In situ radiative transfer in planetary atmospheres

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Objective of the course

- Introduction : context for in situ instruments in planetary atmospheres (Earth excluded)
- Overview of the mathematical context of radiative transfer in planetary atmospheres in a simplified frame
- Relations between science objectives and physical observables for both remote sensing / in situ experiments
- Study case on Titan for some Cassini/Huygens instruments

Sounding planetary atmospheres with photons

Photons as sounders of physical properties:

Which physical parameters can be measured (in gas, hazes, clouds)?

- Composition
- Temperature
- Pressure
- Structure (variations with heights)
- Winds
- ……

Observables :

- Energy of the radiation field
- Angular variations
- Spectral variations

Spectral variations : 1) Molecular spectroscopy

Variations with wavelength give access to pristine atmospheric parameters through molecular bands

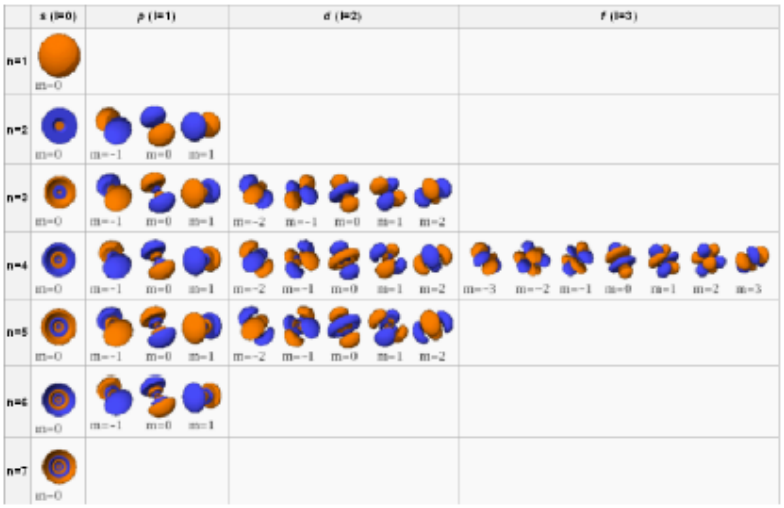
- Electronic transition (UV, vis.)
- Vibrational (ro-vibrational) transition (IR)
- Rotational transition (submm)

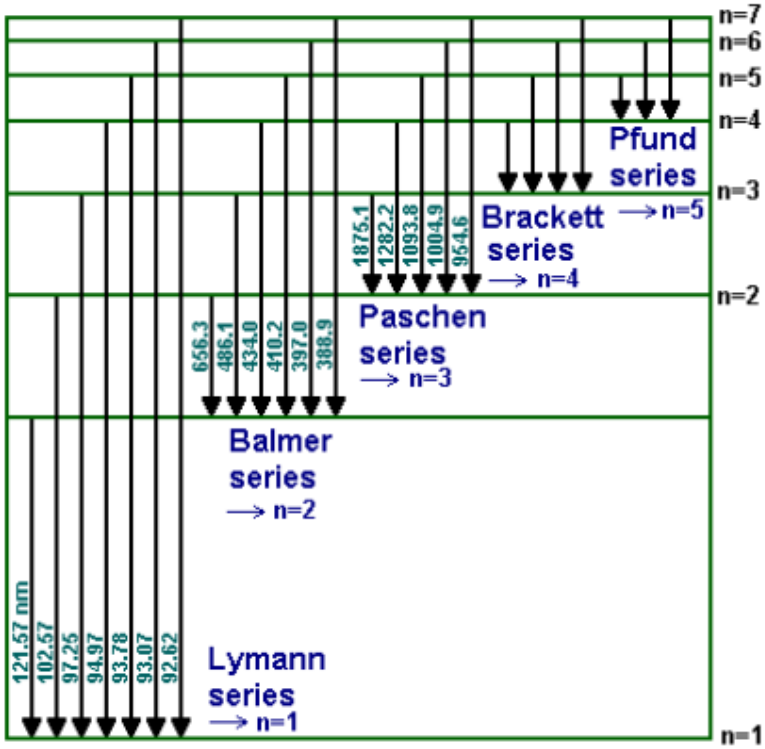
Electronic transitions

Standard case: the hydrogen atoms

Transitions between electronic orbitals (quantum number n)

Domain : UV - visible





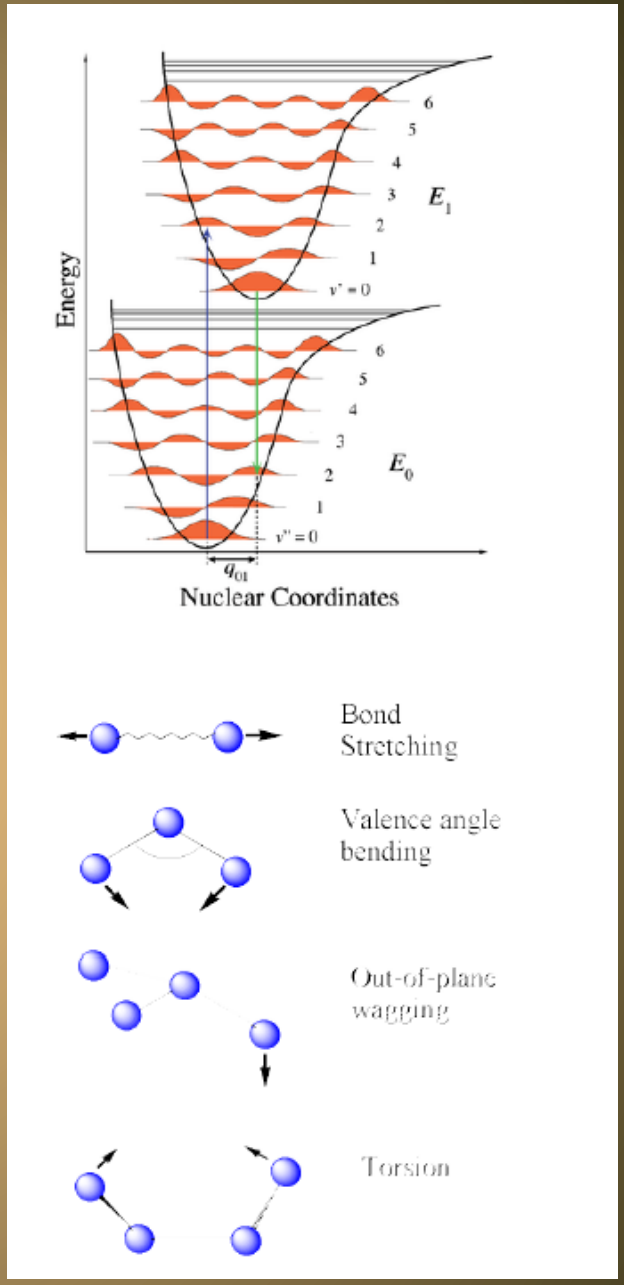
Vibrational transitions

Quantification of vibrations in molecules

Diatomic : 1 vib. Mode

Polyatomic : many different modes

Domain : infrared

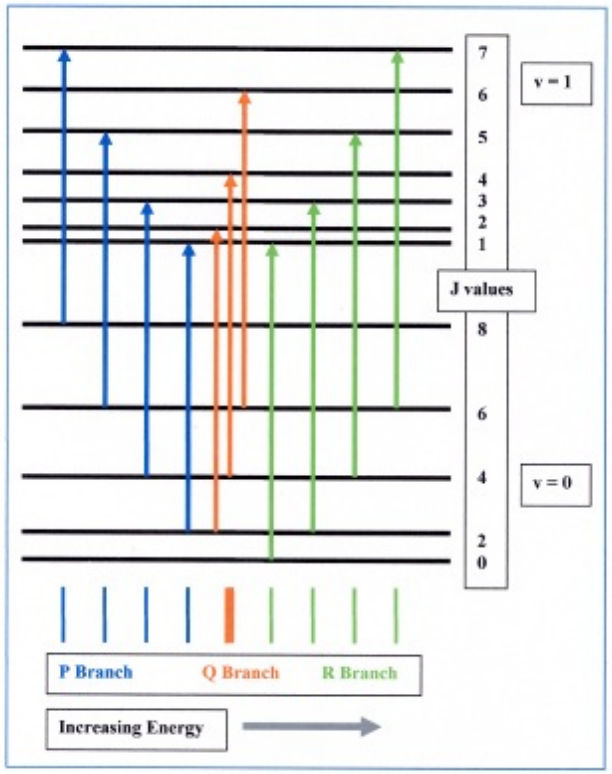


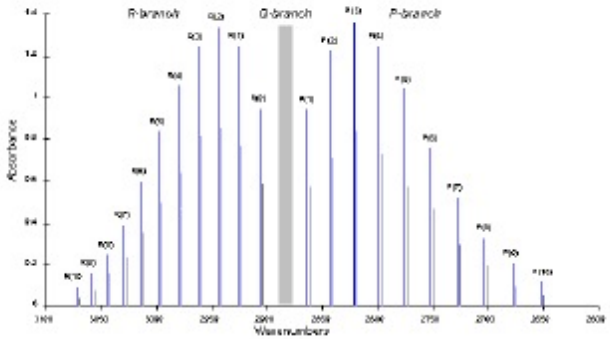
Rotational / ro-vibrational transitions

Quantification of rotation : domain : millimeter wave

Combination of vibration-rotation = main domain in infrared

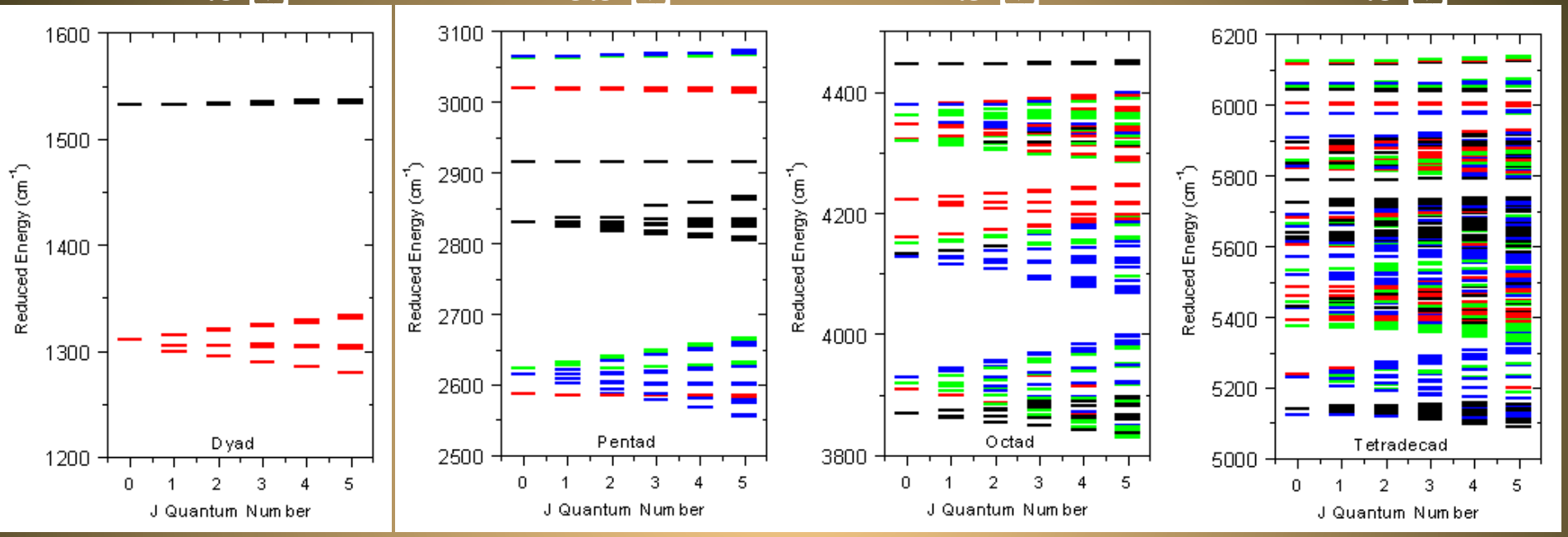
Can be very complex…





CH_4 : vibration/rotation bands

7.8 m | 3.3 m | 2.3 m | 1.8 m



Dyad	Pentad	Octad	Tetradecad
2 vibrational states	5 vibrational states	8 vibrational states	14 vibrational states
2 sublevels	9 sublevels	20 sublevels	60 sublevels

Wenger and Champion, JQSRT, 1998

Spectral and angular variations: 2) Scattering

Modulation of the planetary spectrum through scattering give access to haze/cloud properties

- Particles absorb and diffuse light anisotropically => angular variations to determine shape and size distribution of particles
- Spectral variations => composition constraints

Radiative transfer

Consider the radiation through energetic parameters : approximation radiation field reduced to energy propagation:

Quantum effects, interference effects are contained in the spectral parameters, but continuity equations themselves are restricted to classic parameters

Polarization effects are not discussed here, but can be taken into account through fully polarized energetic quantities (Stokes parameters)

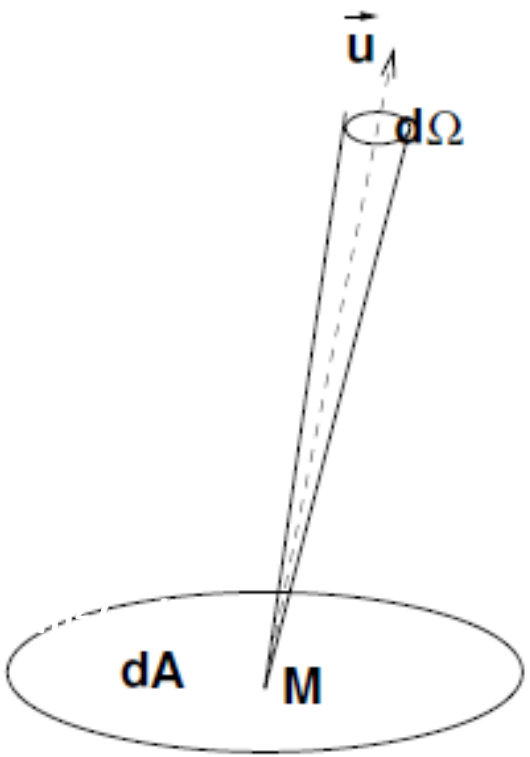
Definitions

Definition I_ν

Rate of radiative transfer energy around a given frequency ν (per frequency unit), per unit of **emitting** surface dA along a given direction u (per **receiving** solid angle around u).

$$I_\nu(M,u) = \frac{d^3P}{dA\,d\nu\,d\Omega}$$

- Mathematical formalization of a light beam.
- In empty space, I_ν is conservative along the optical path.
- If I_ν does not vary with u, the radiation is said to be isotropic.
- I_ν can also be understood as per unit of **receiving** surface and per solid angle filled by the source.



