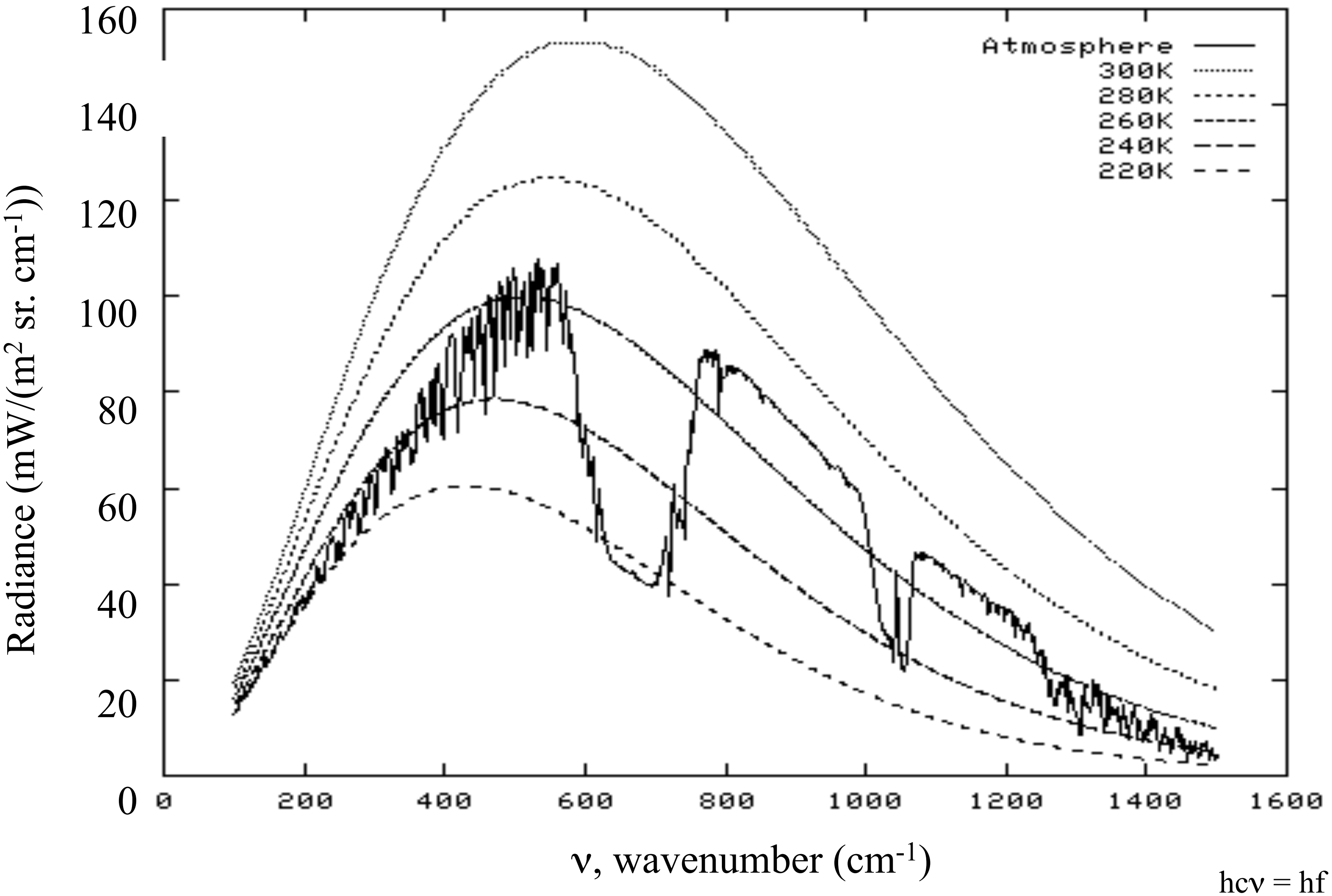


Planck's Law of Blackbody Radiation

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

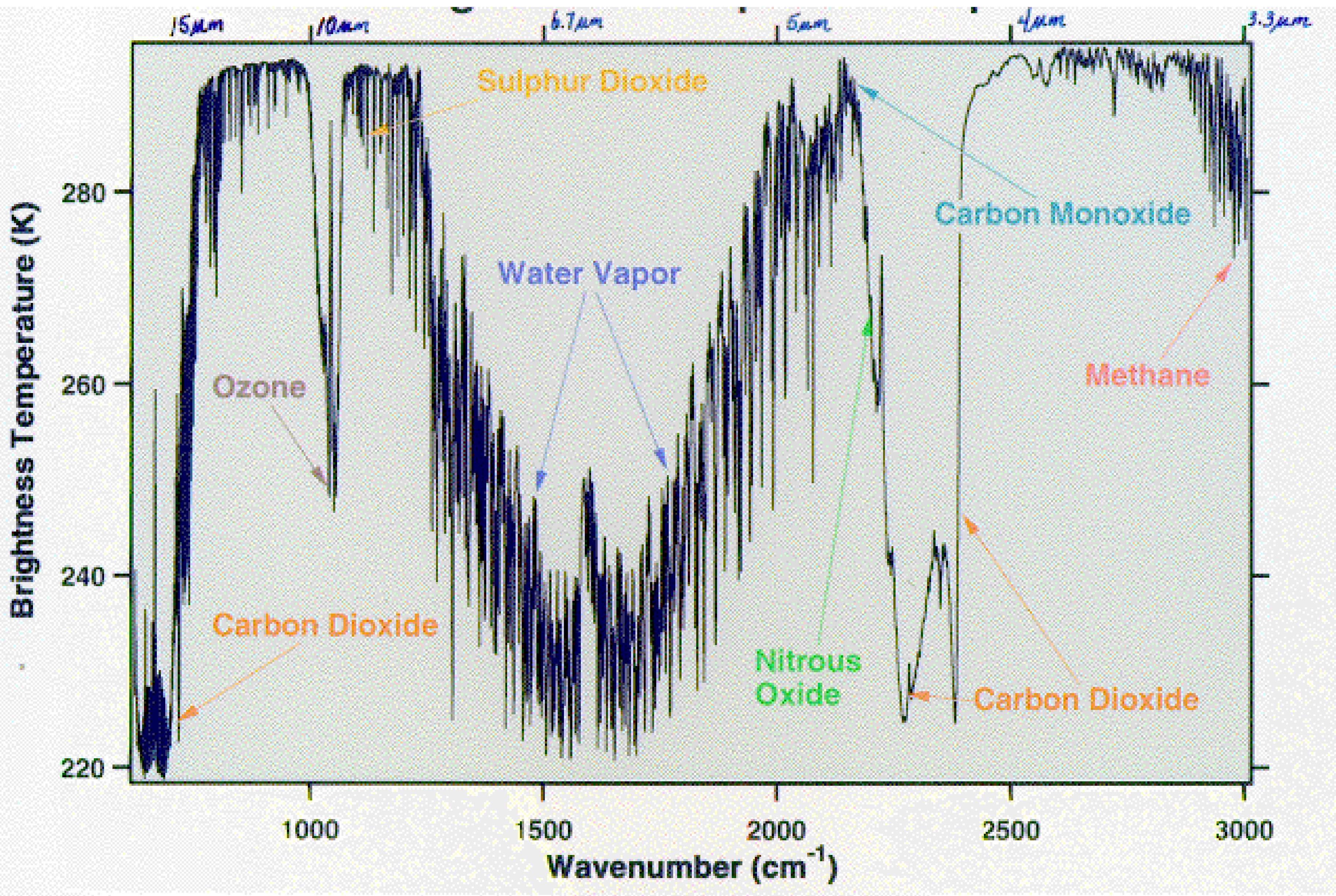


Top-of-Atmosphere Radiance Spectrum, Clear sky example



$hc\nu = hf = hc/\lambda$
ν, wavenumber
f, frequency
λ, wavelength

Top of Atmosphere Brightness Temperature Spectrum

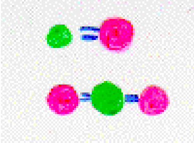


Outline

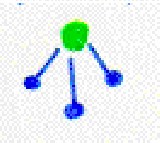
- Molecular Spectroscopy
- Absorption and Emission
- Radiative Transfer
- Various Spectra and Spectral Signatures

Types of molecules:

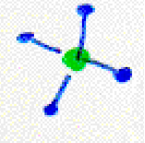
- Linear molecules ($I_C = 0$, $I_A = I_B$)
  - CO, diatomic
  - CO_2, triatomic



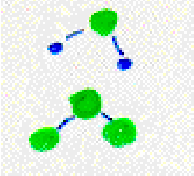
- Symmetric tops ($I_C \neq 0$, $I_A = I_B$)
  - NH_3

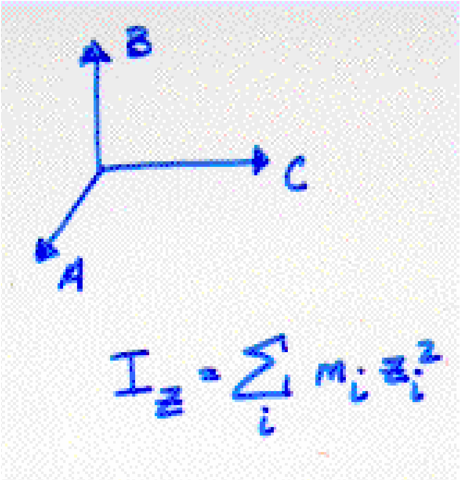


- Spherical symmetric tops ($I_A = I_B = I_C$)
  - CH_4



- Asymmetric tops ($I_A \neq I_B \neq I_C$)
  - H_2O
  - O_3





I_z, moments of inertia

The molecular structures define the allowable energy levels, which then determines the positions of the absorption lines in the spectrum:

$$h\nu = E_{final} - E_{initial} = \Delta E$$

Plank's constant

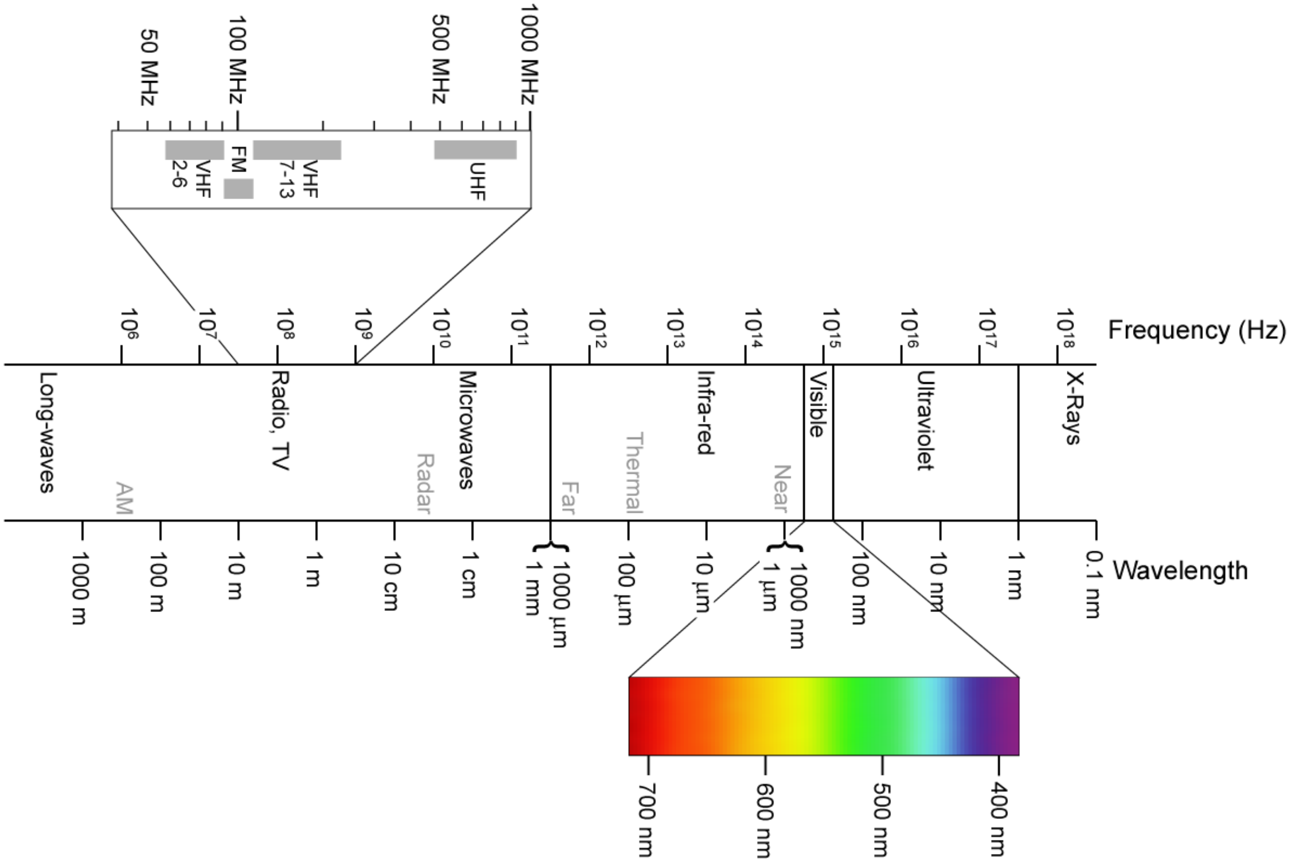
frequency of the absorbed and/or emitted light

Change in the molecules internal energy

Degrees of freedom:

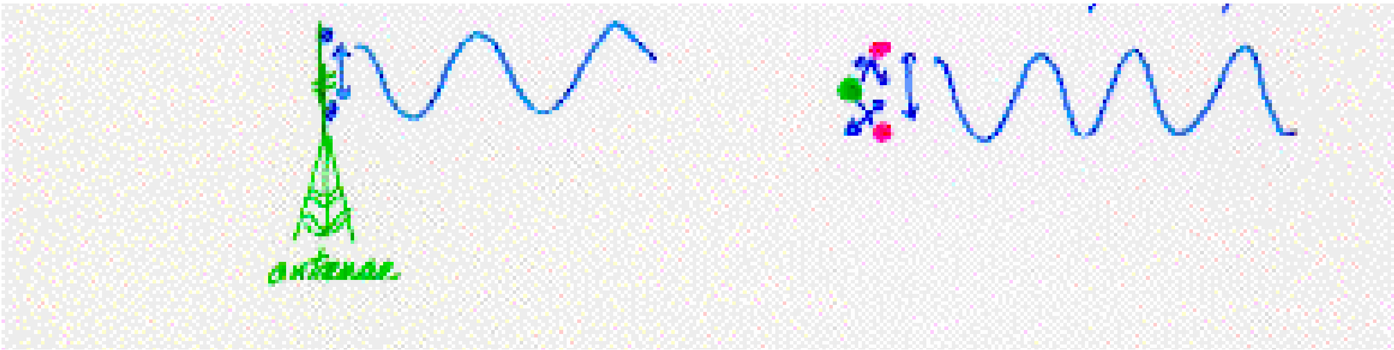
- nuclear
- electronic
- vibration
- rotation
- kinetic
- spin

} relevant in the infrared



Dipole Moments:

- There must be a change in the molecule's net charge distribution for light to be emitted/ absorbed (Stephens, p 88)

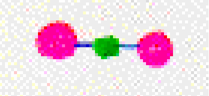


Water vapor:

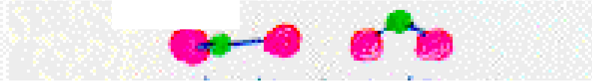
Large dipole moment in equilibrium configuration

Carbon Dioxide:

No dipole moment in equilibrium configuration, but …



Vibration/rotation can induce a dipole



Rotational Energy:

- Rigid Rotor Approximation
  - Classically:

angular momentum = $\vec{L} = \underbrace{I}_{\text{moment of inertia}} \underbrace{\vec{\omega}}_{\text{angular velocity}}$

rotational energy = $E_r = \frac{\vec{L}^2}{2I} = \frac{1}{2} I \omega^2$

* L is continuous *

  - Quantum Mechanics:

$\vec{L} = \hbar\sqrt{J(J+1)}$ with $J = 0, 1, 2, 3, \ldots$

$E_{r,J} = B\,J(J+1) = B, 2B, 6B, 12B, \ldots$

B "rotational constant" = $h^2/8\pi^2 c I$

- Non-Rigid Rotor (i.e. stretchy):

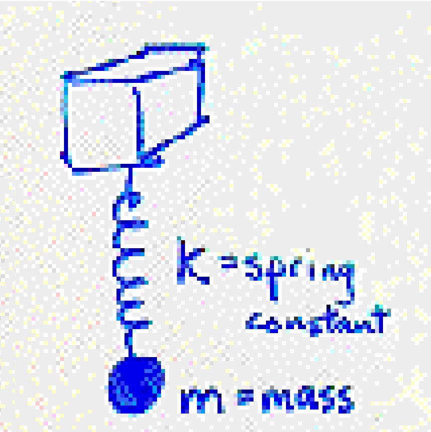
$$E_{rJ} = BJ(J+1) - \underbrace{D\left[J(J+1)\right]^2}_{\text{centrifugal distortion term}} \quad \text{with } D \simeq 4B^3/\omega^2$$

Vibrational Energy:

- Classically:

ν' = resonant vibration frequency

$$= \frac{1}{2\pi}\left(\frac{k}{m}\right)^{1/2}$$

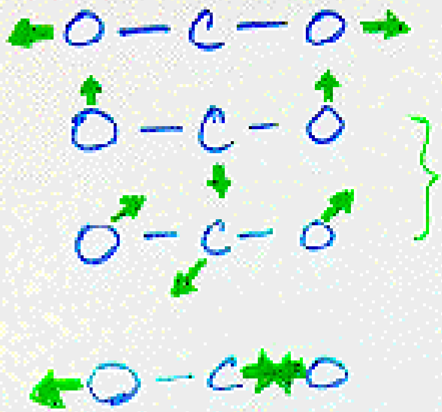


- CO2 example:

ν' = resonant frequency of a SHO

$= (v + \frac{1}{2})\,\nu'$ with $v = 0, 1, 2, 3 \ldots$

$$E_{vib} = h\nu = (v + \tfrac{1}{2})\,h\nu'$$



4 vibrational modes	Selection rules
$\nu' \simeq 1337\ \mathrm{cm}^{-1}$	not infrared active (no change in dipole)
$\nu' = 667\ \mathrm{cm}^{-1}$	$\Delta J = 0, \pm 1$
$\nu' = 2349\ \mathrm{cm}^{-1}$	$\Delta J = \pm 1$

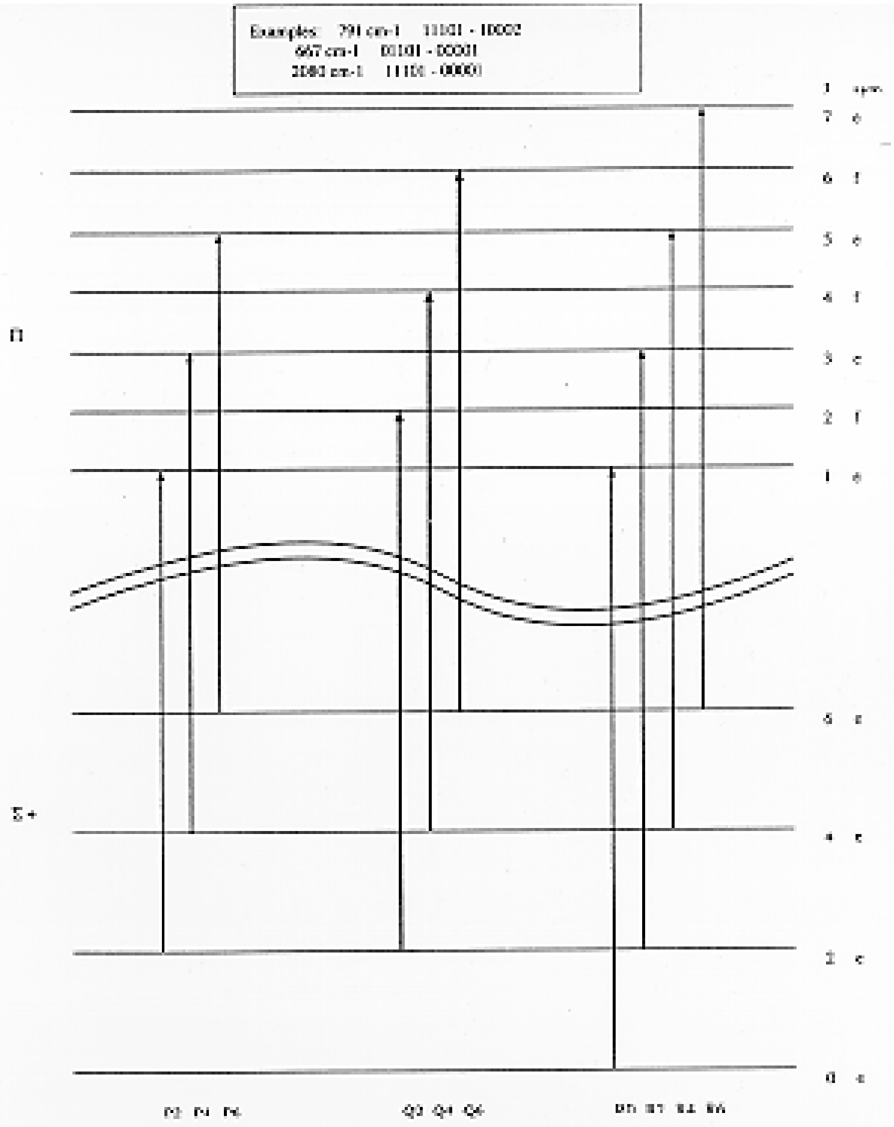
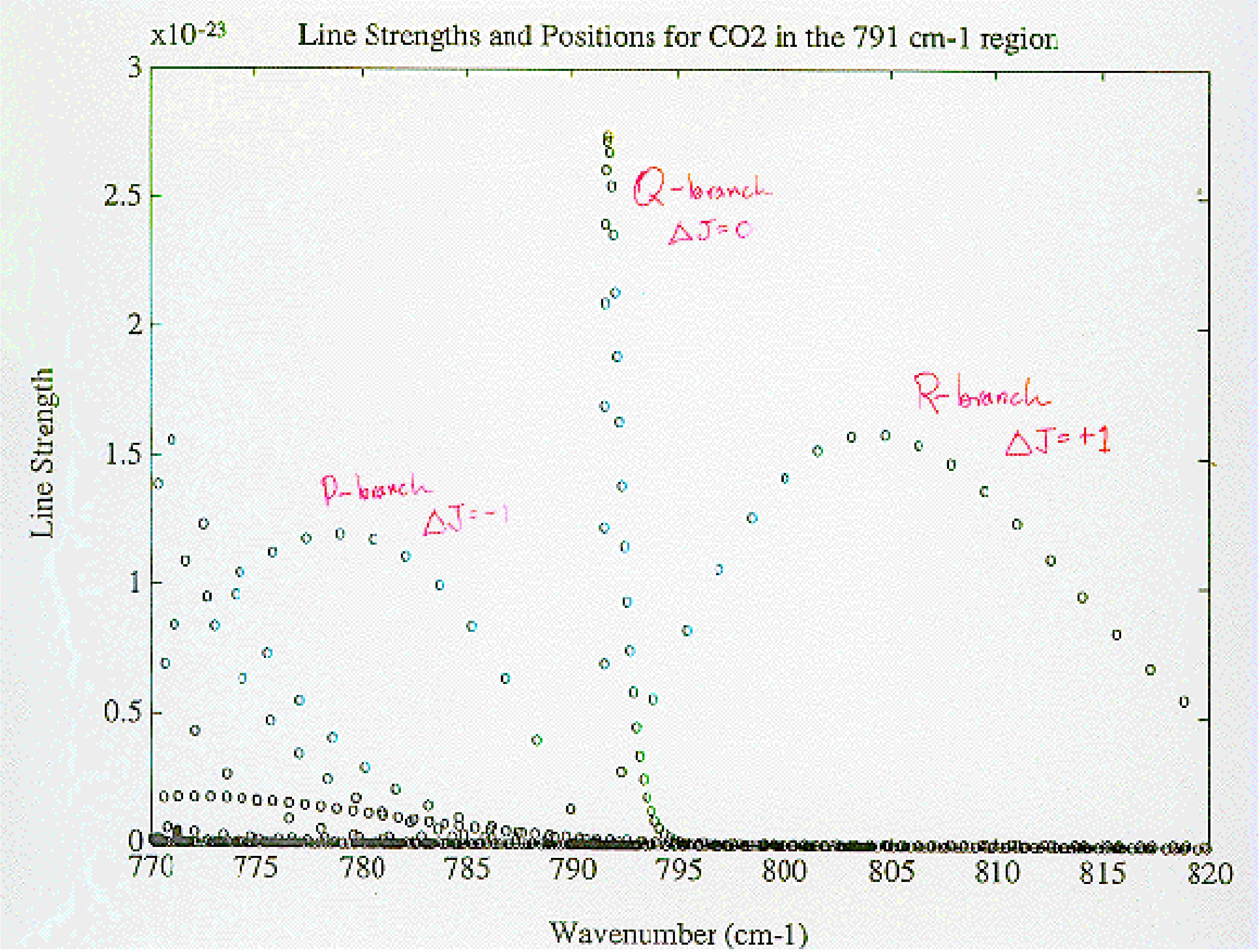


Figure A.6: The energy levels and transitions of a $\Pi \leftarrow \Sigma$ transition. In the Σ state, there is no vibrational angular momentum ($\ell = 0$) and therefore no ℓ-type doubling. The vibrational wavefunction is symmetric so the only remaining rotational energy levels are those of even J values. In the Π state, ℓ=1, resulting in ℓ-type doubling. Because the vibrational wavefunction is asymmetric, every symmetric ℓ-type doubled level does not exist, leaving one rotational level for each J value. Note that there is no J=0 level because ℓ=1.

