Remote Sounding of the atmospheres of Venus and Titan

in the submm-wave region

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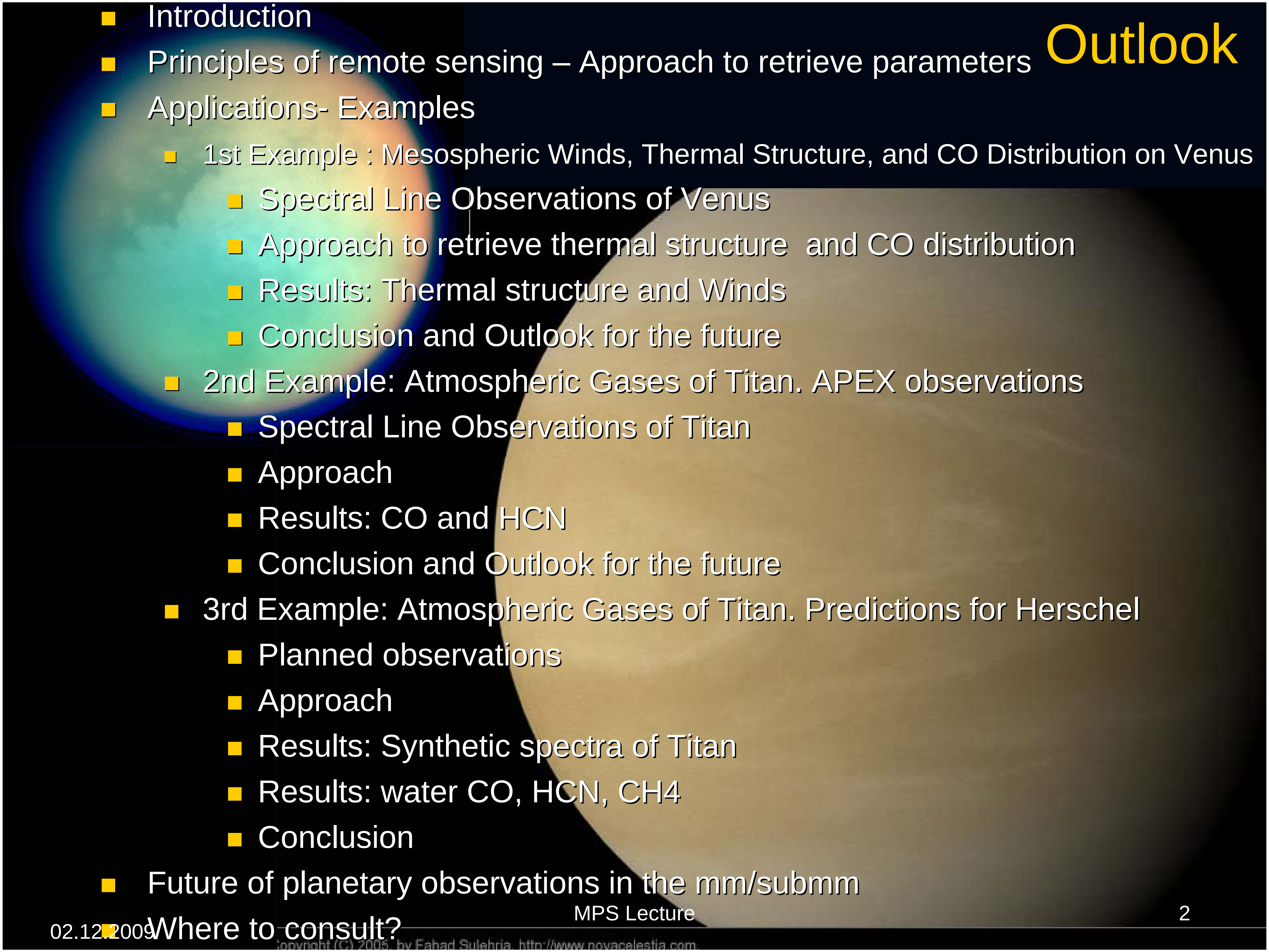
Miriam Rengel

Hartogh P., Jarchow C., Sagawa H.

Outlook



- Introduction
- Principles of remote sensing – Approach to retrieve parameters
- Applications- Examples
  - 1st Example : Mesospheric Winds, Thermal Structure, and CO Distribution on Venus
    - Spectral Line Observations of Venus
    - Approach to retrieve thermal structure and CO distribution
    - Results: Thermal structure and Winds
    - Conclusion and Outlook for the future
  - 2nd Example: Atmospheric Gases of Titan. APEX observations
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    - Approach
    - Results: CO and HCN
    - Conclusion and Outlook for the future
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- Future of planetary observations in the mm/submm
- Where to consult?

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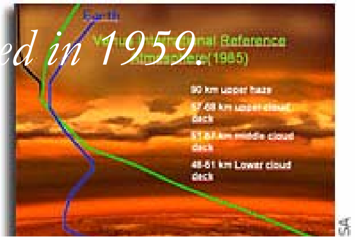
Planetary atmosphere Science:

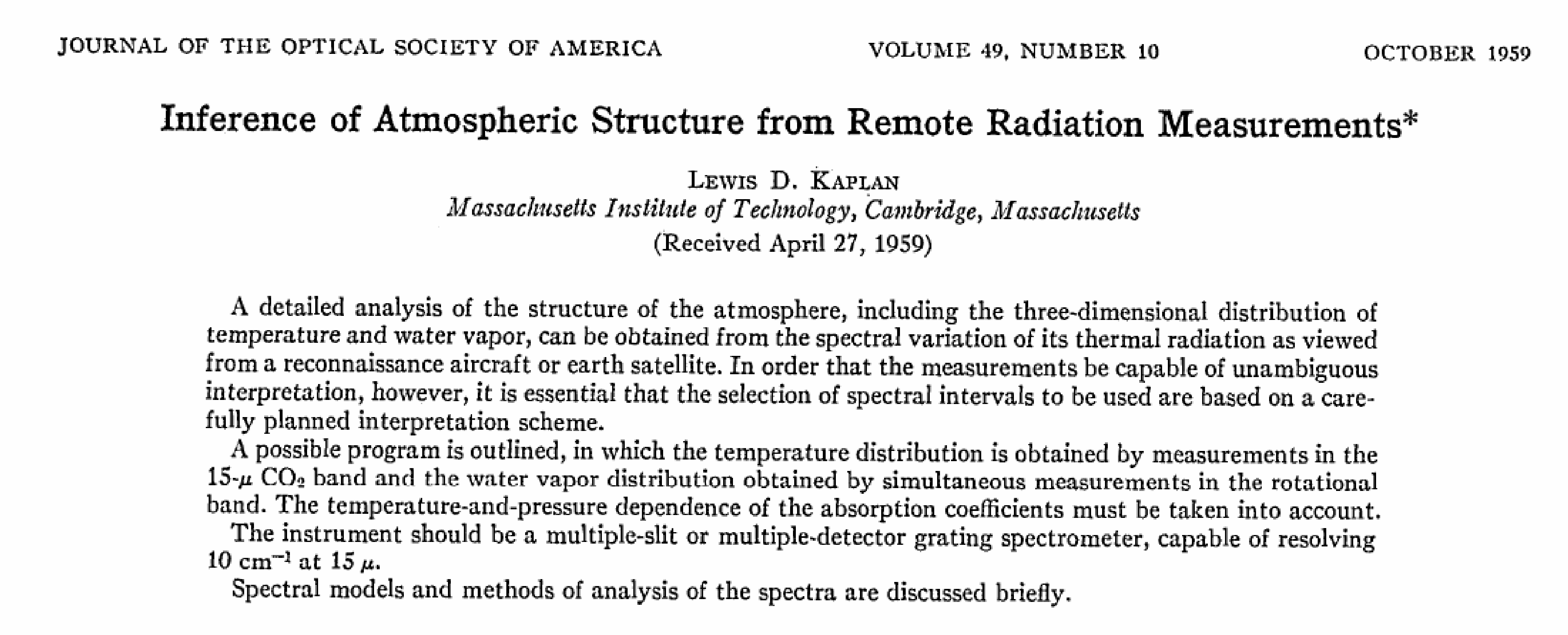
Constraints on

Remote sounding of the atmosphere temperature profile and composition was first suggested in 1959.



Thermal structure

T profiles



JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 49, NUMBER 10 OCTOBER 1959

Inference of Atmospheric Structure from Remote Radiation Measurements*

Lewis D. Kaplan
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received April 27, 1959)

A detailed analysis of the structure of the atmosphere, including the three-dimensional distribution of temperature and water vapor, can be obtained from the spectral variation of its thermal radiation as viewed from a reconnaissance aircraft or earth satellite. In order that the measurements be capable of unambiguous interpretation, however, it is essential that the selection of spectral intervals to be used are based on a carefully planned interpretation scheme.

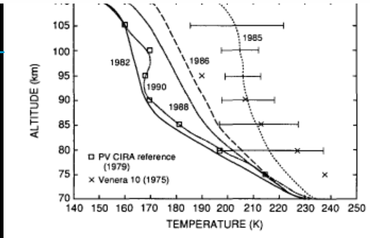
A possible program is outlined, in which the temperature distribution is obtained by measurements in the 15-μ CO_2 band and the water vapor distribution obtained by simultaneous measurements in the rotational band. The temperature-and-pressure dependence of the absorption coefficients must be taken into account.

The instrument should be a multiple-slit or multiple-detector grating spectrometer, capable of resolving 10 cm^{-1} at 15 μ.

Spectral models and methods of analysis of the spectra are discussed briefly.

3D mapping and monitoring

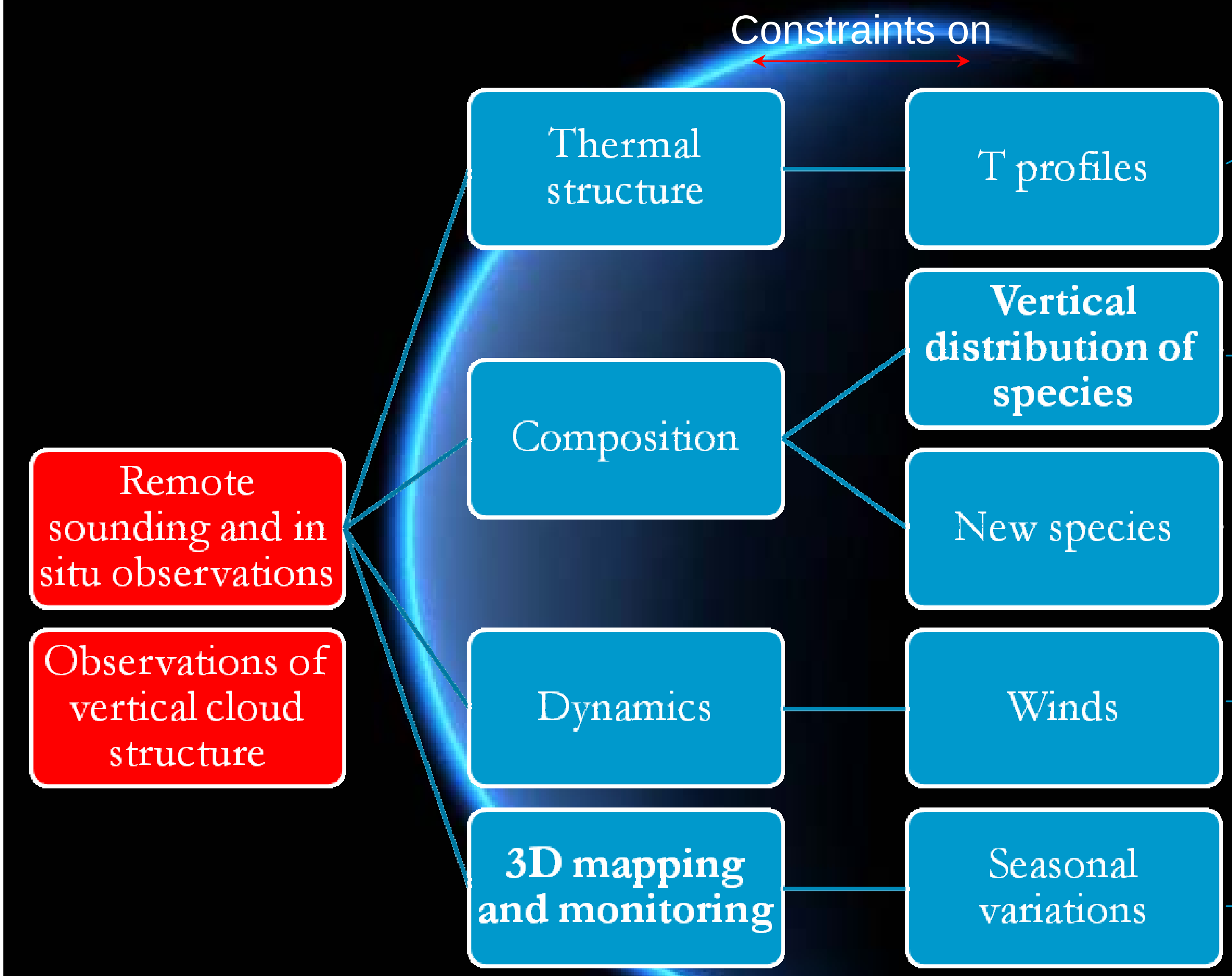
Seasonal variations



➔**Constraints on the origin and evolution of planets and the formation of the solar system**

Clancy and M. 1991

Planetary atmosphere Science:



Constraints on

Remote sounding and in situ observations

Observations of vertical cloud structure

Thermal structure

Composition

Dynamics

3D mapping and monitoring

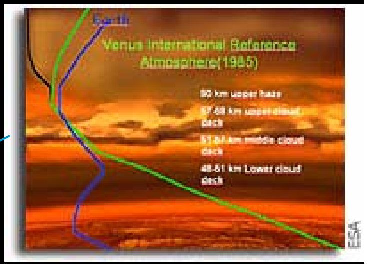
T profiles

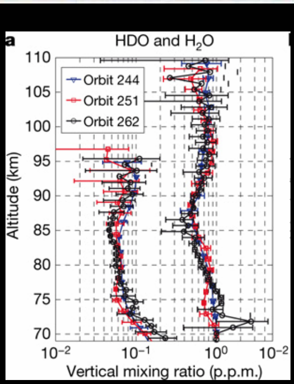
Vertical distribution of species

New species

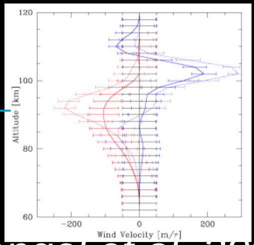
Winds

Seasonal variations

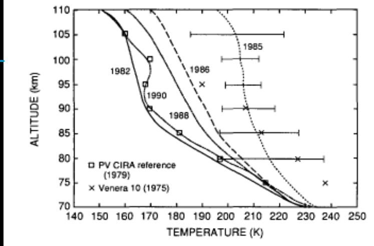




Bertaux et al. 2007



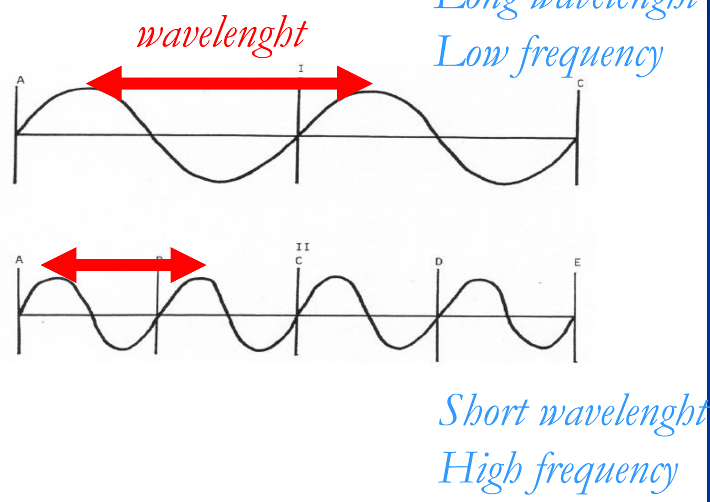
Rengel et al. 2008

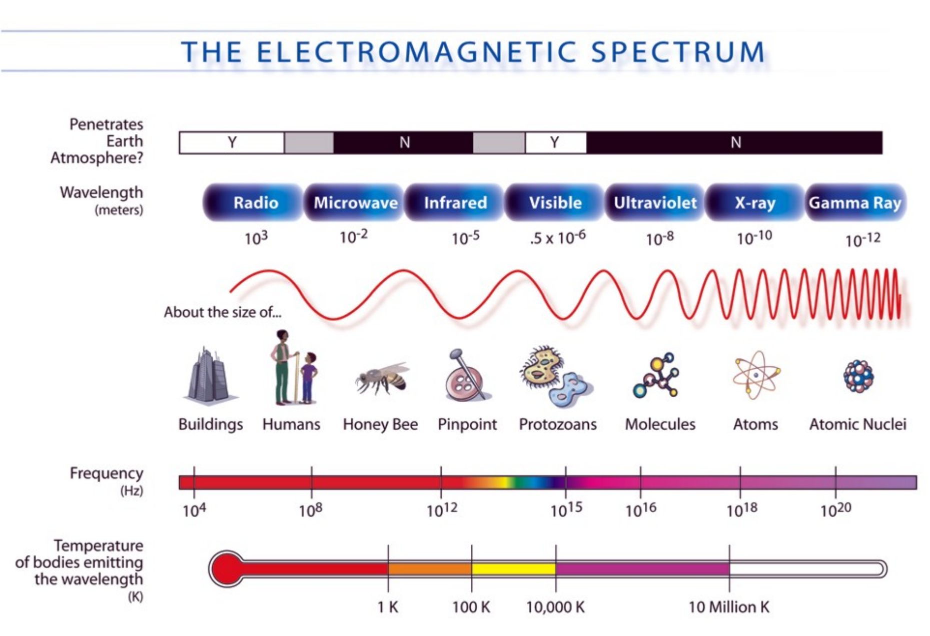


➔Constraints on the origin and evolution of planets and the formation of the solar system

Clancy and M. 1991

What is the sub-mm/mm region?





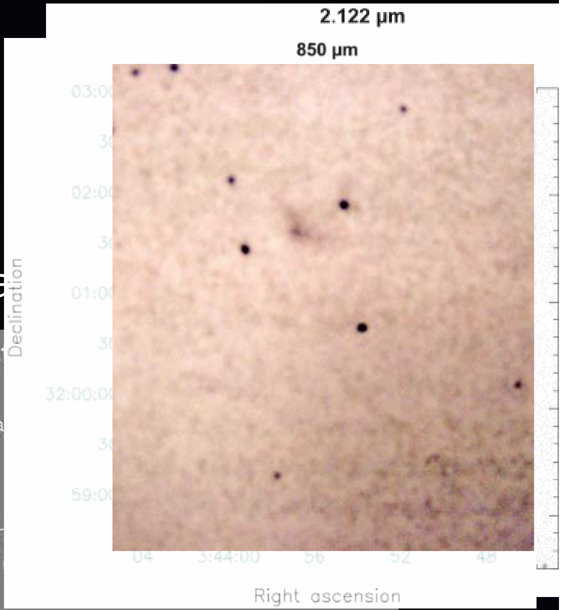
Microwaves

Sub-mm:	0.1mm – 1mm	300GHz-3 THz
mm:	1mm – 10mm	30 GHz -300 GHz
Cm	1cm - 10cm	3 GHz - 30 GHz

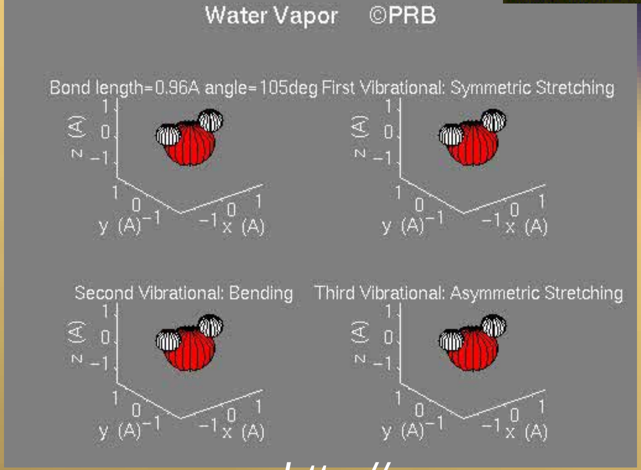
$$f = c/\lambda$$

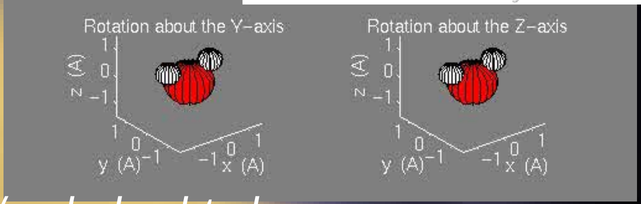
What do we detect in the sub-mm and FIR region?

thermal radiation!!!!