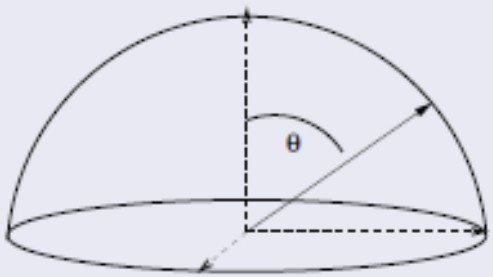
- Note It can also be defined with respect to wavelength (I_λ) or wavenumber (I_σ)

Spectral flux

Definition

First moment of I_ν with respect to the direction.

$$F_\nu = \iint_{4\pi\ \mathrm{sr}} I_\nu \cos\theta \, d\Omega$$



- in $\mathrm{W/m^2/Hz}$ (in SI)
- Actually observable quantity
- Conveys information about energy transport: if I_ν is isotropic, there is not net flux ($F_\nu = 0$).

Note F_ν is sometimes divided into upward and downward fluxes, in which case the integration should be performed only over the relevant hemisphere.

Sources and sinks in radiative transfer equations

Absorption The radiative energy is transferred to the matter.

Scattering Matter locally disturbs the electromagnetic field, which results (far away) in a spatial deviation of the optical path.

Emission Matter loses energy to the electromagnetic field, whether in a spontaneous event or induced by the radiation field.

Remarks

- Absorption + Scattering = Extinction
- Emission processes are often divided into:

  Thermal Emission Provided enough interaction events between matter and radiation, both end up sharing the same temperature T: Black body model

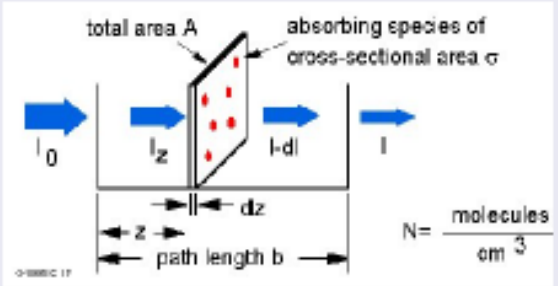
  Non-Thermal Emission
  - Fluorescence (decay of electronic or molecular excited states)
  - Acceleration of charged particles: *Bremsstrahlung*, cyclotron, synchrotron

The radiative transfer equation

Beer-Lambert's Law

- $I_\nu(s)$: spectral radiance at s abscissa.
- $I_\nu(s+ds) = I_\nu(s)\,[1 - \sigma_\nu n(s)\,ds]$ with $n(s)$ local density of extinctors and σ_ν the extinctors' cross-section.

- Yields
  $I_\nu(s) = I_\nu(0)\exp\left(-\int_0^s \sigma_\nu n(s)\,ds\right)$.
- If $n(s) = n$ is constant,
  $I_\nu(s) = I_\nu(0)\exp\left(-n\sigma_\nu s\right)$



Optical depth τ_ν

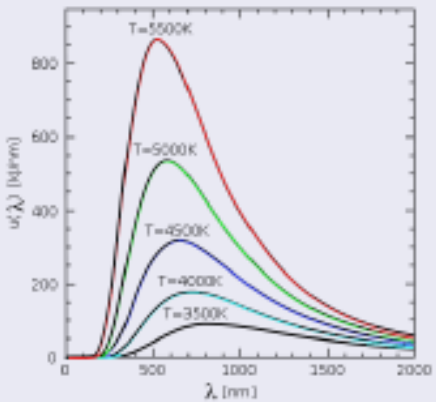
- $d\tau_\nu = n(s)\sigma_\nu\,ds$
  - Dimensionless quantity. Natural coordinate for radiative transfer
    - $\tau \gg 1$: *optically thick* medium
    - $\tau \ll 1$: *optically thin* medium
- Beer-Lambert's Equation becomes $dI_\nu = -I_\nu\,d\tau_\nu$
  - In case of emission, it becomes $dI_\nu = -I_\nu + S_\nu$ with S_ν the *source* term.

Thermal equilibrium

Planck's Law (Black Body Radiation)

$$I_\nu(T) = B_\nu(T) = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1}$$

$$I_\lambda(T) = B_\nu(T) = \left(\frac{2hc^2}{\lambda^5}\right)\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1}$$



Wien's Law I_λ reaches its maximum at $\lambda_m\ [\mu\text{m}] \approx \frac{3000}{T\ [\text{K}]}$

Nesting $\forall\lambda, T_1 > T_2 \Rightarrow I_\lambda(T_1) > I_\lambda(T_2)$

Stefan's Law $F = \int F_\nu\, d\nu = \sigma T^4$ for a surface emitting in an hemisphere.

Kirchhoff's Law (only valid at local thermodynamical equilibrium)

Absorbance = Emissivity

Absorbance A_ν fraction of incoming radiation (at a frequency ν) absorbed by an object. $A_\nu = 1$ at all frequencies for a black body.

Emissivity ε_ν ratio between the thermal emission of an object (at a frequency ν) and the black body emission for the same frequency and temperature.

Physical parameters in scattering

Definitions

Single scattering albedo ϖ_0 Refers to the proportion of extinction due to scattering (vs absorption)

Phase function $p\left((\theta,\varphi) \rightarrow (\theta',\varphi')\right)$ Angular probability density function between incoming and scattered beams.

- Often normalized so that $\iint p(\theta,\varphi,\theta',\varphi')\, d\Omega' = 1$.
- It is often assumed that $p = p(\Theta)$ with Θ the scattering angle.
- p can differ for various polarization states of the incident beam.

Asymmetry parameter g First moment of p with respect to Θ.

- Isotropic scattering ($p = 1/4\pi\,\mathrm{sr}^{-1}$) implies $g = 0$. **The converse is not true!** (e.g. Rayleigh scattering).
- $g = 1$ is equivalent with full forward scattering (i.e. no scattering at all!). $g = -1$ with full backwards scattering.

Scattering regimes

Common scattering regimes in planetary atmospheres

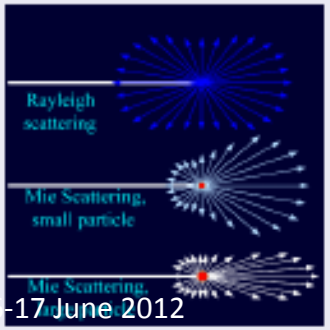
Rayleigh Scattering occurs when scattering particles are much smaller than radiation wavelength.

- Cross-section proportionnal to λ^{-4}: matters most in the UV/Visible, can often be neglected in the thermal IR.
- Polarizing scattering

Optical Refraction occurs when particles are large compared to the radiation wavelength. Standard Snell-Descartes laws for a medium of a given refractive index.

Mie Theory occurs with spherical scattering particles (e.g. liquid droplets)

- Vanishes into Rayleigh regime from small particles, and optical regime for big particles.
- Polarizing scattering, complex phase functions. Depends on the (complex) refractive index of the material.



Usual approximations

Grey approximation

- No dependency on ν.
- Only valid for limited spectral bands, with thermal ($\lambda > 5\,\mu$m) and solar components ($\lambda < 5\,\mu$m) usually considered separately.

Plane-parallel approximation

- Standard geometry for atmospheres much thinner than planetary radius and not too horizontal line-of-sights.
- Angles defined with respect to a common vertical (zenith-nadir) z axis. $0 < \theta < \pi$: zenithal angle, $0 < \varphi < 2\pi$: azimuth. Standard notation $\mu = \cos\theta$
- Vertical coordinate is the optical depth along the vertical direction from zenith to nadir. Horizontally invariant.

Two-stream approximation

- $I_\nu = I^+$ for $\mu > 0$ and $I_\nu = I^-$ for $\mu < 0$. Direct beam intensity I_0 is computed separately.
- Enables explicit solving of the radiative transfer equation.
- Accurate enough for flux computation, not for intensities!

Planetary radiative transfer equation

Radiative transfer equation (plane-parallel)

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$

with

$$S_\nu(\tau;\mu,\varphi) = (1-\varpi_0)\, B_\nu\,[T(\tau)] + \varpi_0 \int_0^{2\pi} \int_{-1}^{1} I_\nu(\tau;\mu',\varphi') P(\mu',\varphi';\mu,\varphi)\, d\mu'\, d\varphi'$$

- No analytic solution in the general case...

Radiative Transfer equations (two-stream, no thermal source)

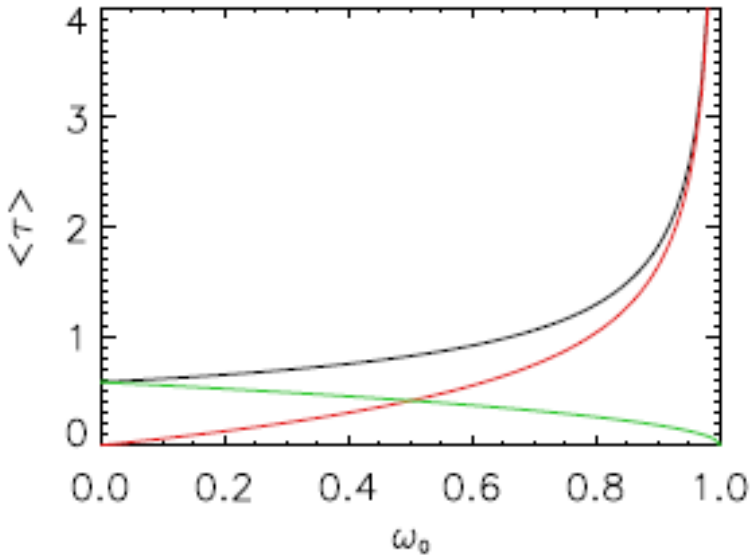
$$\begin{cases} \dfrac{1}{\sqrt{3}} \dfrac{dI^+}{d\tau} = I^+ - \dfrac{\varpi_0}{2}\left[(1+g)I^+ + (1-g)I^-\right] - \dfrac{\varpi_0}{4\pi} I_0 e^{-\tau/\mu_0} \\ -\dfrac{1}{\sqrt{3}} \dfrac{dI^-}{d\tau} = I^- - \dfrac{\varpi_0}{2}\left[(1-g)I^+ + (1+g)I^-\right] - \dfrac{\varpi_0}{4\pi} I_0 e^{-\tau/\mu_0} \end{cases}$$

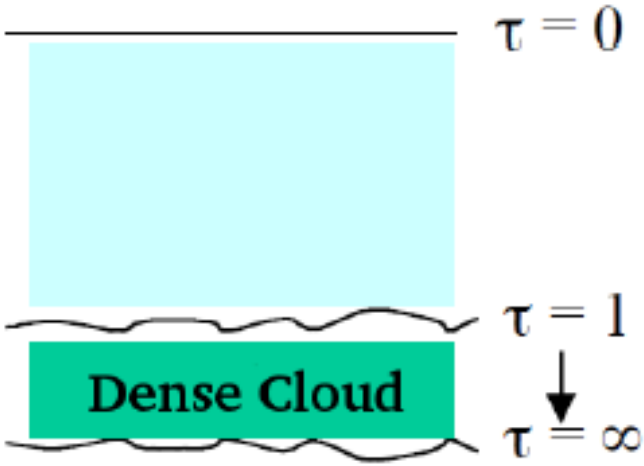
Penetration depth of sunlight

- Penetration depth of reflected sunlight
  - $I^+(\tau)/I^+(0) = e^{-\sqrt{3(1-\varpi_0)}\tau}$: average optical depth $\bar{\tau} = 1/\sqrt{3(1-\varpi_0)}$
  - at this depth, $\bar{\tau}_{\text{scat}} = \varpi_0\bar{\tau} = \varpi_0/\sqrt{3(1-\varpi_0)}$ and $\bar{\tau}_{\text{abs}} = (1-\varpi_0)\bar{\tau} = \sqrt{(1-\varpi_0)/3}$.
  - A lower ϖ_0 implies a shallower sounding.
- Possible uses

  Known absorption profile measuring optical properties of scattering particles (ϖ_0, particle density, size, etc.)

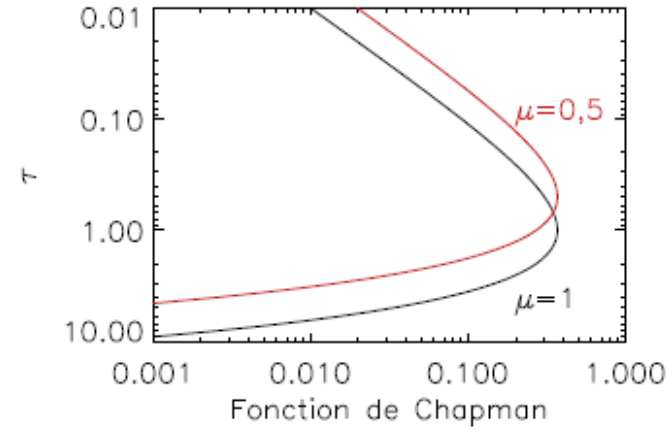
  Known scattering profile measuring the absorption vertical profile.