E_{final}

$E_{initial}$


x10-23
Line Strengths and Positions for CO2 in the 791 cm-1 region
Line Strength
Wavenumber (cm-1)
0
0.5
1
1.5
2
2.5
3
770
775
780
785
790
795
800
805
810
815
820
Q-branch
ΔJ=0
P-branch
ΔJ=-1
R-branch
ΔJ=+1

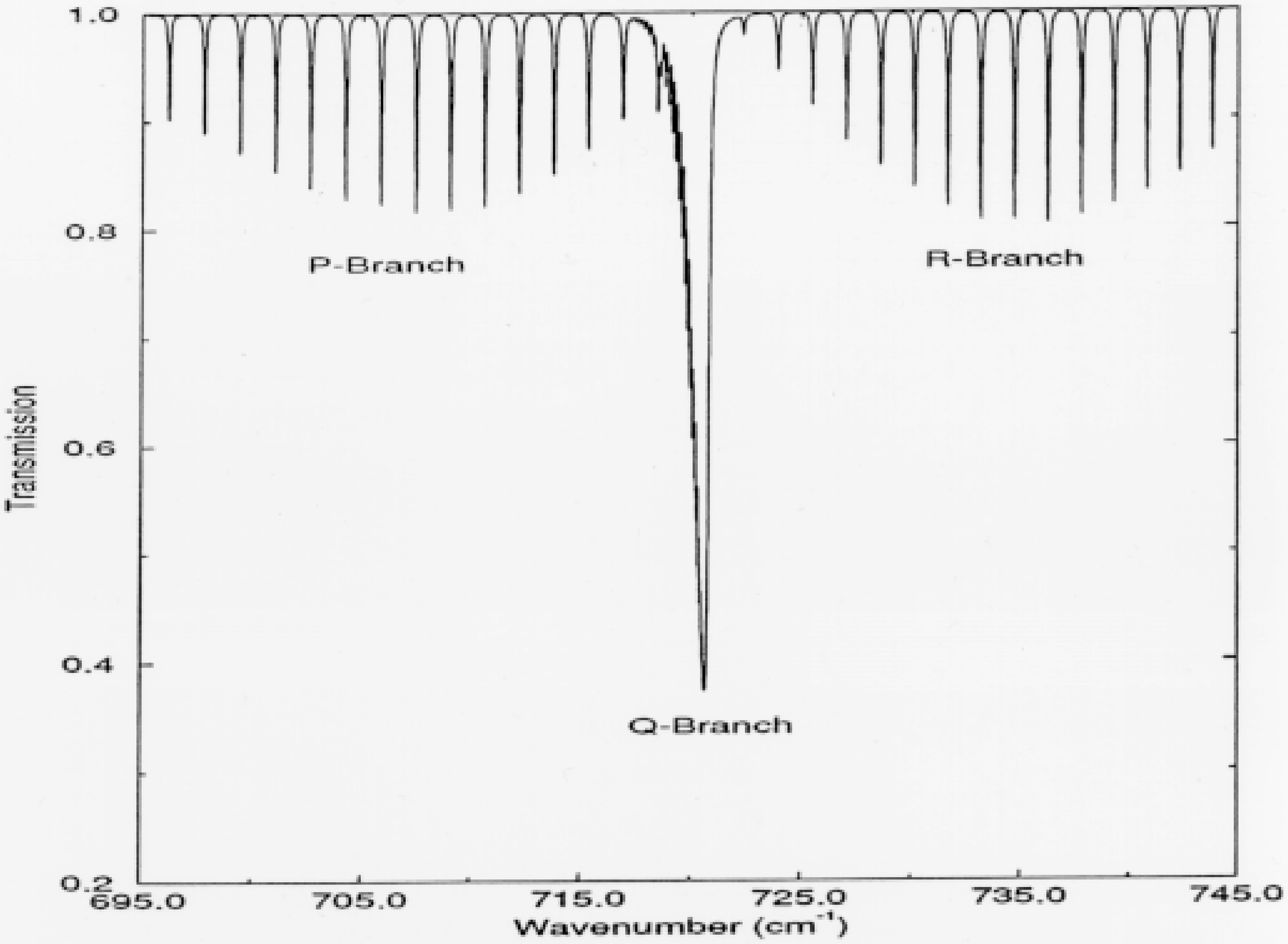
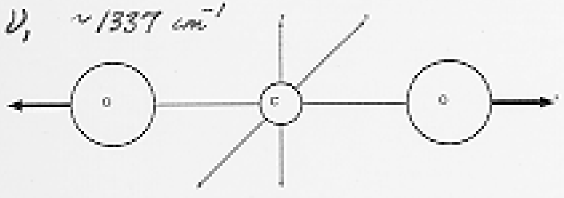


Figure 3: A Typical Perpendicular Band: the 10001 ← 01101 Transition. The P and R-branches are similar to those of a parallel band. The Q-branch is positioned at the vibrational frequency of 720 cm^{-1} and is not just one spectral line, but many positioned right next to each other.

CO_2 Vibration – Rotation Spectra

$$E(v,J) = \underbrace{h\nu(v+\frac{1}{2}) - xh\nu(v+\frac{1}{2})^2 + \ldots}_{\text{vibration}} + \underbrace{B_\nu[J(J+1)-\ell^2] - D_\nu[J(J+1)-\ell^2]^2 + \ldots}_{\text{rotation}}$$

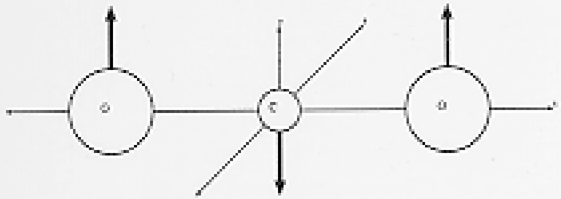
ν_1 ~1337 cm^{-1}



symmetric stretch

ν_2 ~667 cm^{-1}

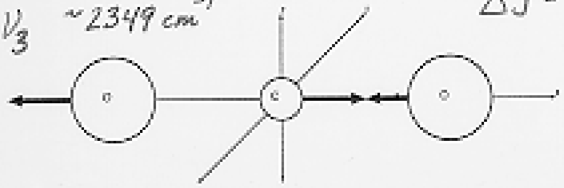
$\Delta J = 0, \pm 1$



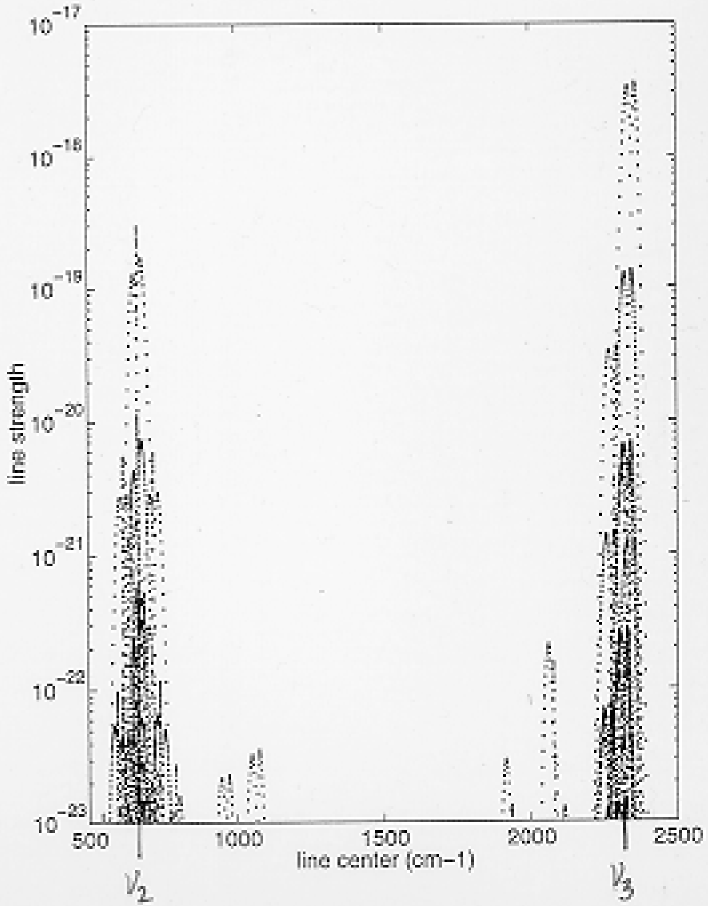
Degenerate Bend

ν_3 ~2349 cm^{-1}

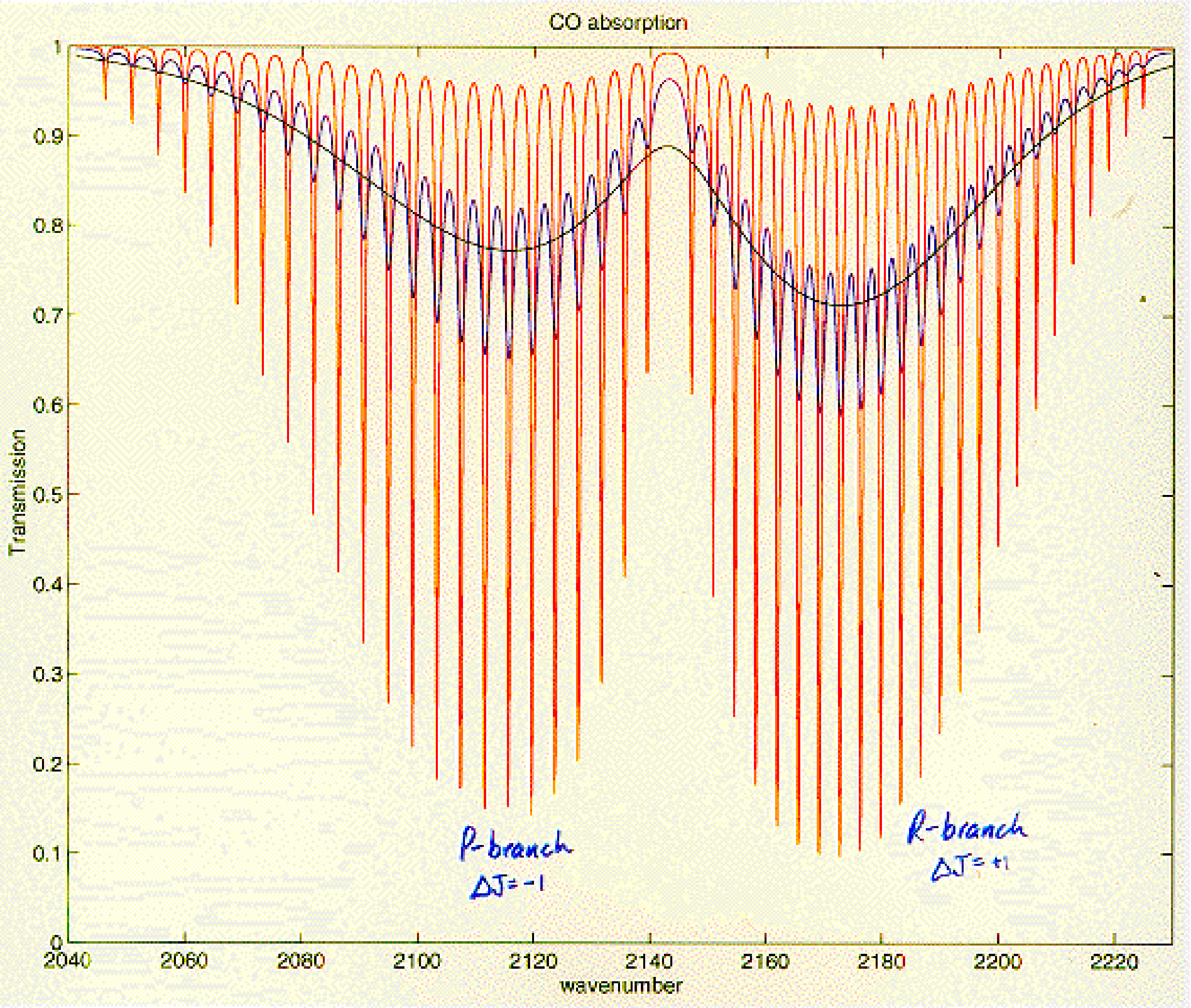
$\Delta J = \pm 1$



Asymmetric stretch



CO: No Q-branch



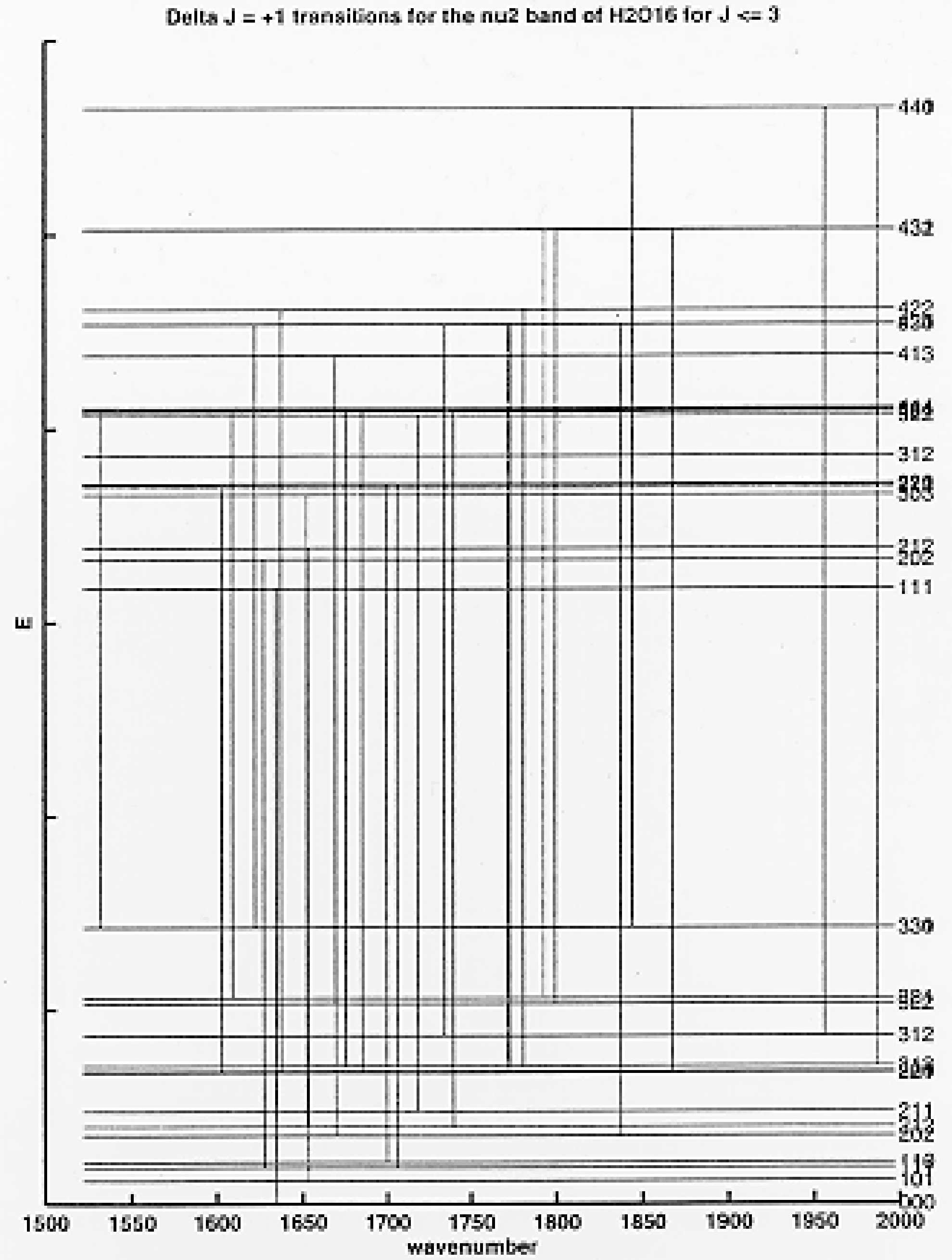


Figure D.3: Fundamental ν_2 $H_2^{16}O$ transitions for ΔJ=1 and $|J| \leq 3$.

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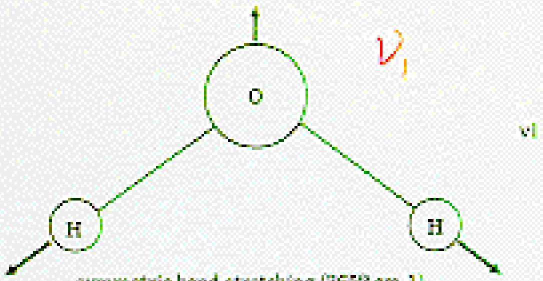
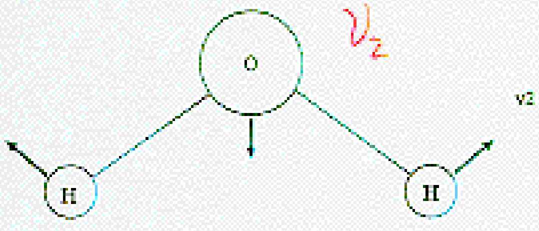
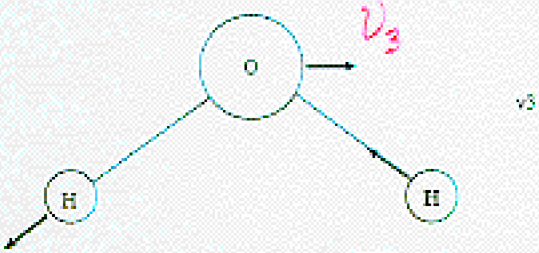
H_2O Vibration – Rotation Spectra



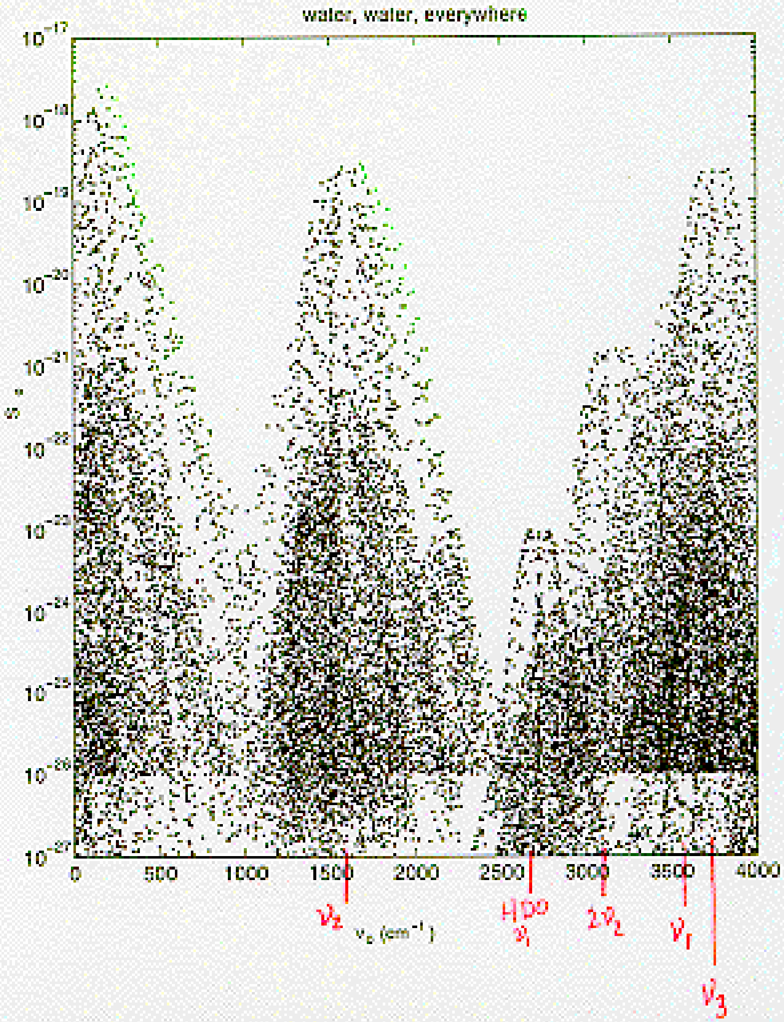
symmetric bond stretching (3652 cm-1)