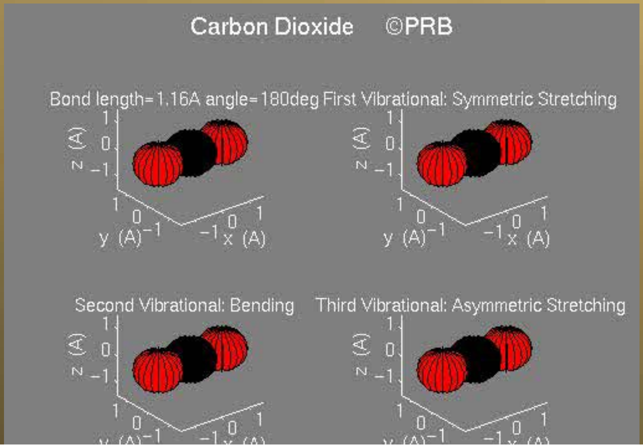


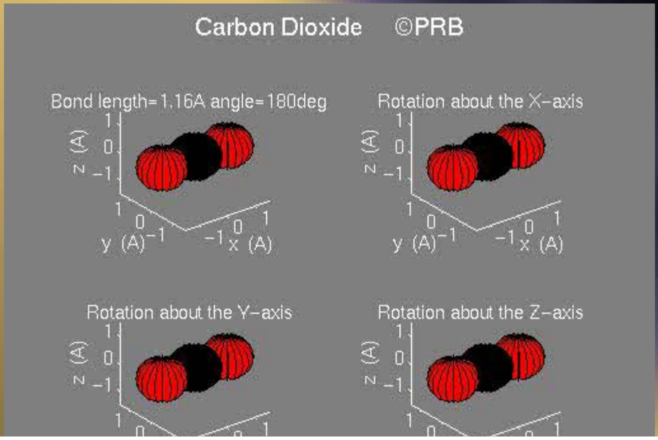
IR radiation interacts with molecular vibrations, sub-mm intera





http://www.ems.psu.edu/~bannon/moledyn.html

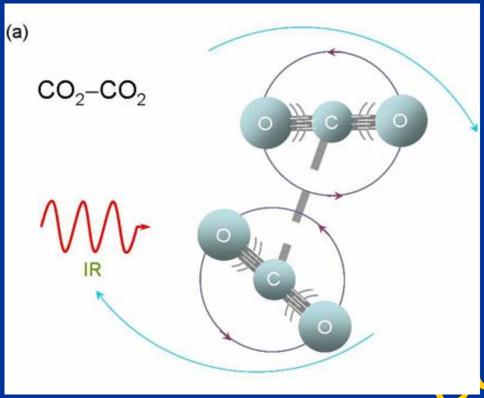




But, how the spectrum is formed?

The absorption of gases is due to both vibration-rotational bands and collision induced absorptions.

Two vibrating CO2 molecules as they intercept IR radiation (red wavy line) during a collision.



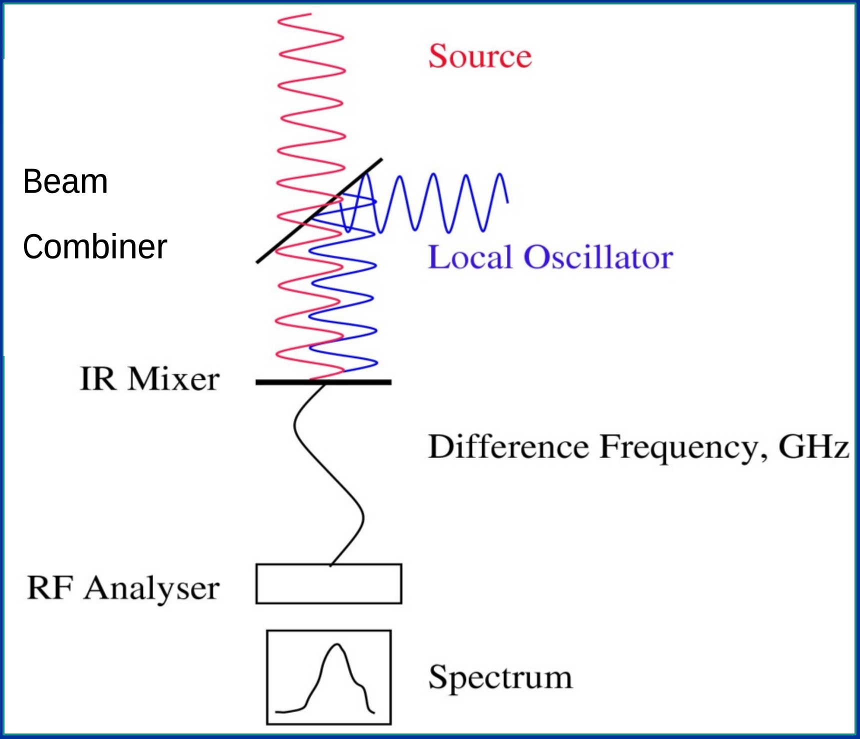
Radiation is absorbed; half is transferred to the rotation of the molecules, and half goes toward translation making the two molecules move faster relative to each other (blue arrows).

But, how to detect so extremately week emission?

We need:

- For deriving the temperature profile: **resolve the spectral shape**
- For detecting weak and narrow lines of molecular species: **very high spectral resolution**

Heterodyne Technique



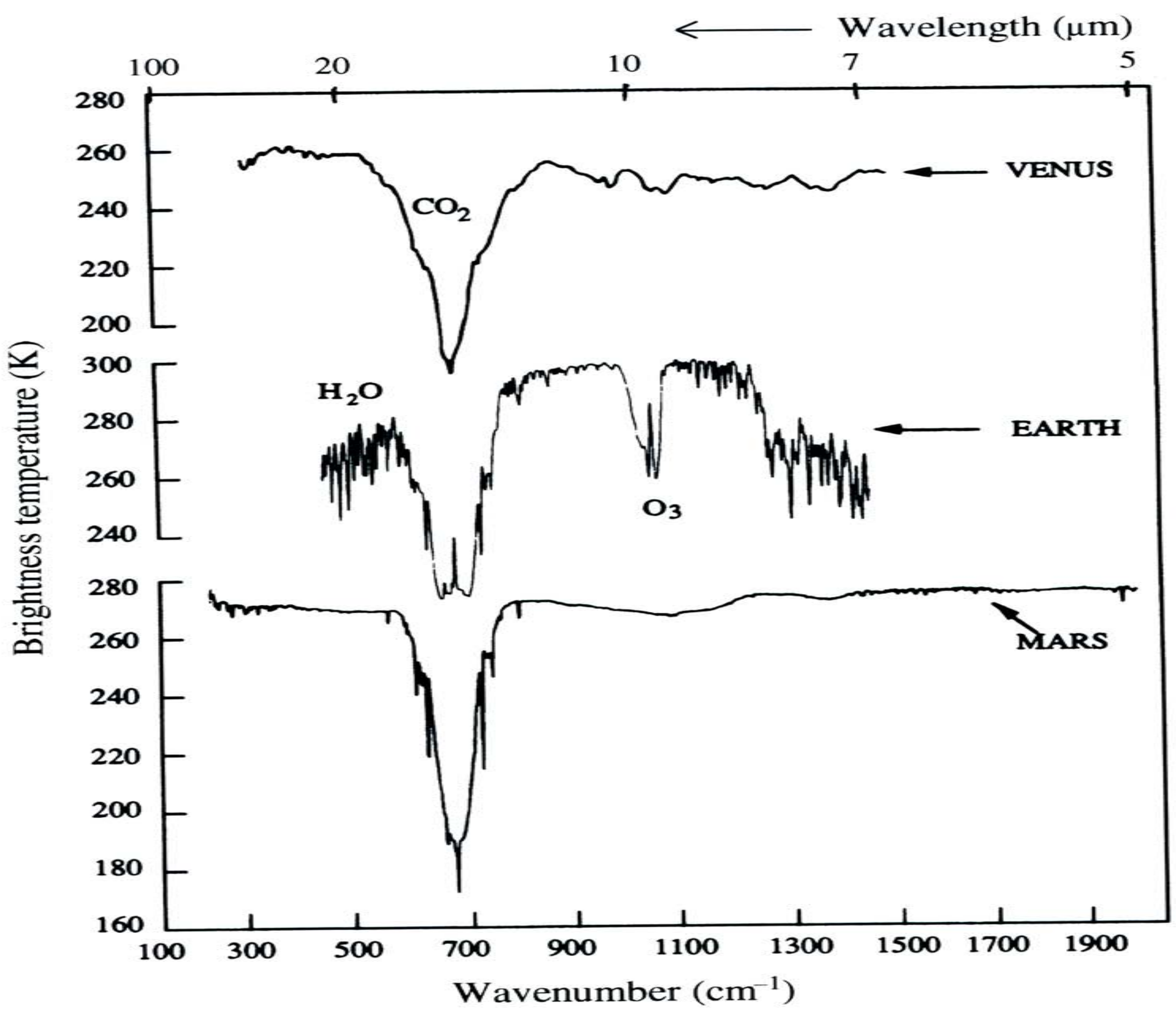
The source signal is combined with the signal of the LO .

Mixing shifts signal (preserving spectroscopic information)

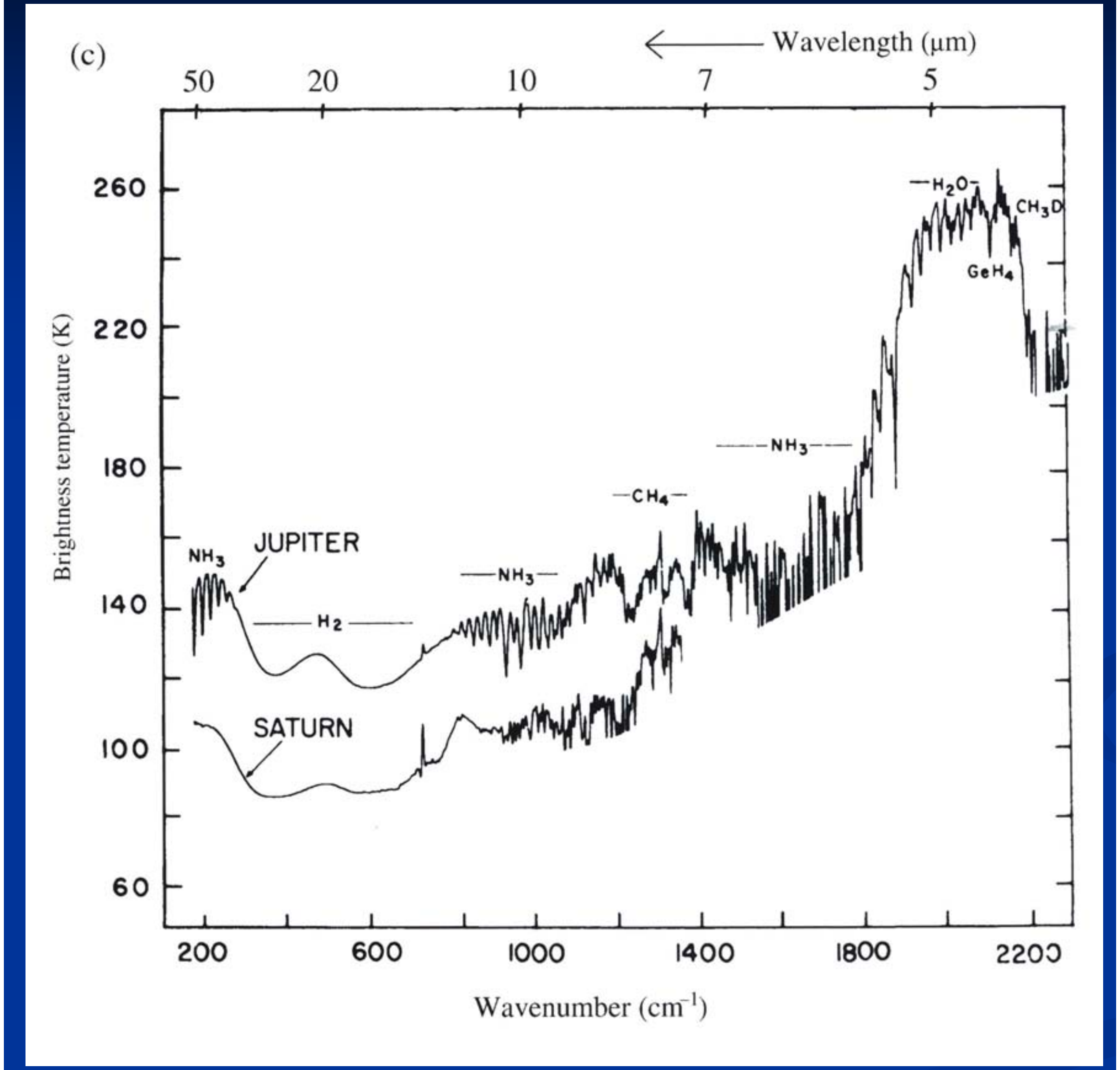
RF signal processing, amplification, analysis, etc. does not add noise

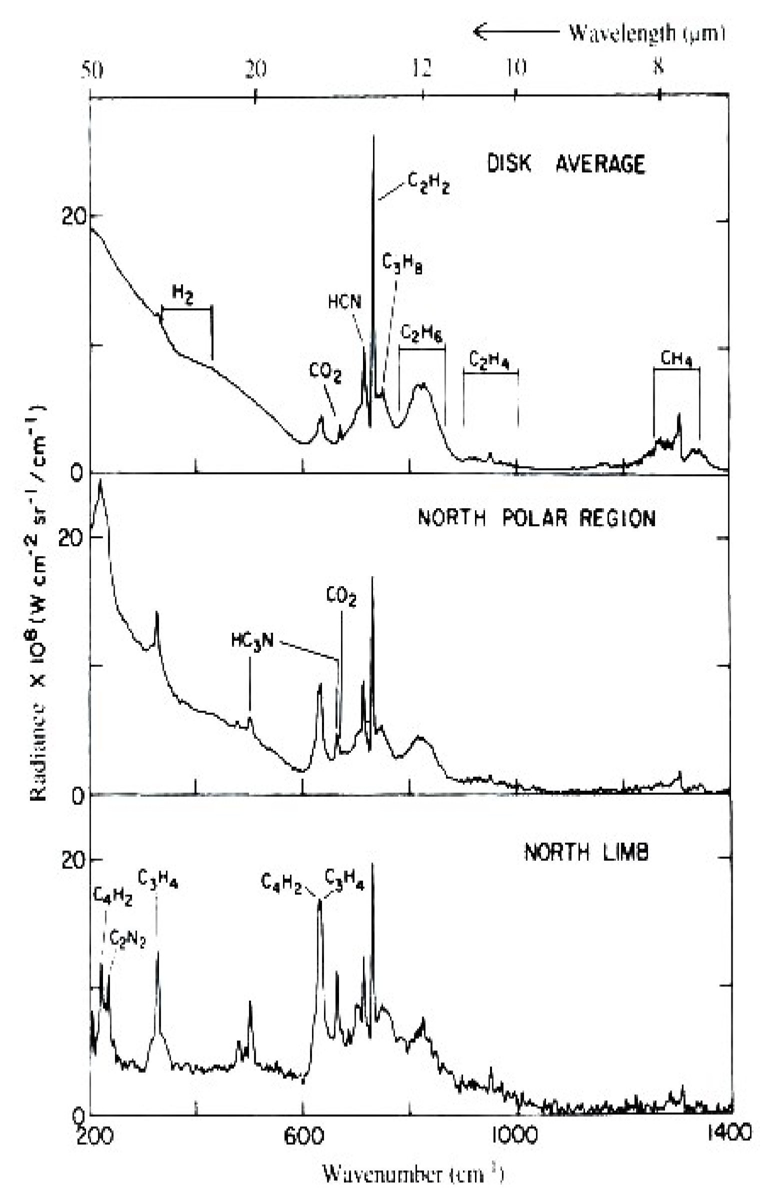
The main advantage is the capability to provide high-resolution spectroscopy!