Weighting function for RT in thermal regime

- Definition
  - $I_\nu(0) = \int_0^\infty WF(p) B_\nu\left[T(p)\right] d\ln p$
  - $WF(p) = e^{-\tau/\mu} \frac{d(\tau/\mu)}{d\ln p} = \frac{dT_\nu}{d\ln p}$ with the transmission factor $T_\nu = \exp\left(-\tau_\nu/\mu\right)$
  - Contribution Function CF defined by $CF(p) = WF(p) B_\nu\left[T(p)\right]$
- Chapman Function
  - **Hypotheses**
    - Uniformly mixed absorber ;
    - Cross-section σ_ν uniform ;
    - Isothermal hydrostatic atmosphere.
  - $d\tau_\nu = -k_\nu\, dz = -\sigma_\nu n(z)\, dz = \frac{\sigma_\nu H}{kT} dp$
  - $WF(p) = \frac{\tau_\nu}{\mu} e^{\tau_\nu/\mu} = \frac{\sigma_\nu H p}{\mu k T} e^{-\sigma_\nu H p/\mu k T}$
  - $WF(\ln p)$ **Chapman Function**
    - peaks near $\tau \sim 1$
    - Typical height $\Delta z \sim H$



Summary

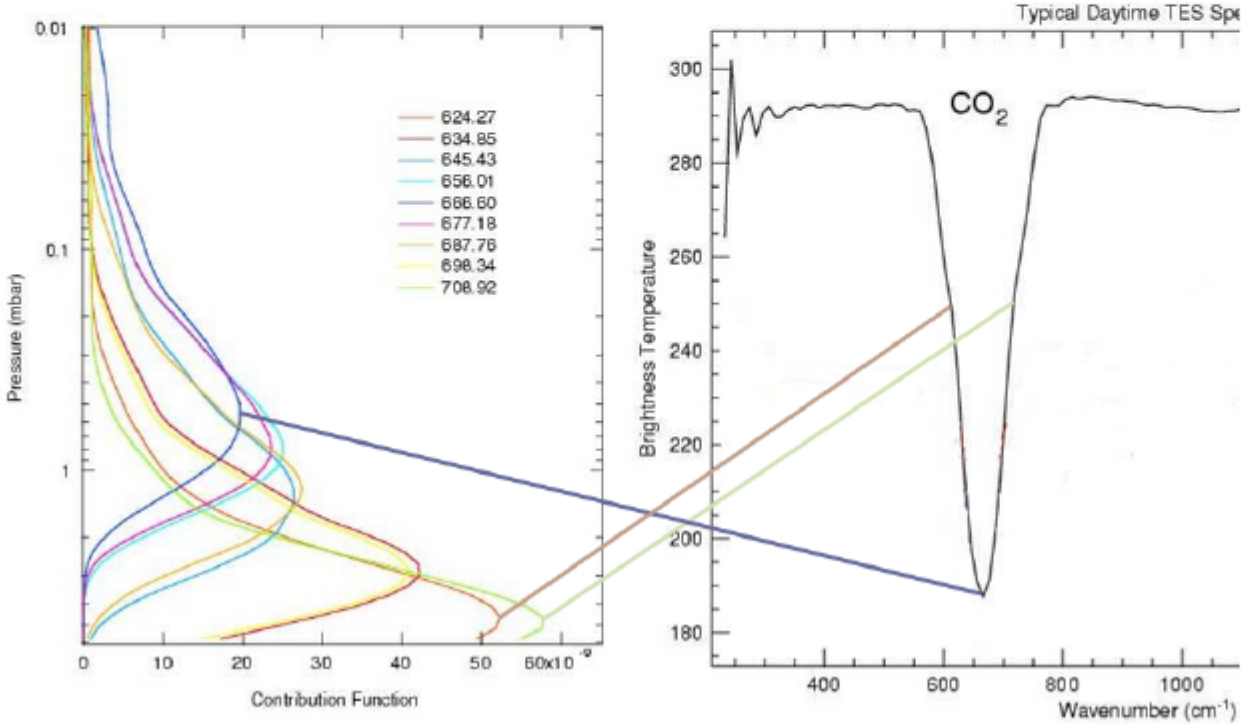
Thermal emission comes mainly from layers centered on $\tau = \mu$

Warning

If non-isothermal, $CF(p)$ may differ a lot from $WF(p)$!

Thermal sounding

- Principle
  - A **uniformly mixed** IR-absorbing species is used (eg: CO_2 on Earth) and whose σ_ν is known.
  - Computation of each $WF(p)$ with varying ν, peaking at p_ν^0
  - $I_\nu(0) \simeq B_\nu \left[T(p_\nu^0)\right]$
  - $T(p)$ is then retrieved on a certain p range



Composition sounding

- Principle
  - Species of unknown vertical distribution but known σ_ν.
  - $T(p)$ profile known.
  - Brightness temperature T_ν^B yields sounded level p_ν^0 : $T_\nu^B = T\left(p_\nu^0\right)$
  - **Column density** between p_ν^0 and observer knowing σ_ν.
  - Inversion is possible above the minimum of p^0 with respect to ν.
  - **Difficulties** : several species may contribute to IR absorption, scattering by aerosols, sufficient spectral resolution required
- Lines seen in emission or absorption

s Curvilinear abscissa oriented towards observer

Emission if $dT/ds > 0$

Absorption if $dT/ds < 0$

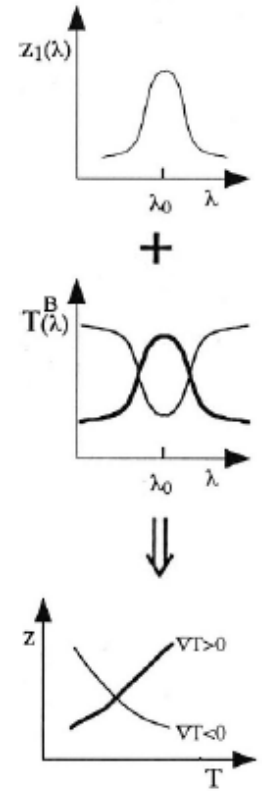


Figure: Line profiles as seen from above.

In situ vs remote comparison

Advantages

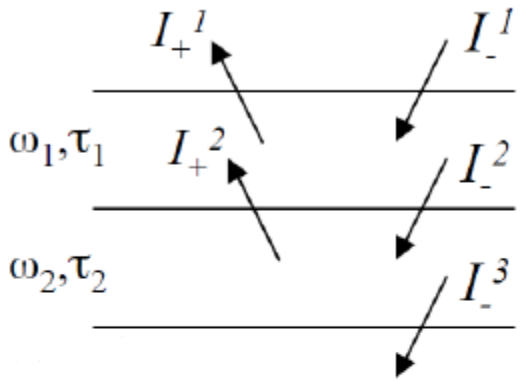
- Access to $\tau \gg 1$ (as defined downward from space) for an observer deep into the atmosphere
- Valuable scientific information from 4π sr instead of $< 2\pi$ sr.
- A vertically mobile instrument will help in solving amibguities usually encountered with remote observations (relative contribution of IR absorbing various species) since the probed layers will move along.

Drawbacks

- Engineering constraints more challenging in an atmosphere: weight, size, cost, power, thermal design, etc.
- Therefore, usually lower spatial and spectral resolution than achievable from space.
- Single use instruments most of the time, except on a landing station (which do not move vertically). Limited horizontal coverage.

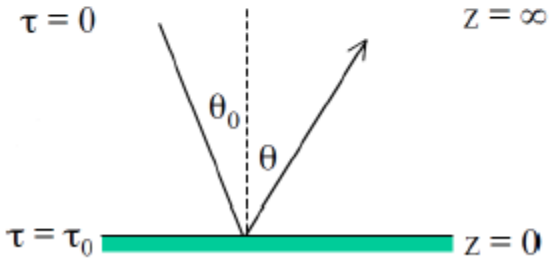
Inhomogeneous atmospheres

- **Layering** into homogeneous layers whose reflexion R_i transmission T_i coefficients are computed
  - In the semi-infinite case, $T = 0$ and $R = \Lambda$
- **Adding method**: layers are then iteratively combined in pairs



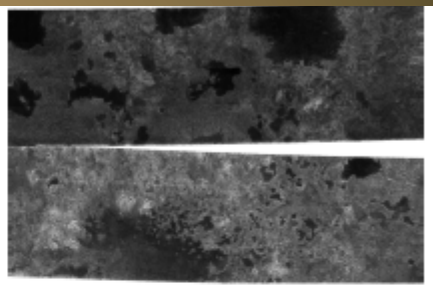
$$R_{1+2} = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \; ; \; T_{1+2} = \frac{T_1 T_2}{1 - R_1 R_2}$$

- Cloud/reflecting surface+ non-scattering atmosphere ($\tau_{\text{scat}} = \varpi\tau \ll 1$)
  - Then: $I_\nu(0) = R(\mu,\varphi;\mu_0,\varphi_0) F_0 e^{-\tau_\nu\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)}$
  - Measuring $\tau_\nu = \int_0^\infty \sigma_\nu n(z)\, dz =$ $\sum_i \sigma_\nu^i \int_0^\infty n_i(z)\, dz = \sum_i \sigma_\nu^i a_i$
  - **Yeilding column density a_i of absorber i.**

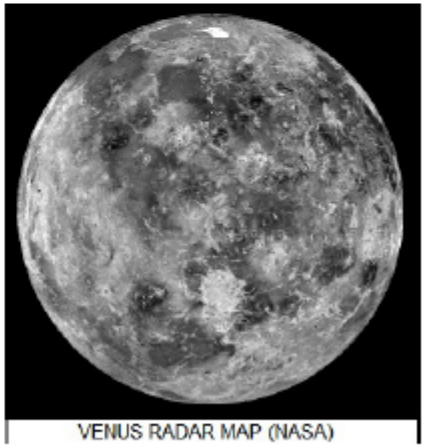


Active sounding : radar, lidar

- Principle
  - Study of reflected/scattered radiation whose emission was controlled by the observer.
    - Access to round-trip duration: altimetry.
- Use in planetary science
  - Radar Study of surface properties: rugosity, state of matter (liquid vs. solid)
  - Lidar Optical analog: properties of scattering particles (size, shape, composition, etc.) and/or gaseous scattering (Rayleigh) or absorption.



Titan *(Cassini)*



Venus *(Magellan)*

In situ vs remote

Advantages

- Mostly similar to the ones discussed previously. vertical profiling possible during descent whereas remote sounding only yields column densities.
- Lidars much more useful (radio opacities substantially lower than visible/UV opacities in planetary atmospheres)

Drawbacks

- Mostly similar to the ones discussed previously, except that lidars on landing stations have a potential high scientific value for a lifetime comparable with orbiter instruments.
- Lidars/radars only probe in a few selected wavelengths to be carefully chosen.

In situ : measurement from inside the radiative field

Main difference with remote sensing :

Access to forward measurement (I^+): direct measurement of extinction coefficient

Observations for different azimuts => access to phase function

Measurement along the descent => direct measurement of the radiative transfer equation elements (vertical resolution)

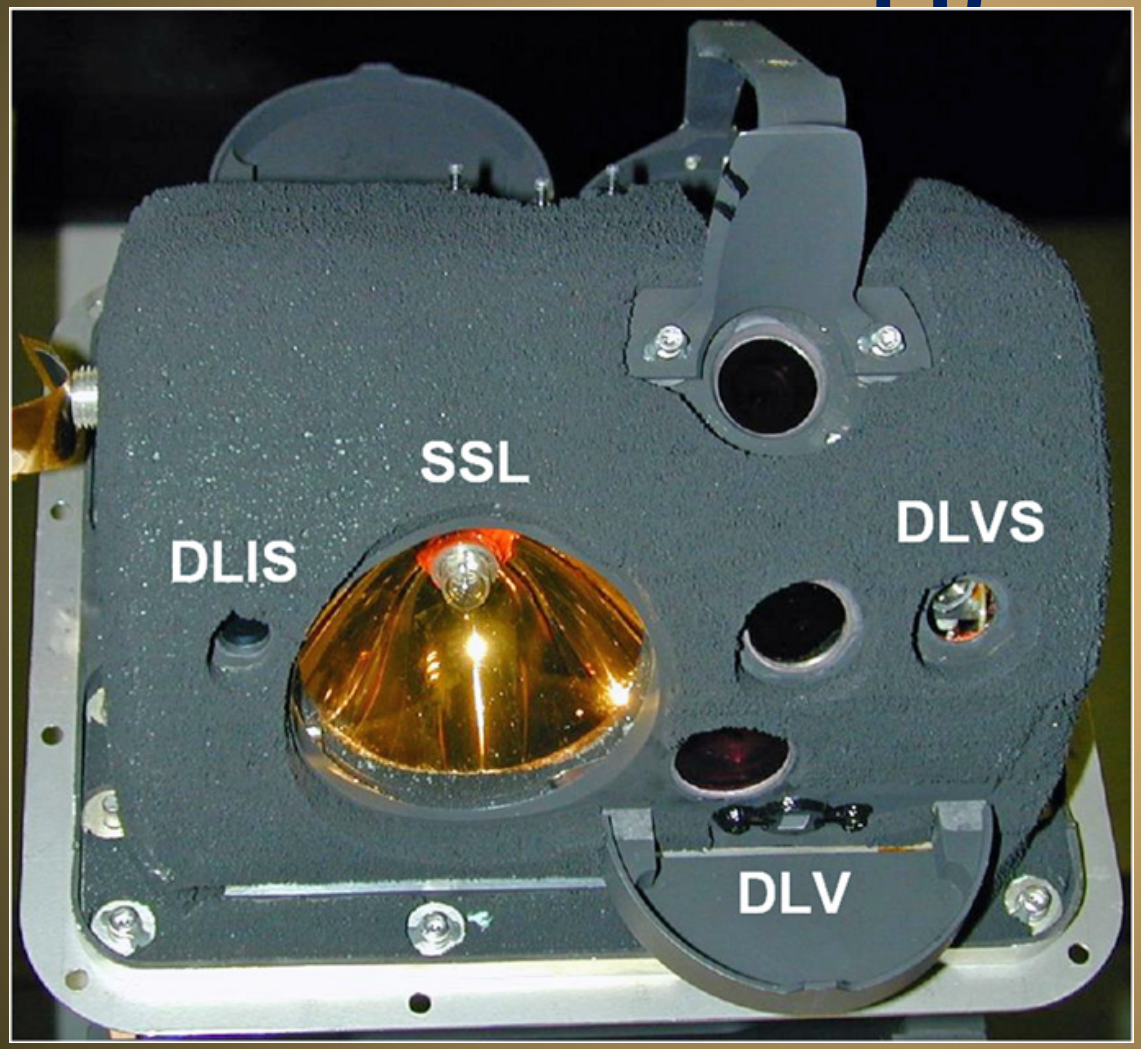
Study case : an application to Titan from the observations of DISR/Huygens

- Cassini/Huygens mission at Titan:

Provides a full descent observation with in situ instrument of radiative transfer from UV to IR (DISR on Huygens)

Provides comparison with remote sensing instrument (UVS and VIMS on Cassini)

Descent Imager/Spectral Radiometer (DISR on Huygens probe, M. Tomasko PI)