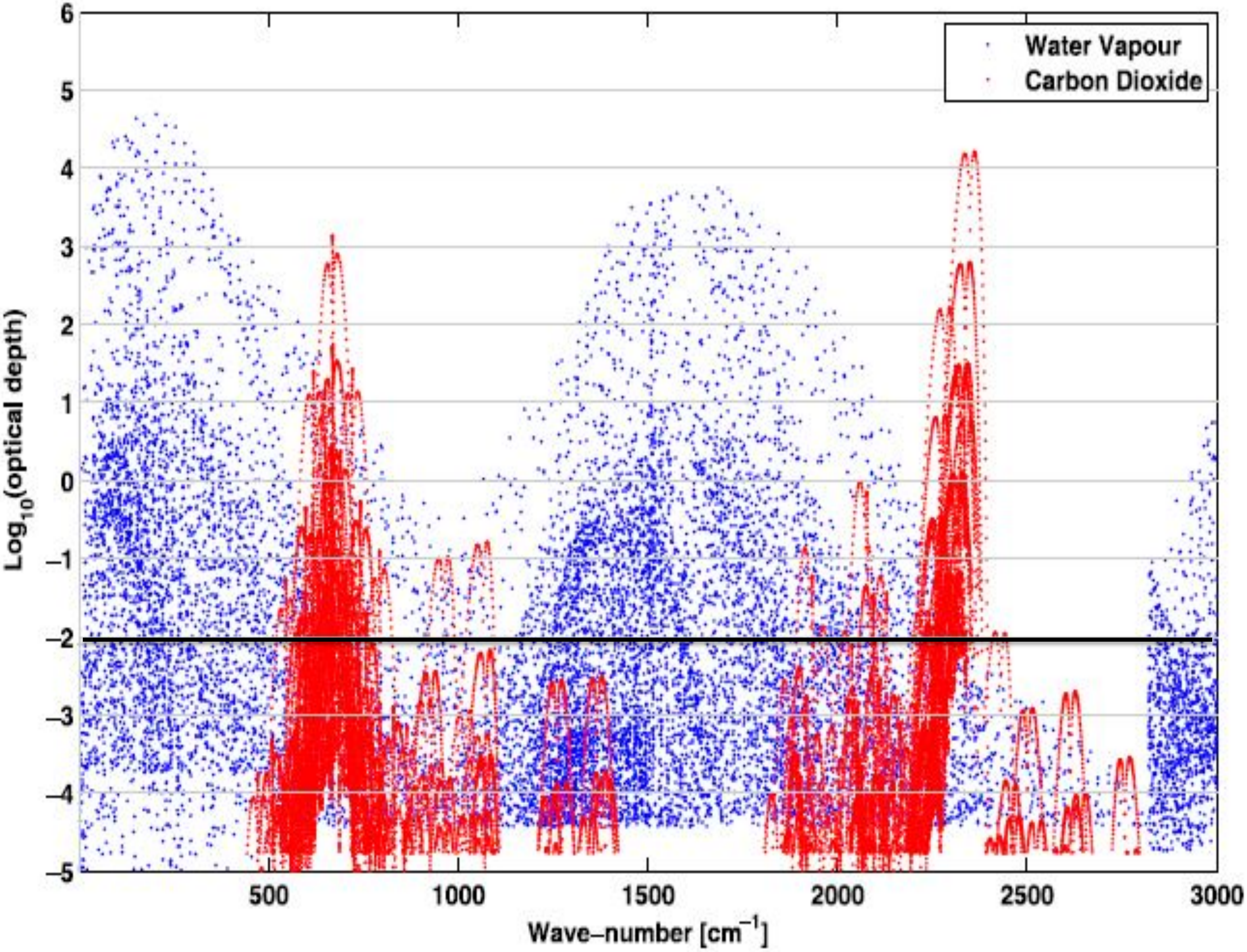


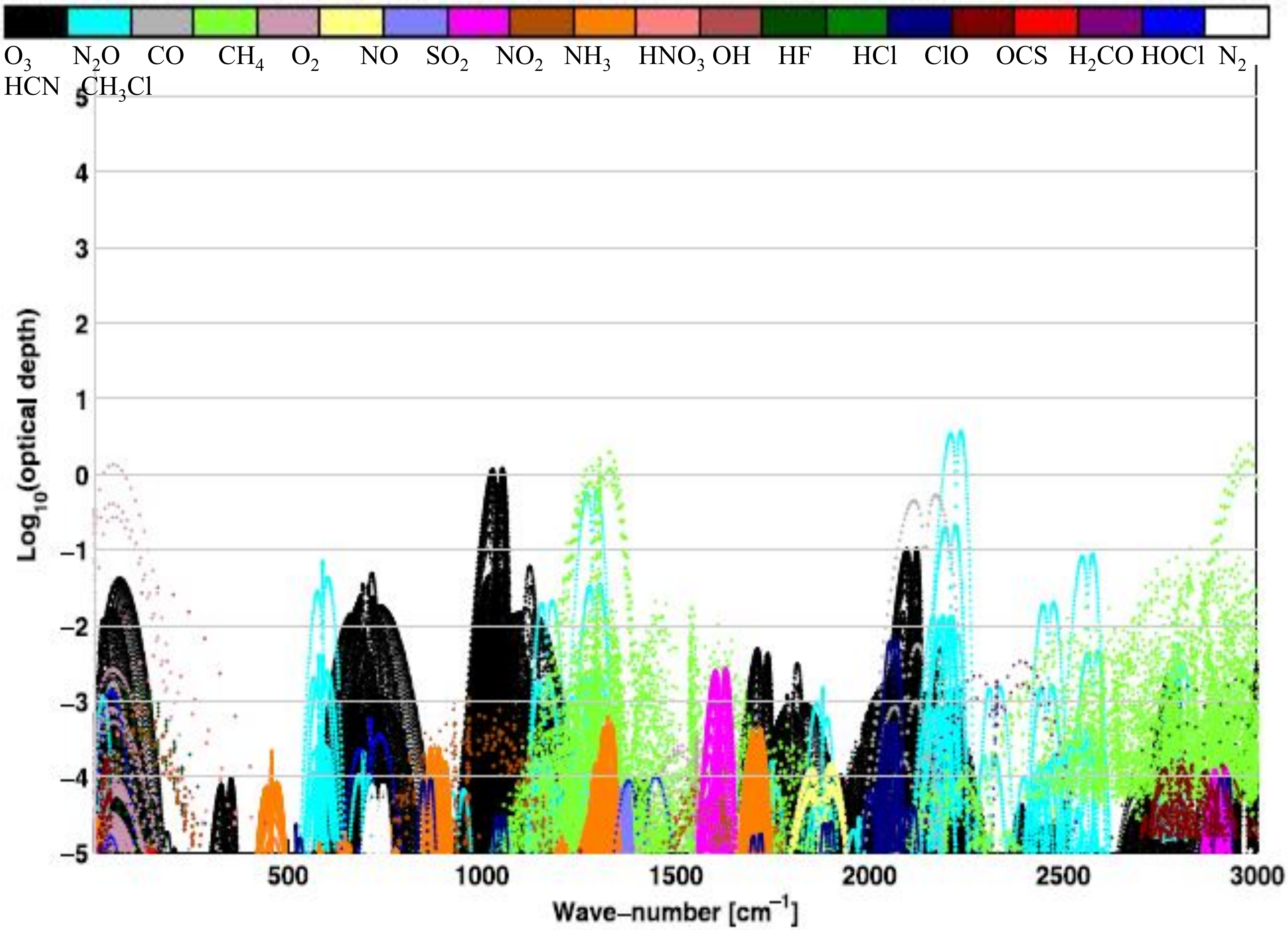
angle-bending vibration (1595 cm-1)



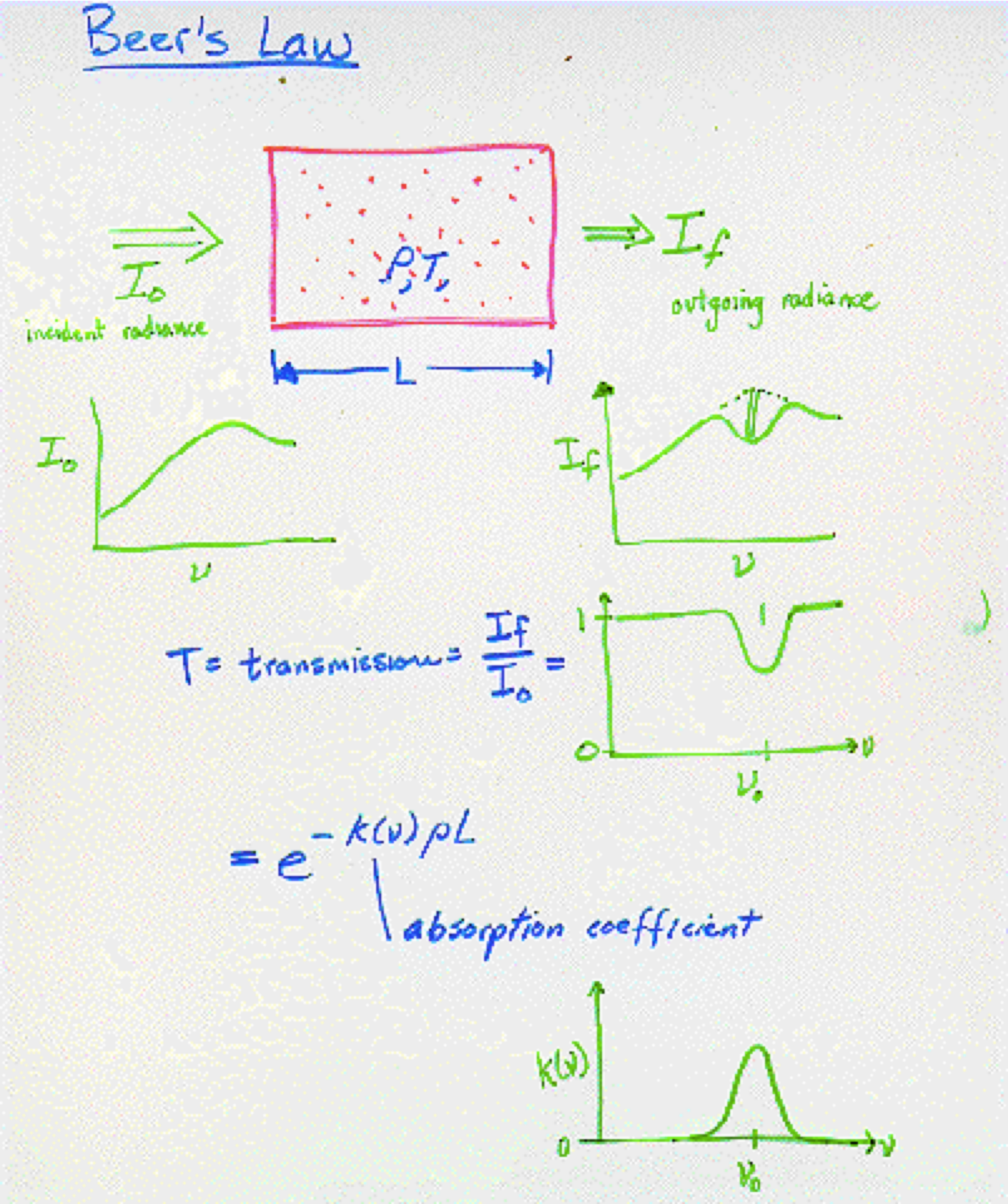
antisymmetric bond-stretching (3756 cm-1)




Water Vapour
Carbon Dioxide
Log$_{10}$(optical depth)
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
500
1000
1500
2000
2500
3000
Wave−number [cm^{-1}]


O_3 HCN
N_2O CH_3Cl
CO
CH_4
O_2
NO
SO_2
NO_2
NH_3
HNO_3
OH
HF
HCl
ClO
OCS
H_2CO
HOCl
N_2
Log_{10}(optical depth)
5
4
3
2
1
0
−1
−2
−3
−4
−5
500
1000
1500
2000
2500
3000
Wave−number [cm^{-1}]

Beer's Law



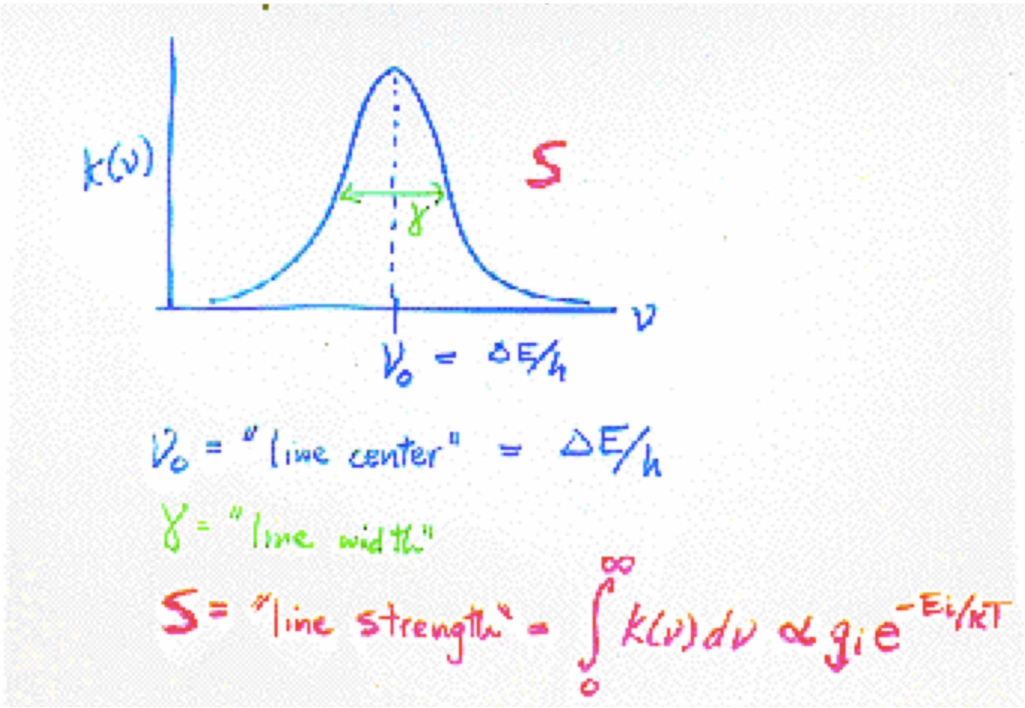
T = transmission = $\frac{I_f}{I_0}$ =

$= e^{-k(\nu)\rho L}$

absorption coefficient

Spectral Lines:

- Line parameters

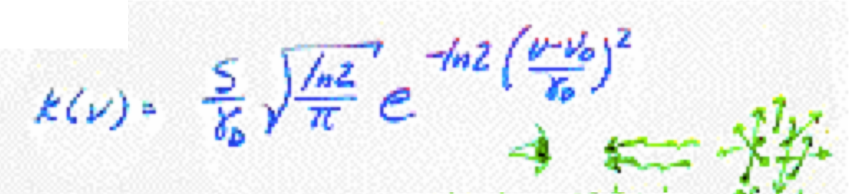


ν_0 = "line center" = $\Delta E/h$

γ = "line width"

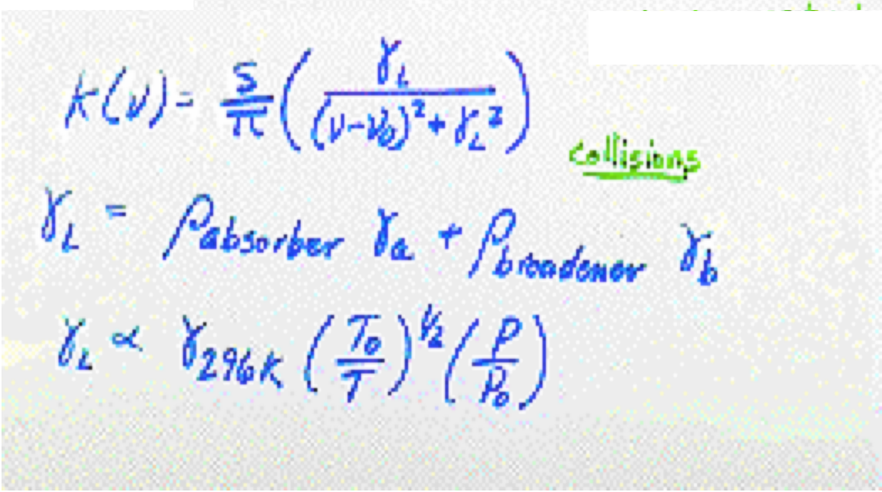
S = "line strength" = $\int_0^\infty k(\nu)\,d\nu \propto g_i e^{-E_i/kT}$

- Common Lineshapes:
  - Doppler:



$$k(\nu) = \frac{S}{\gamma_D}\sqrt{\frac{\ln 2}{\pi}}\, e^{-\ln 2\left(\frac{\nu-\nu_0}{\gamma_D}\right)^2}$$

- Lorentz:



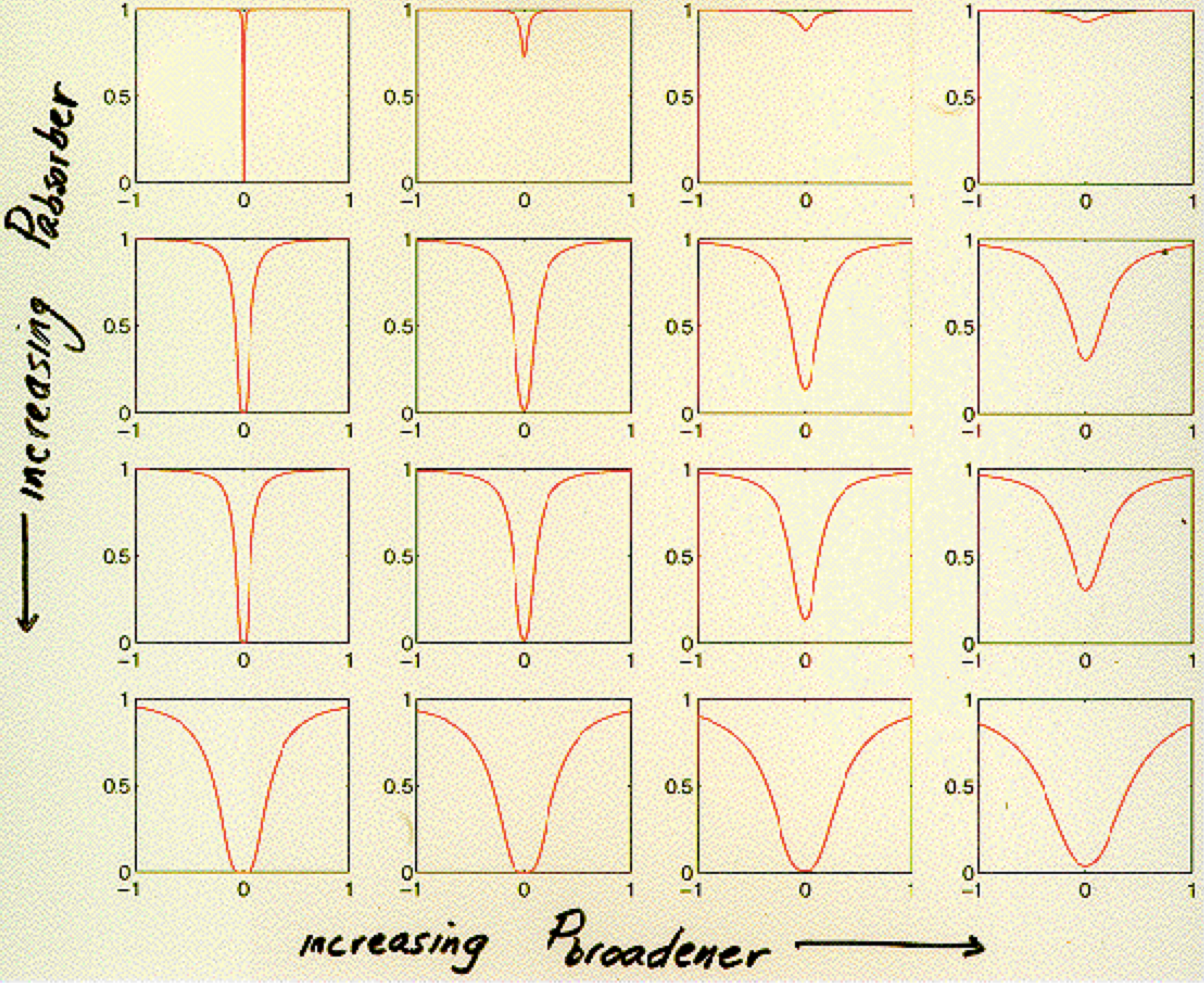
$$k(\nu) = \frac{S}{\pi}\left(\frac{\gamma_L}{(\nu-\nu_0)^2+\gamma_L^2}\right)$$