Thermal emissions spectra of terrestrial planets



Thermal emission spectra of Giants and Titan





Spectrometry of the thermal radiation

- Wavelength range mid – far-IR *(3 – 1000 μm)*
- *Wavelength range microwaves (0.1mm- 10cm)*
- Good sensitivity to
  - *1. atmospheric temperature and*
  - *2. total number of molecules*
- Both day and night side observations
- Multiple scattering is usually of minor importance

How? Ingredients

Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

Technique to retrieve profiles of temperature and volume mixing ratio

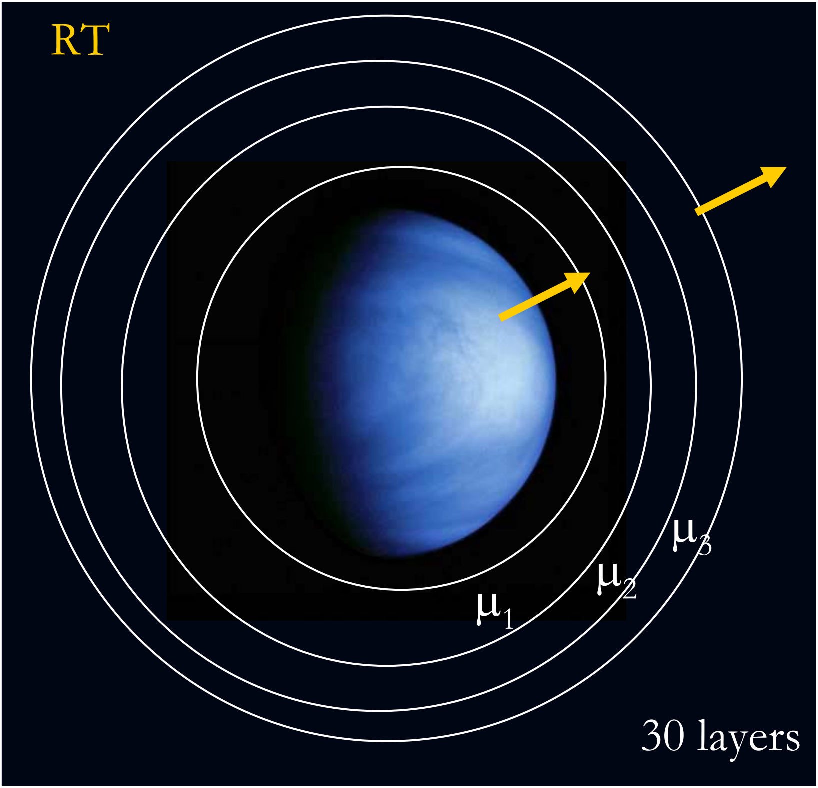
Input parameters → Abundance profiles → Radiative Transfer → Synthetic Spectra → Comparison with data

Optimal estimation algorithm

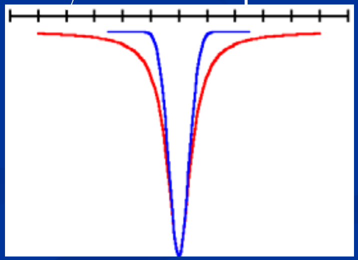
T profile →

P profile →

Vmr profile →

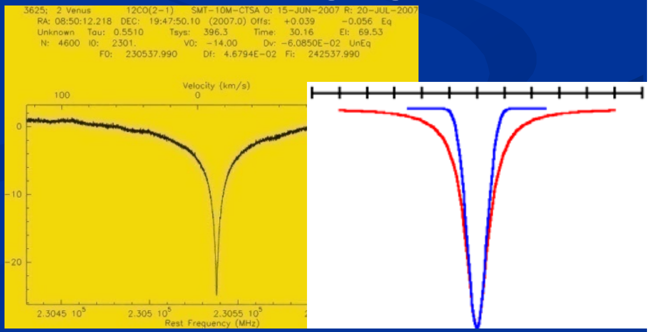


→ Synthetic spectra



↓ Fitting algorithm

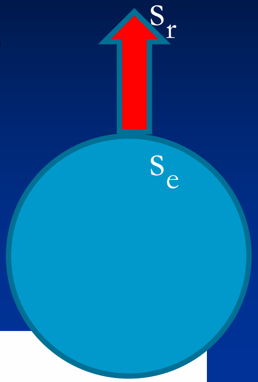
μ_i=absorption coefficient



```
3625;  2 Venus        12CO(2-1)    SMT-10M-CTSA O: 15-JUN-2007 R: 20-JUL-2007
 RA: 08:50:12.218  DEC:  19:47:50.10  (2007.0) Offs:   +0.039       -0.056  Eq
 Unknown    Tau:  0.5510       Tsys:    396.3        Time:    30.16        El:  69.53
  N:  4600   I0:    2301.            V0:  -14.00       Dv: -6.0850E-02  UnEq
                 F0:    230537.990        Df:  4.6794E-02   Fi:    242537.990
```

New set of parameters ←

Physical and mathematical basis of the forward and retrieval models



RT : Asuming LTE,

Specific intensity of the radiation at S_r

$$I_\nu(s_r) = I_\nu(s_e)e^{-\tau_\nu(s_e,s_r)} + \int_{s_e}^{s_r} \alpha_\nu(s)B_\nu(T)e^{-\tau_\nu(s,s_r)}\,ds.$$

Radiation entering the atmosphere

$$T_B(\nu,s_r) \equiv \frac{c^2}{2k_B\nu^2} I_\nu(s_r)$$

$$\tau_\nu(s_1,s_2) = \int_{s_1}^{s_2} \alpha_\nu(s')\,ds'$$

opacity

Absorption coefficient

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

Source function

T_B= brightness temperature
h= Planck's constant
c= speed of light
k_B= Botzmann's constant

Retrieval model: Inverse problem and OEM

$$y = F(x,b) + \varepsilon_y$$

$$\hat{x} = I(y,b,c)$$

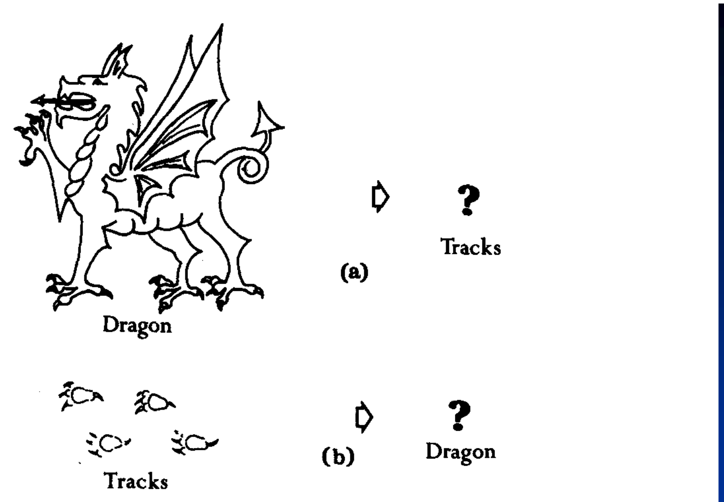


Figure 1.5 (*a*) The direct problem: Describe the tracks of a given dragon. (*b*) The inverse problem: Describe a dragon from its tracks.

y = measurements
F = Forward model
x = unknown parameters to be retrieved (T, abundances)
b = remaining model parameters
Ey = error

c = additional parameters (a priori)

$$\chi^2 = (y - F(x,b))^T S_y^{-1} \cdot (y - F(x,b)) + (x - x_a)^T \cdot S_a^{-1} \cdot (x - x_a)$$

x_a = a priori state vector
S_y = error covariance matrix for y
S_a = error covariance matrix por x_a

Weighting functions

$$K_x = \left.\frac{\partial F(x,b)}{\partial x}\right|_{x_a,b_a}, \quad K_b = \left.\frac{\partial F(x,b)}{\partial b}\right|_{x_a,b_a}$$

OEM solution

$$\hat{x}_{n+1} = x_a + (K_x^T \cdot S_y^{-1} \cdot K_x + S_a^{-1} + \gamma \cdot U)^{-1}$$
$$\times [K_x^T \cdot S_y^{-1} \cdot \{(y - F(\hat{x}_n, b)) + K_x \cdot (\hat{x}_n - x_a)\} + \gamma \cdot U(\hat{x}_n - x_a)]$$

Gamma = Levenberg-Marquardt parameter
U = unit matrix (S_a^{-1})

Principles of the temperature remote sensing

- **In strong bands thermal radiation forms at different altitudes depending on wavelength (*τ ~ 1 rule*)**
- **Gas should be well mixed, not variable, with known abundance**
- **Local thermodynamic equilibrium (LTE)**
- **Vertical resolution ~ half a scale height**

$$\int_{+\infty}^{-\infty} B_\nu[T(\xi)]\cdot K_\nu(\xi)d\xi = \mathrm{I}(\nu)$$

$$B_\nu[T] = B_\nu[T_0] + \frac{\partial B}{\partial T}\Delta T(\xi)$$

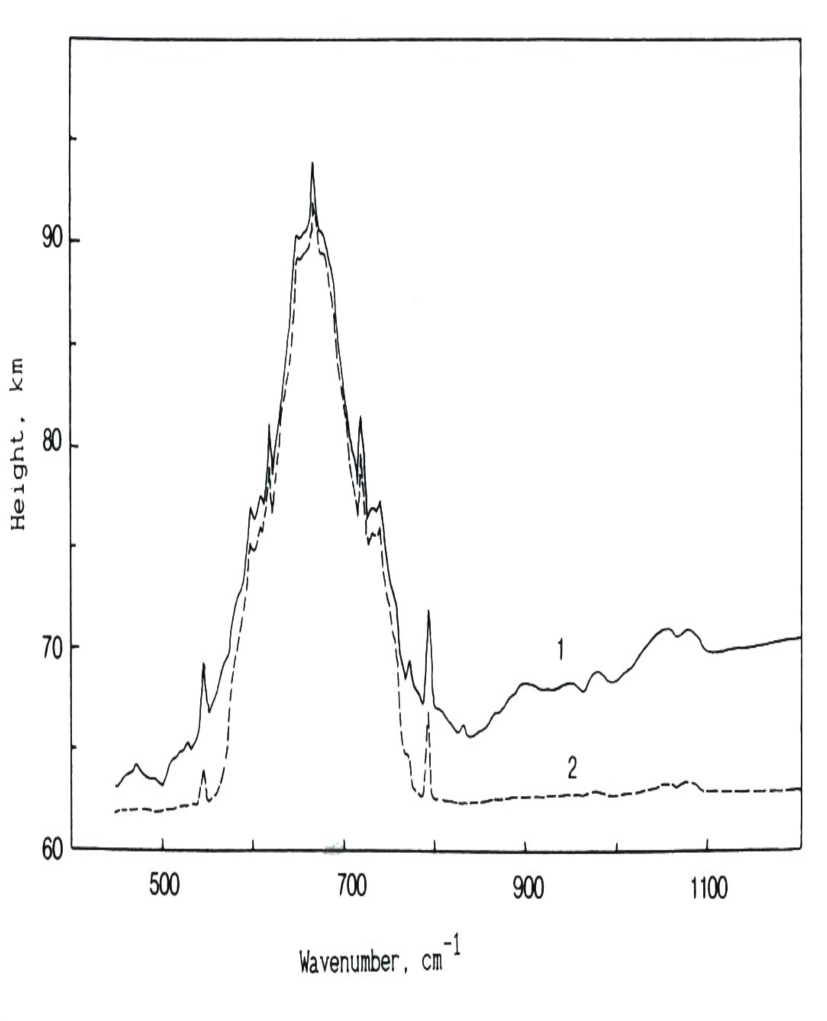
$$\int_{+\infty}^{-\infty} K_\nu(\xi)\cdot\frac{\partial B}{\partial T}[T_0]\cdot\Delta T(\xi)d\xi = \mathrm{I}_\nu - \mathrm{I}_\nu[T_0]$$

Temperature retrieval is an ill-posed problem.

Special stabilization (regularization) methods are required

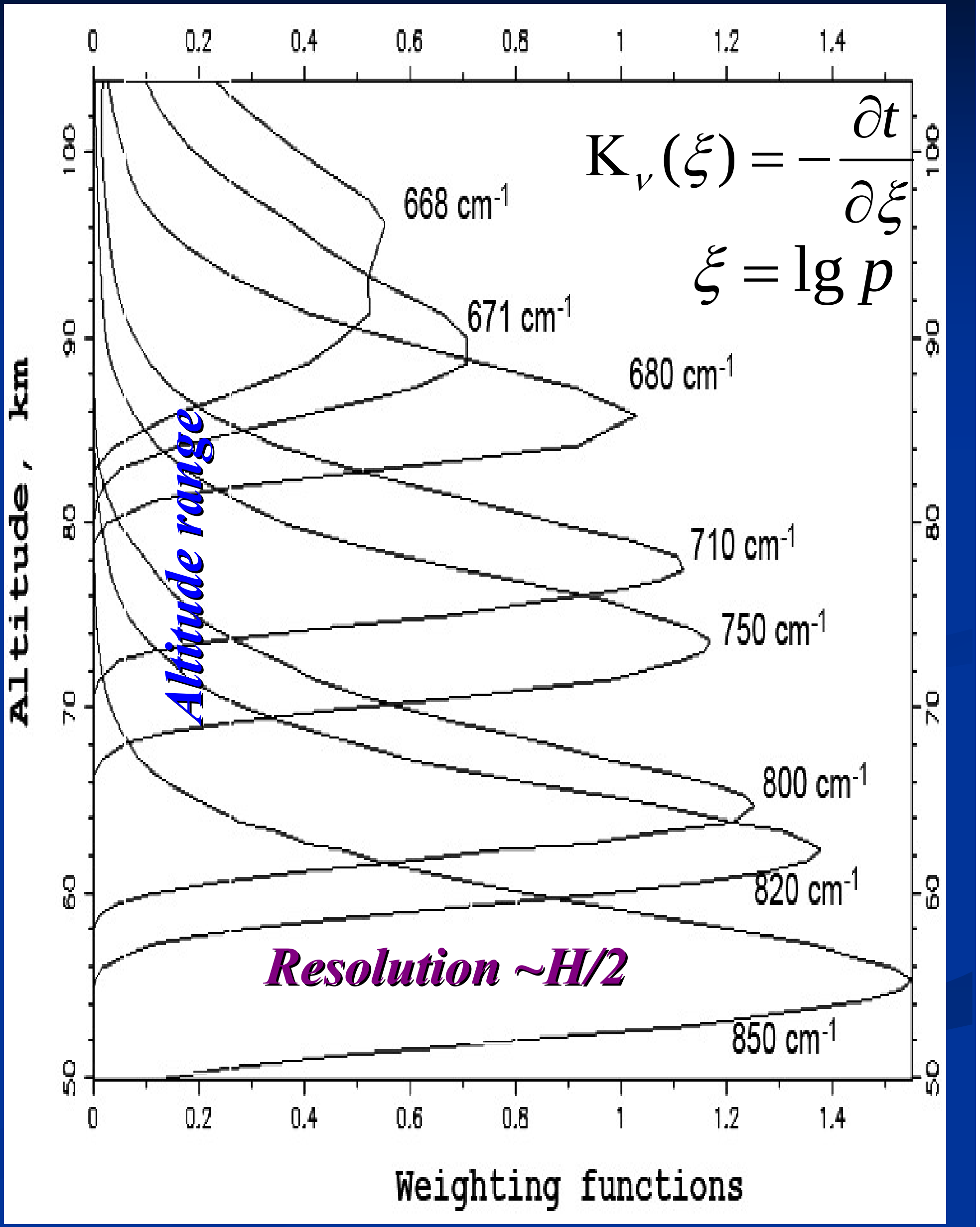
Vertical sounding of the temperature structure

Altitude of the level $\tau = 1$



Wavenumber, cm^{-1}

$\tau \sim 1$ rule



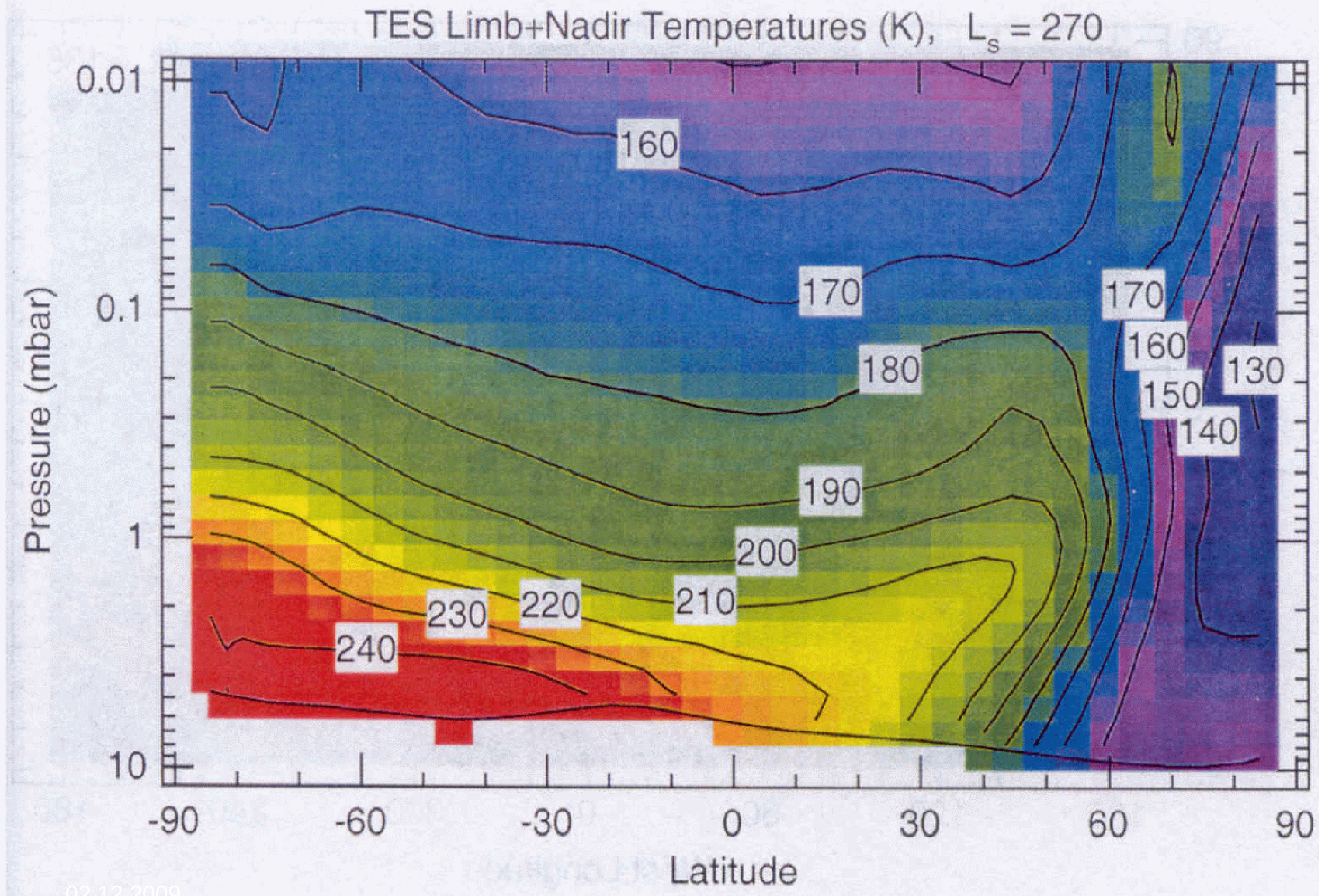
$$K_\nu(\xi) = -\frac{\partial t}{\partial \xi}$$