DLV Downward-LookingVioletPhotometer

DLVS Downward-LookingVisibleSpectrometer

DLIS Downward-LookingInfraredSpectrometer

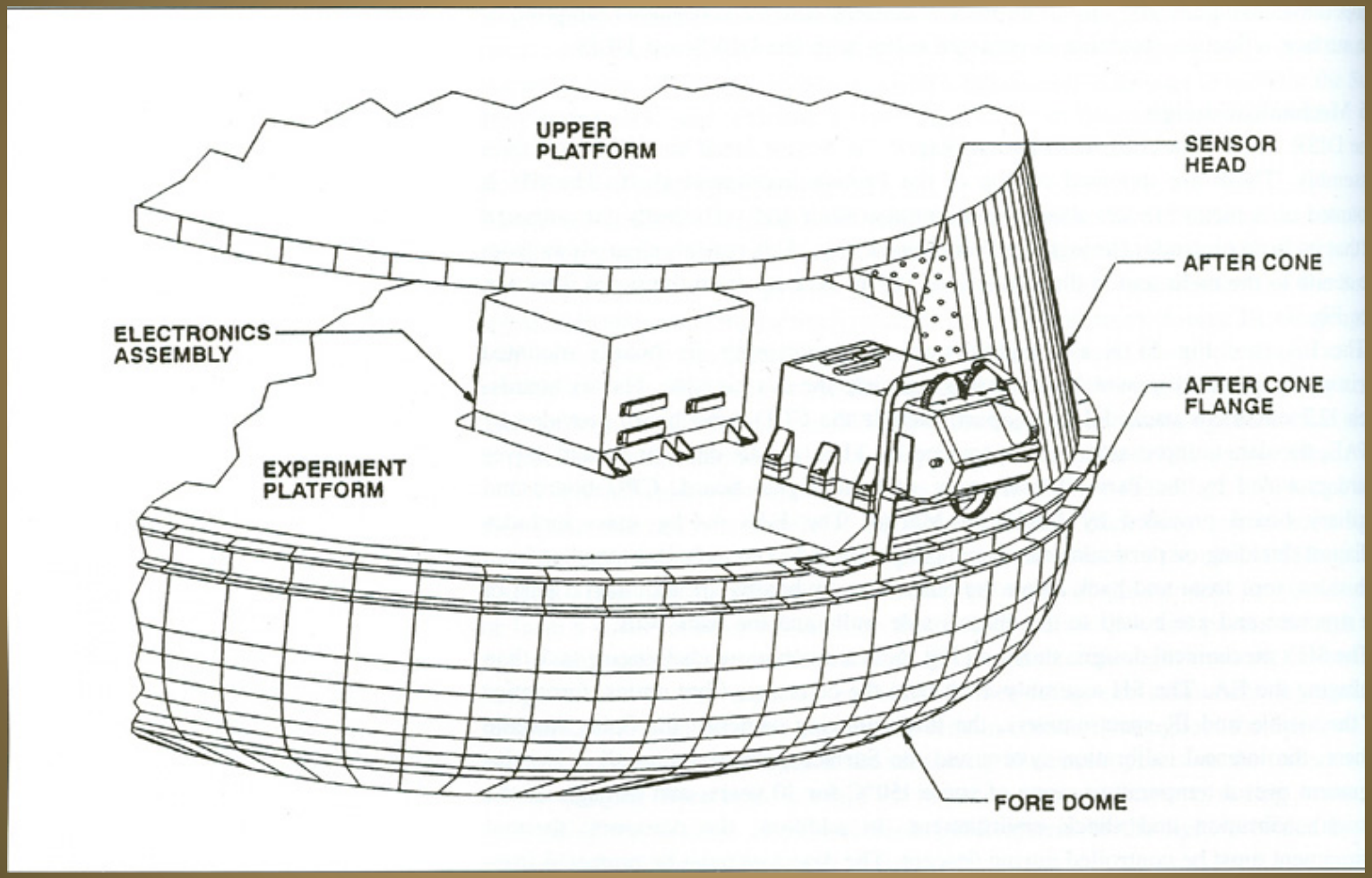
ULVS Upward-LookingVisibleSpectrometer

ULIS Upward-LookingInfraredSpectrometer

SSL SurfaceScienceLamp

VLNS VeryLowNearSurfaceMode

DISR implementation on Huygens



DISR upward looking instruments

Upward-Looking Instrument	Azimuth Range	Zenith Range	Spectral Range (nm)	Spectral Scale (per pixel)	Spatial Scale (per pixel)	Pixel Format
Violet Photometer (ULV)	170°	5°–88°	350–480	–	–	1
Visible Spectrometer (ULVS)	170°	5°–88°	480–960	2.4 nm	–	8 × 200
Infrared Spectrometer (ULIS)	170°	5°–88°	870–1700	6.3 nm	–	132
Solar Aureole (SA 1) Vertical Polarization	6°	25°–75°	500±25	–	1°	6 × 50
Solar Aureole (SA 2) Horizontal Polarization	6°	25°–75°	500±25	–	1°	6 × 50
Solar Aureole (SA 3) Vertical Polarization	6°	25°–75°	935±35	–	1°	6 × 50
Solar Aureole (SA 4) Horizontal Polarization	6°	25°–75°	935±35	–	1°	6 × 50
Sun Sensor (SS) (64° cone FOV)	64° cone	25°–75°	939±6	–	–	1

DISR downward looking instrument

Downward-Looking Instrument	Azimuth Range	Nadir Range	Spectral Range (nm)	Spectral Scale (per pixel)	Spatial Scale (per pixel)	Pixel Format
Violet Photometer (DLV)	170°	5°–88°	350–480	–	–	1
Visible Spectrometer (DLVS)	4°	10°–50°	480–960	2.4 nm	2°	20 × 200
Infrared Spectrometer (DLIS)	3°	15.5°–24.5°	870–1700	6.3 nm	–	132
High-Resolution Imager (HRI)	9.6°	6.5°–21.5°	660–1000	–	0.06°	160 × 256
Medium-Resolution Imager (MRI)	21.1°	15.75°–46.25°	660–1000	–	0.12°	176 × 256
Side-Looking Imager (SLI)	25.6°	45.2°–96°	660–1000	–	0.20°	128 × 256

DISR optical design

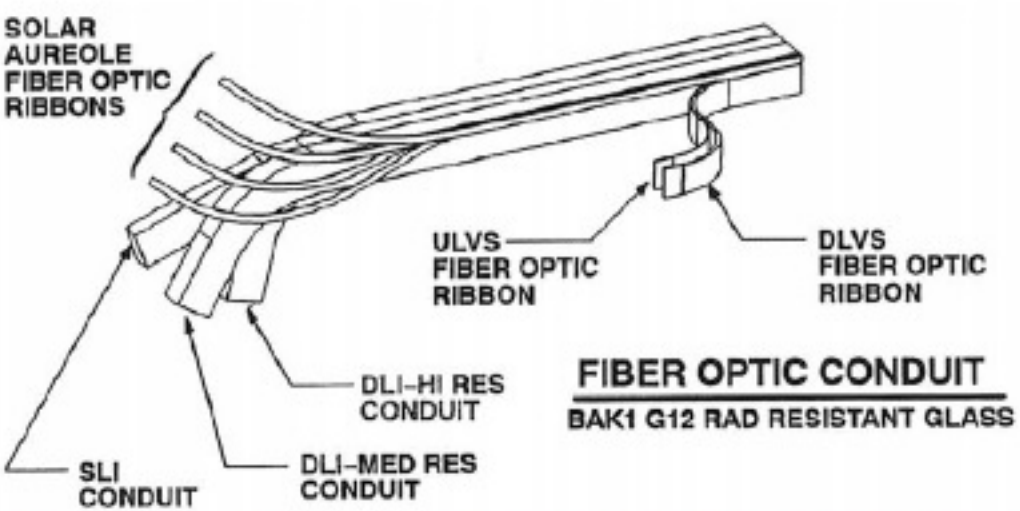


Figure 3. The layout of the fiber optic conduit which brings light from the three imagers, from the four-channel solar aureole camera, and from the upward-looking and downward-looking visible spectrometer to the face of the CCD detector (right hand end of the conduit).

Upward/downward vis. spectrometers

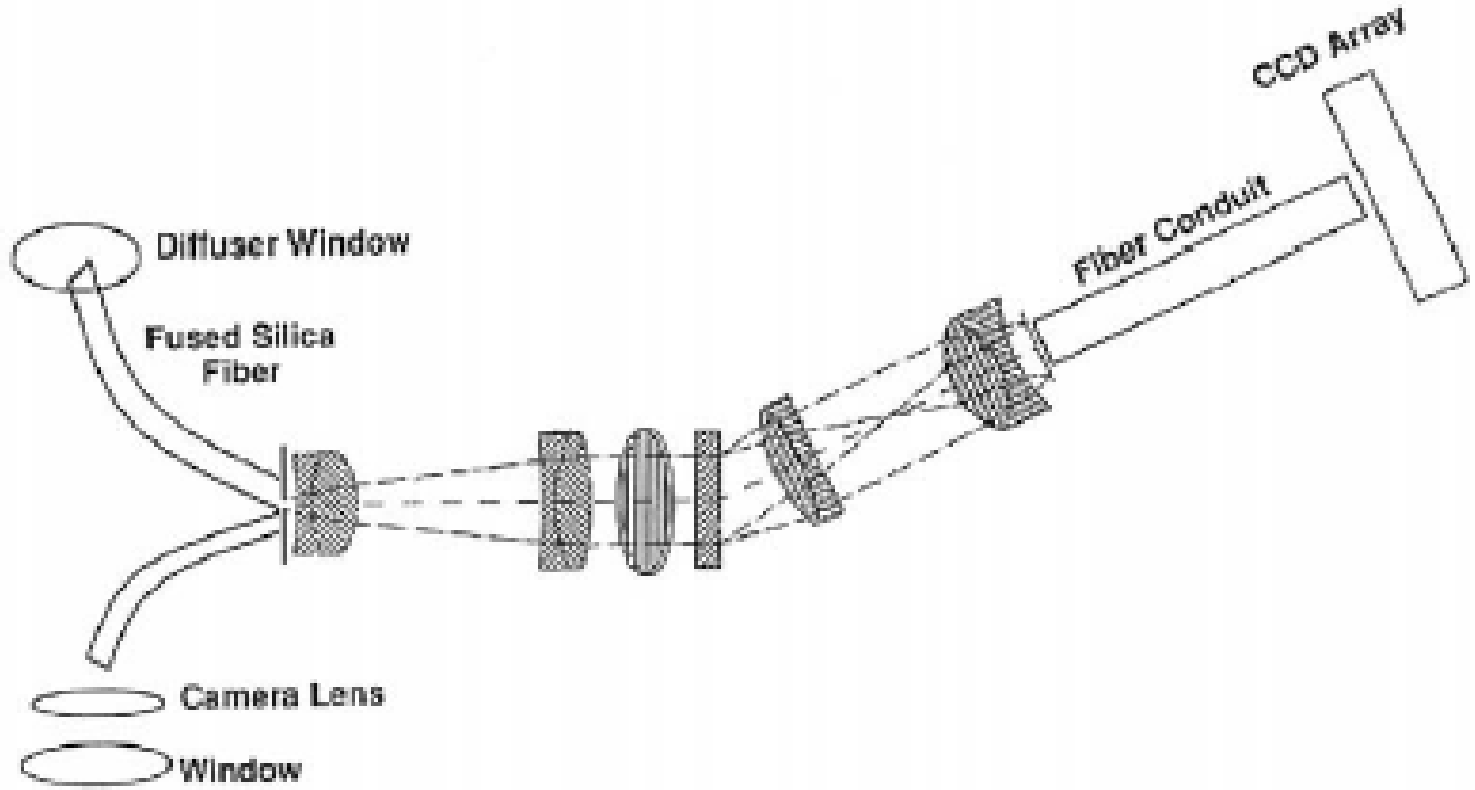


Figure 5. The schematic layout of the components of the upward and downward-looking visible spectrometer. The upward looking input views the bottom of a diffuser. The downward looking input uses a lens to project the entrance slit onto a $4^{\circ} \times 40^{\circ}$ region that extends from 10° to 50° nadir angle.