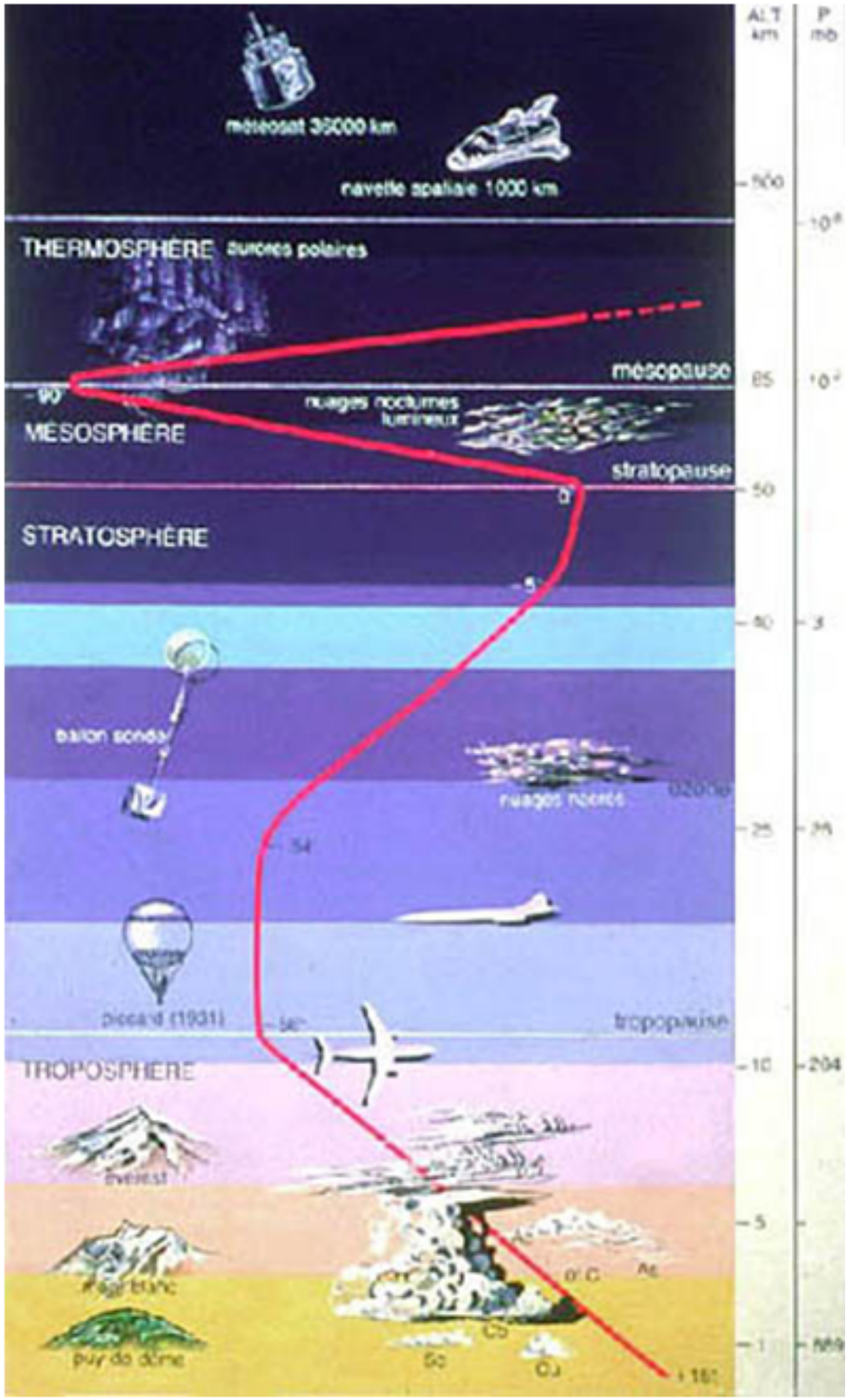
collisions

$$\gamma_L = P_{absorber}\,\gamma_a + P_{broadener}\,\gamma_b$$

$$\gamma_L \propto \gamma_{296K}\left(\frac{T_0}{T}\right)^{1/2}\left(\frac{P}{P_0}\right)$$

Lorentz Profiles




ALT km
P mb
météosat 36000 km
navette spatiale 1000 km
500
10⁻⁶
THERMOSPHÈRE
aurores polaires
mésopause
85
10⁻²
-90°
nuages noctumes lumineux
MÉSOSPHÈRE
stratopause
0°
50
STRATOSPHÈRE
-5°
40
3
ballon sonde
nuages nacrés
ozone
25
25
-54°
piccard (1931)
-56°
tropopause
TROPOSPHÈRE
10
204
everest
5
Ac
Ci Cs
As
mont blanc
Cb
Sc
Cu
1
899
+15°
puy de dôme

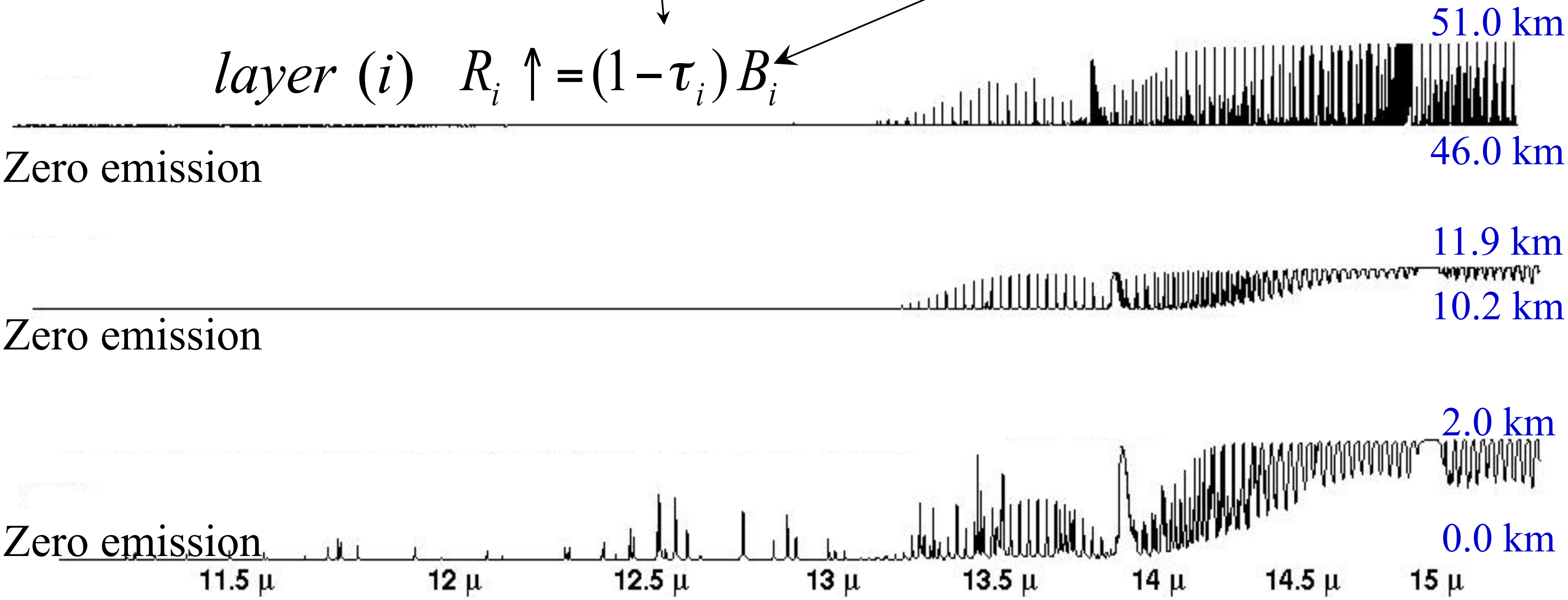
Layer Atmospheric Transmission and Emission

Plank's function of this layer temperature

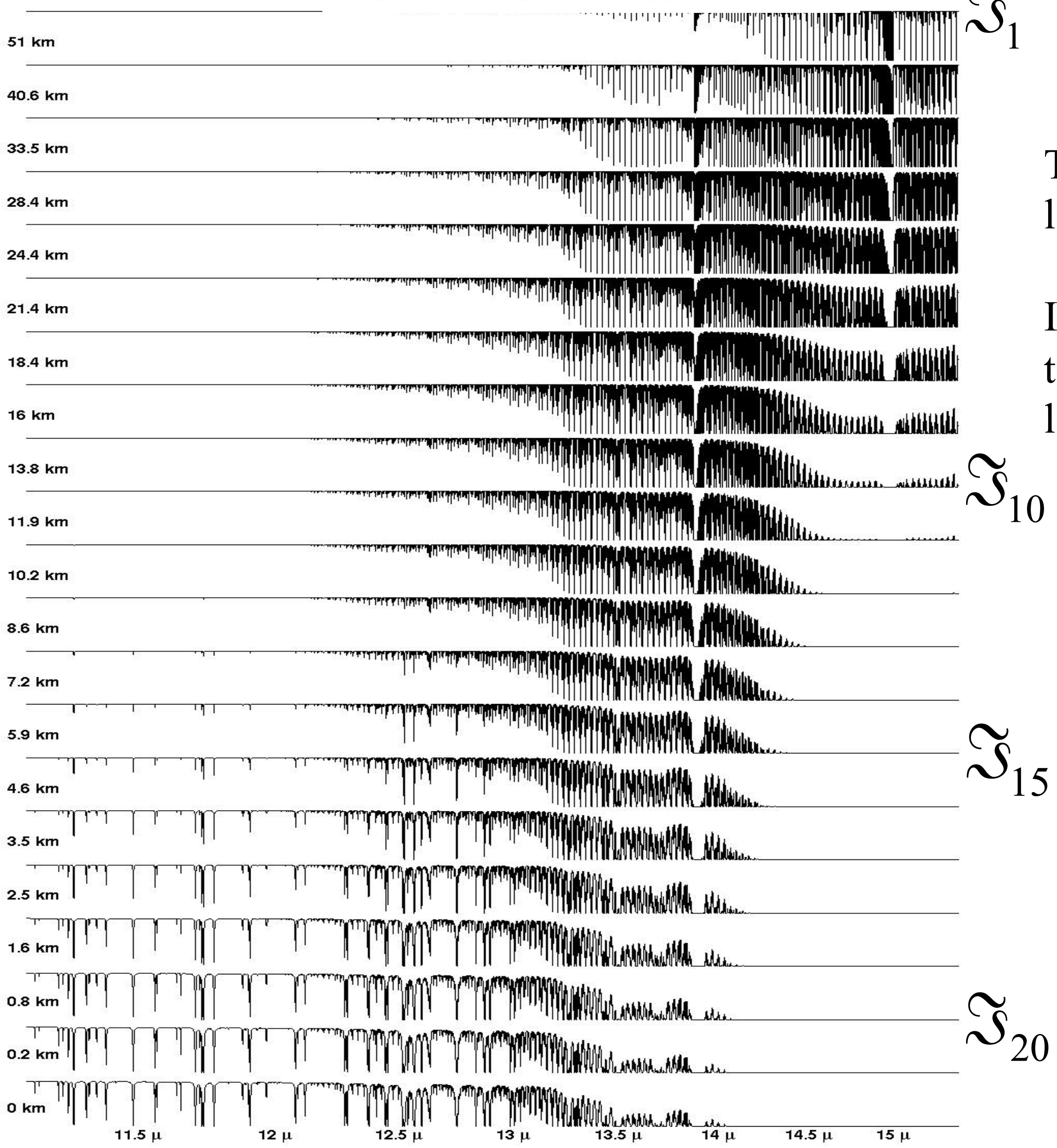
Transmission of this layer = τ_i

Emission from this layer = R_i

$$\text{layer } (i) \quad R_i \uparrow = (1-\tau_i)\, B_i$$

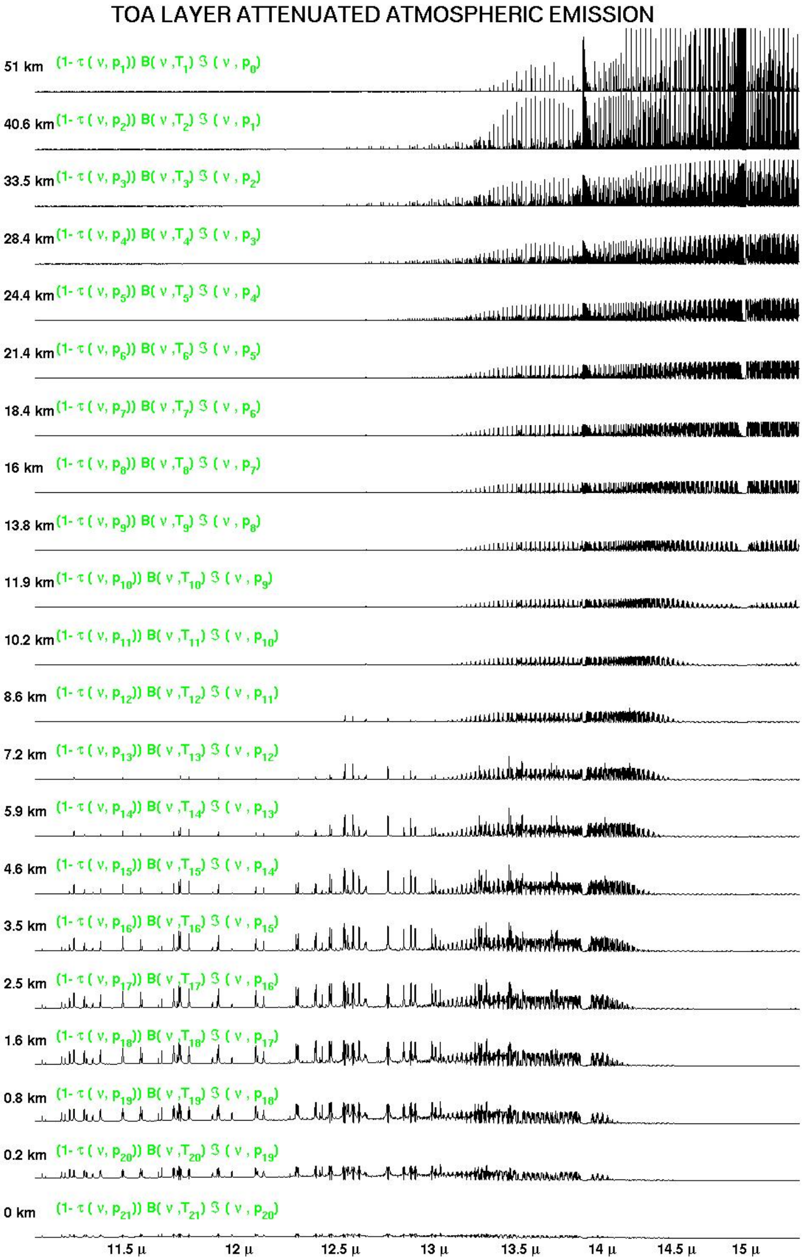


TOA Transmittance



Total transmittance $\mathfrak{I}$ from a layer at z altitude to the TOA.

Is the transmission of that layer, times the transmission of all layers above



TOA layer attenuated atmospheric Emission:

This is the emission that is received at the satellite from each layer after attenuation through next (upper) layers.

$$R_i = (1-\tau_i)B_i\,\Im_{(i-1)}$$

$$R_{22} = (1-\tau_{22})B_{22}\,\Im_{21}$$

Total emission received by the satellite from all layers of the atmosphere:

Equals the summation of the attenuated emission from each layer :

$$R\uparrow=\sum_{i=1}^{n}(1-\tau_i(\nu,z_i))\,B_i(\nu,Ts_i)\,\Im_i(\nu,z_i)$$

where

(Ts_i) *is surface temperature*

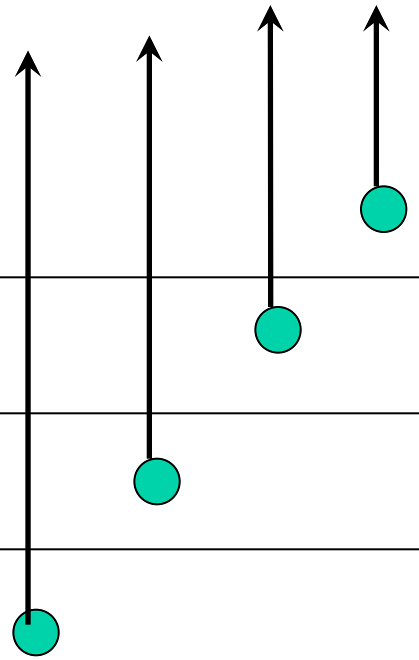
$\nu =$ *frequency (spectral band)*

$n =$ *numberoflayers*

This is equivalent to:

$$R\uparrow=\sum \mathrm{B}_i\,(\Im_{i-1}-\Im_i)$$

Example of the summation of attenuated emission from 4 layers:



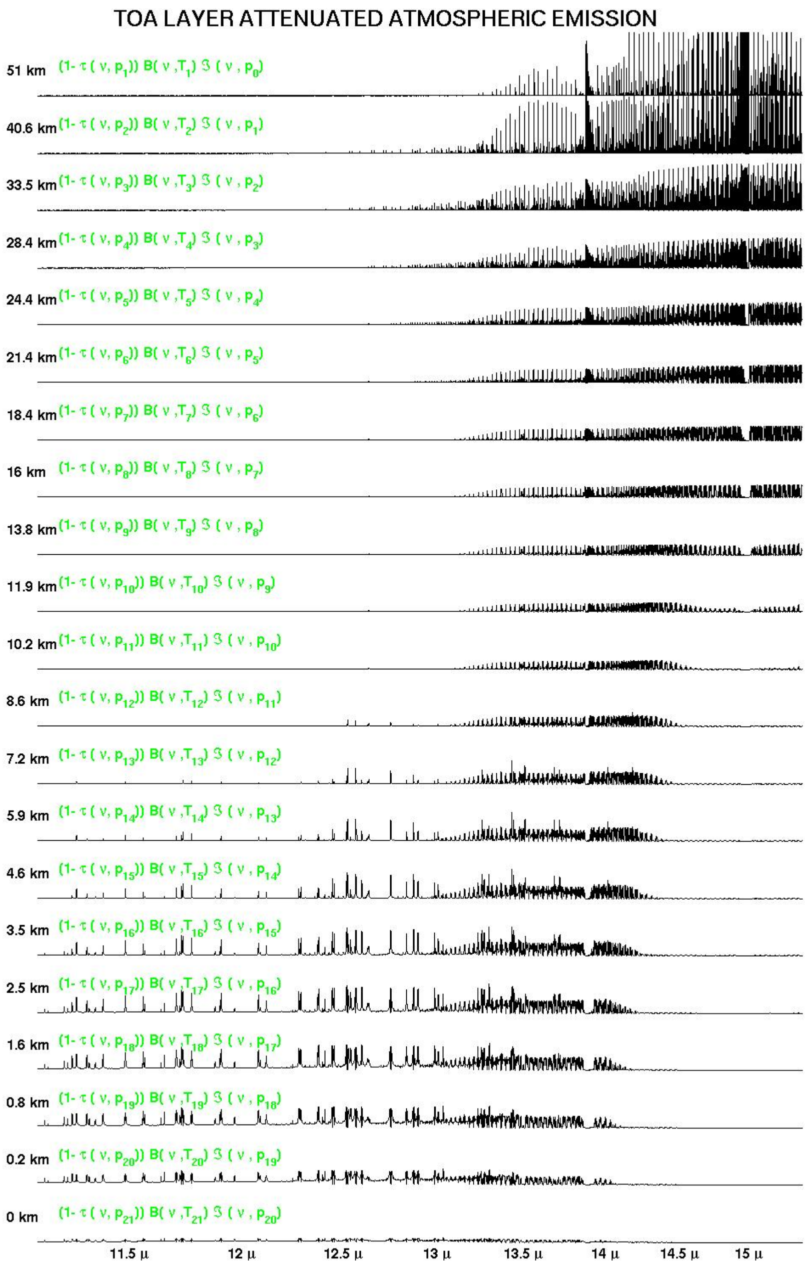
	Transmittance from each layer	Emission from each layer	Radiation from each layer to TOA
1	τ_1	$(1-\tau_1)B_1$	$(1-\tau_1)B_1$
2	τ_2	$(1-\tau_2)B_2$	$(1-\tau_2)\tau_1 B_2$
3	$\tau_3 \int$	$(1-\tau_3)B_3$	$(1-\tau_3)\tau_2\tau_1 B_3$
4	τ_4	$(1-\tau_4)B_4$	$(1-\tau_4)\tau_3\tau_2\tau_1 B_4$

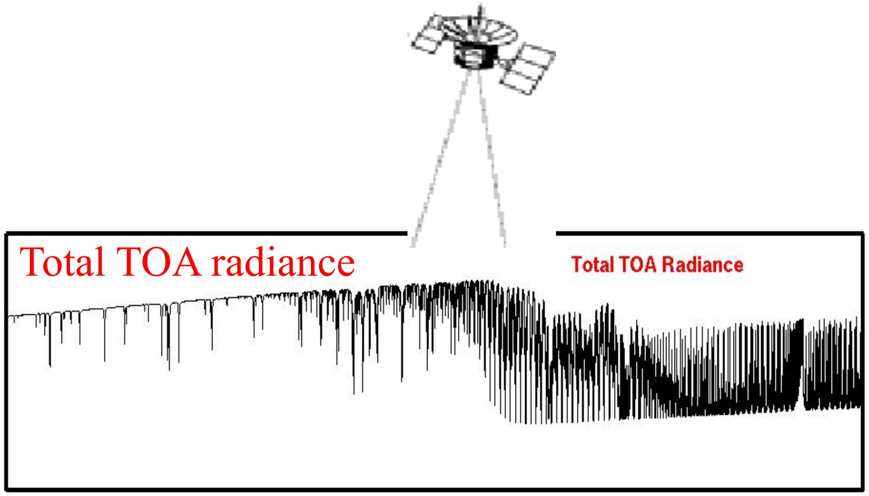
Example of decomposition of one term

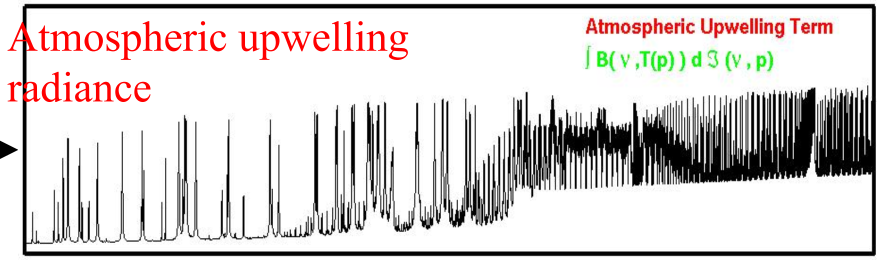
$$(1-\tau_3)\tau_2\tau_1 B_3 = (\tau_2\tau_1 - \tau_3\tau_2\tau_1)B_3 = (\Im_2 - \Im_3)B_3$$

Hence, the radiance at the TOA integrated over the atmospheric column is:

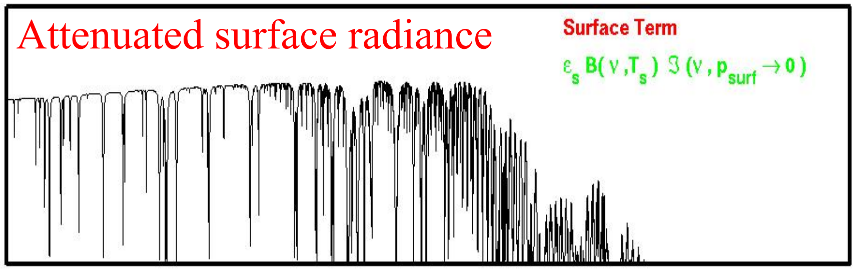
$$R\uparrow = \sum_{1}^{n} (\Im_{i-1}(\upsilon,p) - \Im_i(\upsilon,p))\, B_i(\upsilon,p) \equiv \int B_i\, d\Im_i \equiv \int B_i \frac{d\Im_i}{dp} dp$$