$$\xi = \lg p$$

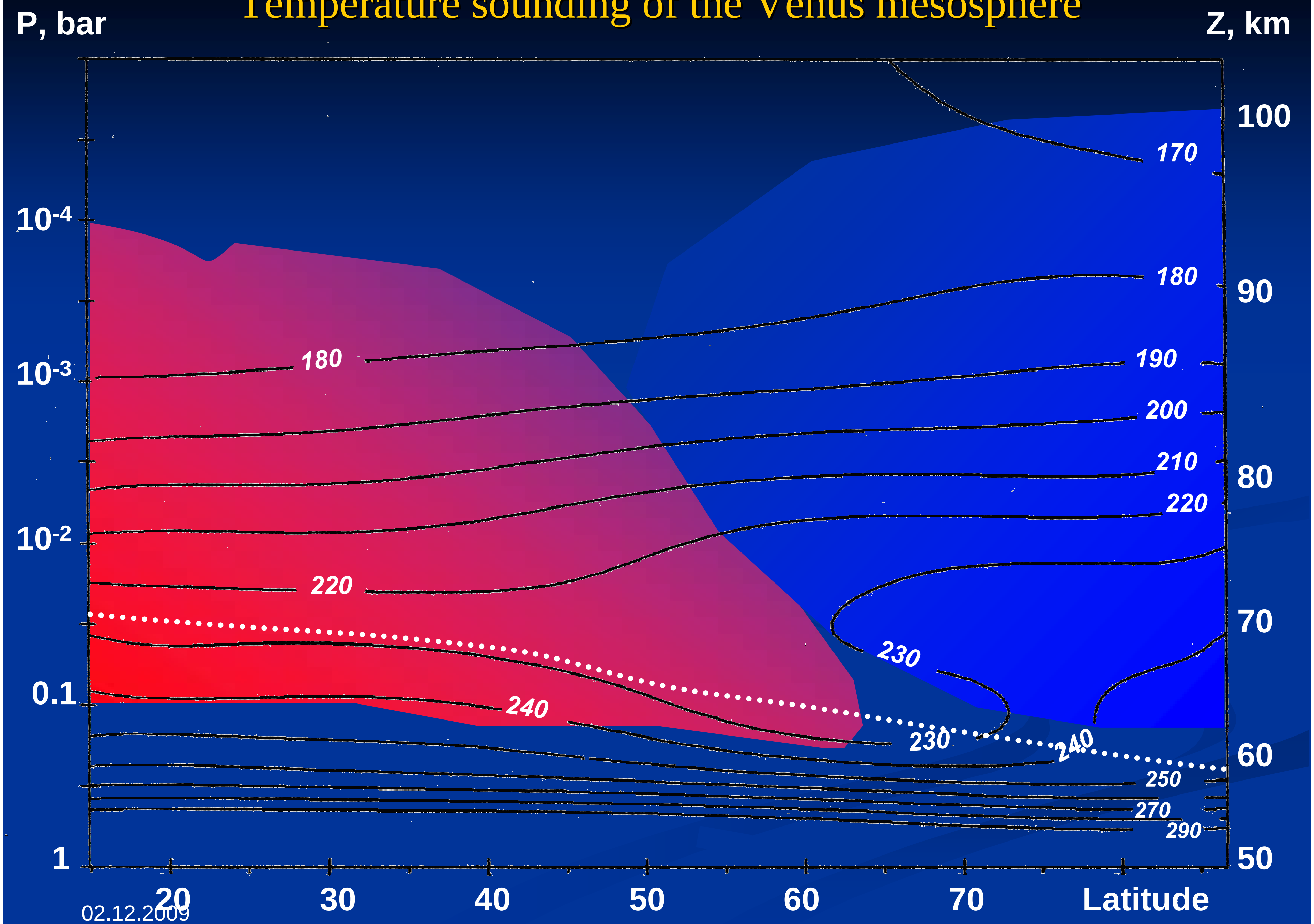
Altitude range

Resolution ~H/2

Mars atmospheric temperatures



Temperature sounding of the Venus mesosphere



02.12.2009

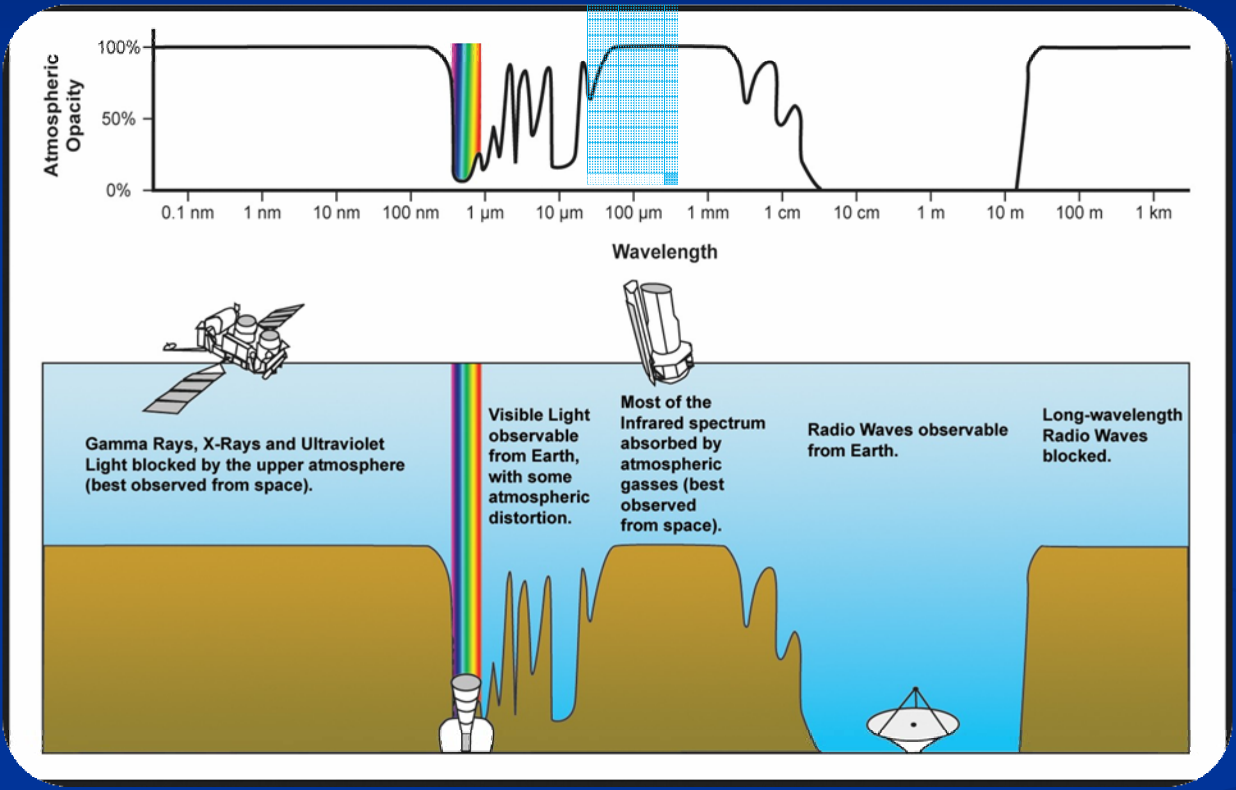
Ground-based observations of planetary atmospheres

The Earth´s Atmospheric Window

Space-based astronomy

Herschel

the Earth’s atmosphere is partially transparent



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

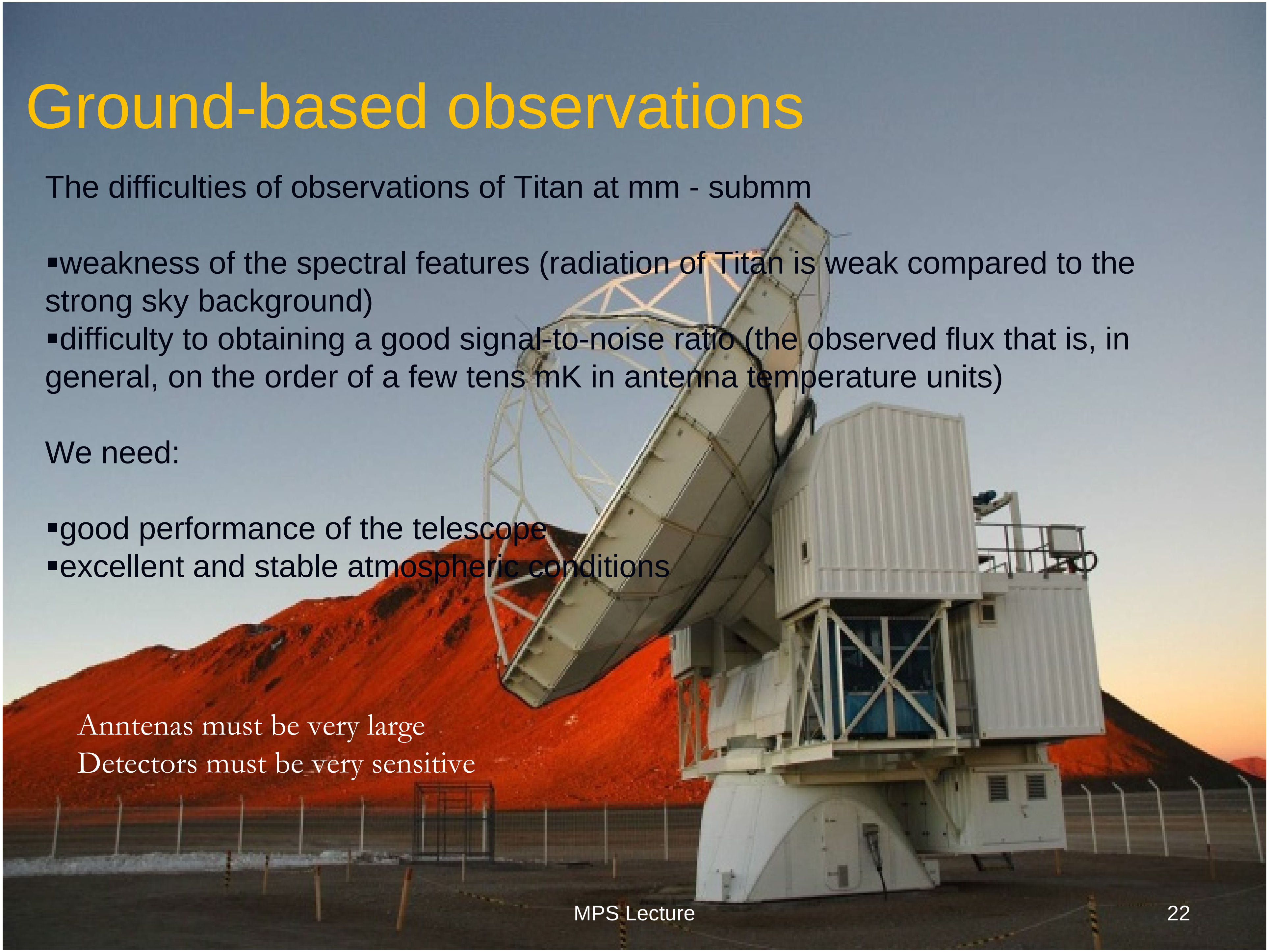
Long-wavelength Radio Waves blocked.

Ground-based astronomy

numerous water vapour absorption bands: observing sites have to be dry, cool, and with stable weather conditions

These various atmospheric 'windows' determine which kinds of astronomy can be done from the ground, and which have to be done from space.

Ground-based observations



The difficulties of observations of Titan at mm - submm

- weakness of the spectral features (radiation of Titan is weak compared to the strong sky background)
- difficulty to obtaining a good signal-to-noise ratio (the observed flux that is, in general, on the order of a few tens mK in antenna temperature units)

We need:

- good performance of the telescope
- excellent and stable atmospheric conditions

Anntenas must be very large
Detectors must be very sensitive

Example 1

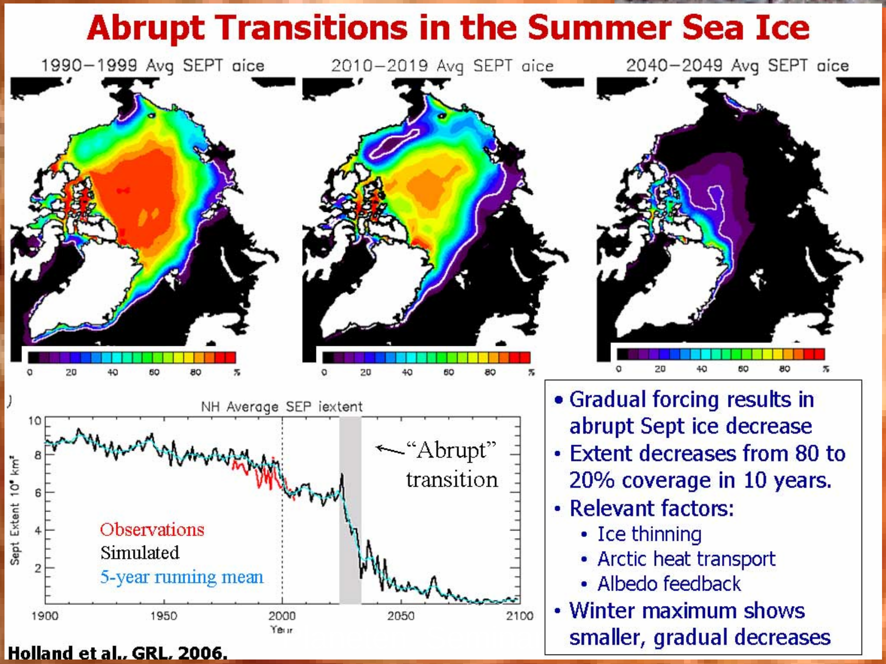
Mesospheric Winds, Thermal Structure, and CO Distribution on Venus

Example 1

Why study Venusian atmospheric dynamics ?

- To understand the possible consequences of future climate changes on Earth


Polar bear forages on dry ground, Barrow AK © 2002 Braasch


Abrupt Transitions in the Summer Sea Ice

1990–1999 Avg SEPT aice

2010–2019 Avg SEPT aice

2040–2049 Avg SEPT aice

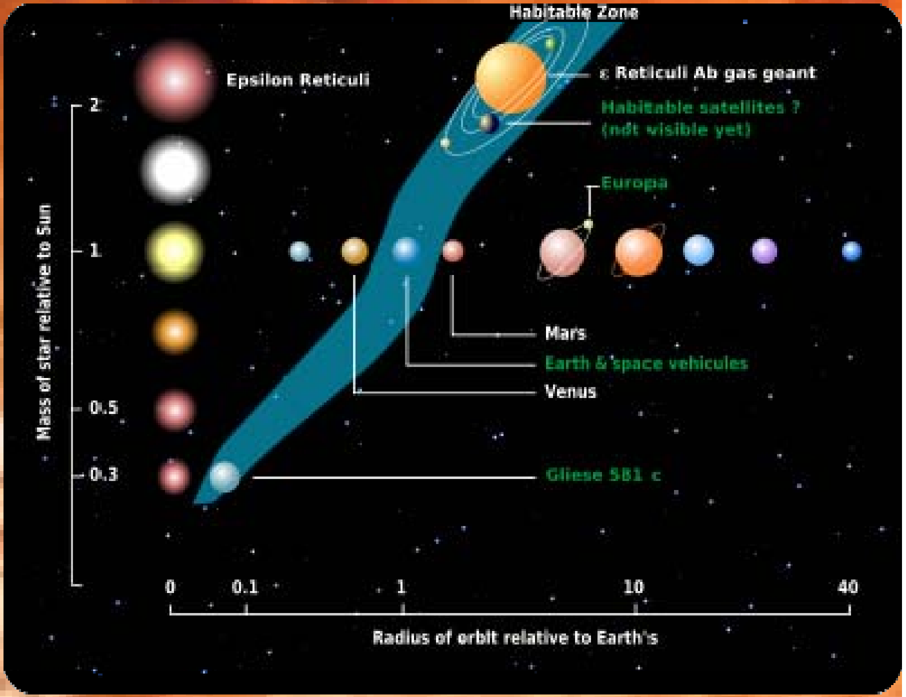
- Gradual forcing results in abrupt Sept ice decrease
- Extent decreases from 80 to 20% coverage in 10 years.
- Relevant factors:
  - Ice thinning
  - Arctic heat transport
  - Albedo feedback
- Winter maximum shows smaller, gradual decreases

Holland et al., GRL, 2006.

Example 1

Why study Venusian atmospheric dynamics ?

- To assess extrasolar planet‘s habitability



Example 1

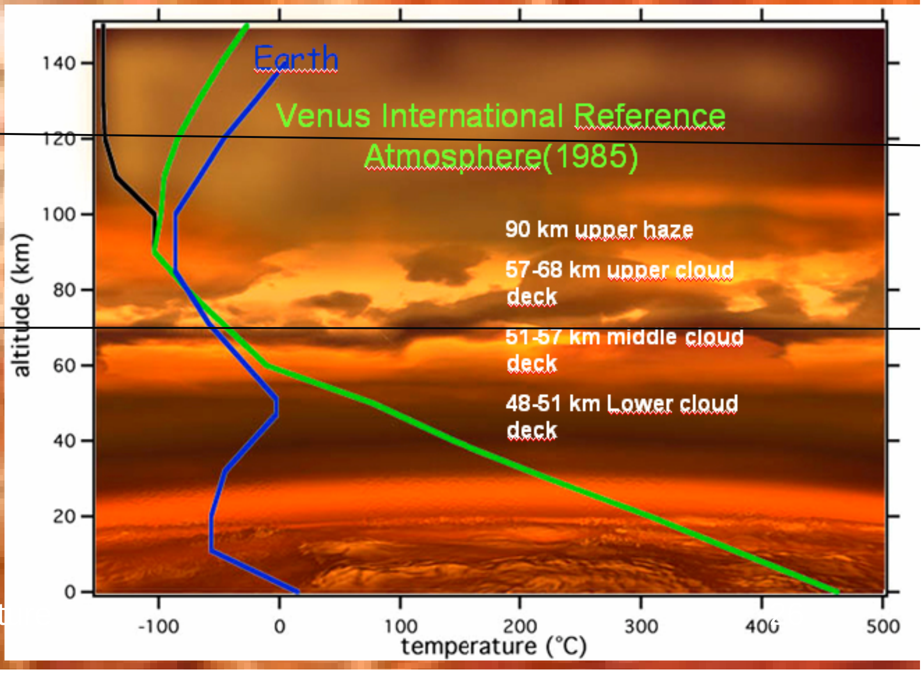
Why study Venusian atmospheric dynamics ?

- To learn about Venus itself

The atmosphere of Venus can be vertically split into three different dynamical regions :
(1) the ***troposphere***: below 70 km:
(2) the ***thermosphere***, above z = 120 km :
(3) the ***mesosphere***, between z=70 and 120 km.

❖ Combination of two different wind regimes
sub-solar to anti-solar flow pattern
time-variable retrograde super rotation

❖acts as a transition region



Example 1

On 5th June 2007: NASA **MESSENGER** spacecraft encompassed a flyby to Venus
ESA´s Venus Express orbites around Venus

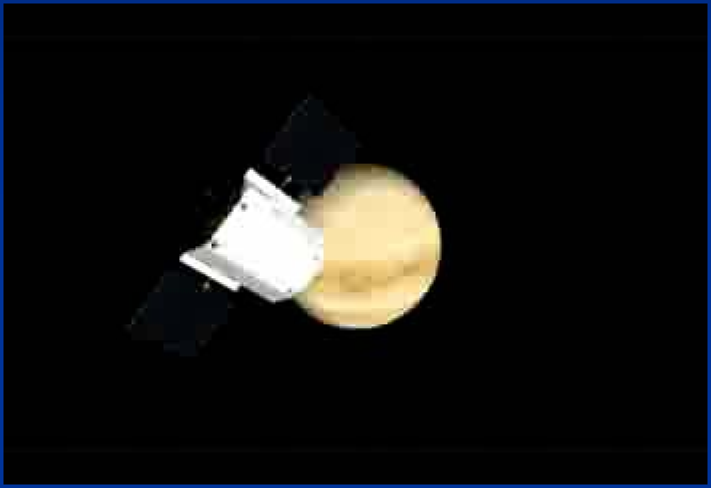
Credits:JHU/APL

Both spacecrafts carried out multi-point observations of the Venusian atmosphere for several hours.