CCD surface repartition

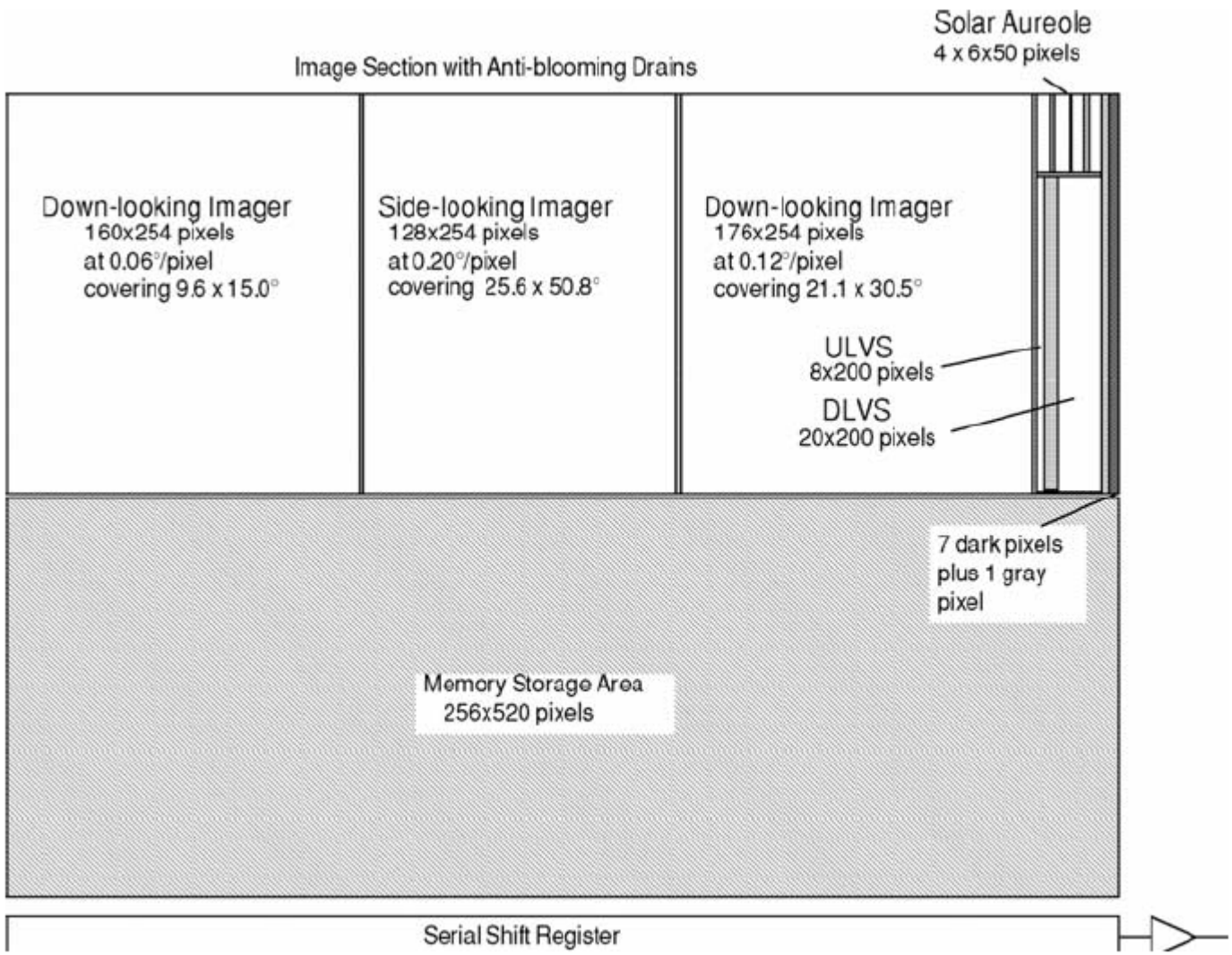
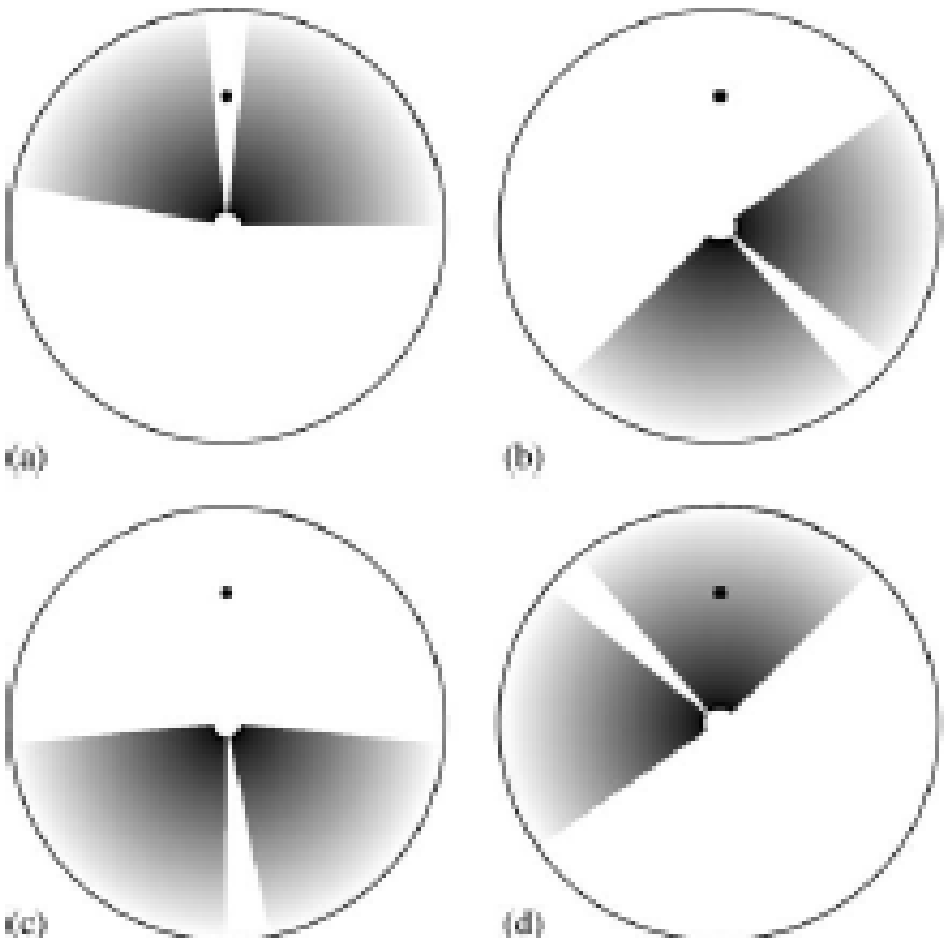


Figure 8. Layout of the face of the CCD detector.

Estimate of t from ULVS

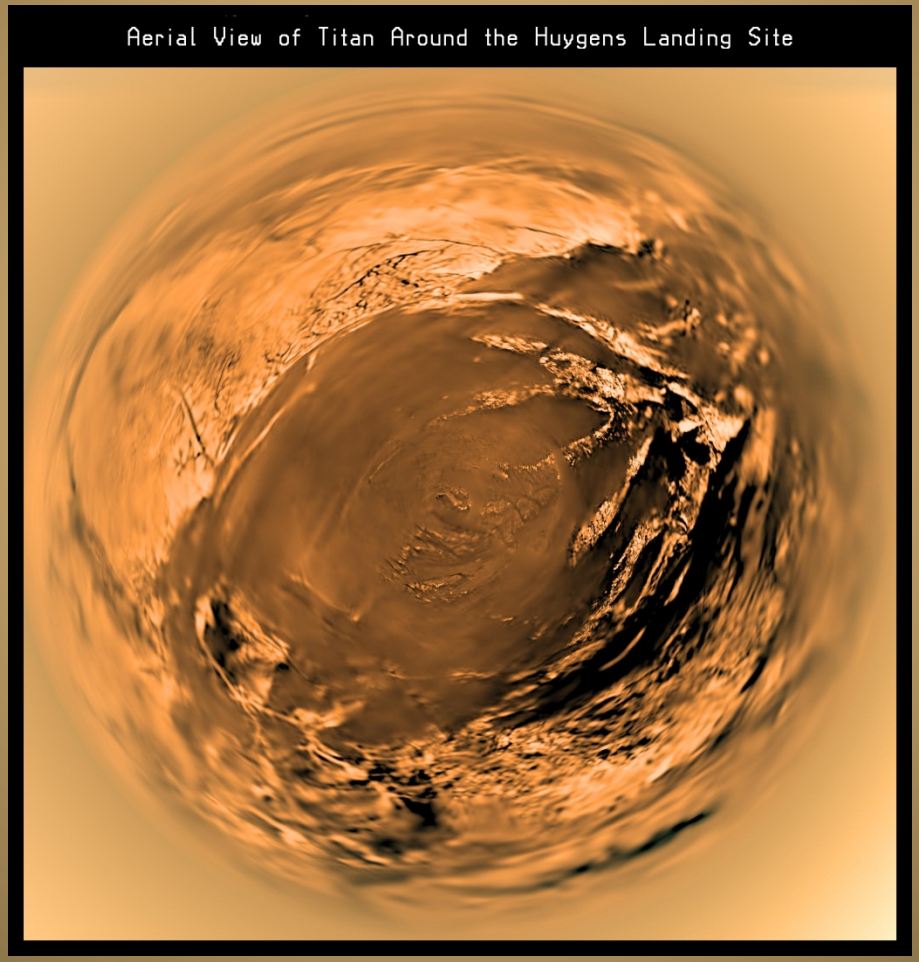
$$F_{\odot}(z)\cos\theta_{\odot} = [F_b(z) + F_d(z)] - [F_a(Z) + F_c(z)],$$



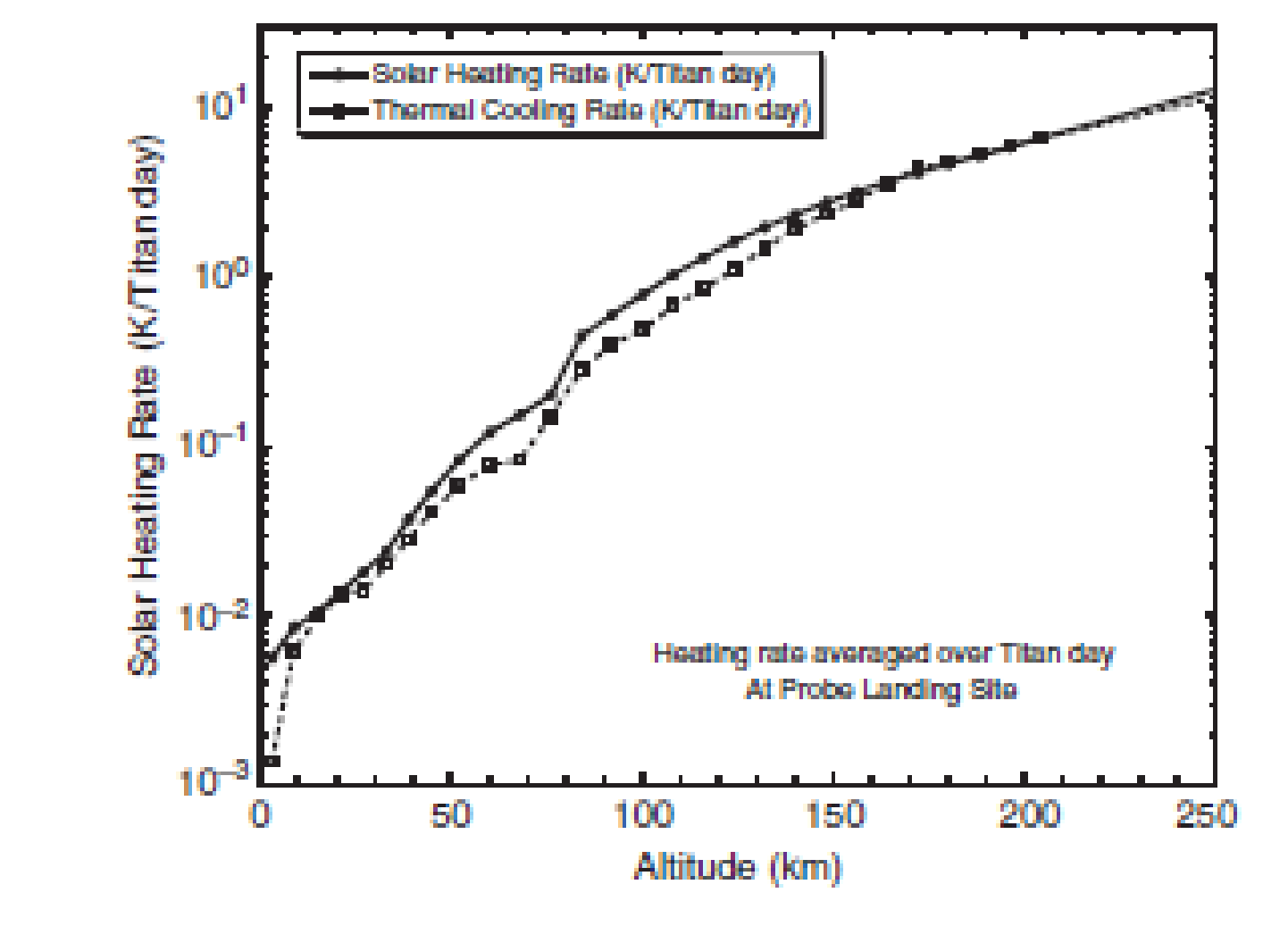
Observations at 4 different azimuts

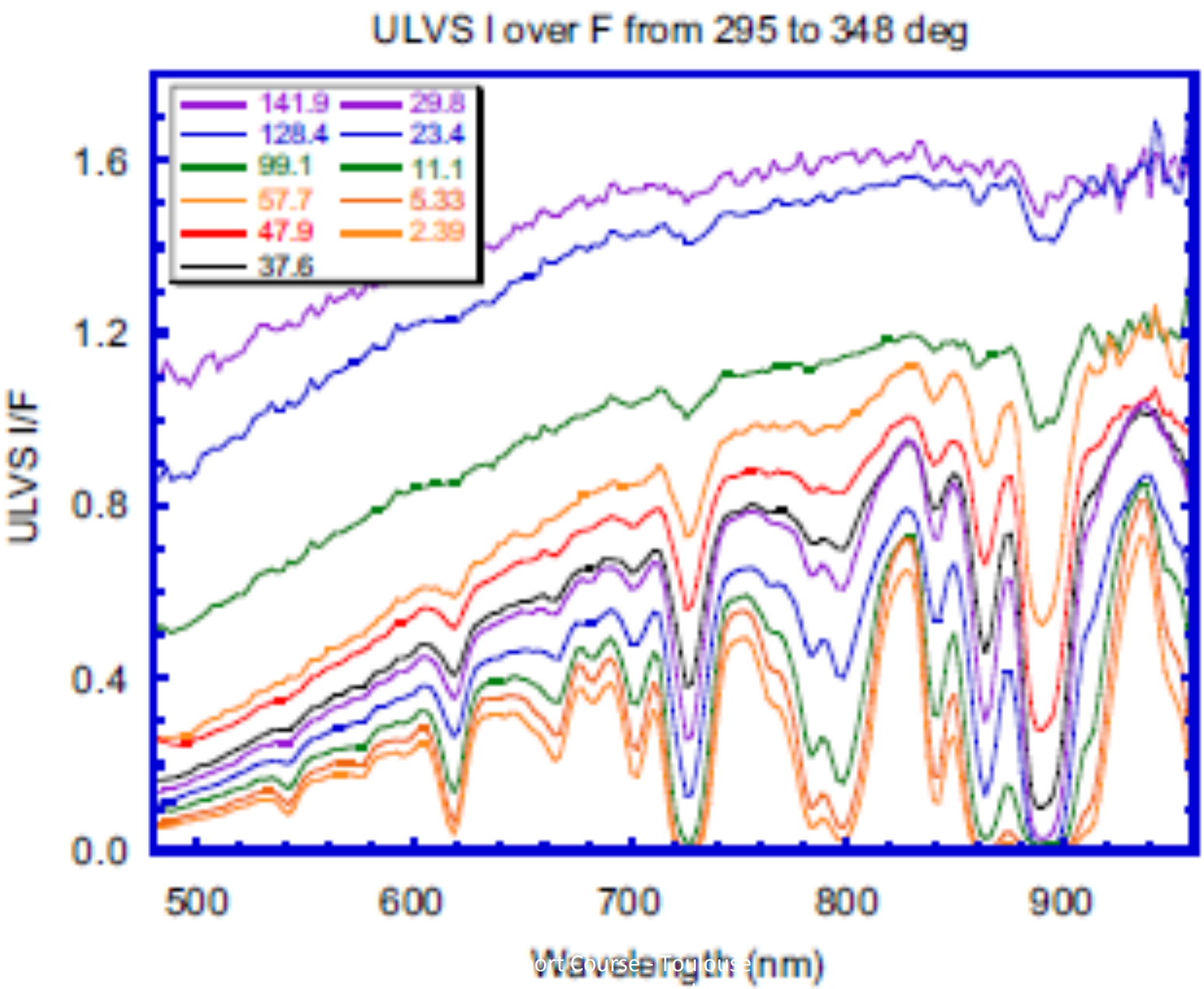
$$\tau(z) = \cos\theta_{\odot} \ln \frac{F_{\odot}(\mathrm{TOA})}{F_{\odot}(z)},$$