Total TOA radiance

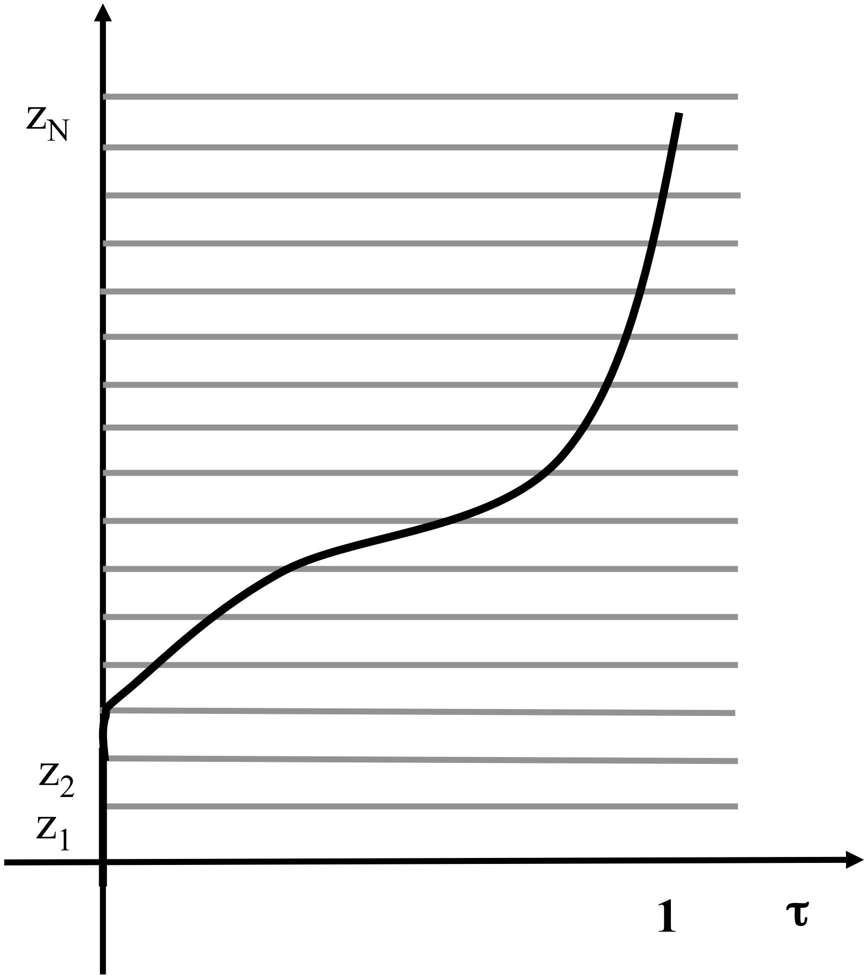

Atmospheric upwelling radiance

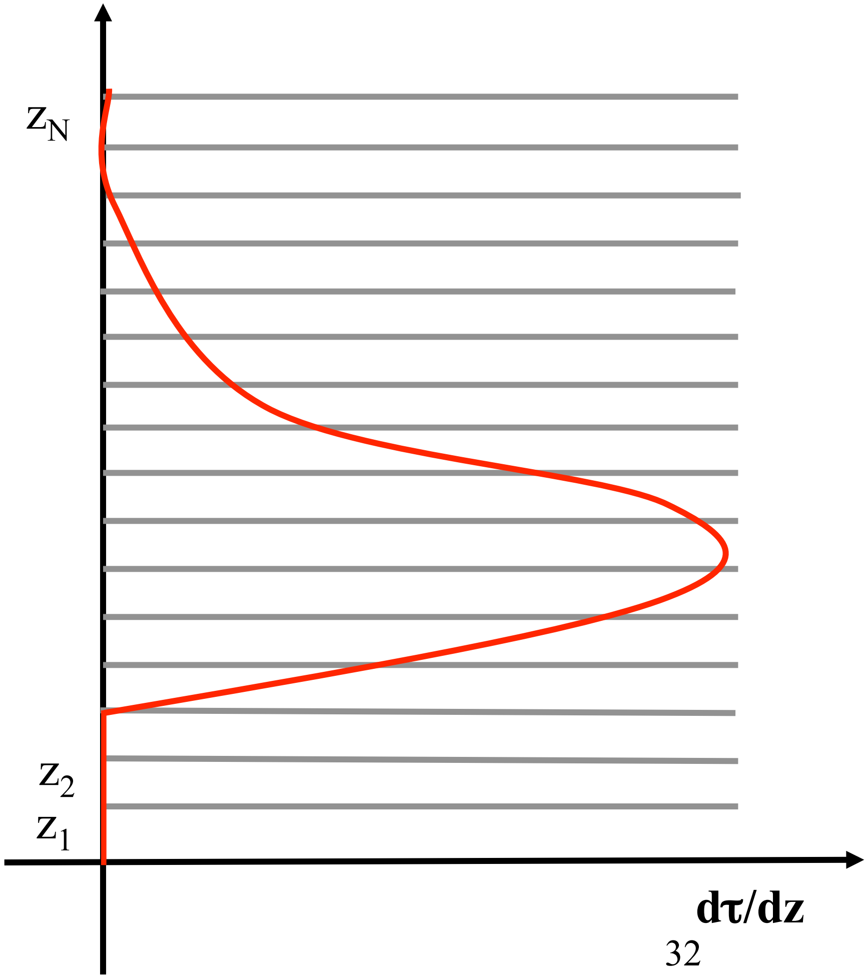
$$R\uparrow = \int B(\upsilon,T_p)\Im_s(\upsilon,z_p) = \int B(\upsilon,T_p)\,\frac{d\Im_s(\upsilon,z_p)}{dp}\,dp$$

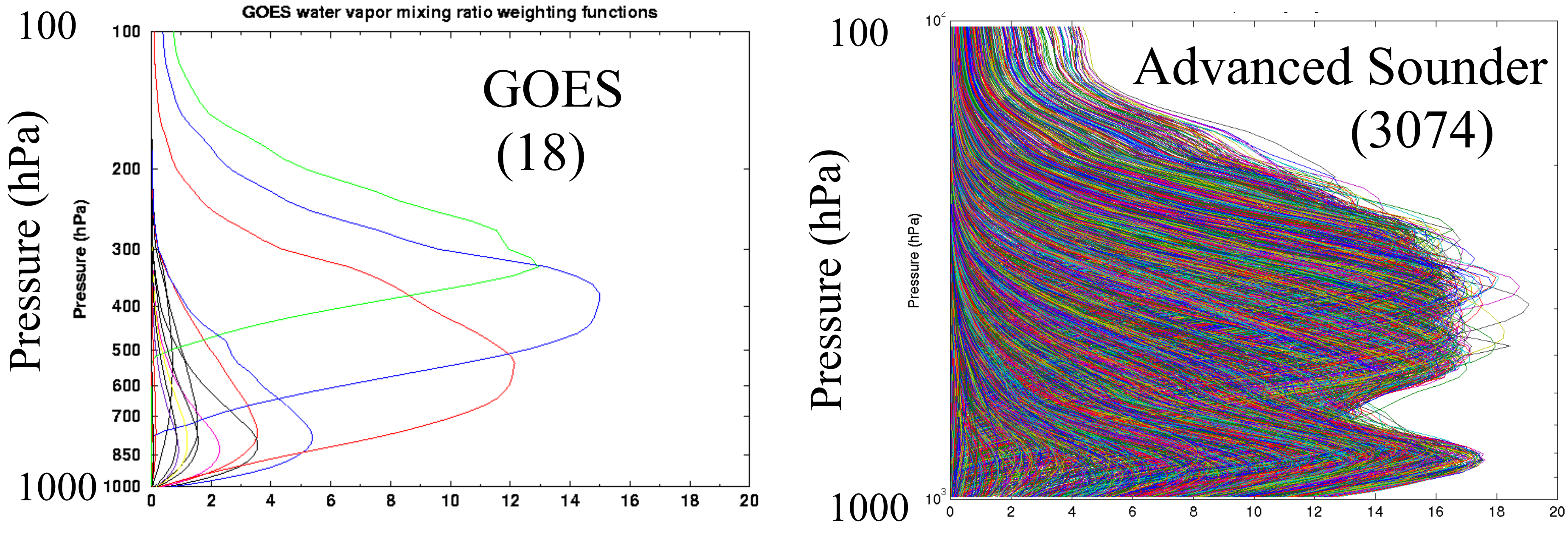

Attenuated surface radiance

$$R_s = \varepsilon_s B(\upsilon,T_s)\Im_s(\upsilon,z_s)$$

Weighting Functions



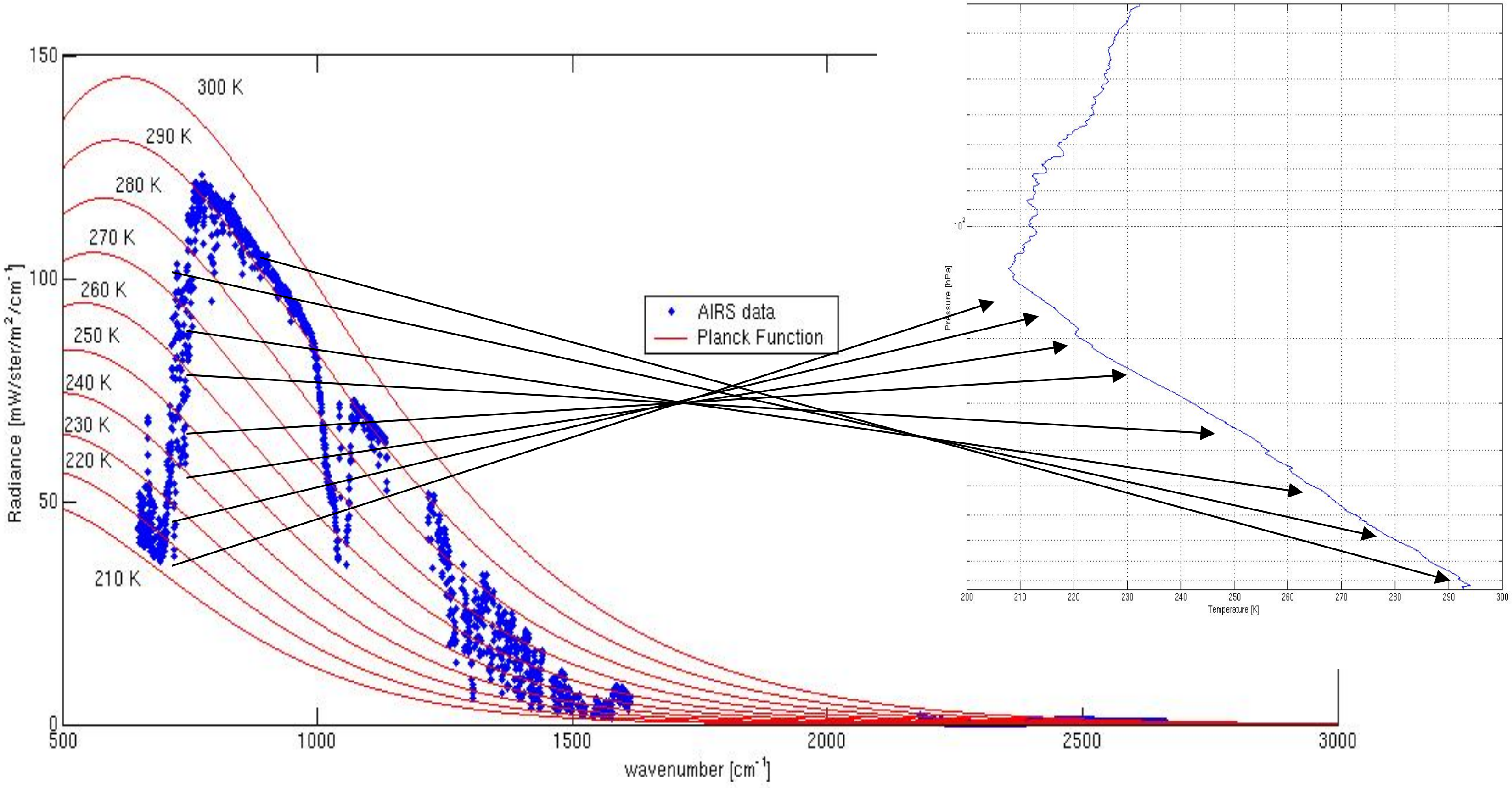




Moisture Weighting Functions

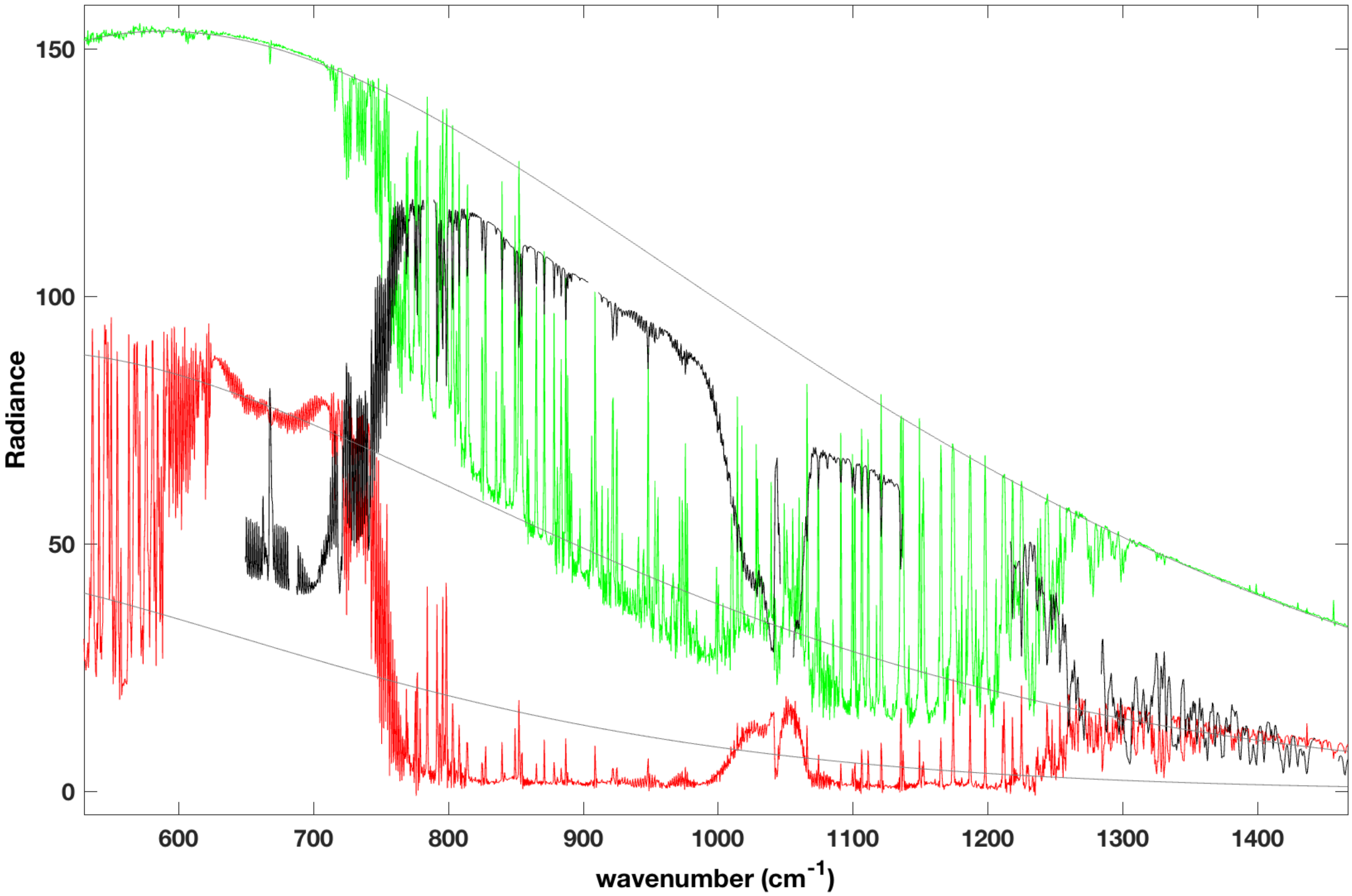
High spectral resolution advanced sounder will have more and sharper weighting functions compared to current GOES sounder. Retrievals will have better vertical resolution.

High Spectral Resolution

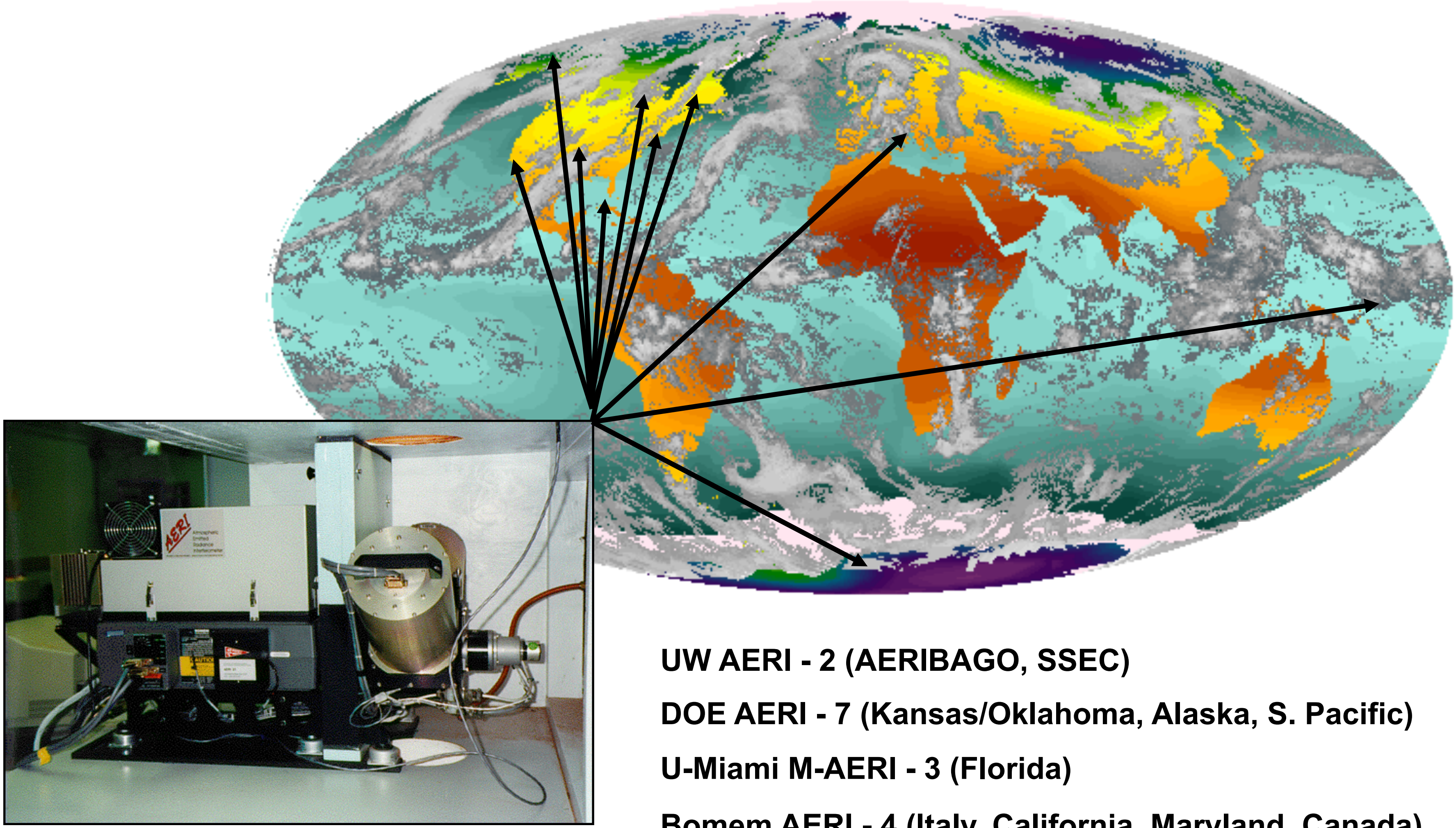


Sampling over rotational bands

So we know what the black curve is now. What are the green and red?



AERI SYSTEMS AROUND THE WORLD



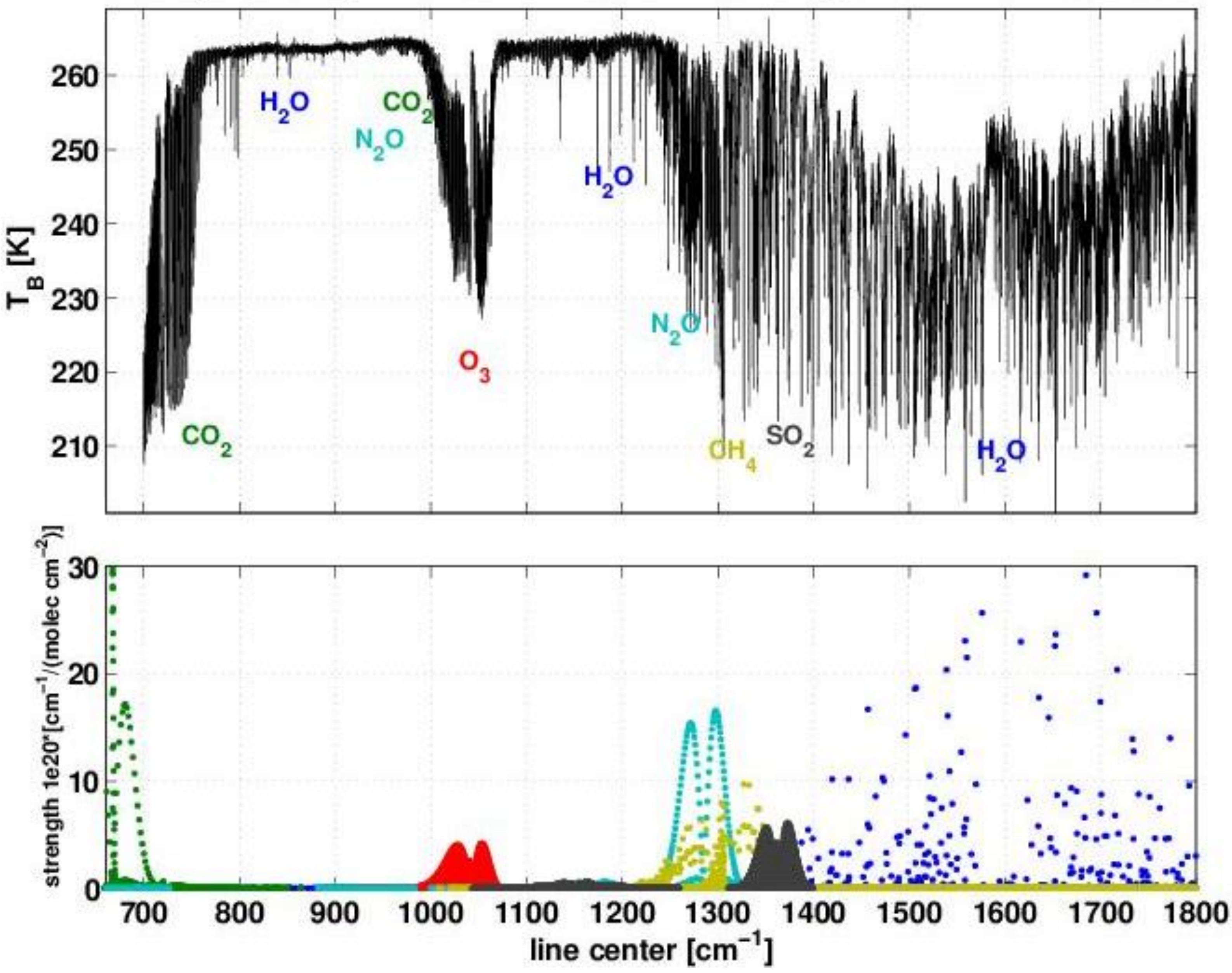
UW AERI - 2 (AERIBAGO, SSEC)