Example 1

A 1st coordinated observational campaign [23 May – 9 June (later) 2007]:

Space



Credits:JHU/APL

Spacecrafts & Satellites:
Venus Express
Messenger

Remote sensing from Earth - radio, submillimetre, infrared and visible -

IRTF Texes
JCMT-15m
VLT-UVES
Keck-HIRES
OHP/Sophie
Nobeyama
IRAM-30m
SMT

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41012

Example 1

A 2nd coordinated observational campaign [January – June 2009]:

Space

Remote sensing from Earth - radio, submillimetre, infrared and visible -

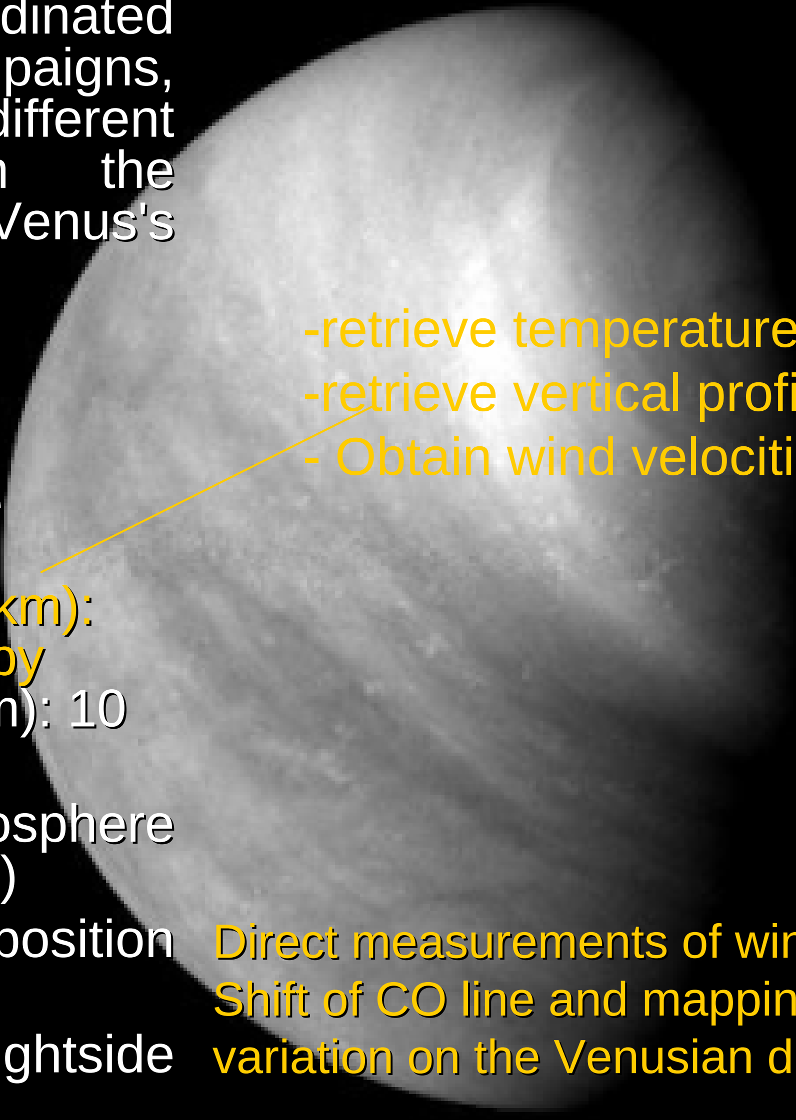
Credits:JHU/APL

Spacecrafts & Satellites:
Venus Express

Keck-HIRES
APO/ARCES
CFHT/ESPaDOnS
Okayama/HIDES
AAT/IRIS 2
JCMT-HARP/ACSIS
SMA
SMT
CARMA
Kitt Peak/THIS

Example 1

Science Goals



During the coordinated ground-based campaigns, observations by the different teams focuses on the atmosphere above Venus's cloud layer and include:

- Wind measurements at different altitudes
  - cloud top level: visible spectroscopy
  - mesosphere (90-105 km): mm/submm spectroscopy
  - thermosphere (120 km): 10 µm observations
- Morphology of the mesosphere airglow emission (O, O_2)
- Mesospheric composition (H_2O, SO, SO_2, HCl)
- Deep atmosphere nightside composition

-retrieve temperature vertical profiles

-retrieve vertical profiles of CO

- Obtain wind velocities

Direct measurements of wind from Doppler Shift of CO line and mapping the wind velocity variation on the Venusian disk

Credits: ESA

How? Ingredients

Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

Example 1

II.- Spectral Line Observations of Venus

Between 7.6.07 and 16.6.07 (1st campaign)

10-m Submillimeter Telescope
(HHSMT, Arizona)

Instrumentation used:

Receivers: 345 SIS, 2mmJT/1.33JT ALMA
[320-375] [210-279] GHz

Backends:

- Chirp Transform Spectrometer (**40 kHz)**
- Acousto-Optical-Spectrometers (AOS´s)
- Forbes Filterbanks (FFBS)

Results:

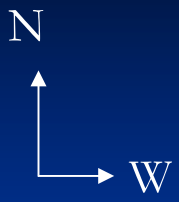
36 spectral line observations of Venus with the lines

CO J=3-2 - 15 min - SIS-345
^{13}CO J=2-1 - 30 min - 1.3mm ALMA
^{12}CO J=2-1 - 150 min - 1.3mm ALMA

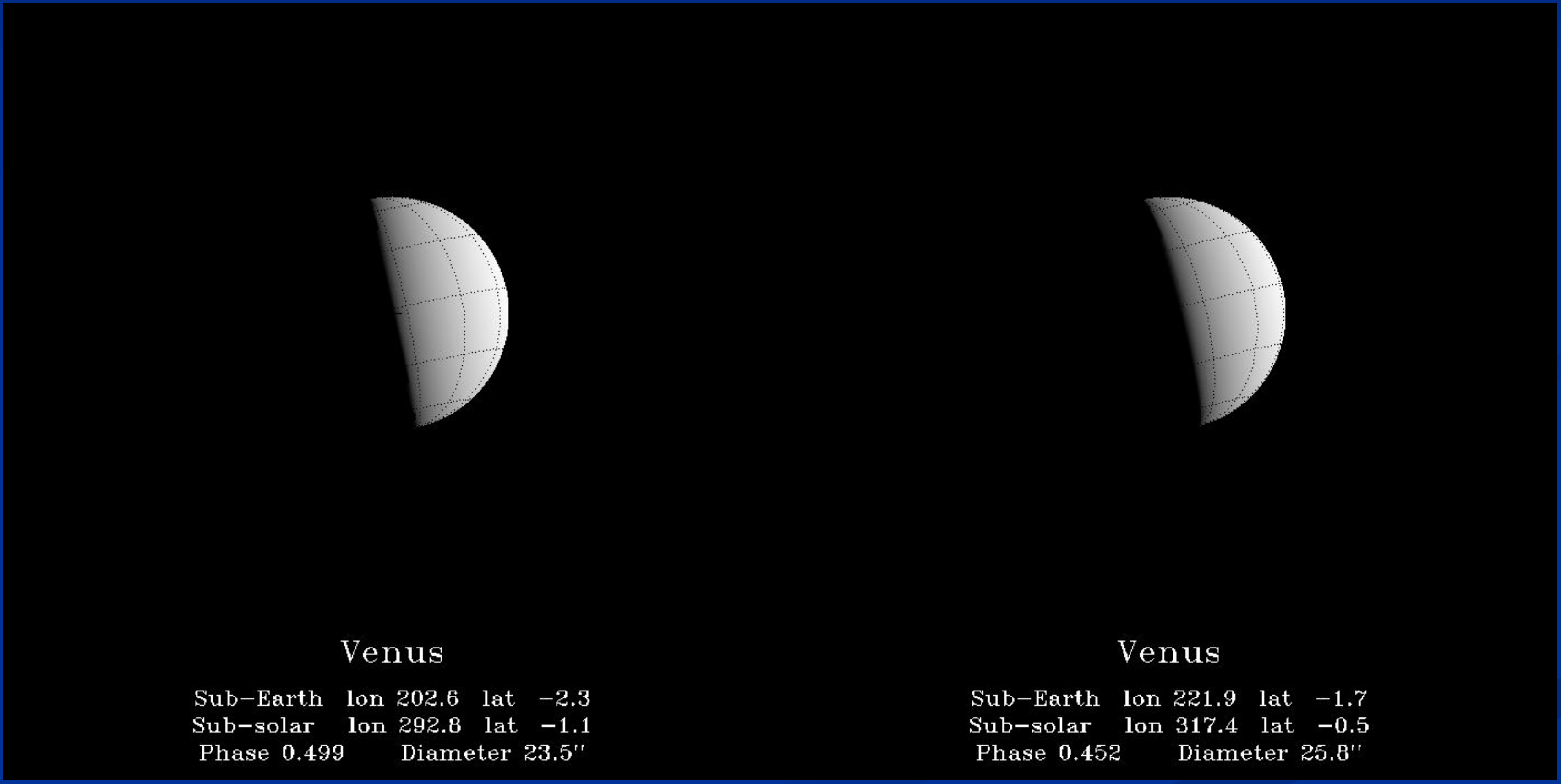
at 15 different beam positions at the Venus disk

Example 1

Fractional disk illumination



Apparent disk of Venus for 2007 Jun 8 and 16 at 20:00 UT



```
           Venus
Sub-Earth  lon 202.6  lat  -2.3
Sub-solar  lon 292.8  lat  -1.1
 Phase 0.499    Diameter 23.5''
```

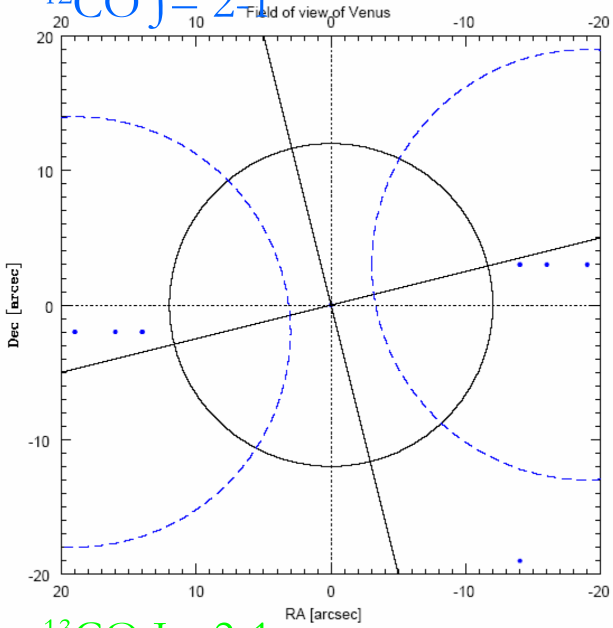
```
           Venus
Sub-Earth  lon 221.9  lat  -1.7
Sub-solar  lon 317.4  lat  -0.5
 Phase 0.452    Diameter 25.8''
```

49.9 %

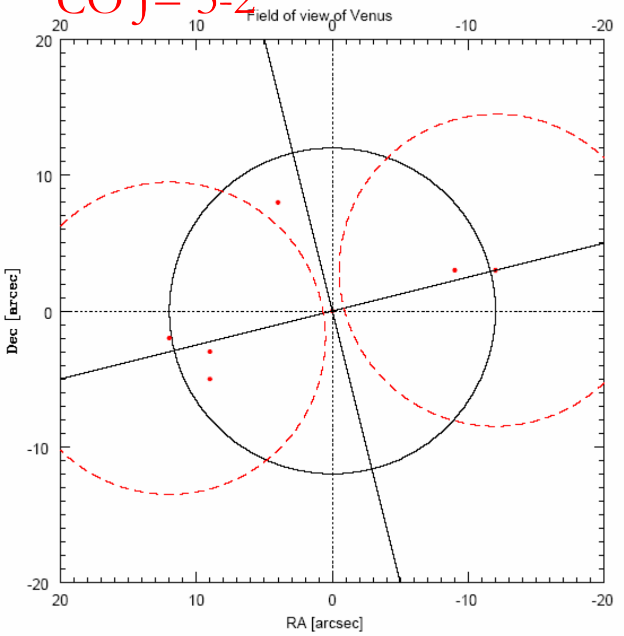
45.3 %

Example 1

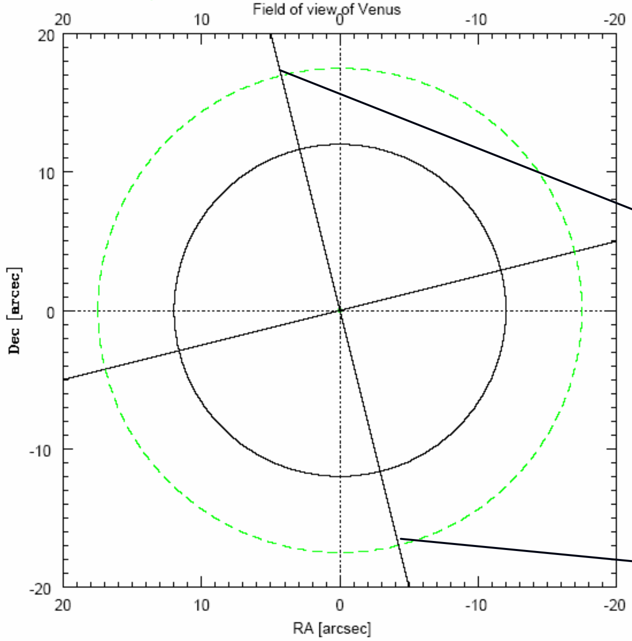
^{12}CO J= 2-1



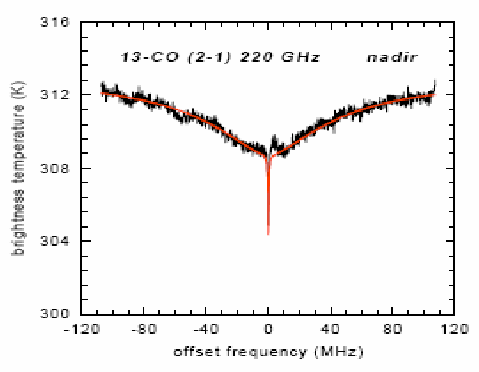
CO J= 3-2



^{13}CO J= 2-1

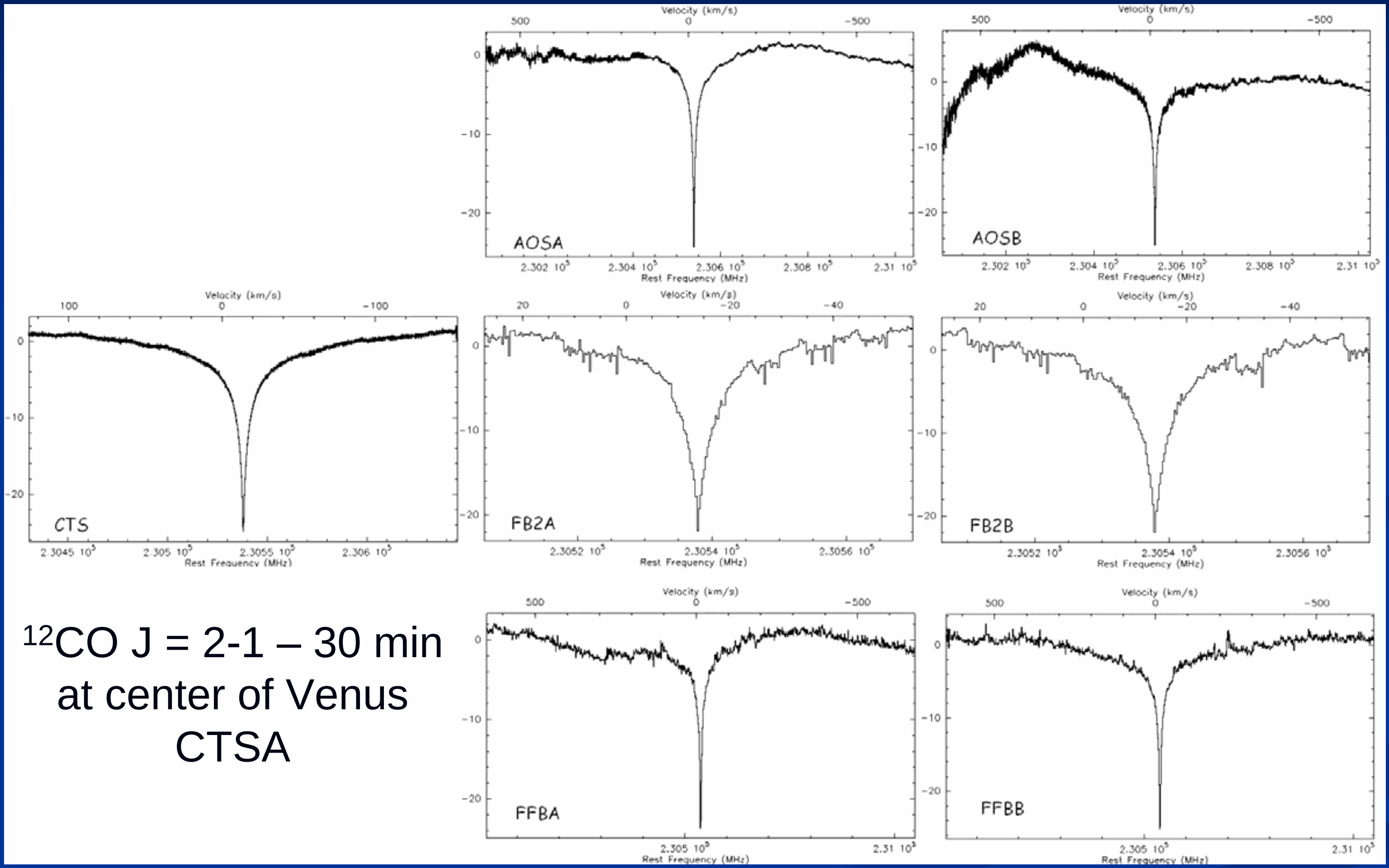


Beam positions on Venus‘s disk



Example 1

Spectra Morphology for the ^{12}CO J = 2-1 line for different backends



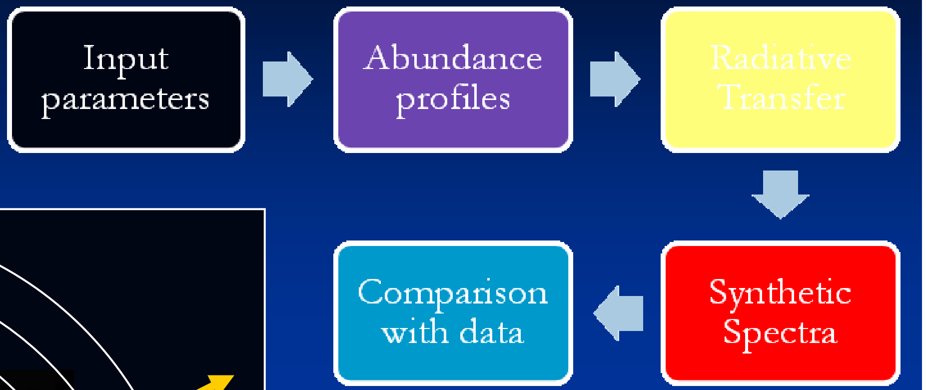
^{12}CO J = 2-1 – 30 min
at center of Venus
CTSA

Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Very narrow, deep absoption lines
are obtained!