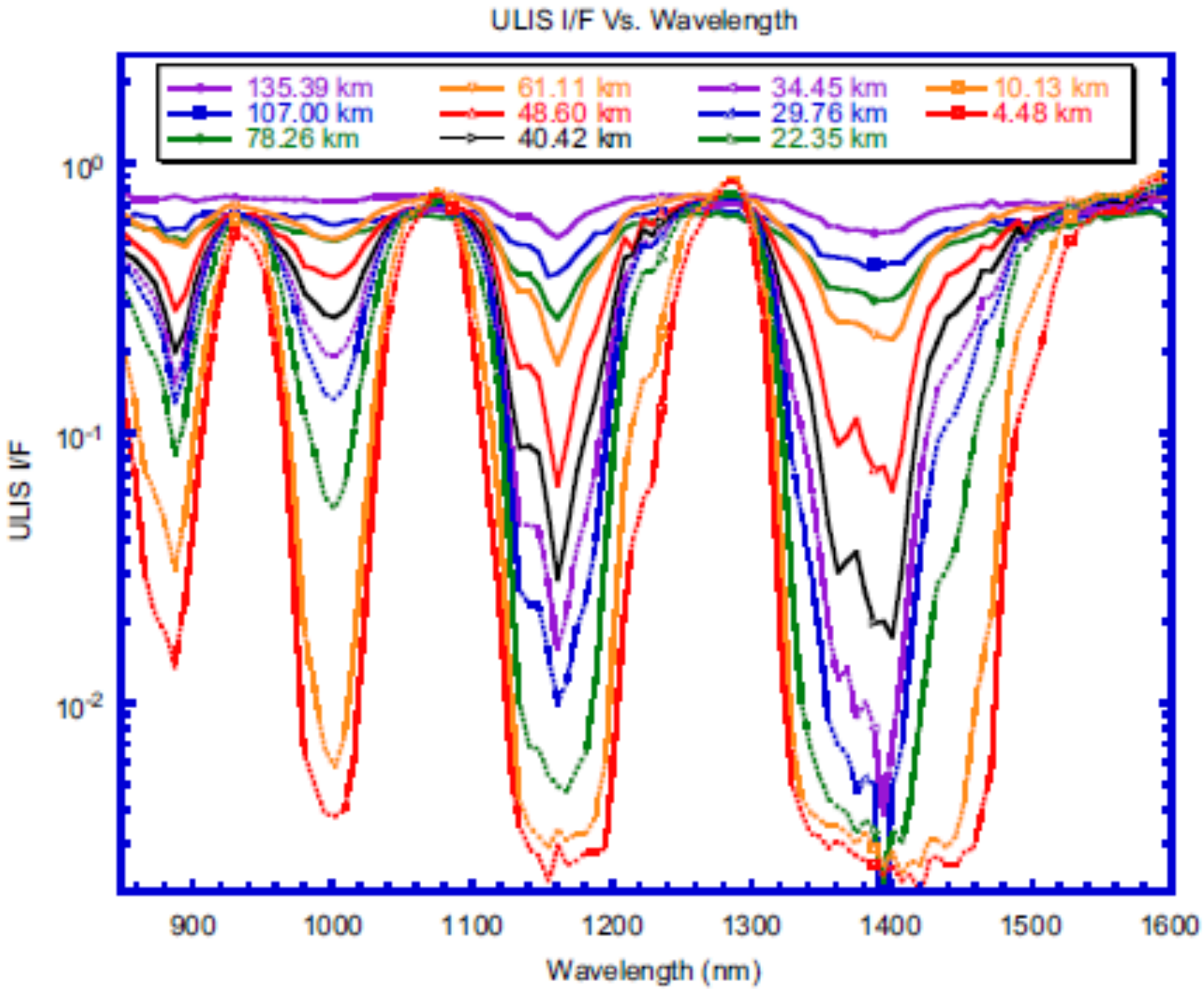
DISR movie



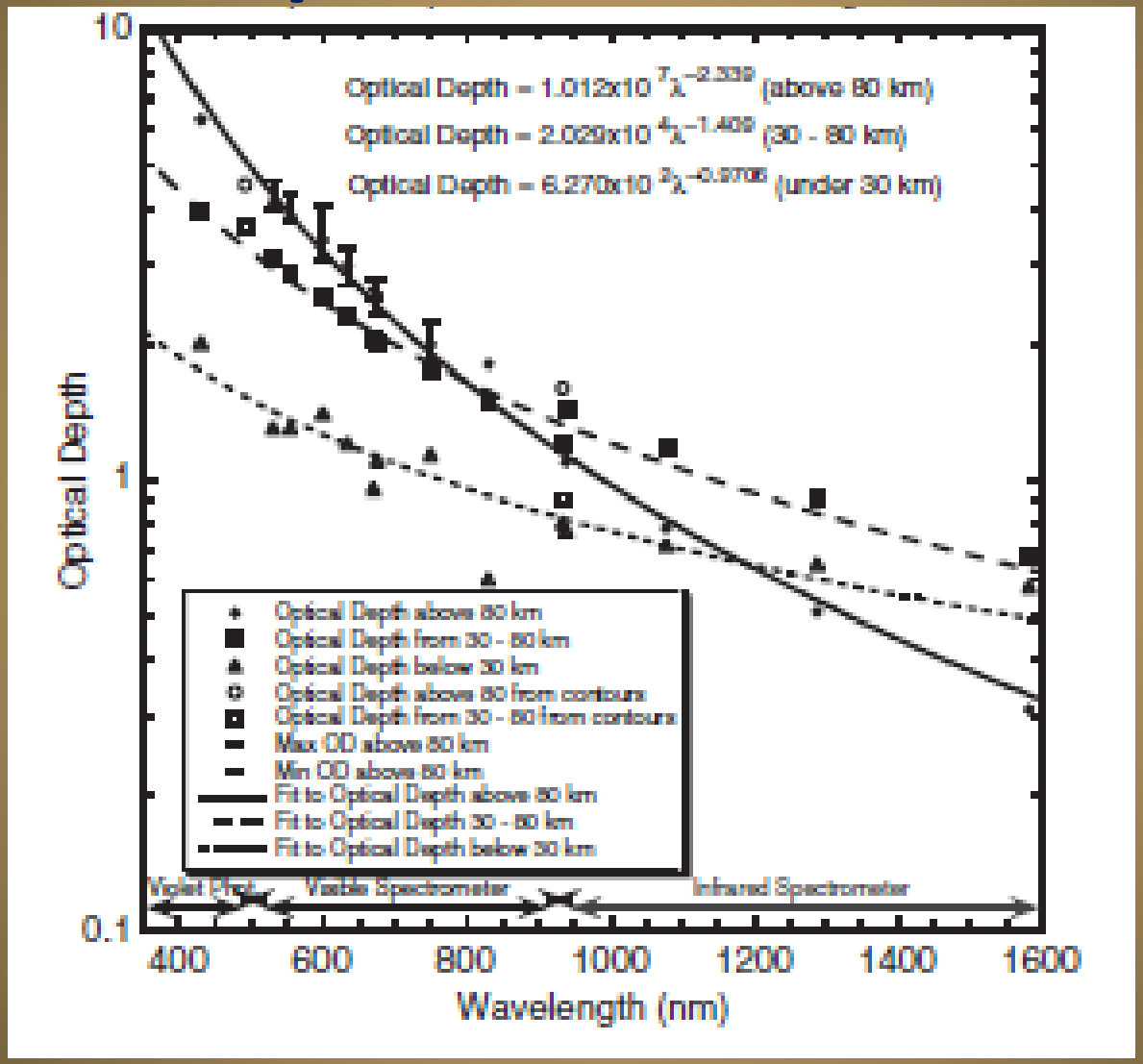
Solar heating and thermal cooling rates vs altitude



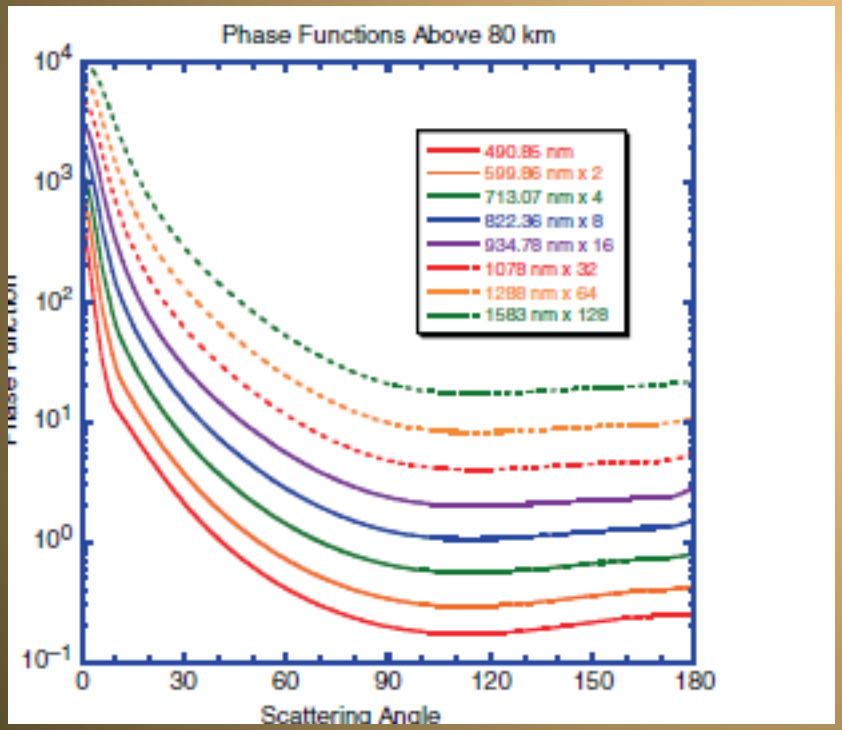

ULVS I over F from 295 to 348 deg
141.9
29.8
128.4
23.4
99.1
11.1
57.7
5.33
47.9
2.39
37.6
1.6
1.2
0.8
0.4
0.0
ULVS I/F
500
600
700
800
900
Wavelength (nm)

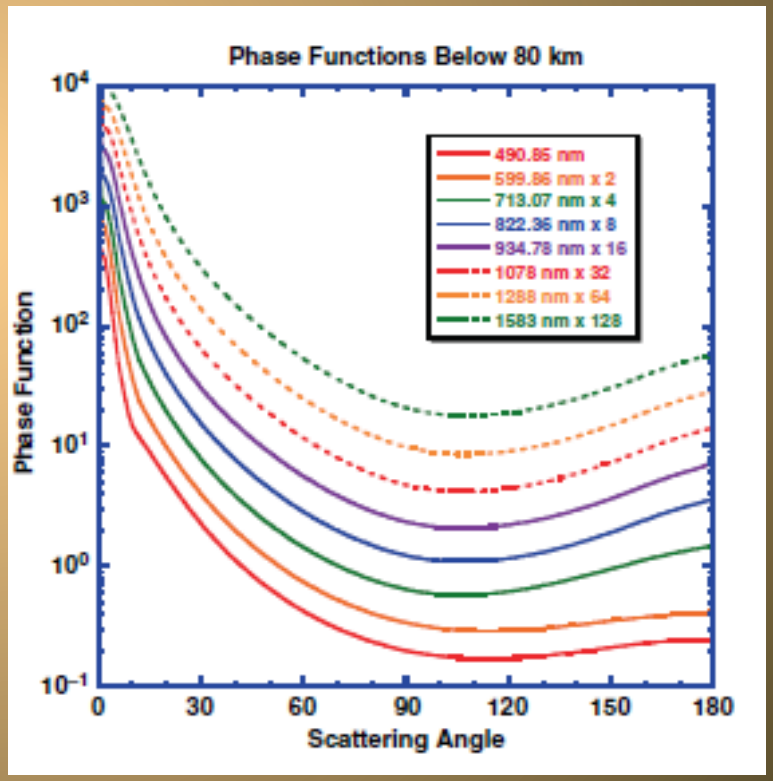

ULIS I/F Vs. Wavelength
135.39 km
107.00 km
78.26 km
61.11 km
48.60 km
40.42 km
34.45 km
29.76 km
22.35 km
10.13 km
4.48 km
ULIS I/F
10^0
10^{-1}
10^{-2}
900
1000
1100
1200
1300
1400
1500
1600
Wavelength (nm)

Optical depths at different altitudes

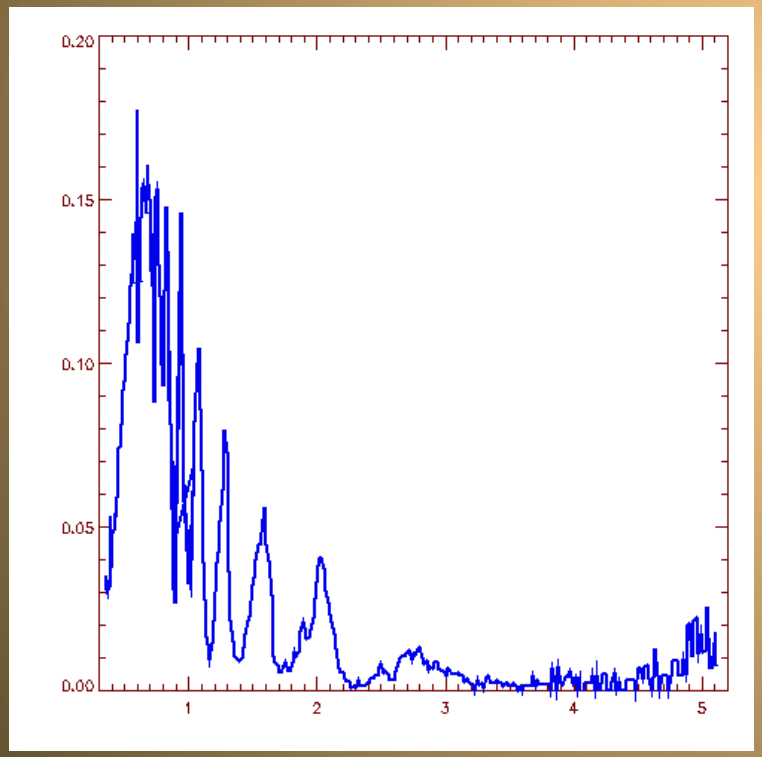


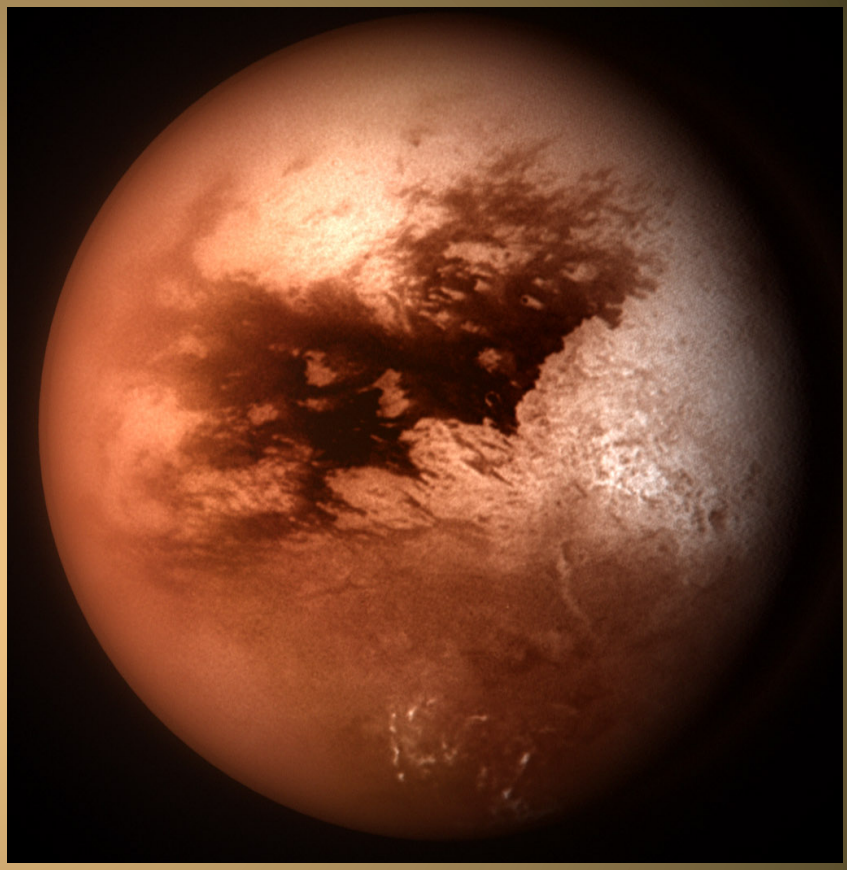
Phase function of aerosols modelled from DISR measurements (sun aureole channel)