DOE AERI - 7 (Kansas/Oklahoma, Alaska, S. Pacific)

U-Miami M-AERI - 3 (Florida)

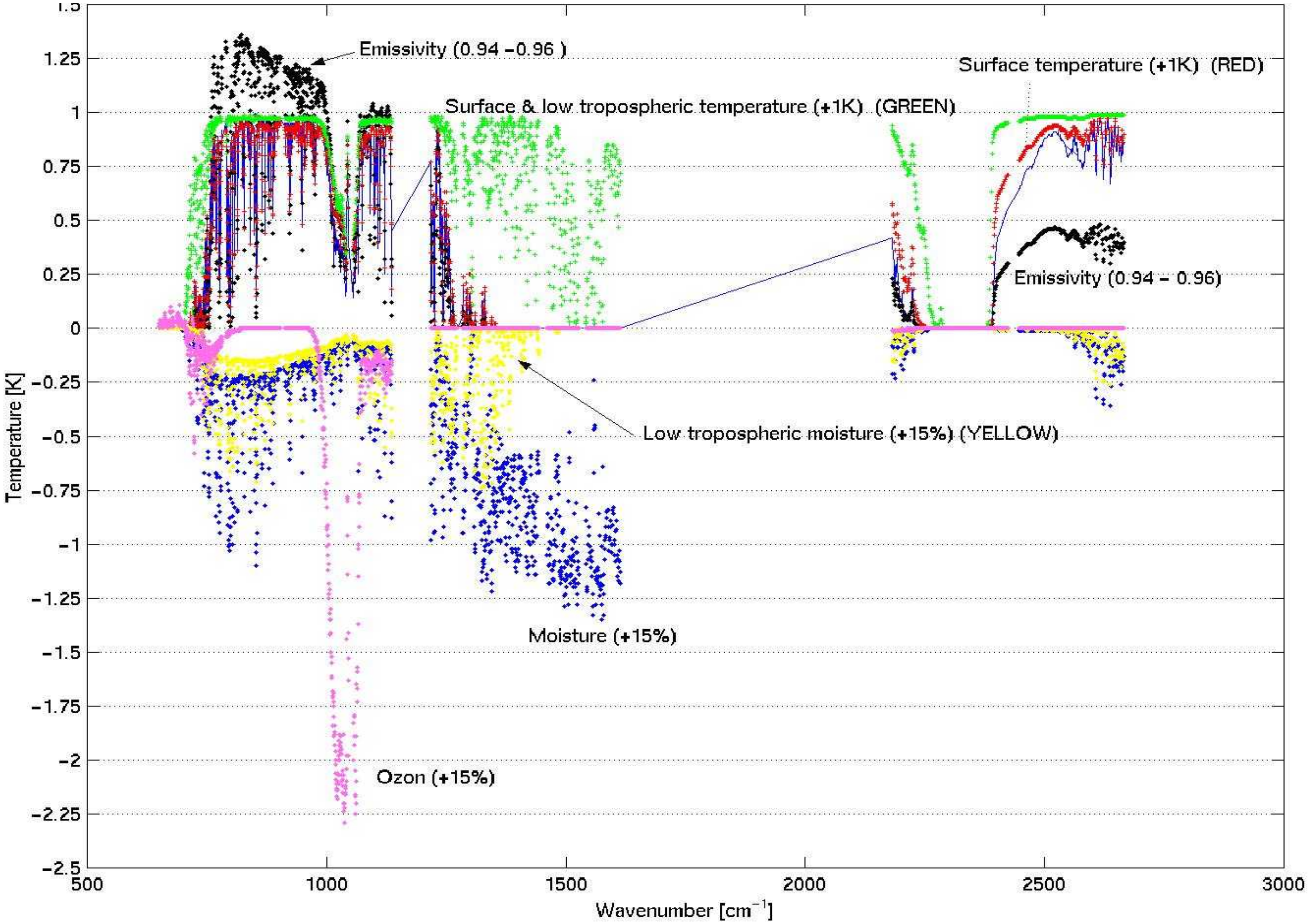
Bomem AERI - 4 (Italy, California, Maryland, Canada)

U Idaho P-AERI - 1 (Antarctica)

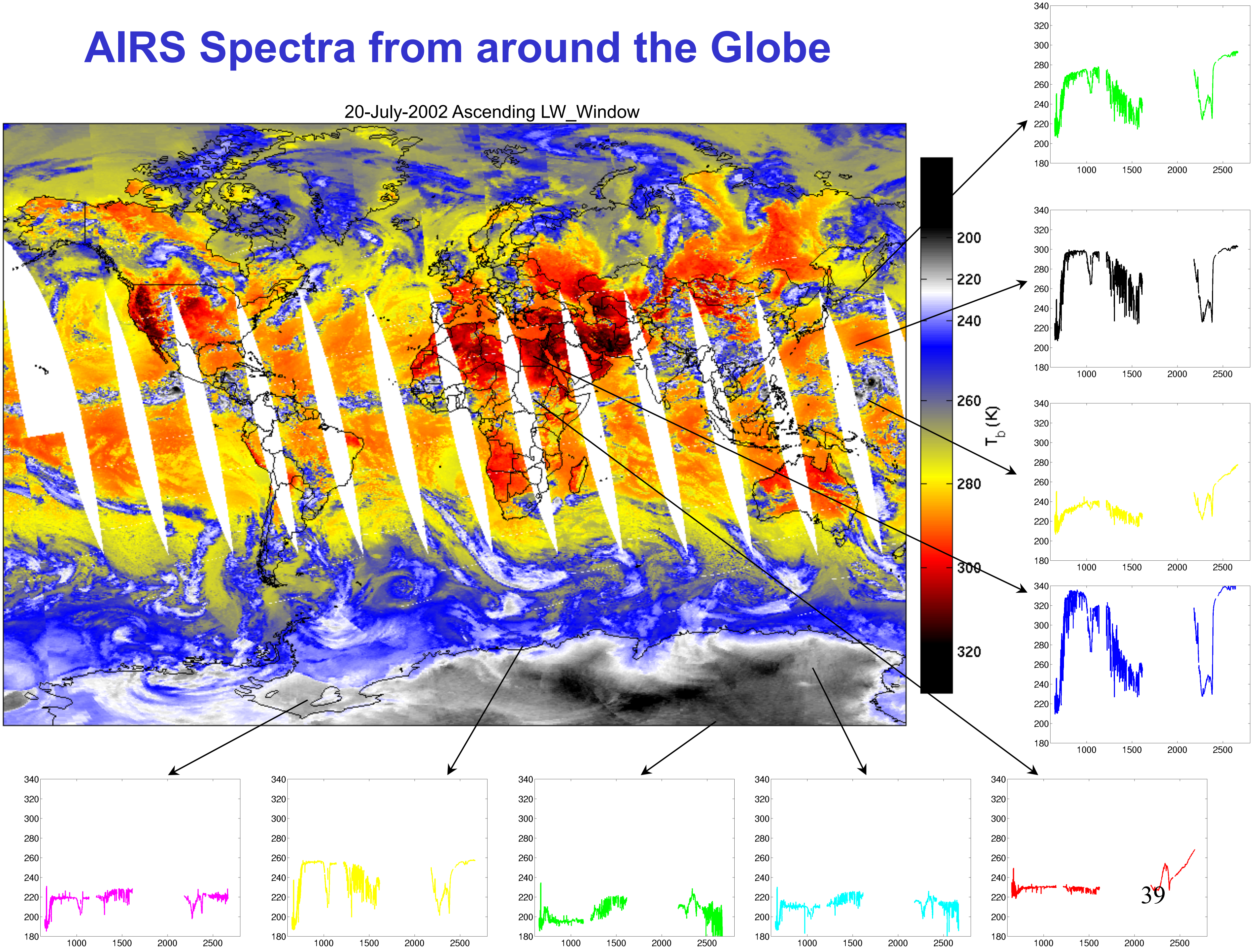


IMG spectrum (WINCE, 970128 over Nebraska) and HITRAN database

AIRS TOA radiance changes (in deg K) to atm & sfc changes

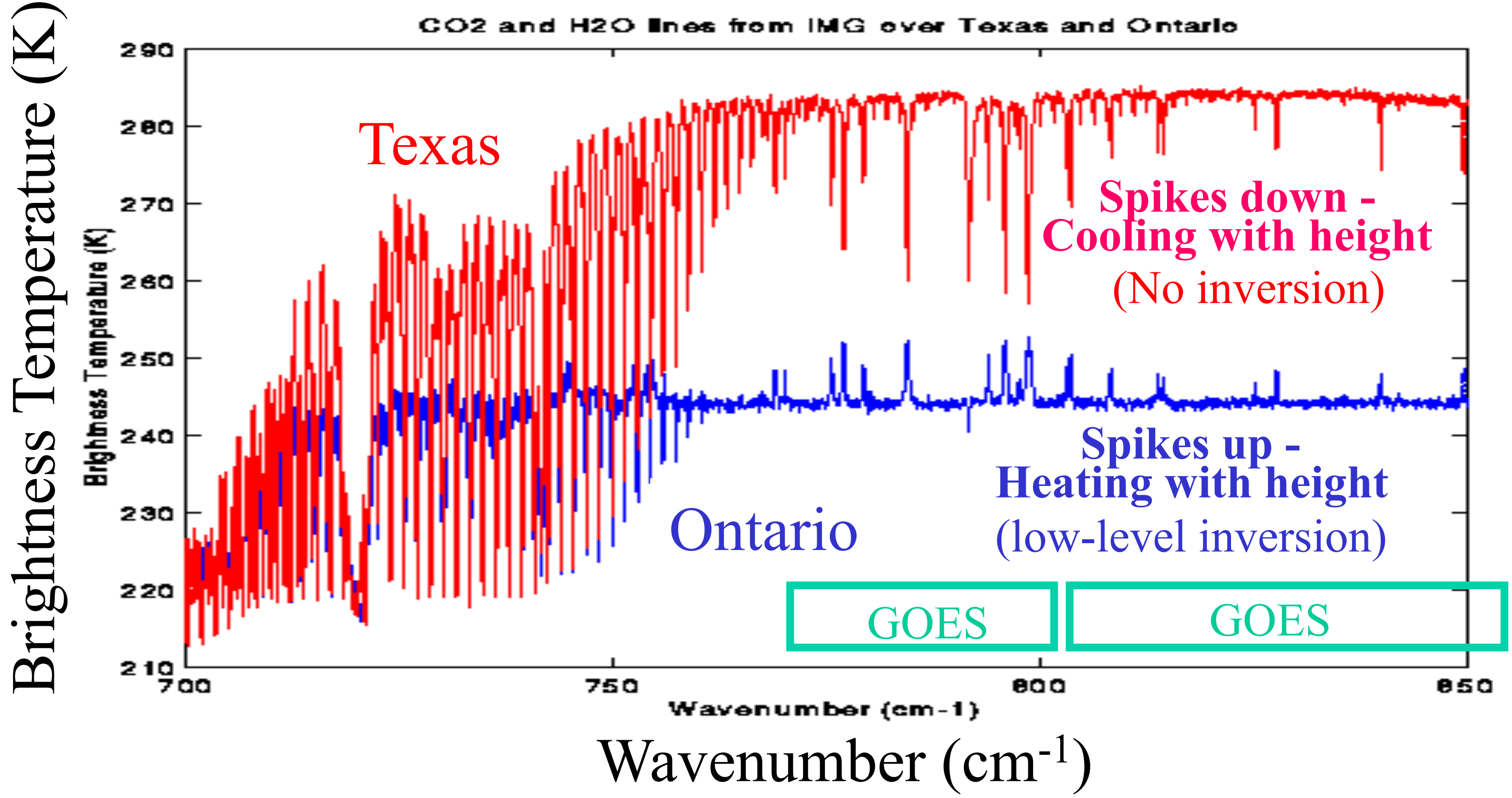


AIRS Spectra from around the Globe



20-July-2002 Ascending LW_Window

Resolving absorption features in atmospheric windows enables detection of temperature inversions



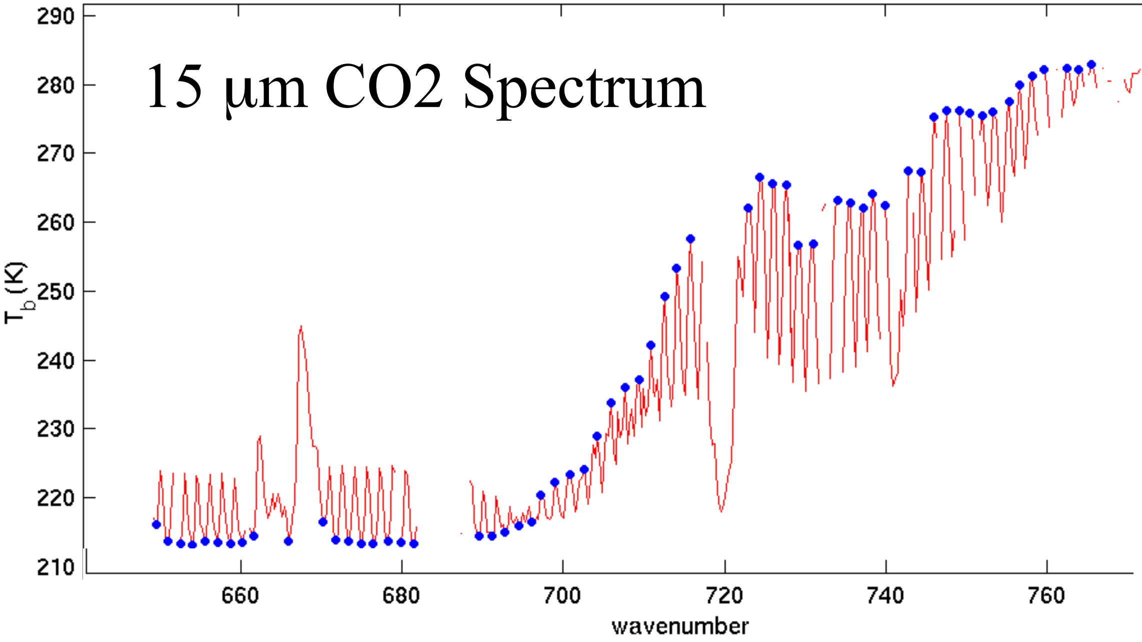
Spikes down -
Cooling with height
(No inversion)

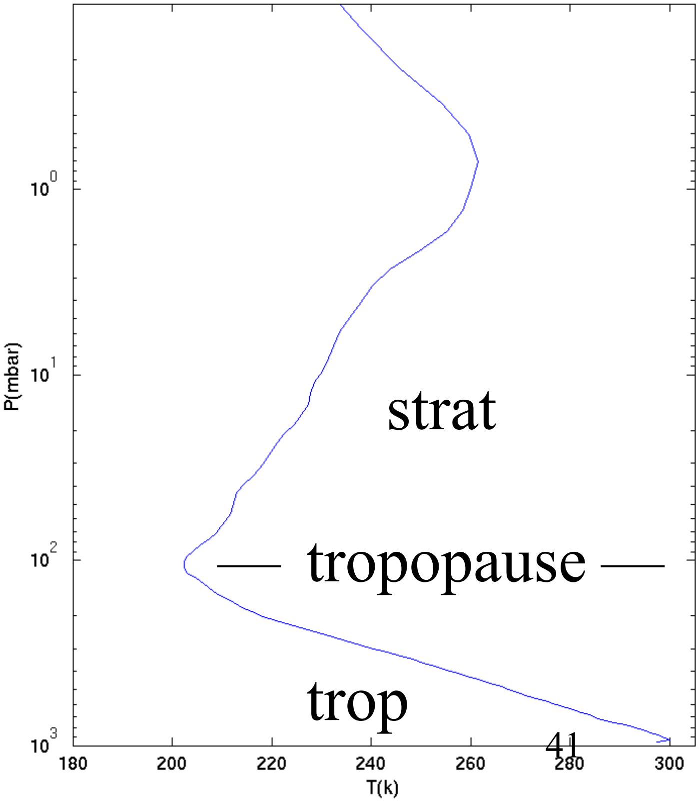
Spikes up -
Heating with height
(low-level inversion)

Detection of inversions is critical for severe weather forecasting. Combined with improved low-level moisture depiction, key ingredients for night-time severe storm development can be monitored.

Twisted Ribbon formed by CO_2 spectrum:

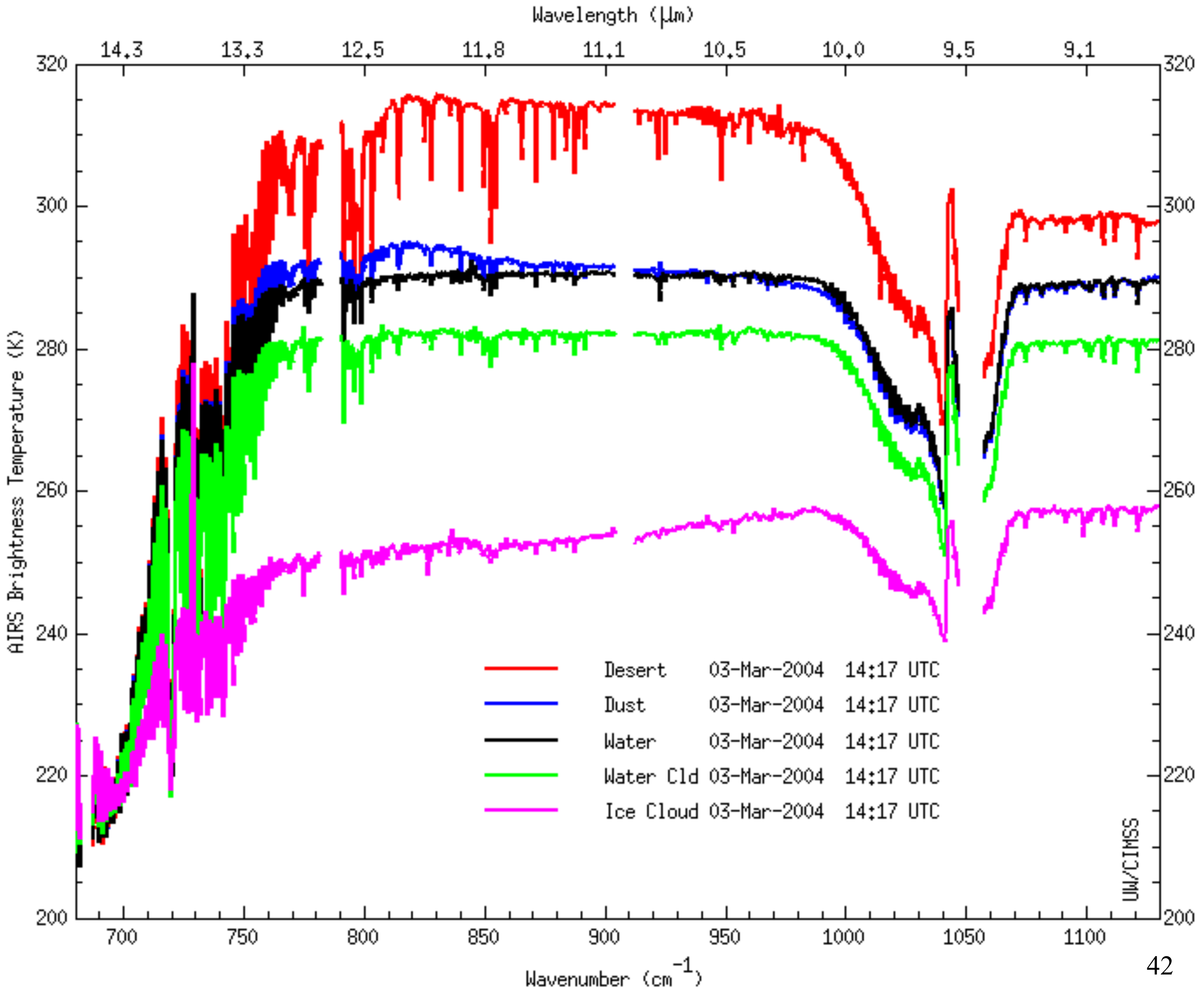
Tropopause inversion causes On-line & off-line patterns to cross



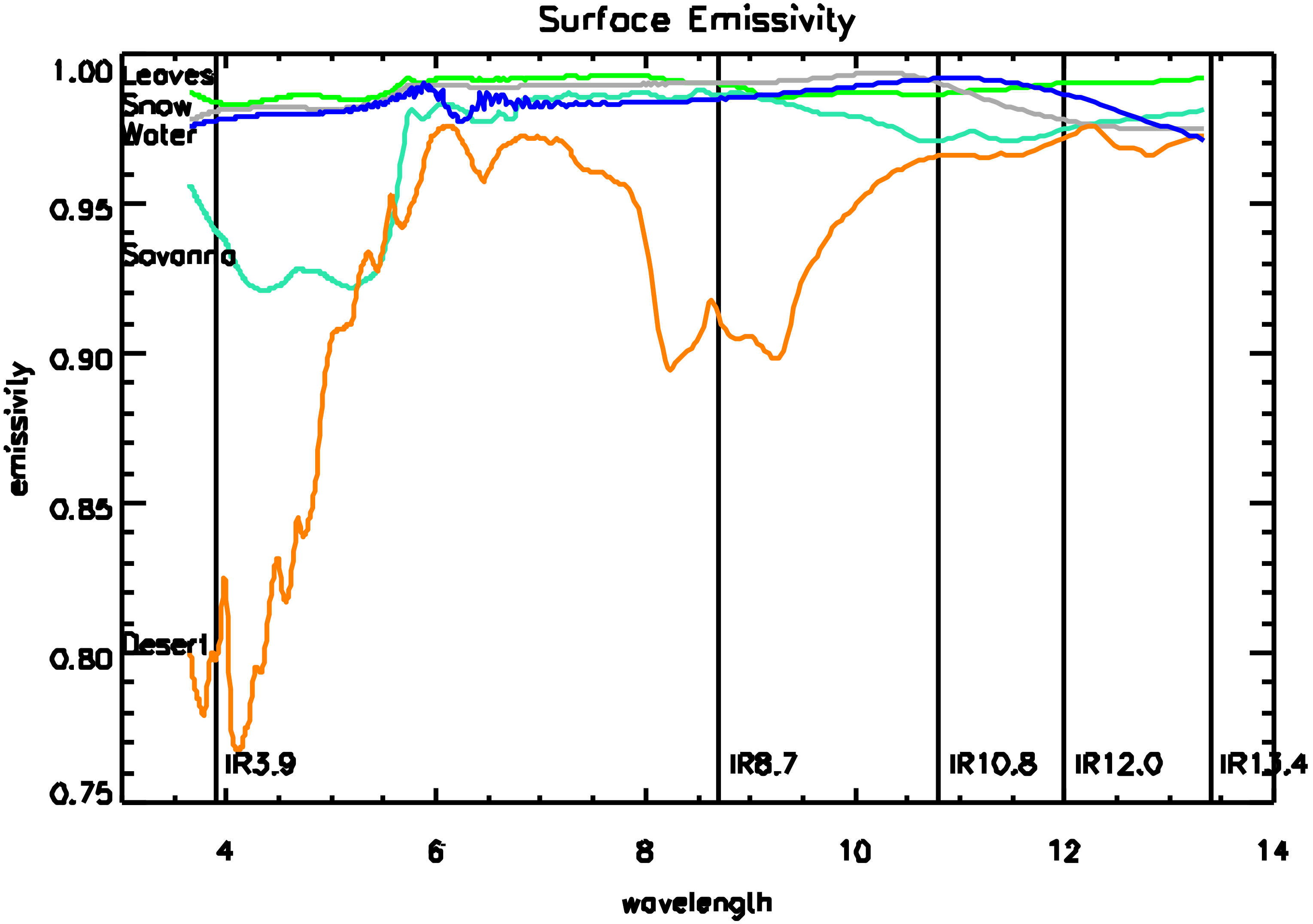


Blue between-line T_b
<u>warmer</u> for tropospheric channels,
<u>colder</u> for stratospheric channels