Example 1

III. Technique to retrieve profiles of temperature and CO volume mixing ratio

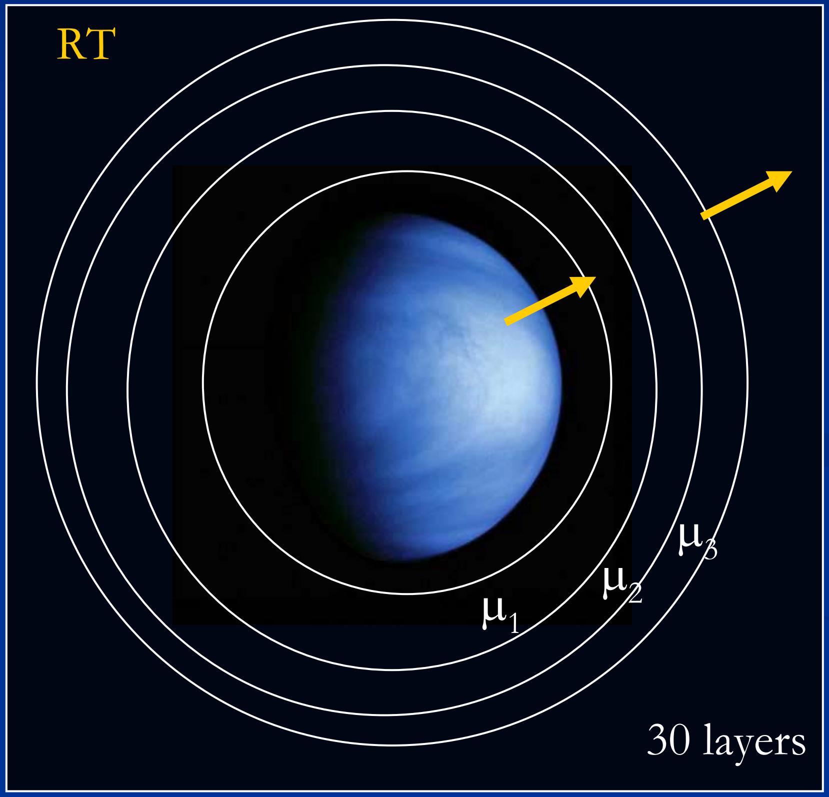


Optimal estimation algorithm

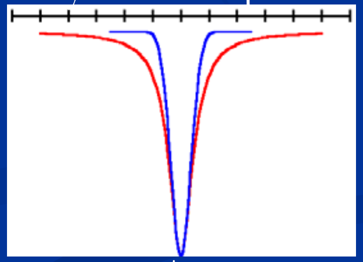
T profile

P profile

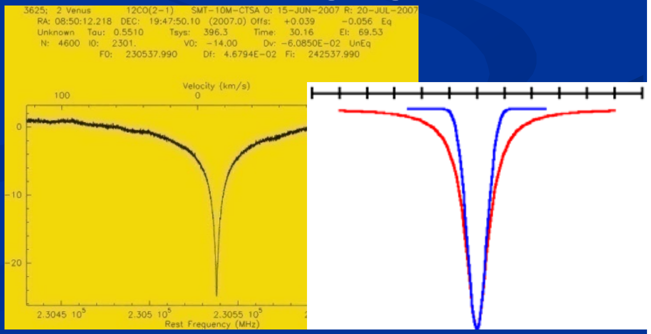
Vmr profile



Synthetic spectra



Fitting algorithm

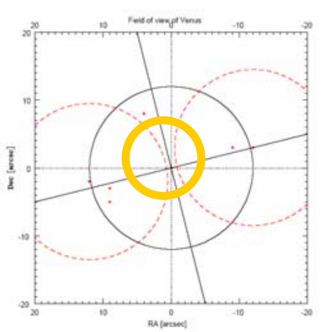


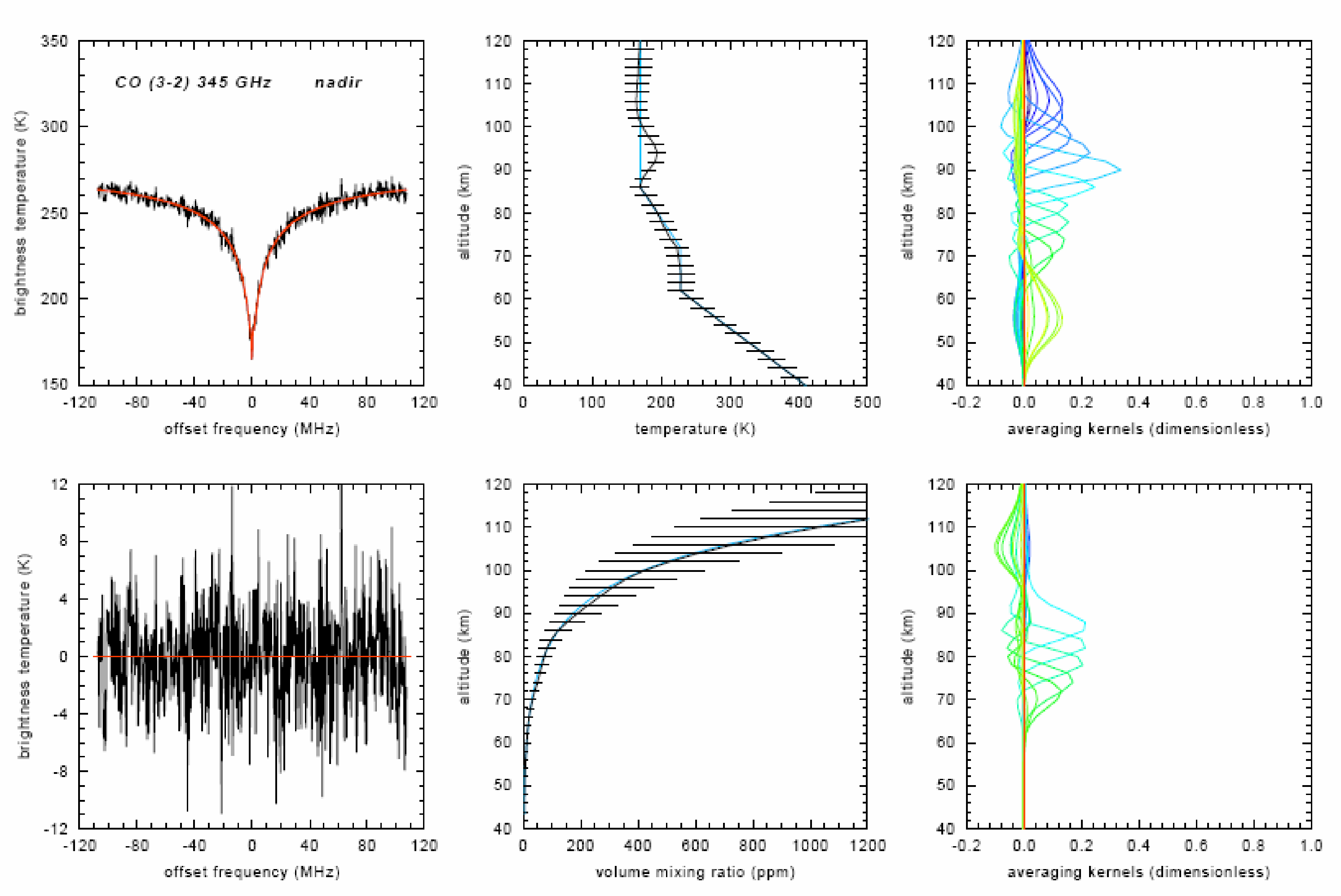
μ_i=absorption coefficient

New set of parameters

Example 1

IV.- Results: Thermal structure and CO Distribution

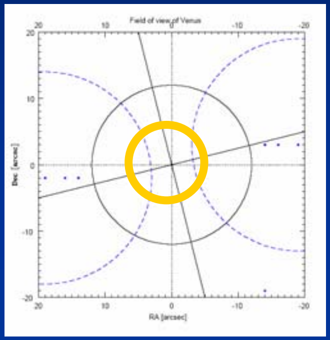


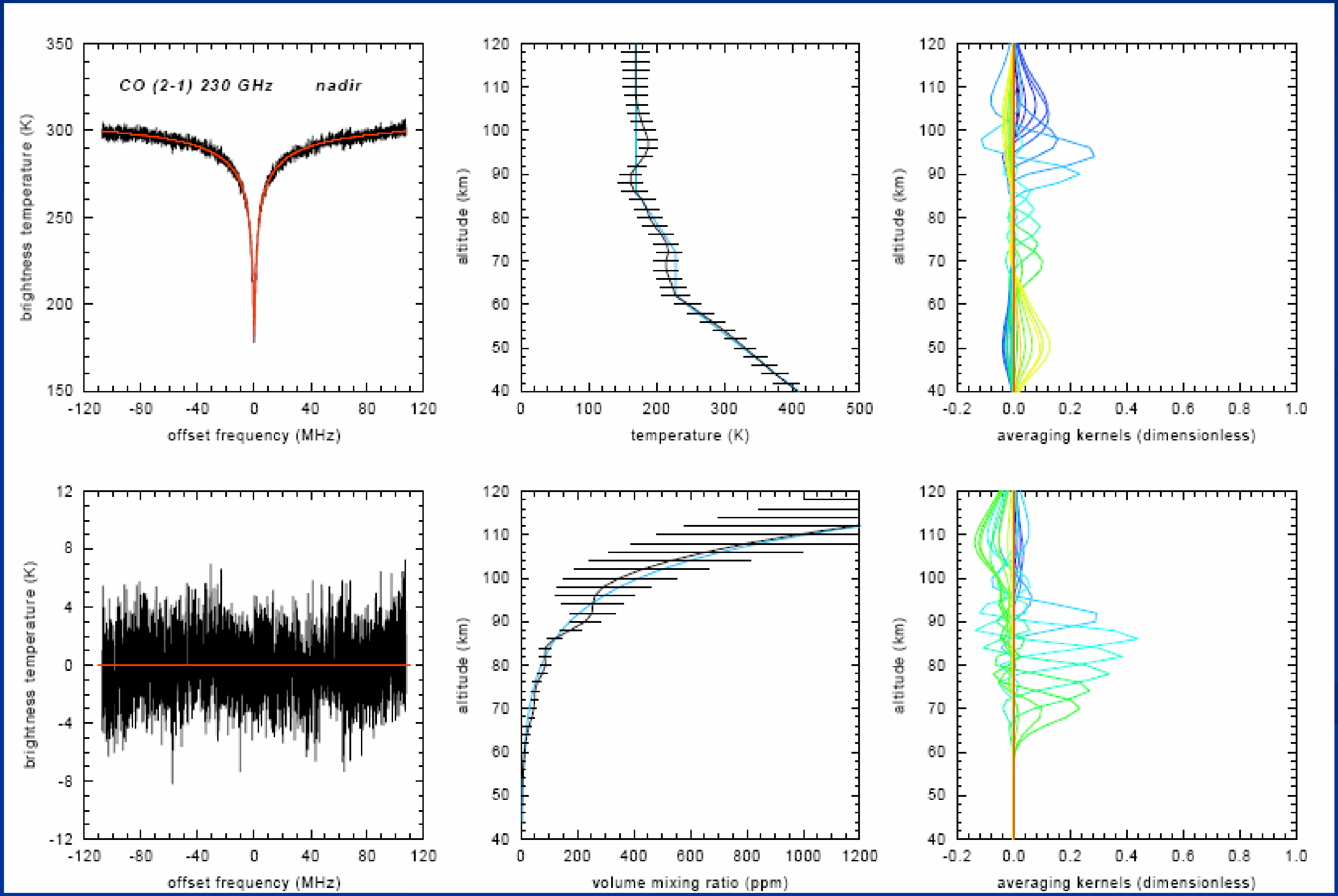


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Thermal structure and CO Distribution

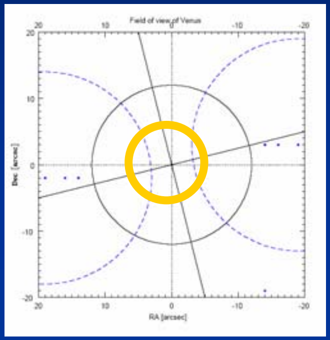


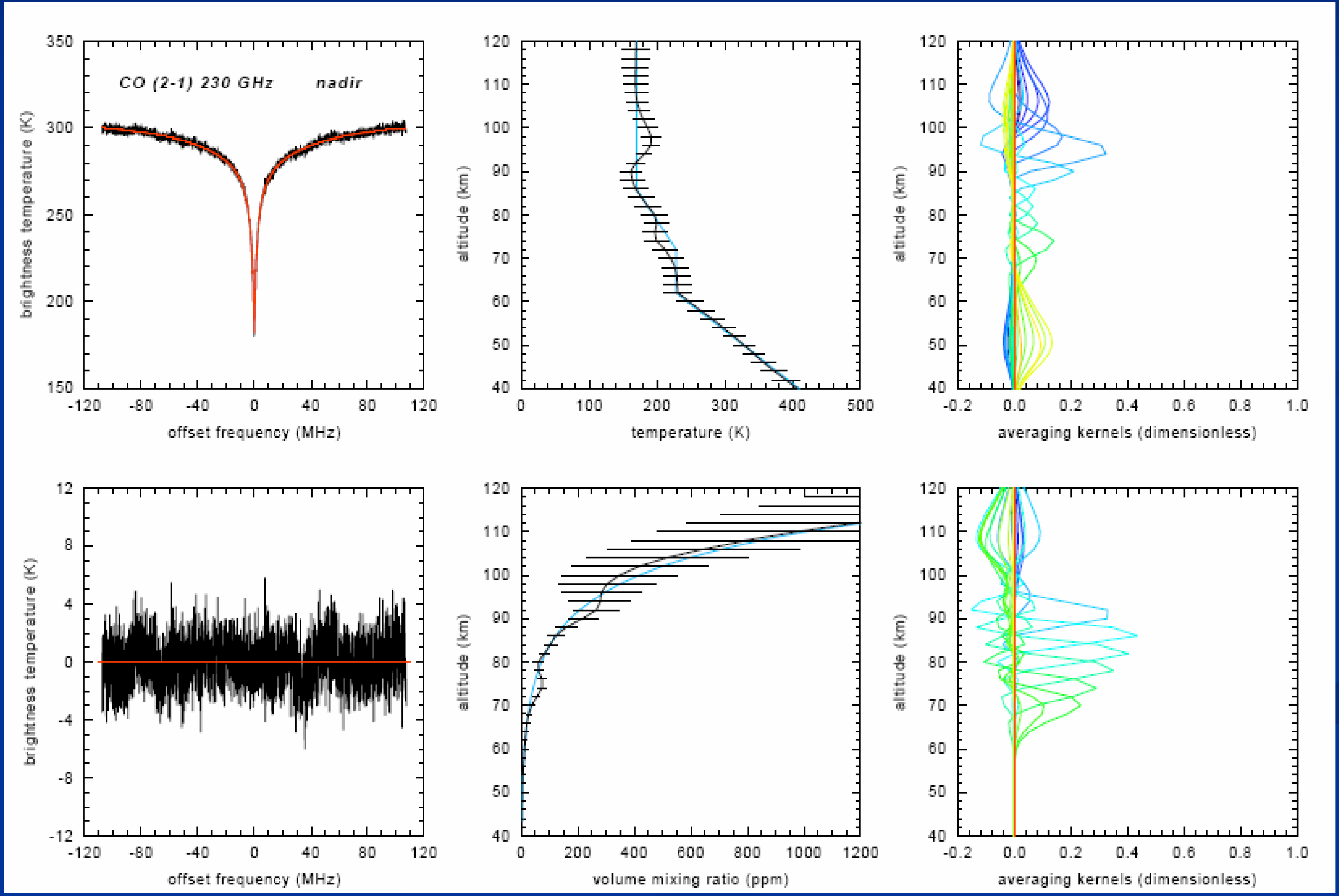


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Thermal structure and CO Distribution

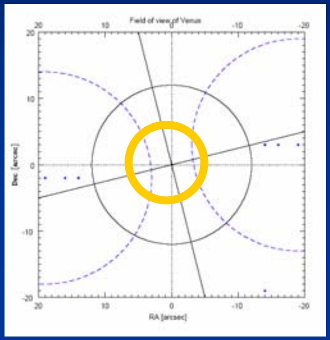


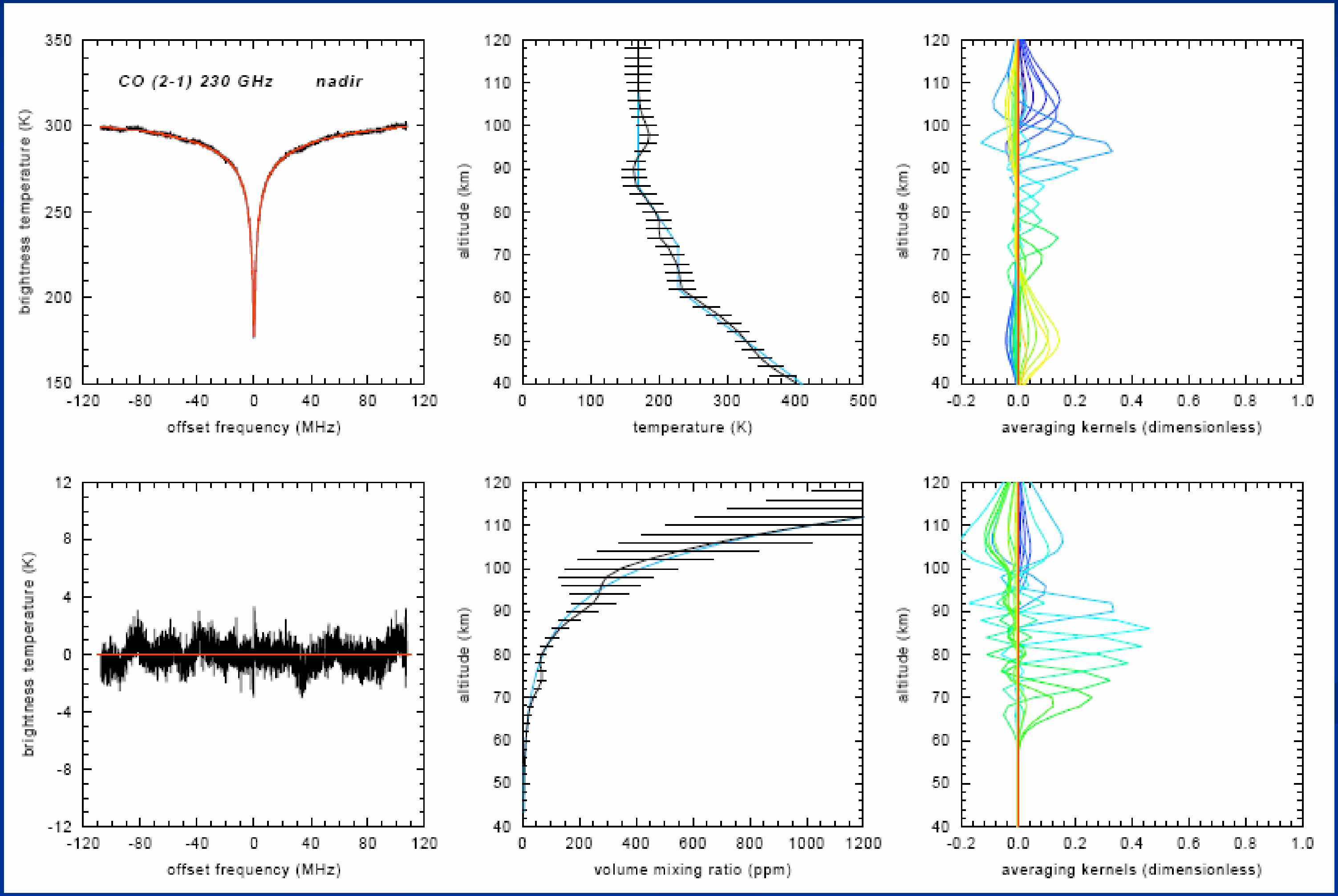


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

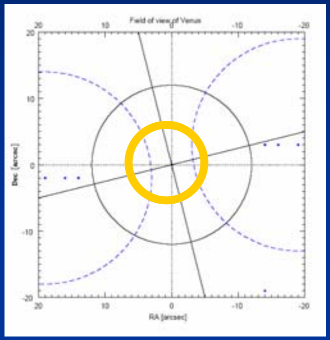
IV.- Results: Thermal structure and CO Distribution