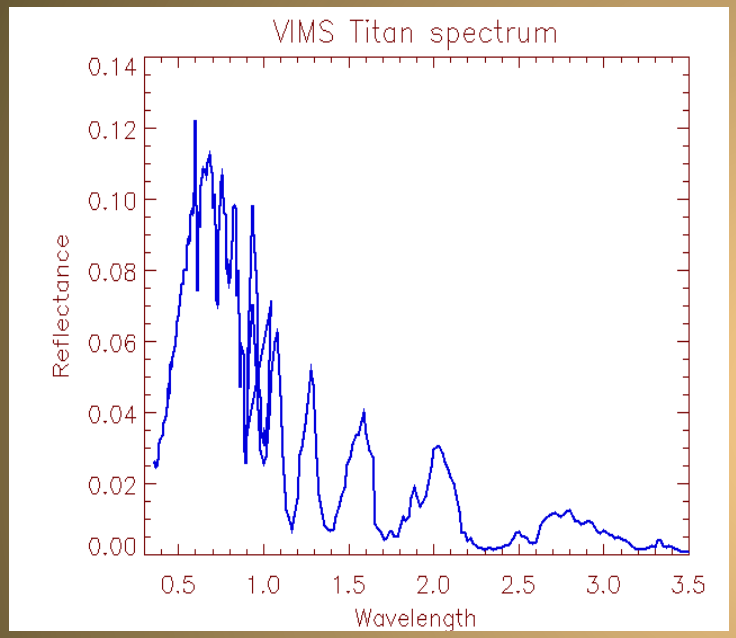
Cassini/VIMS
Titan observations @ T0

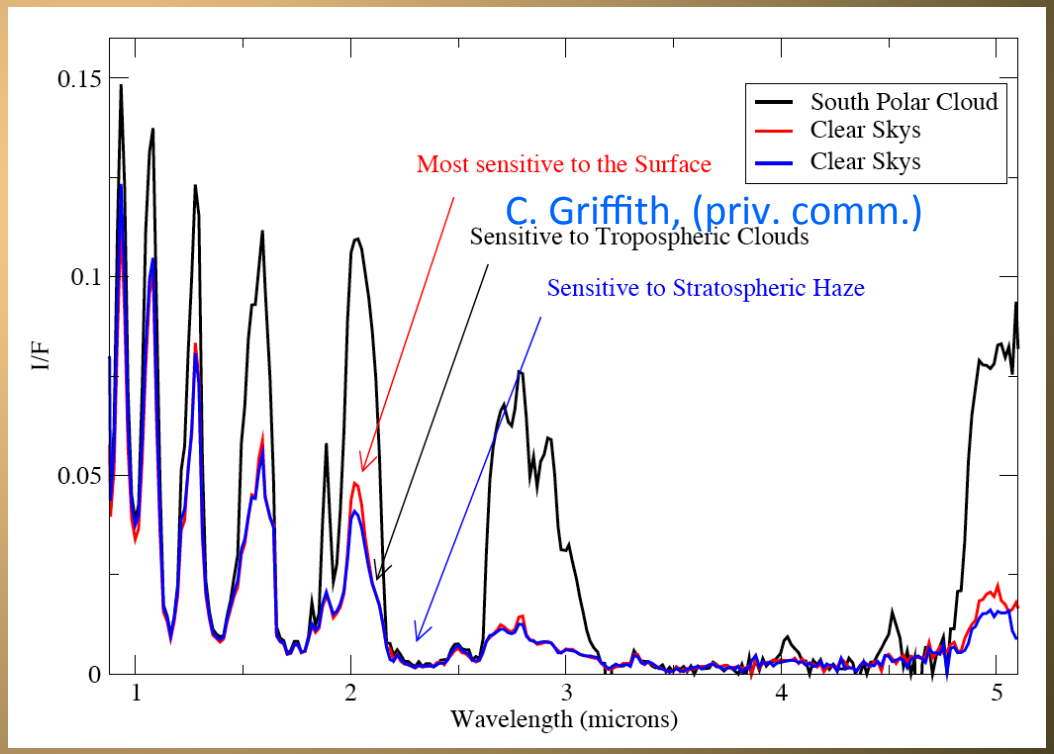




CM_1467449778.cub (#18)
Spectrum in central regions

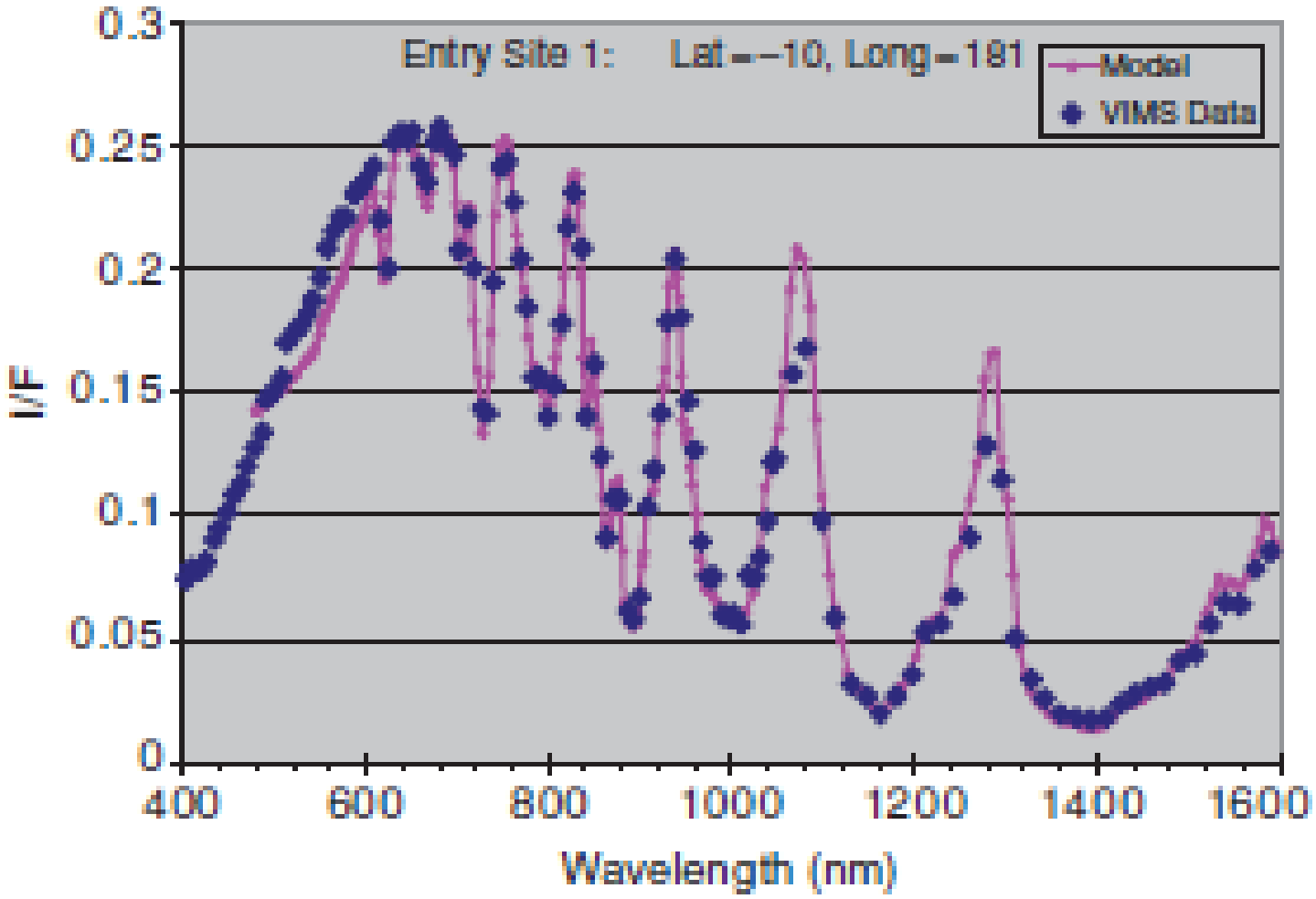
Cassini/VIMS : spectres de Titan



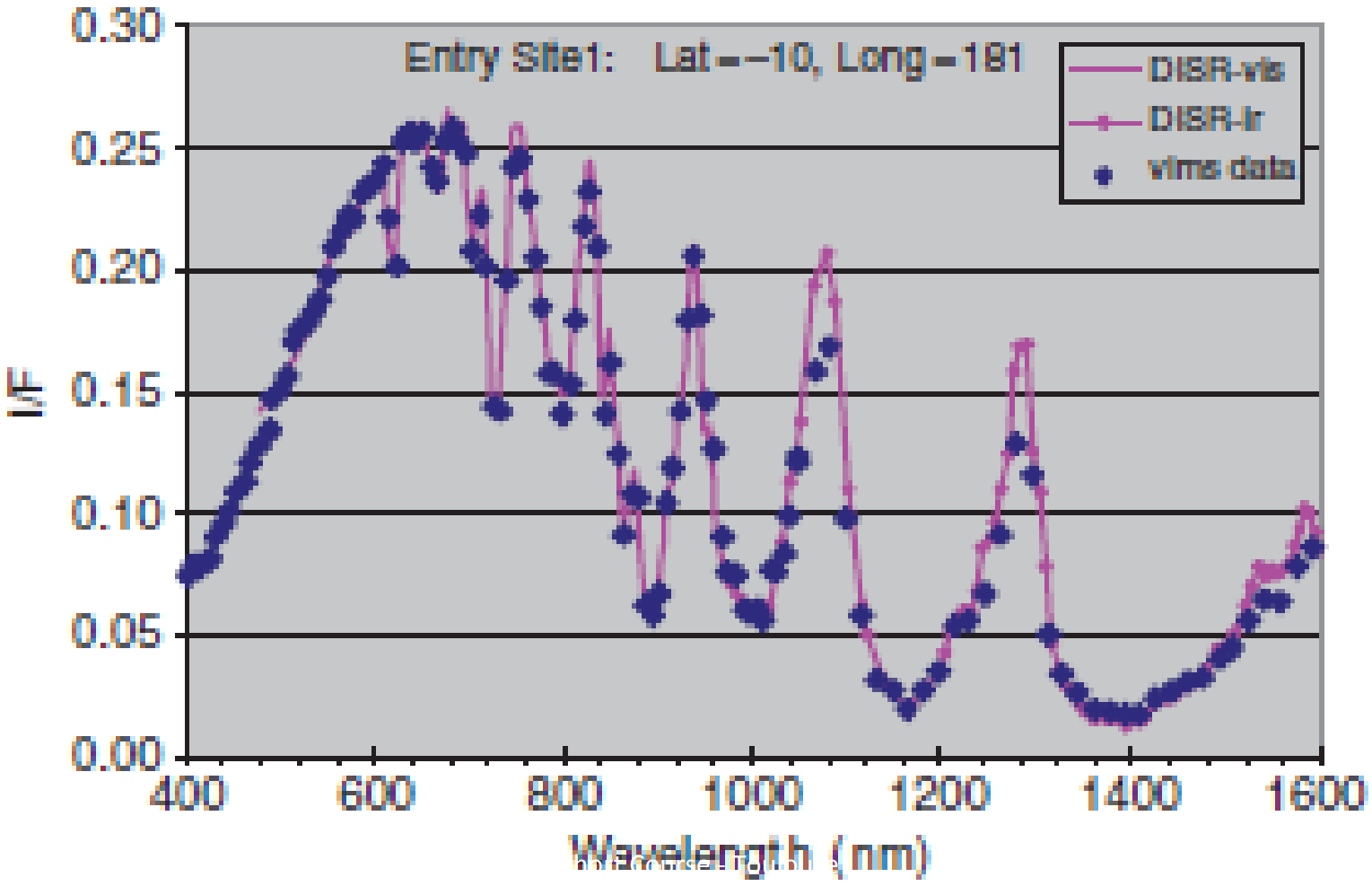


Resolving Power ~ 140

Vims –remote sensing



VIMS – DISR comparison



Key results from DISR

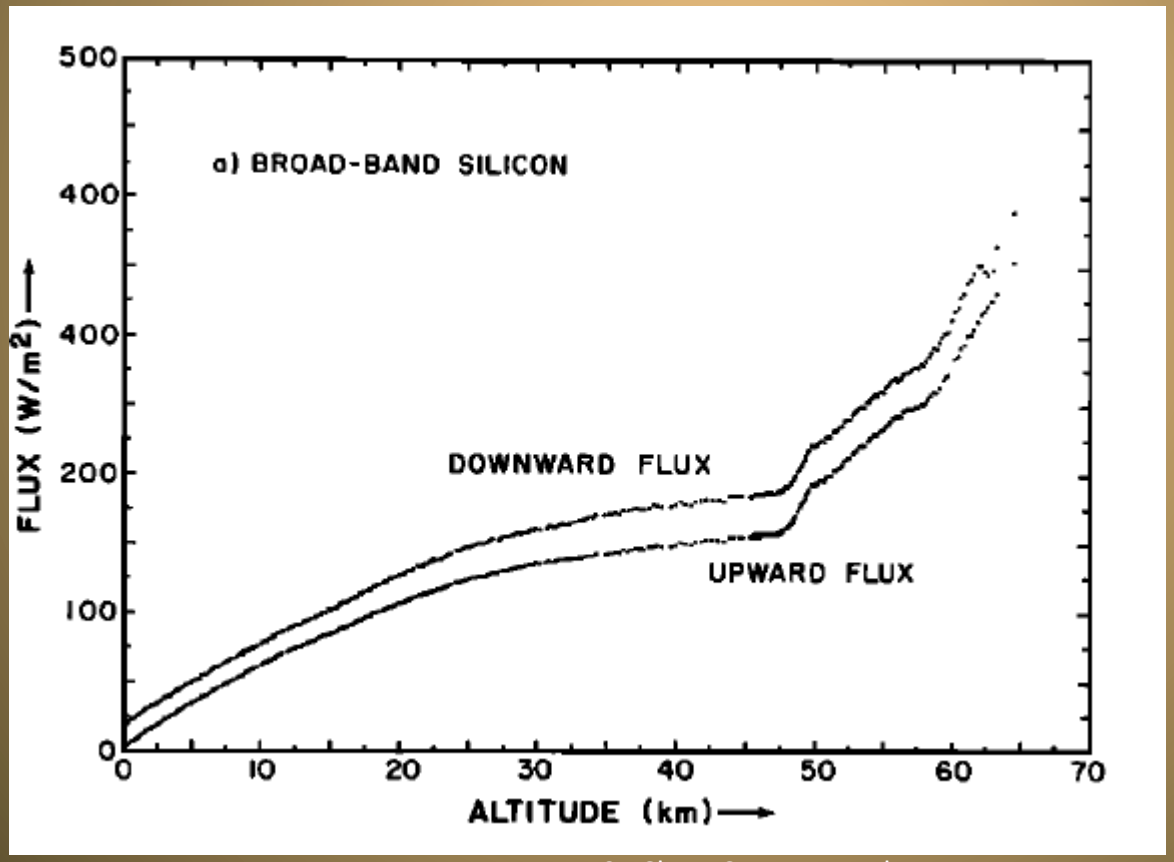
- Aerosol properties on Titan
- Methane abundance at the surface (5.1%) and during the descent
- Descent images of Titan
- Radiative balance of Titan

Venus : a hot sister of Titan

Thermal radiative transfer in remote sensing

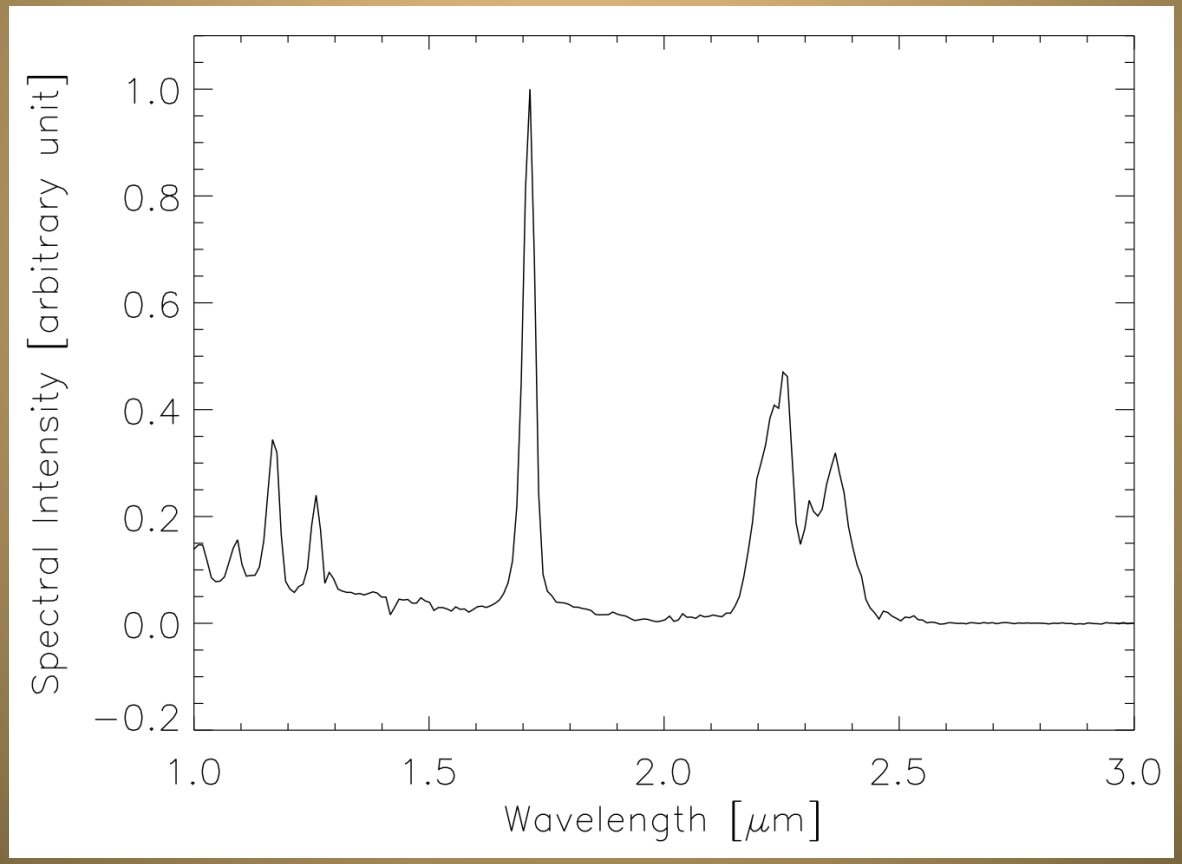
Upward and downward flux from Pioneer Venus

Vs solar flux radiometer on Pioneer Venus probe (LSFR, M. Tomasko et al, JGR 1980)