Signature not available at low resolution

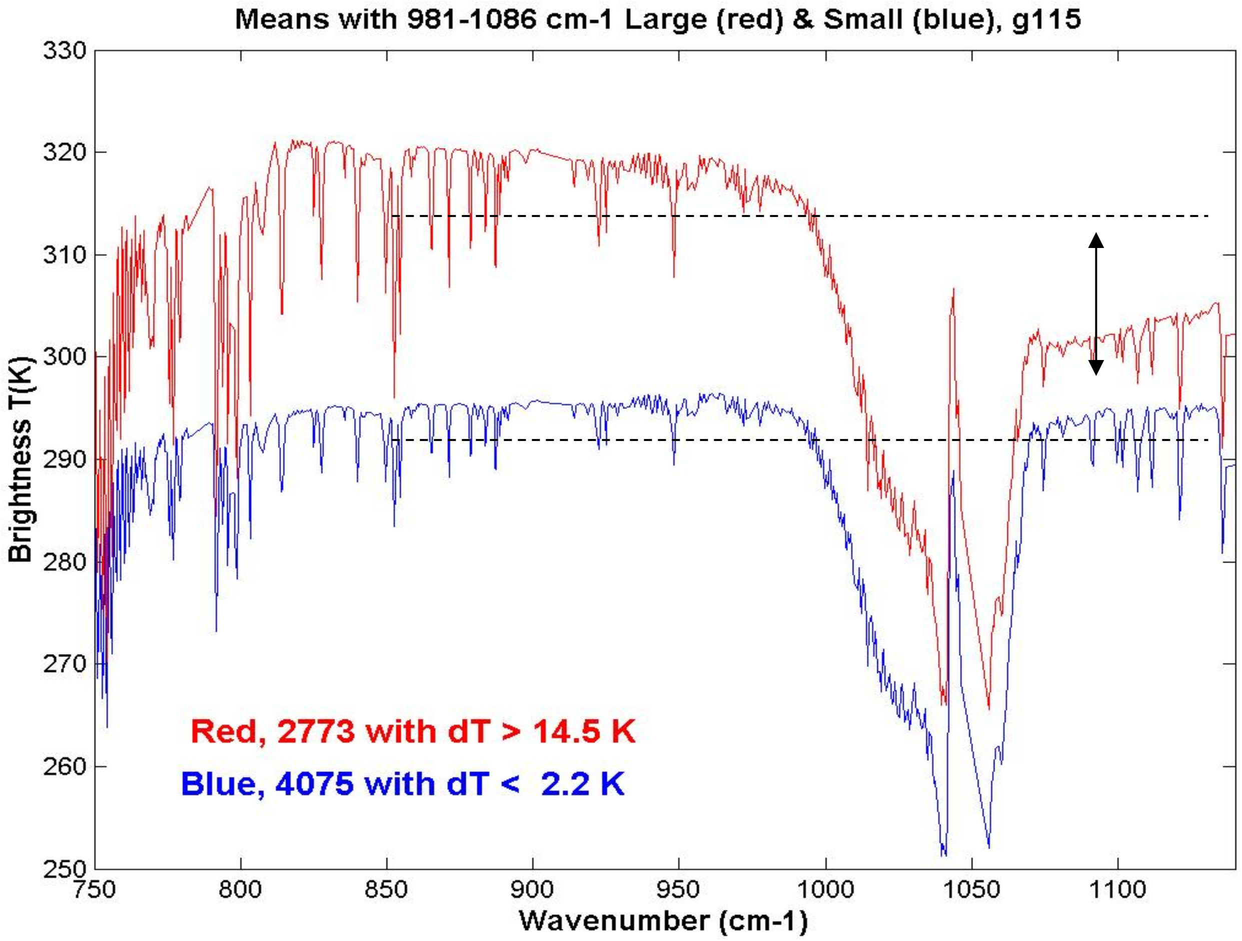

Wavelength (μm)
14.3
13.3
12.5
11.8
11.1
10.5
10.0
9.5
9.1
AIRS Brightness Temperature (K)
320
300
280
260
240
220
200
700
750
800
850
900
950
1000
1050
1100
Wavenumber (cm^{-1})
Desert 03-Mar-2004 14:17 UTC
Dust 03-Mar-2004 14:17 UTC
Water 03-Mar-2004 14:17 UTC
Water Cld 03-Mar-2004 14:17 UTC
Ice Cloud 03-Mar-2004 14:17 UTC
UW/CIMSS

2500 1000 715 cm-1



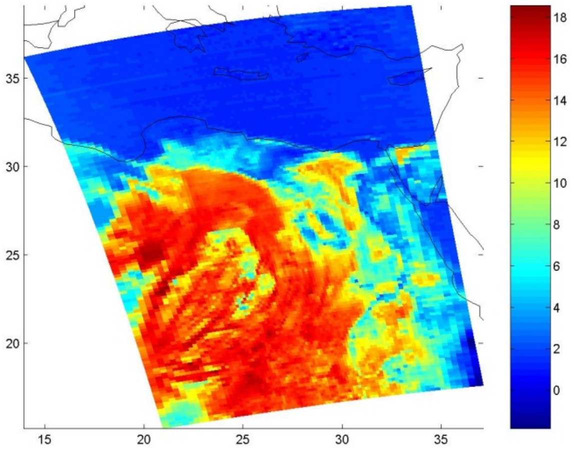
Inferring surface properties with AIRS high spectral resolution data
Barren region detection if T1086 < T981

Barren vs Water/Vegetated

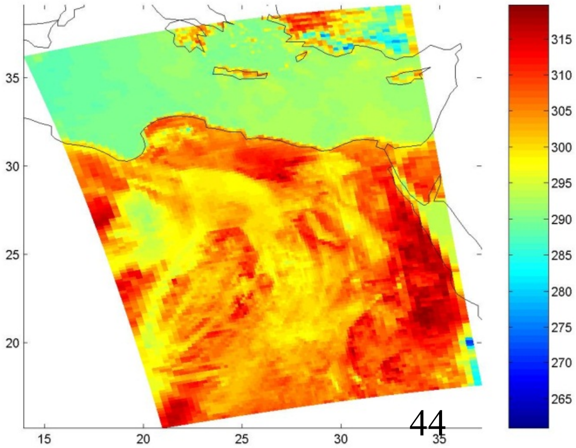


AIRS data from 14 June 2002

T(981 cm^{-1})-T(1086 cm^{-1})



T(1086 cm^{-1})

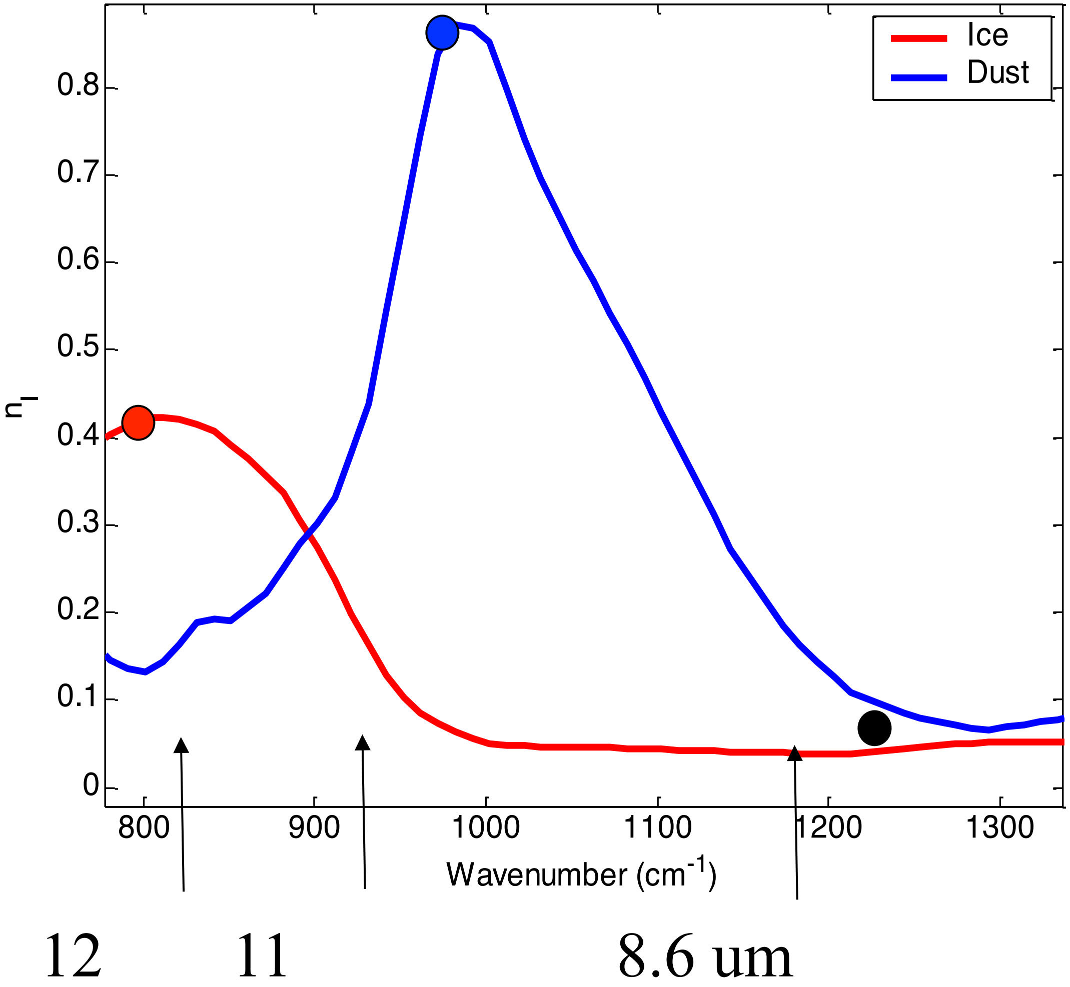


from Tobin et al.

CrIS and IASI Obs of Calbuco volcano eruption on 4/23/2015 @ 0509 UTC

Dust and Cirrus Signals

Imaginary Index of Refraction of Ice and Dust



- Both ice and silicate absorption small in 1200 cm^{-1} window
- In the 800-1000 cm^{-1} atmospheric window:

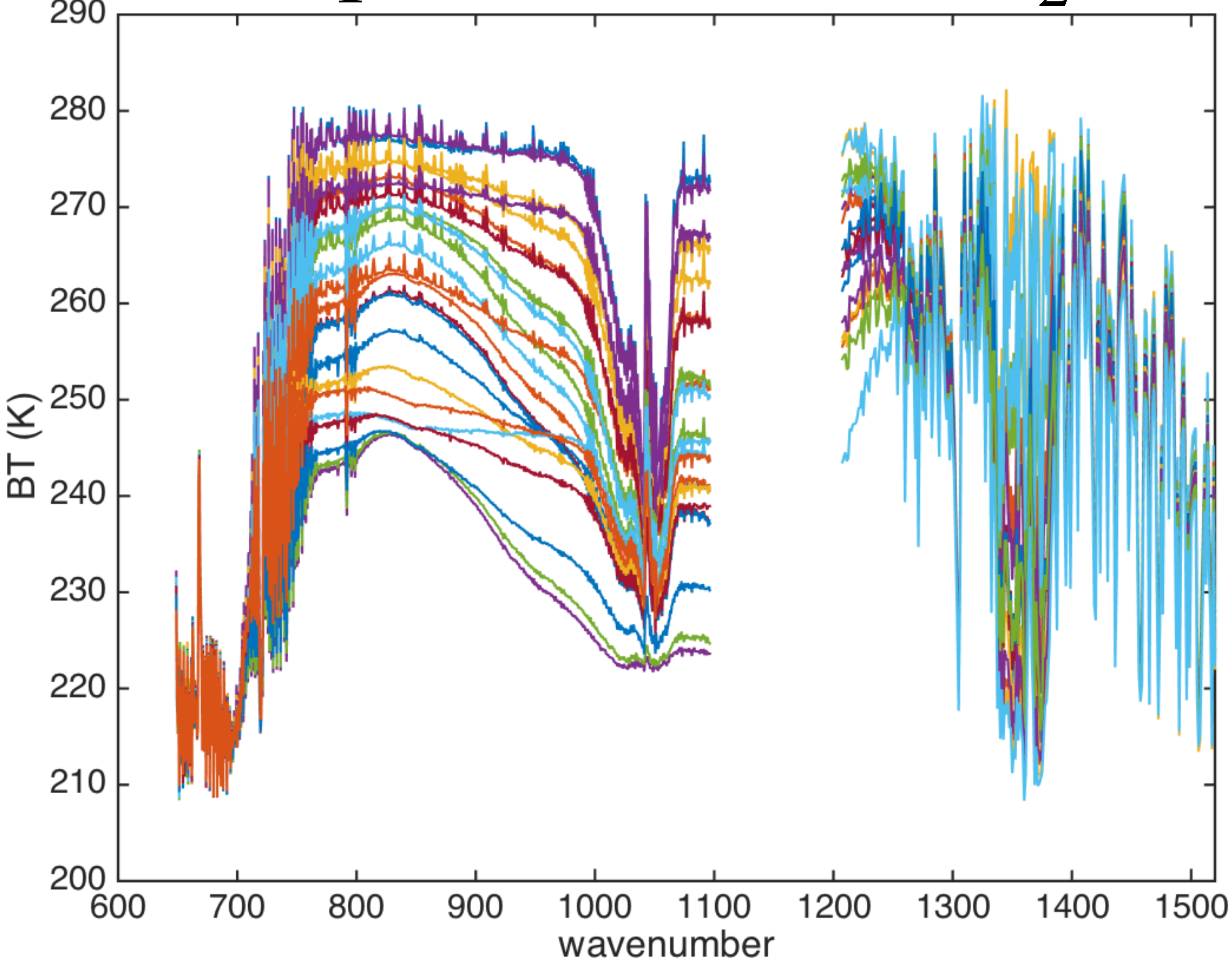
  Silicate index *increases*

  Ice index *decreases*

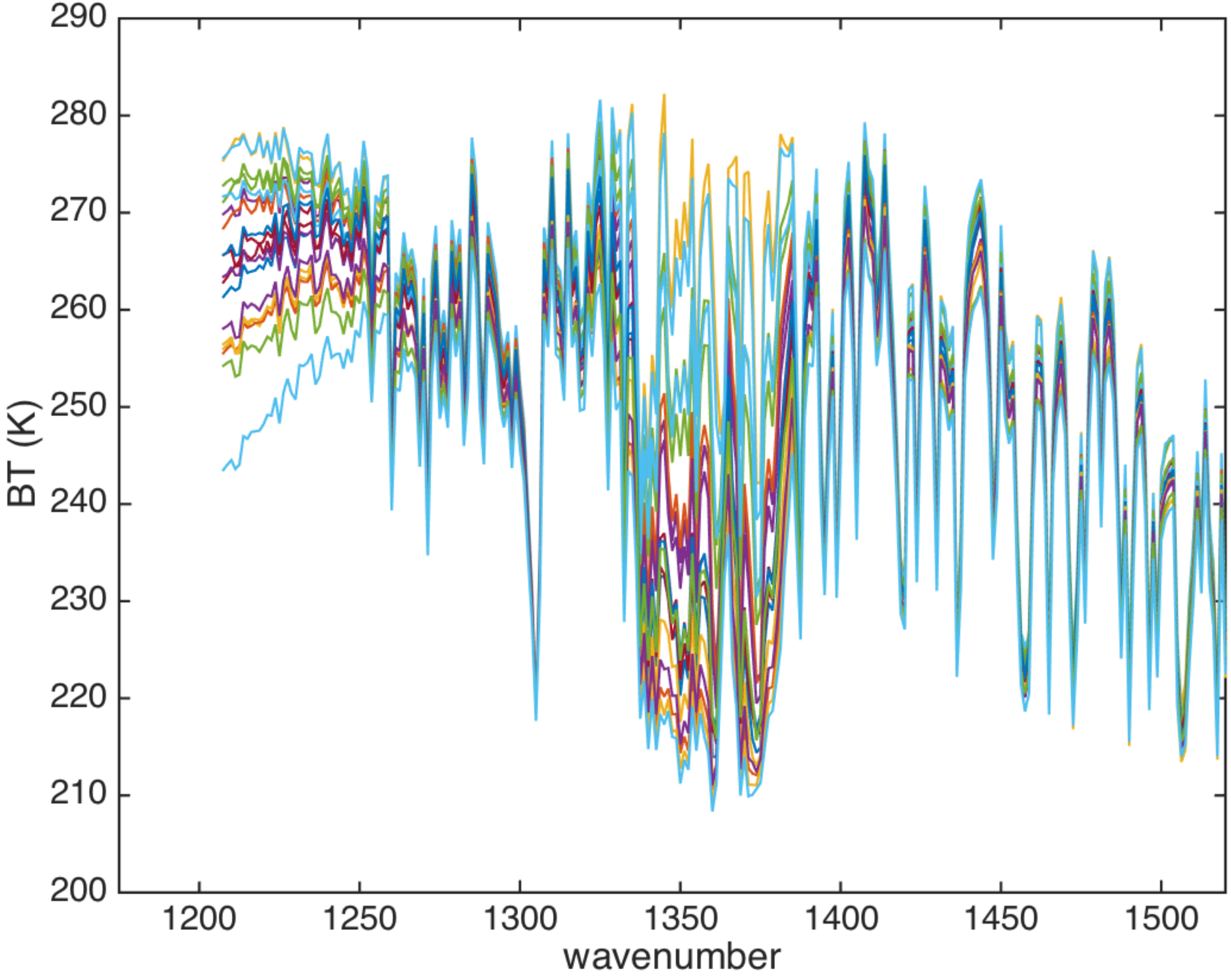
  with wavenumber

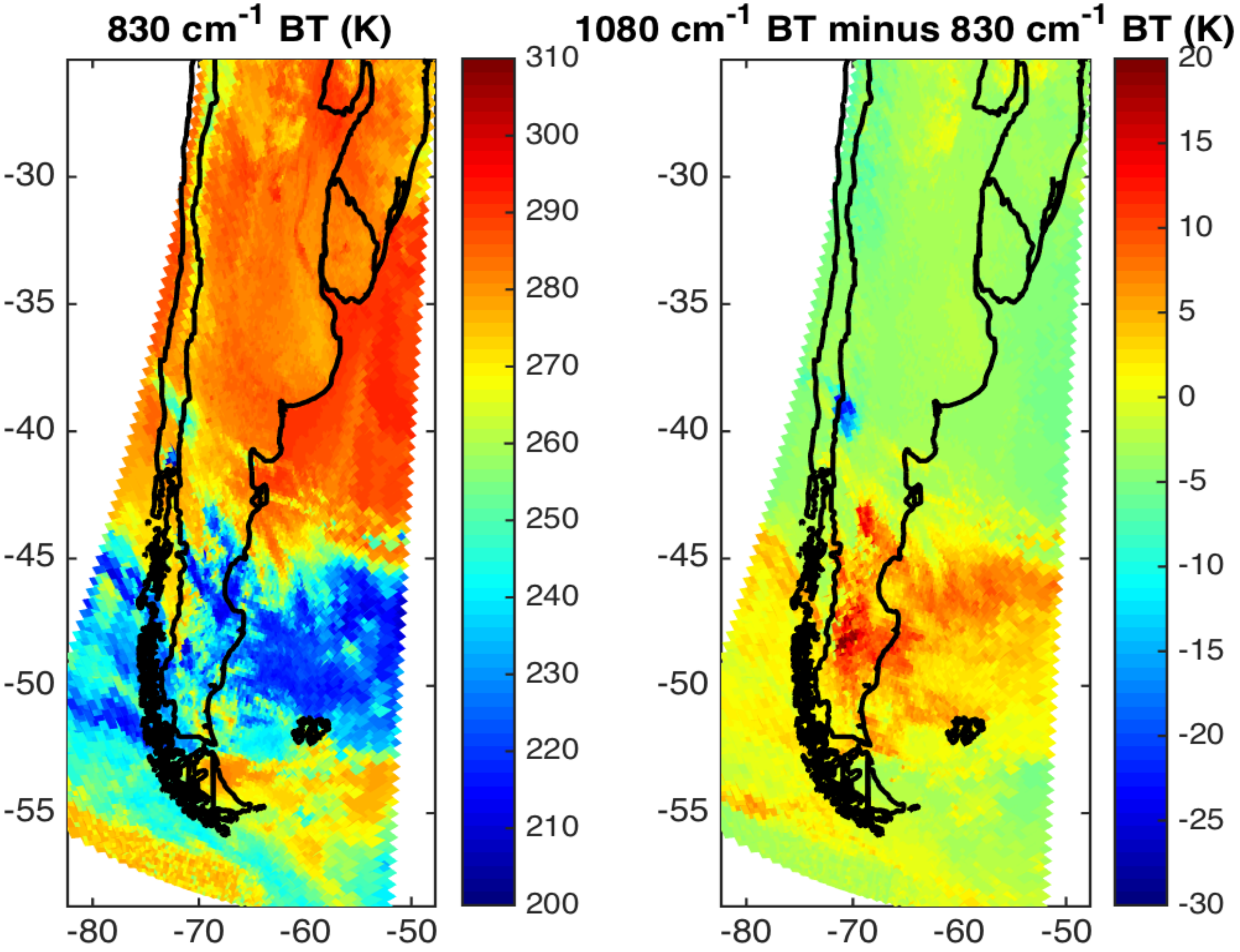
Volz, F.E. : Infrared optical constant of ammonium sulphate, Sahara Dust, volcanic pumice and flash, Appl Optics **12** 564-658 (1973)