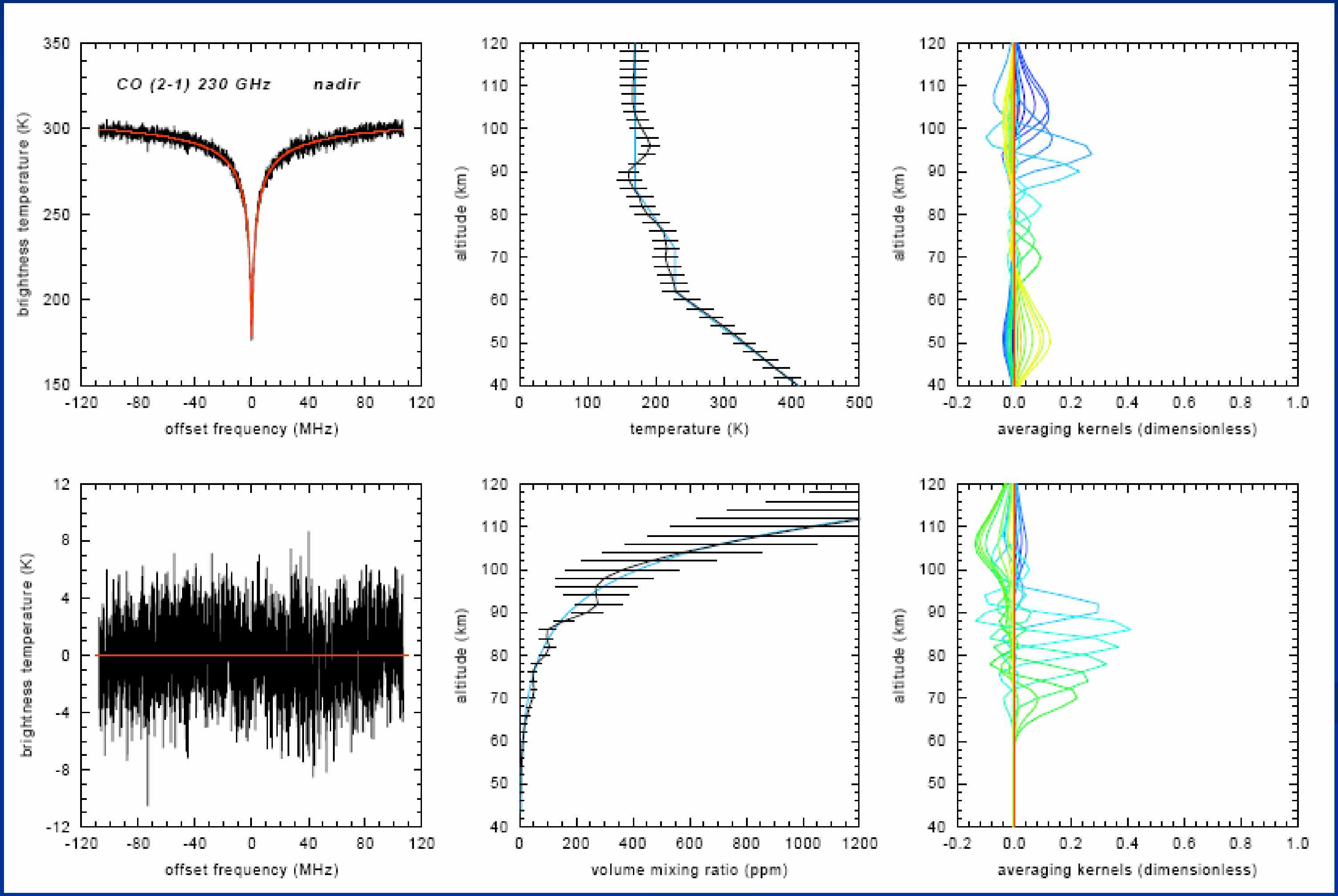




Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

IV.- Results: Thermal structure and CO Distribution

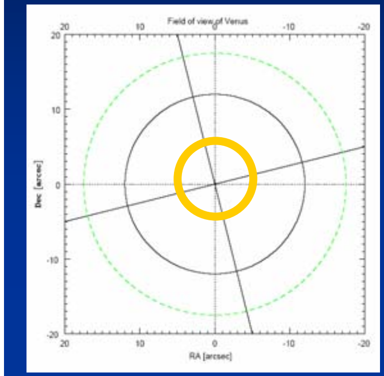


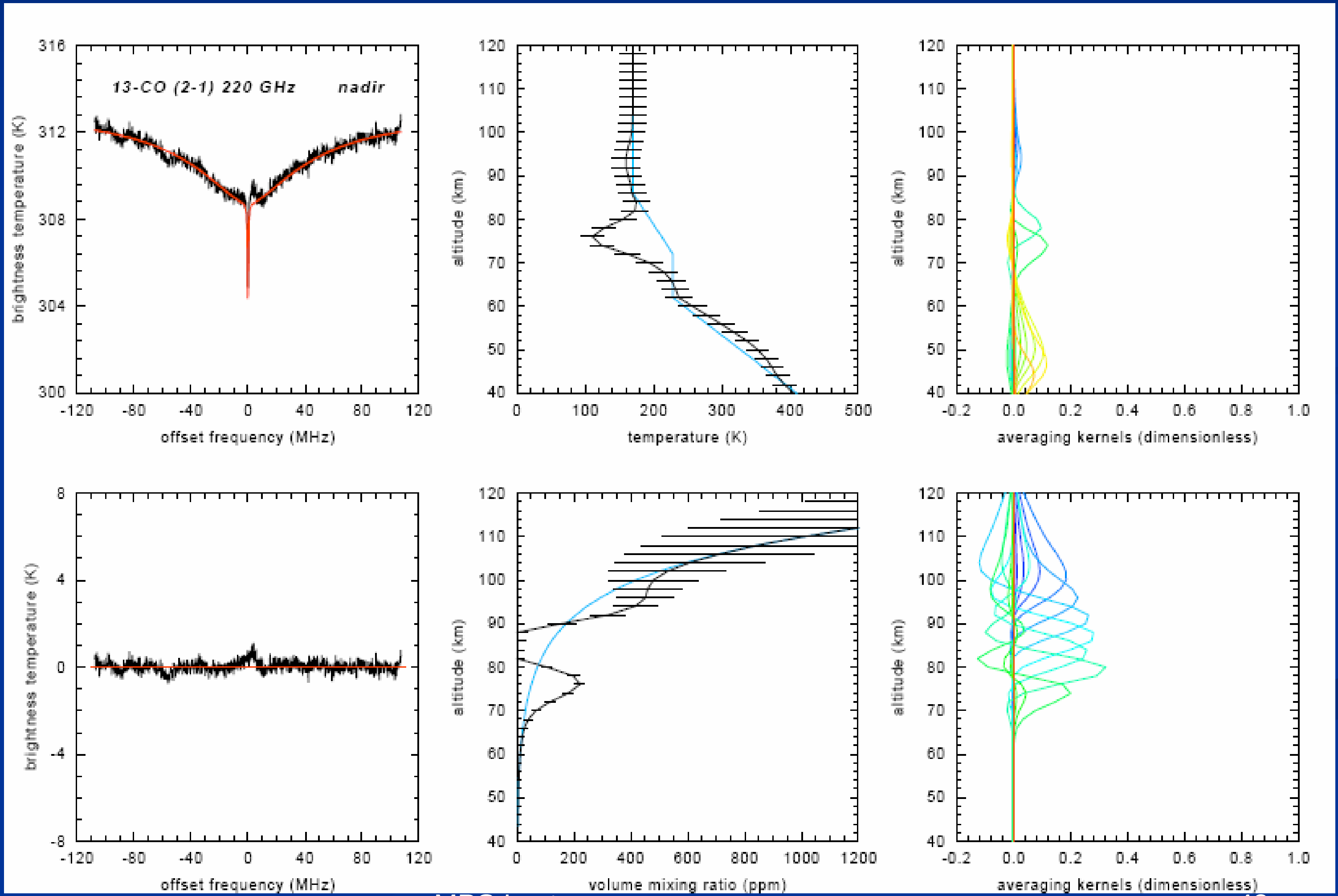


Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Thermal structure and CO Distribution

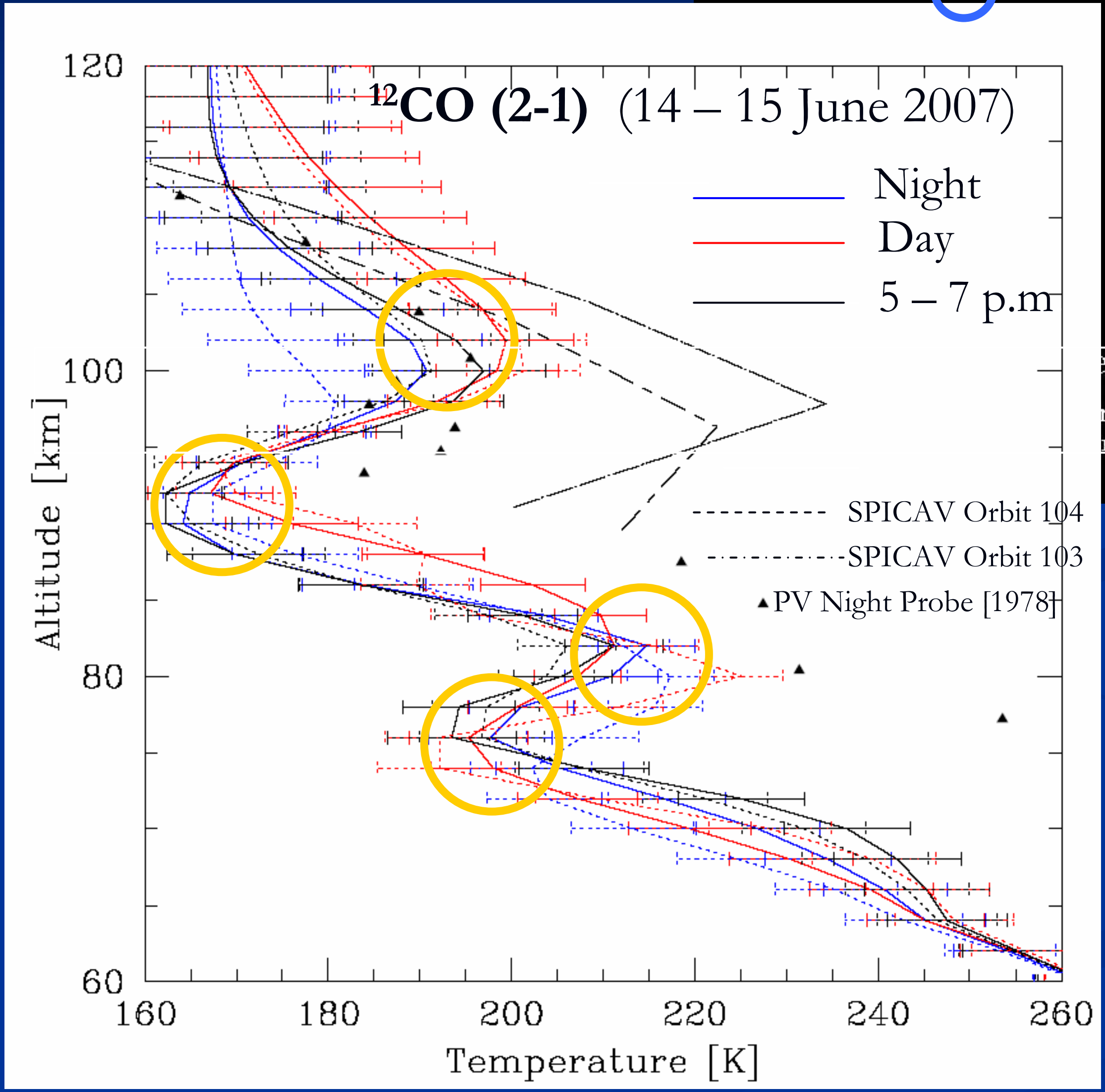


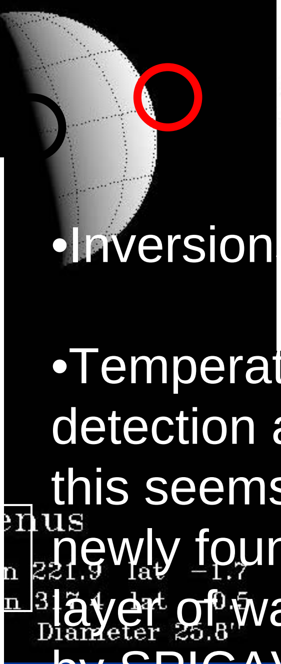


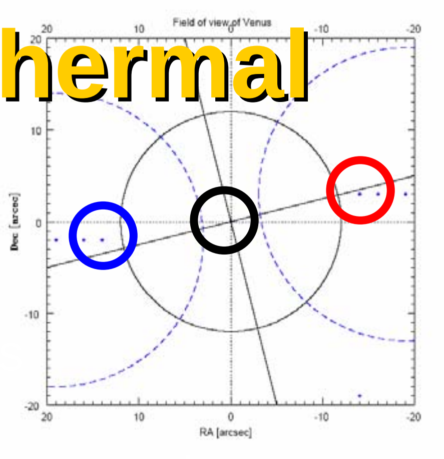
Rengel, Hartogh, Jarchow, PSS 56, 1688, 2008

Example 1

IV.- Results: Changes in the Thermal Structure







- Inversion

- Temperature peak detection at 90-100 km – this seems to support the newly found of the extensive layer of warm air detected by SPICAV (Bertaux et al. 2007).

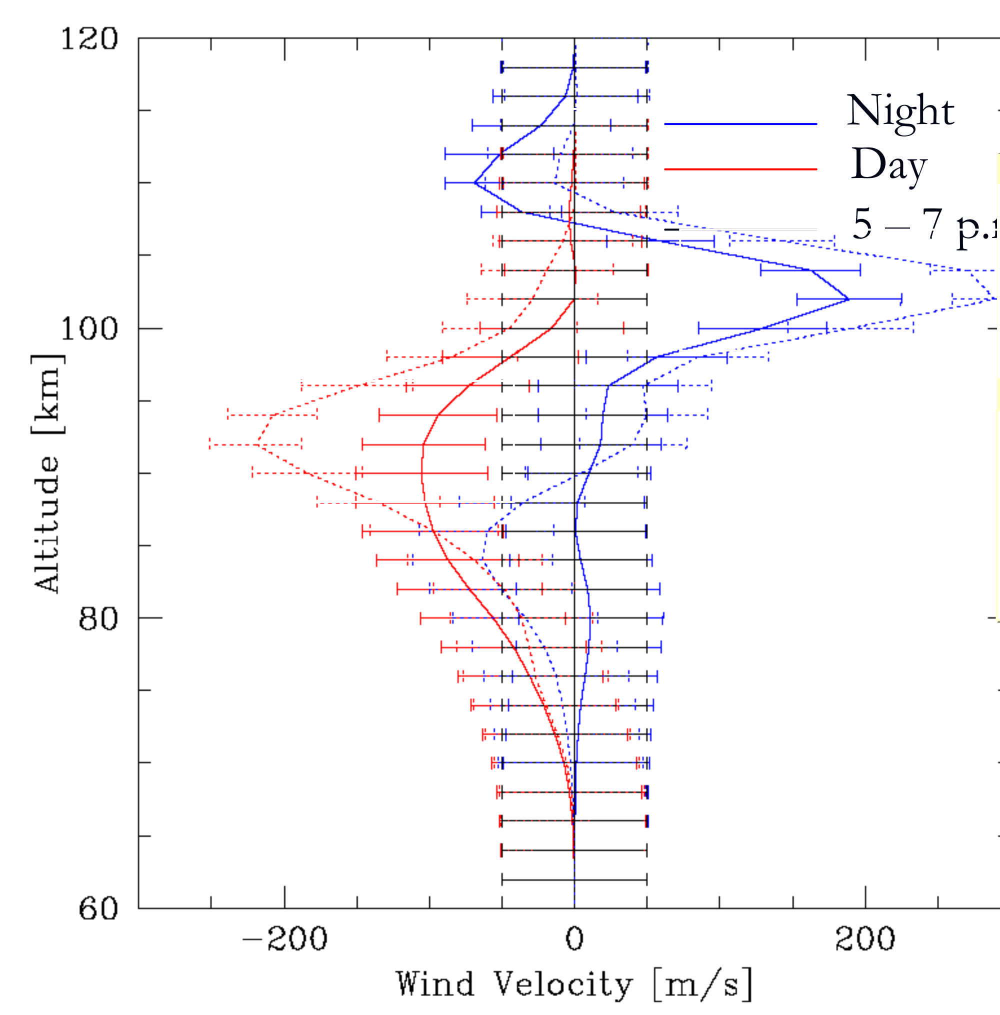
- Day-to-night temperature variations ~25 K at 100 km (15 June)

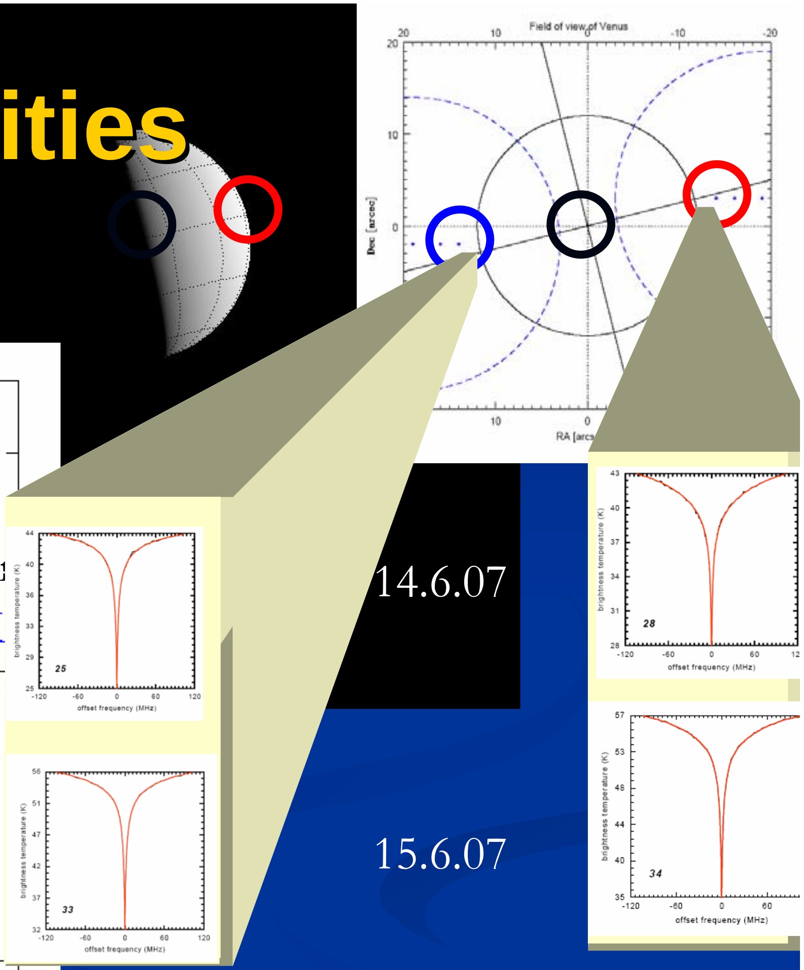
- Temporal diurnal temperature variations ~10 K at 80 km and nocturnal at 100 km.