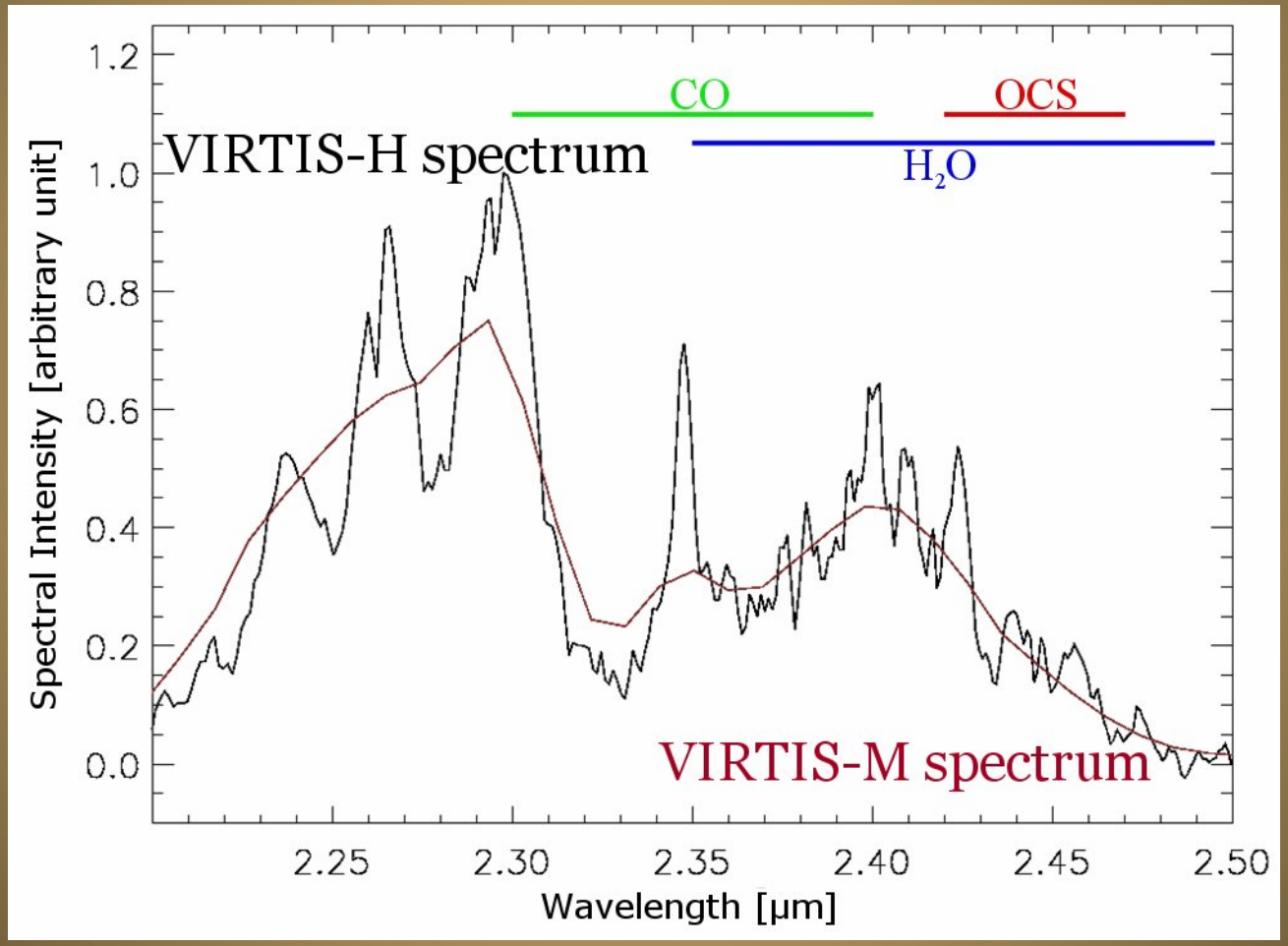


Remote sensing of Venus thermal windows (night side)

- Galileo/NIMS obs. @ Venus : Carlson et al, 1992

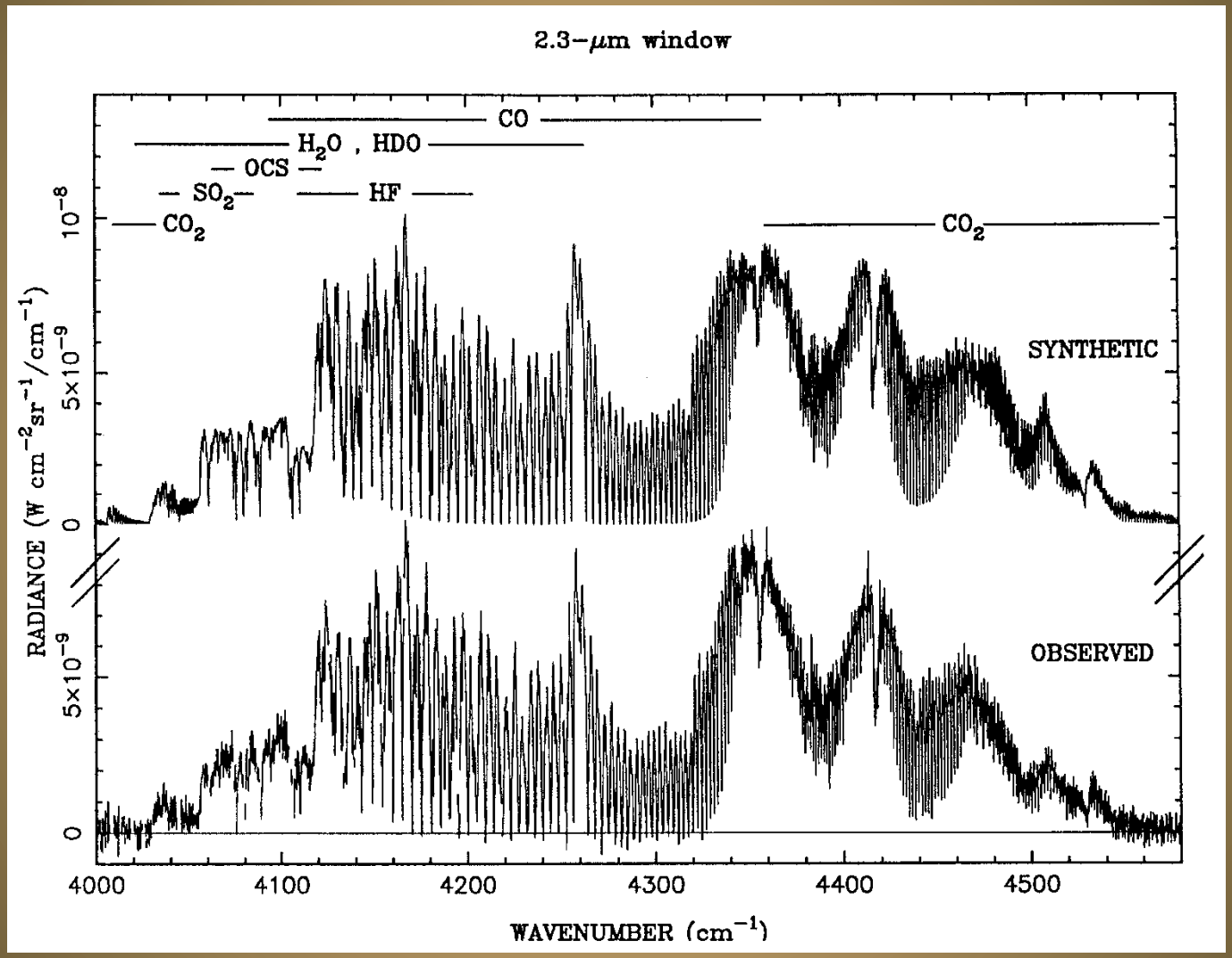


Venus night side spectra
Venus Express / VIRTIS Obs.



Spectroscopie infrarouge de Vénus : mesures de composition

Sounded levels: 25-45 km



CFHT (Hawaï); B. Bézard, C. de Bergh et coll.

Summary

Radiative transfer is a powerful tool to analyze structure of atmospheres from combined in situ and remote sensing instruments.

In situ experiments with entry probe provide a unique way to study the radiative field from inside, measuring directly the different terms of the radiative transfer equations

Combination of remote sensing/in situ has proved to reach unique results on planetary atmospheres (to date : Mars, Venus, Jupiter, Titan)