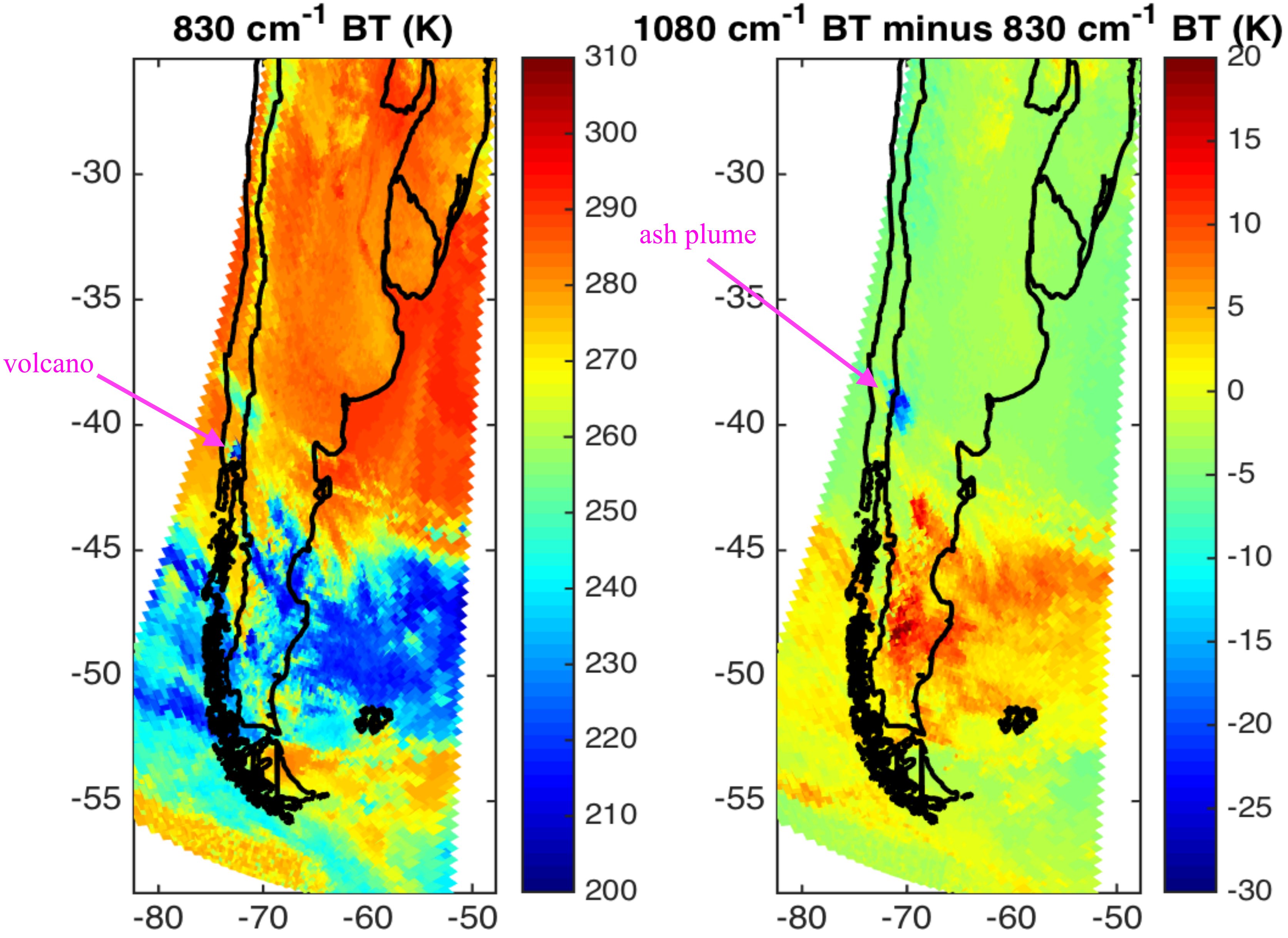
Example spectra of plume north of eruption, ash and SO_2

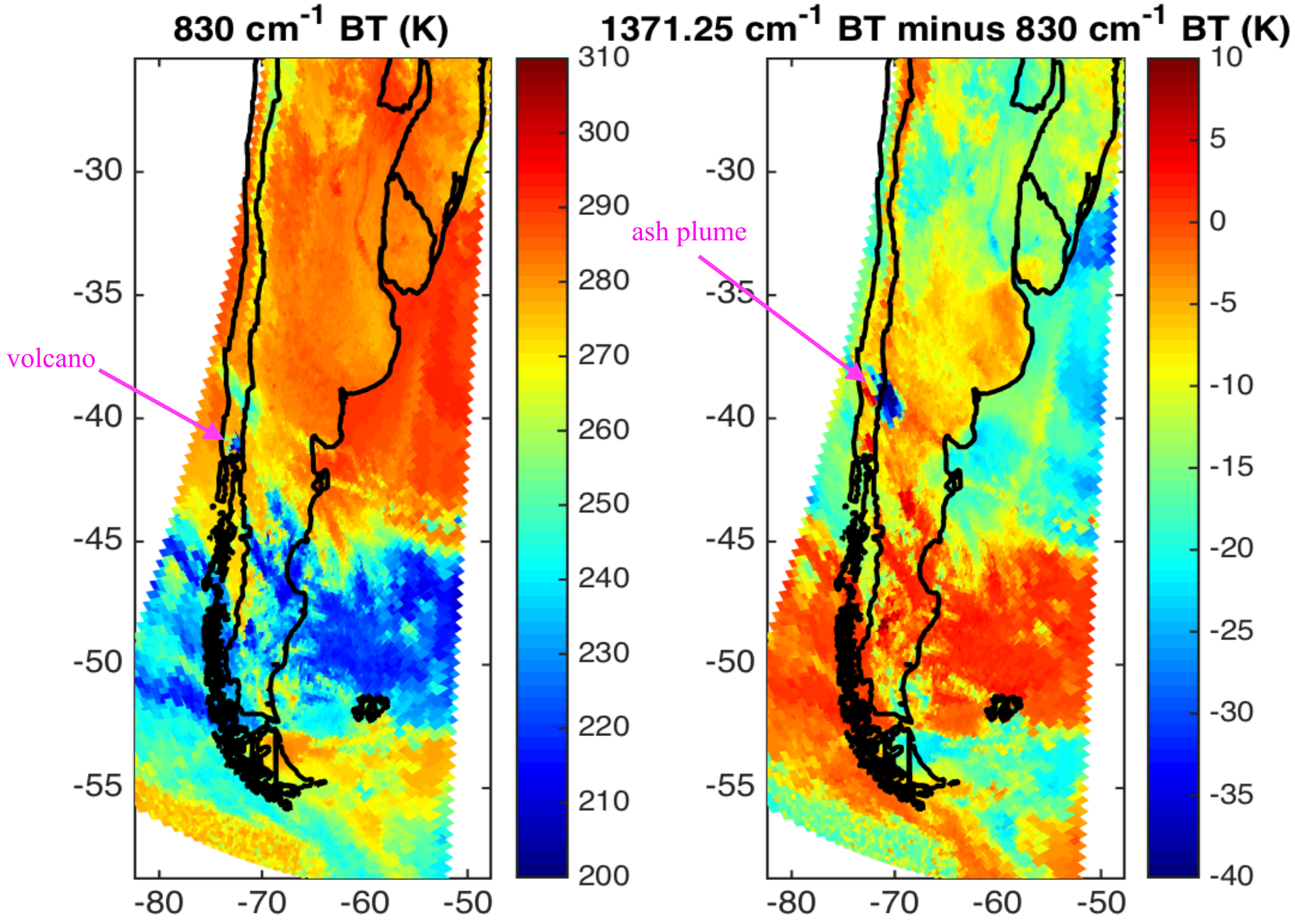


Example spectra of plume north of eruption, ash and SO_2

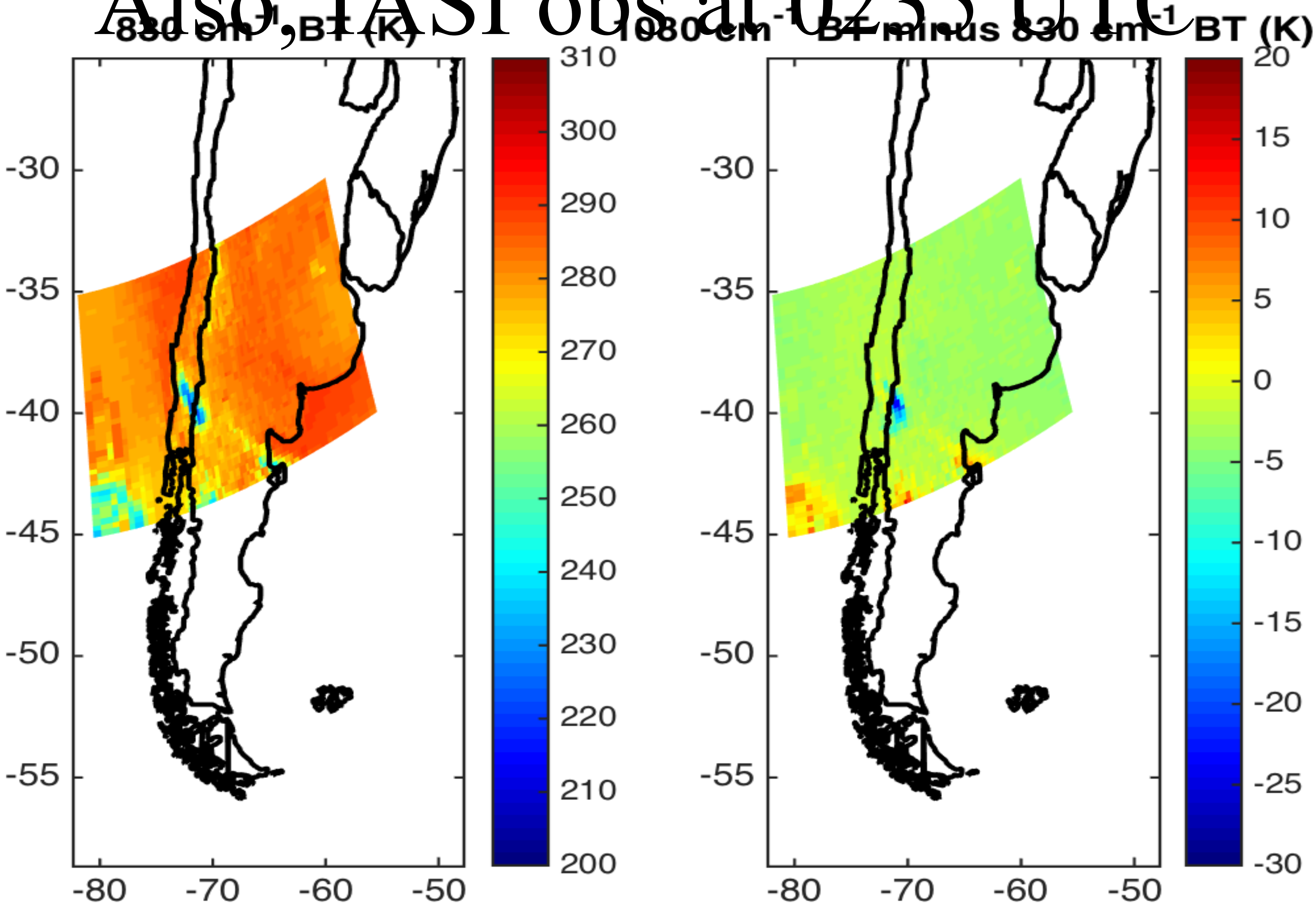



830 cm^{-1} BT (K)
1080 cm^{-1} BT minus 830 cm^{-1} BT (K)
-30
-35
-40
-45
-50
-55
-80
-70
-60
-50
310
300
290
280
270
260
250
240
230
220
210
200
20
15
10
5
0
-5
-10
-15
-20
-25
-30

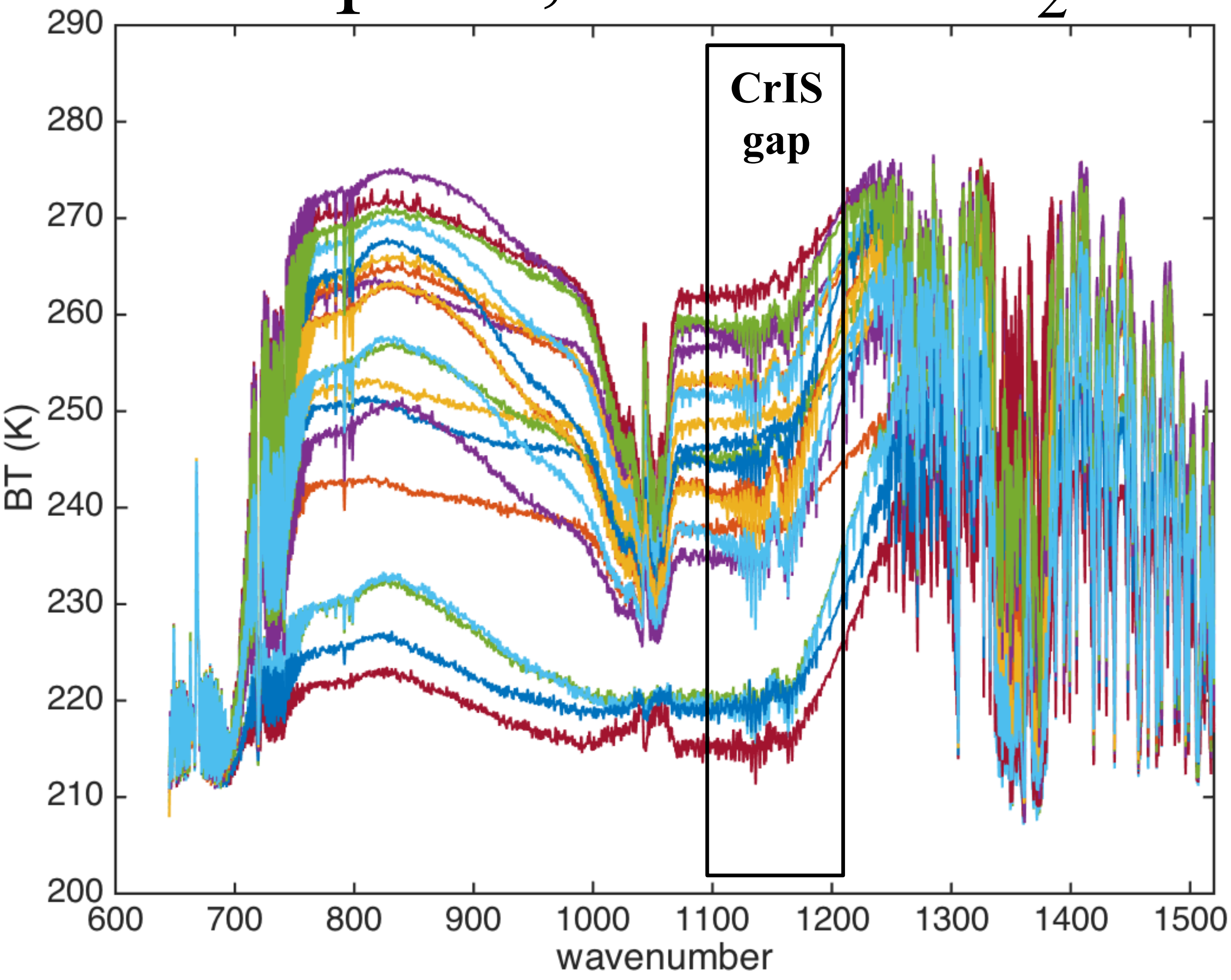

830 cm^{-1} BT (K)
1080 cm^{-1} BT minus 830 cm^{-1} BT (K)
volcano
ash plume
-30
-35
-40
-45
-50
-55
-80
-70
-60
-50
310
300
290
280
270
260
250
240
230
220
210
200
20
15
10
5
0
-5
-10
-15
-20
-25
-30

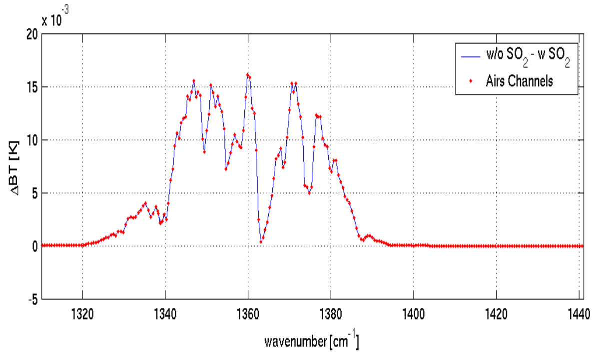

830 cm^{-1} BT (K)
1371.25 cm^{-1} BT minus 830 cm^{-1} BT (K)
volcano
ash plume
-30
-35
-40
-45
-50
-55
-80
-70
-60
-50
310
300
290
280
270
260
250
240
230
220
210
200
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40

Also, IASI obs at 0235 UTC

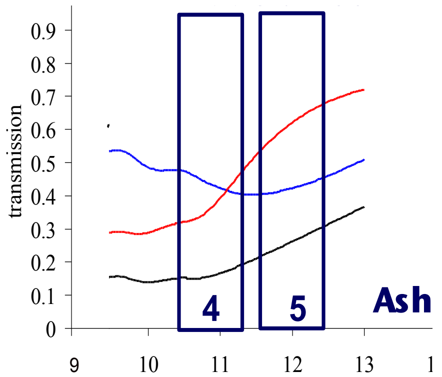


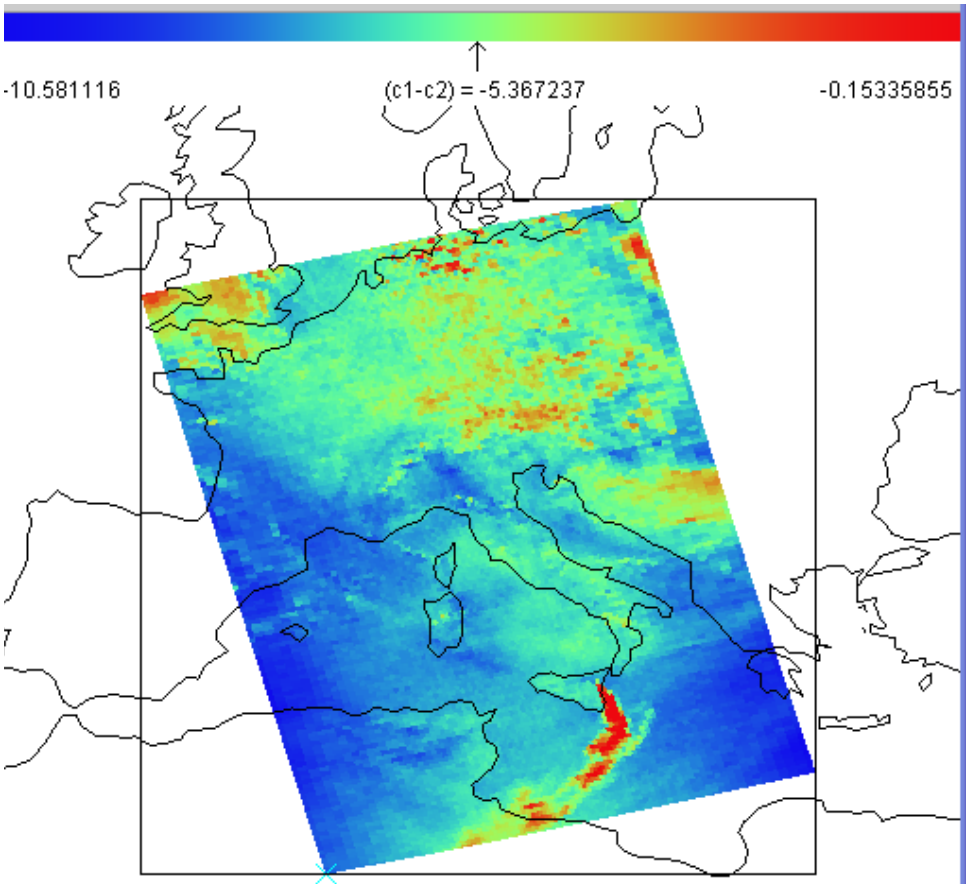
Example spectra of plume north of eruption, ash and SO_2



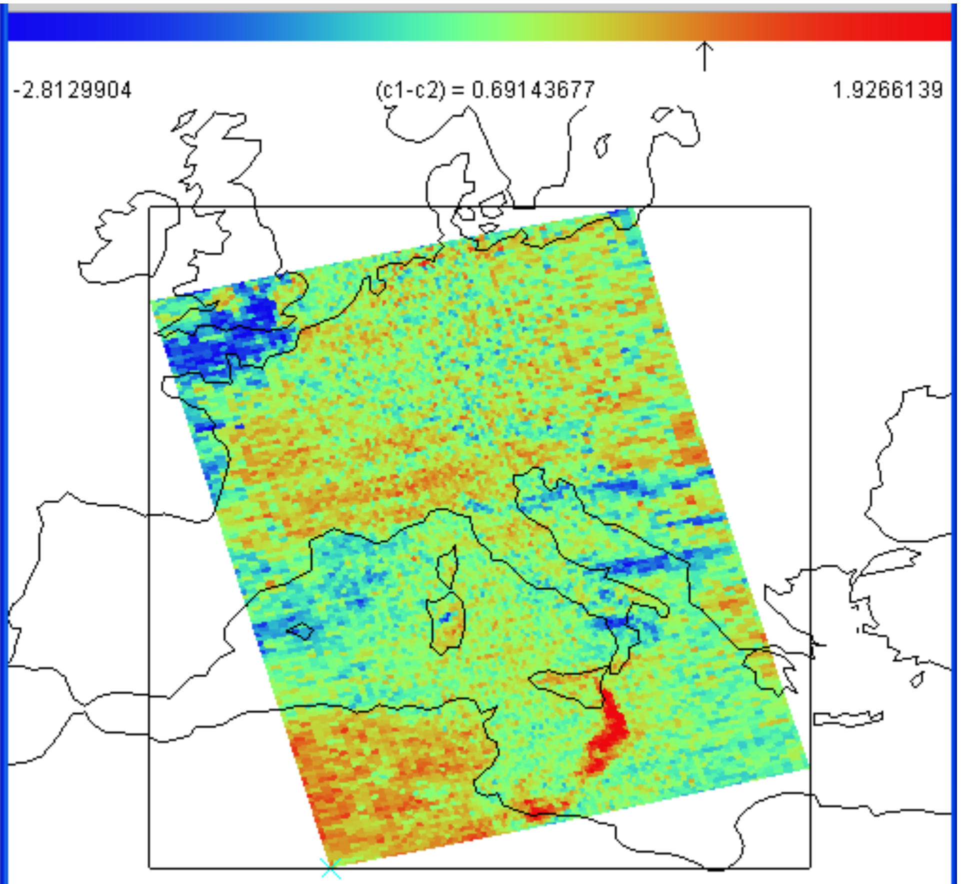


Mt Etna volcanic plume
SO2 (left) from 1284-1345
Ash (right) from 832-900





c1:1284.348, c2:1344.799



c1: 832.810, c2: 899.965