Example 1

IV.- Results: Wind Velocities

^{12}CO (2-1) (14 – 15 June 2007)





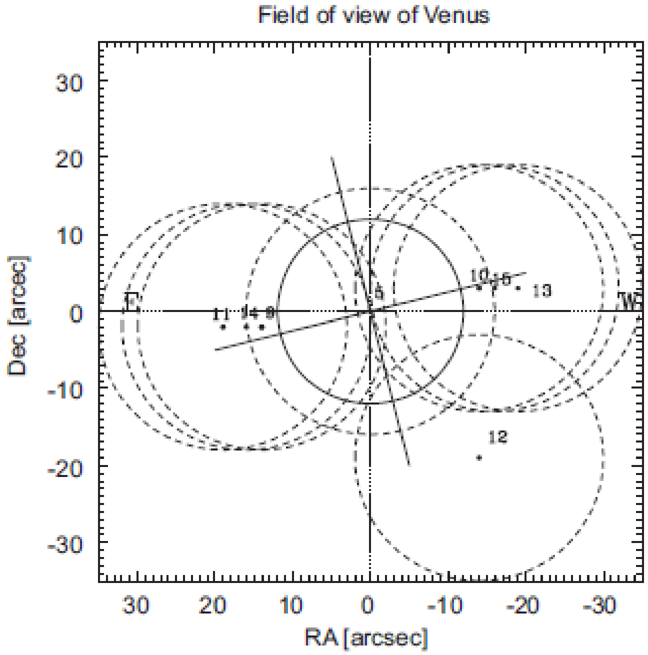
14.6.07

15.6.07

- Day-to-day variations of the wind velocities (at 92 km and 105 km altitude)

Example 1

IV.- Results: Wind Velocities



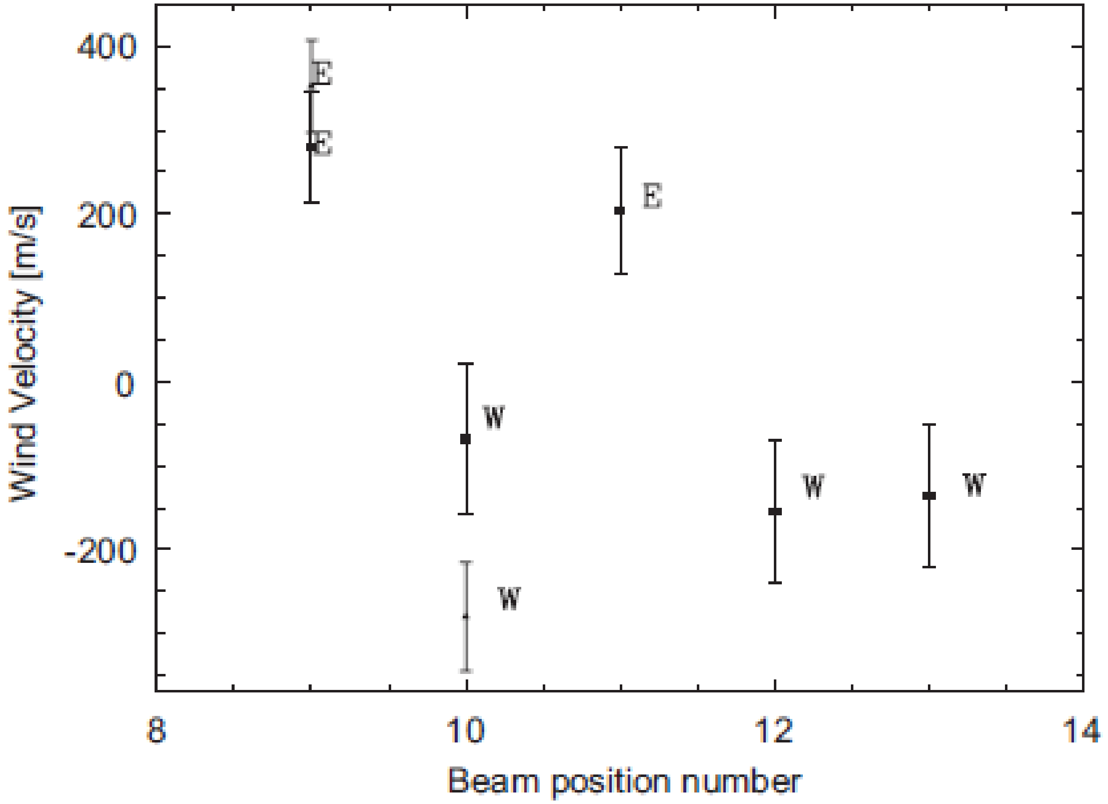
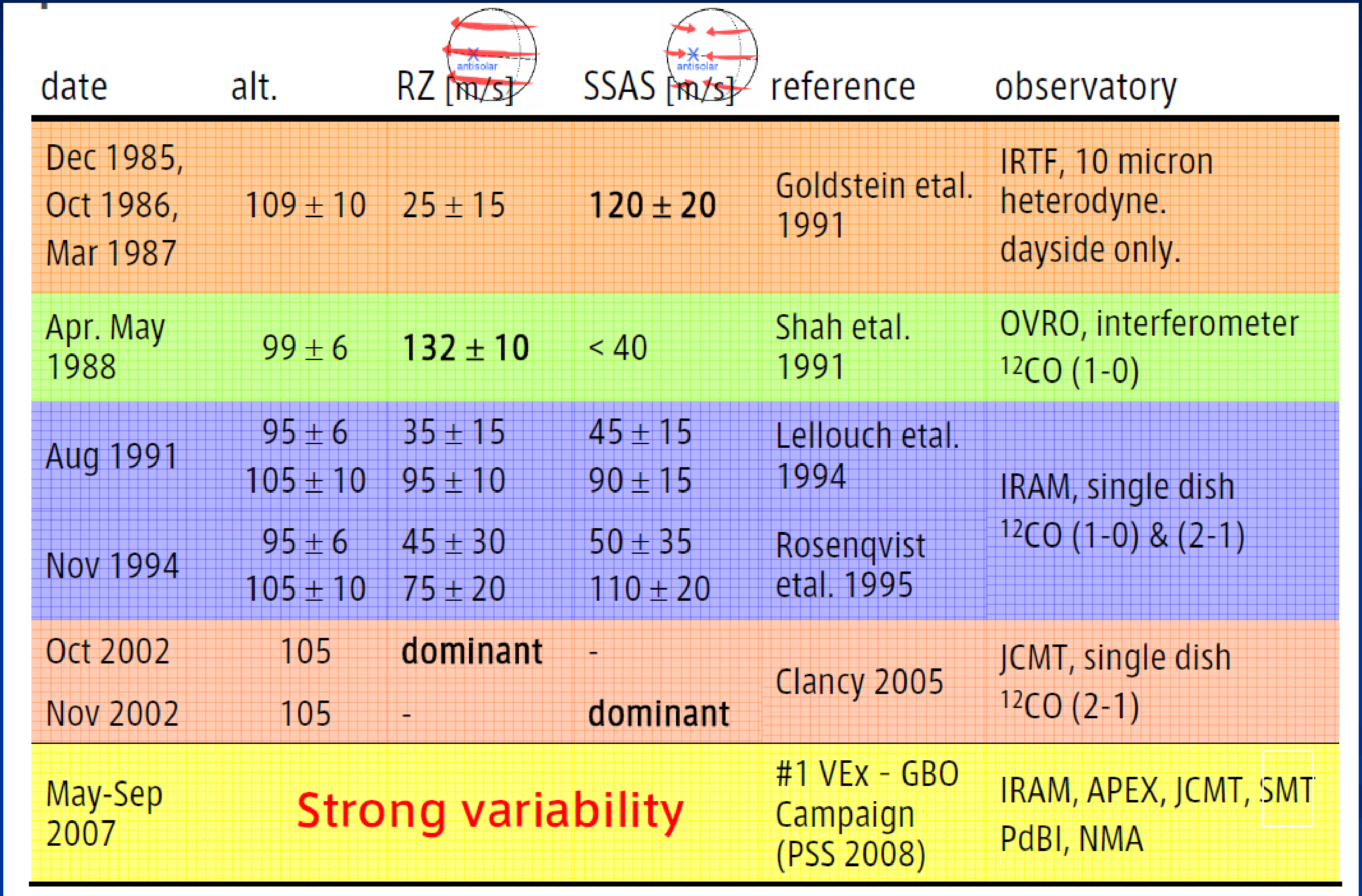


Fig. 15. Retrieved wind velocity measurements for different beam positions on the Venus' disc for two observing days. Squares: 14 June, triangles: 15 June. Retrieved velocity error bars are indicated. E: East, W: West.

Rengel, Hartogh, Jarchow, PSS 56, 2008, 1368

Example 1

Winds measurements



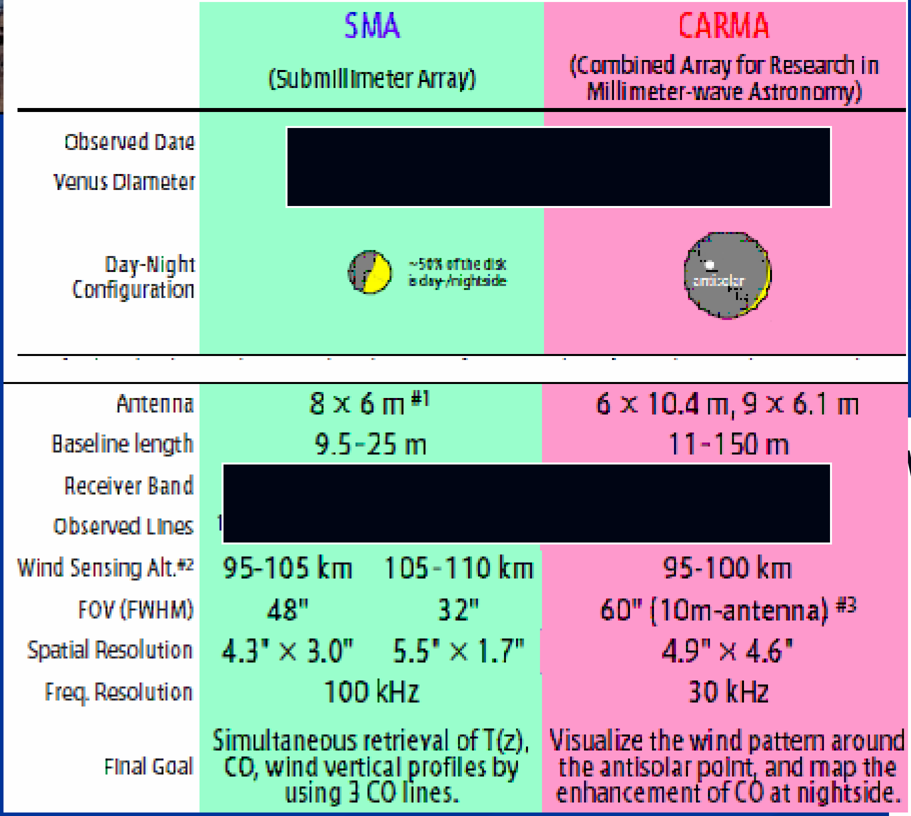
date	alt.	RZ [m/s]	SSAS [m/s]	reference	observatory
Dec 1985, Oct 1986, Mar 1987	109 ± 10	25 ± 15	**120 ± 20**	Goldstein etal. 1991	IRTF, 10 micron heterodyne. dayside only.
Apr. May 1988	99 ± 6	**132 ± 10**	< 40	Shah etal. 1991	OVRO, interferometer ^{12}CO (1-0)
Aug 1991	95 ± 6 105 ± 10	35 ± 15 95 ± 10	45 ± 15 90 ± 15	Lellouch etal. 1994	IRAM, single dish ^{12}CO (1-0) & (2-1)
Nov 1994	95 ± 6 105 ± 10	45 ± 30 75 ± 20	50 ± 35 110 ± 20	Rosenqvist etal. 1995	
Oct 2002	105	**dominant**	-	Clancy 2005	JCMT, single dish ^{12}CO (2-1)
Nov 2002	105	-	**dominant**		
May-Sep 2007	**Strong variability**			#1 VEx - GBO Campaign (PSS 2008)	IRAM, APEX, JCMT, SMT PdBI, NMA

Table credits: Sagawa

Example 1

Interferometric CO observations

→ status:
Data analysis



	SMA (Submillimeter Array)		CARMA (Combined Array for Research in Millimeter-wave Astronomy)
Observed Date	[redacted]	[redacted]	[redacted]
Venus Diameter	[redacted]	[redacted]	[redacted]
Day-Night Configuration	~50% of the disk is day-/nightside		antisolar
Antenna	8 × 6 m [#1]		6 × 10.4 m, 9 × 6.1 m
Baseline length	9.5-25 m		11-150 m
Receiver Band	[redacted]	[redacted]	[redacted]
Observed Lines	[redacted]	[redacted]	[redacted]
Wind Sensing Alt.[#2]	95-105 km	105-110 km	95-100 km
FOV (FWHM)	48"	32"	60" (10m-antenna) [#3]
Spatial Resolution	4.3" × 3.0"	5.5" × 1.7"	4.9" × 4.6"
Freq. Resolution	100 kHz		30 kHz
Final Goal	Simultaneous retrieval of T(z), CO, wind vertical profiles by using 3 CO lines.		Visualize the wind pattern around the antisolar point, and map the enhancement of CO at nightside.

→Succesfully measurements of the wind map at night hemisphere

→Strong spatial inhomogenity in the wind pattern

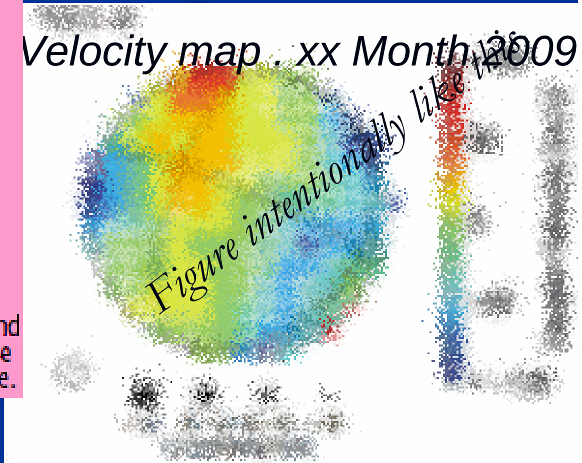
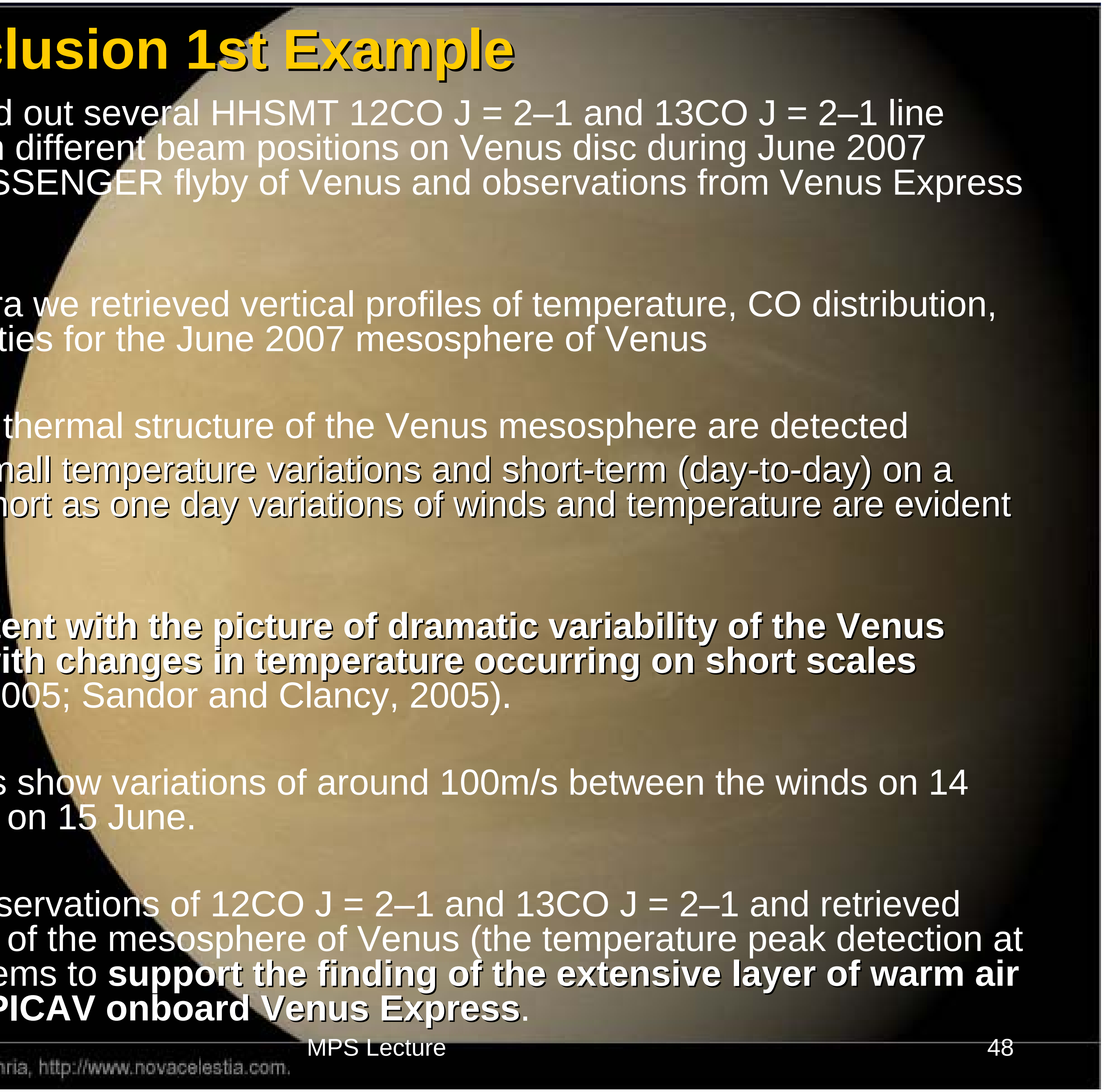

Velocity map , xx Month 2009

Figure intentionally like this

Sagawa, Hartogh, Gurwell, Rengel, Moullet, in preparation

V.- Conclusion 1st Example



- We have carried out several HHSMT 12CO J = 2–1 and 13CO J = 2–1 line observations on different beam positions on Venus disc during June 2007 around the MESSENGER flyby of Venus and observations from Venus Express mission

- From the spectra we retrieved vertical profiles of temperature, CO distribution, and wind velocities for the June 2007 mesosphere of Venus

- Changes in the thermal structure of the Venus mesosphere are detected

  Day-to-night small temperature variations and short-term (day-to-day) on a time scale as short as one day variations of winds and temperature are evident in our data.

  This is consistent with the picture of dramatic variability of the Venus mesosphere with changes in temperature occurring on short scales (Clancy et al., 2005; Sandor and Clancy, 2005).

- Retrieved winds show variations of around 100m/s between the winds on 14 June and those on 15 June.

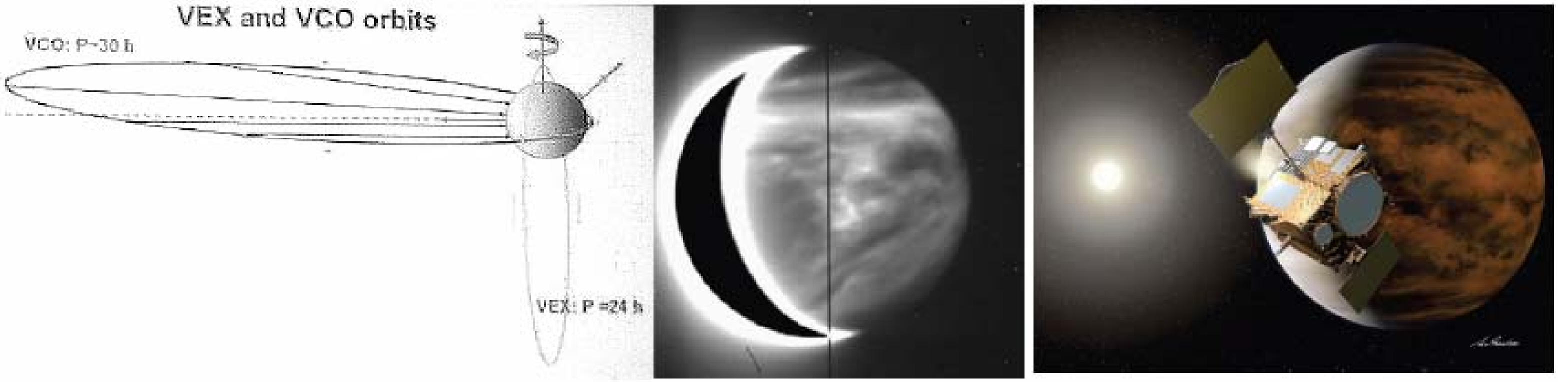
- HHSMT line observations of 12CO J = 2–1 and 13CO J = 2–1 and retrieved thermal profiles of the mesosphere of Venus (the temperature peak detection at 90–100 km) seems to **support the finding of the extensive layer of warm air detected by SPICAV onboard Venus Express**.

VI. - Outlook for the future

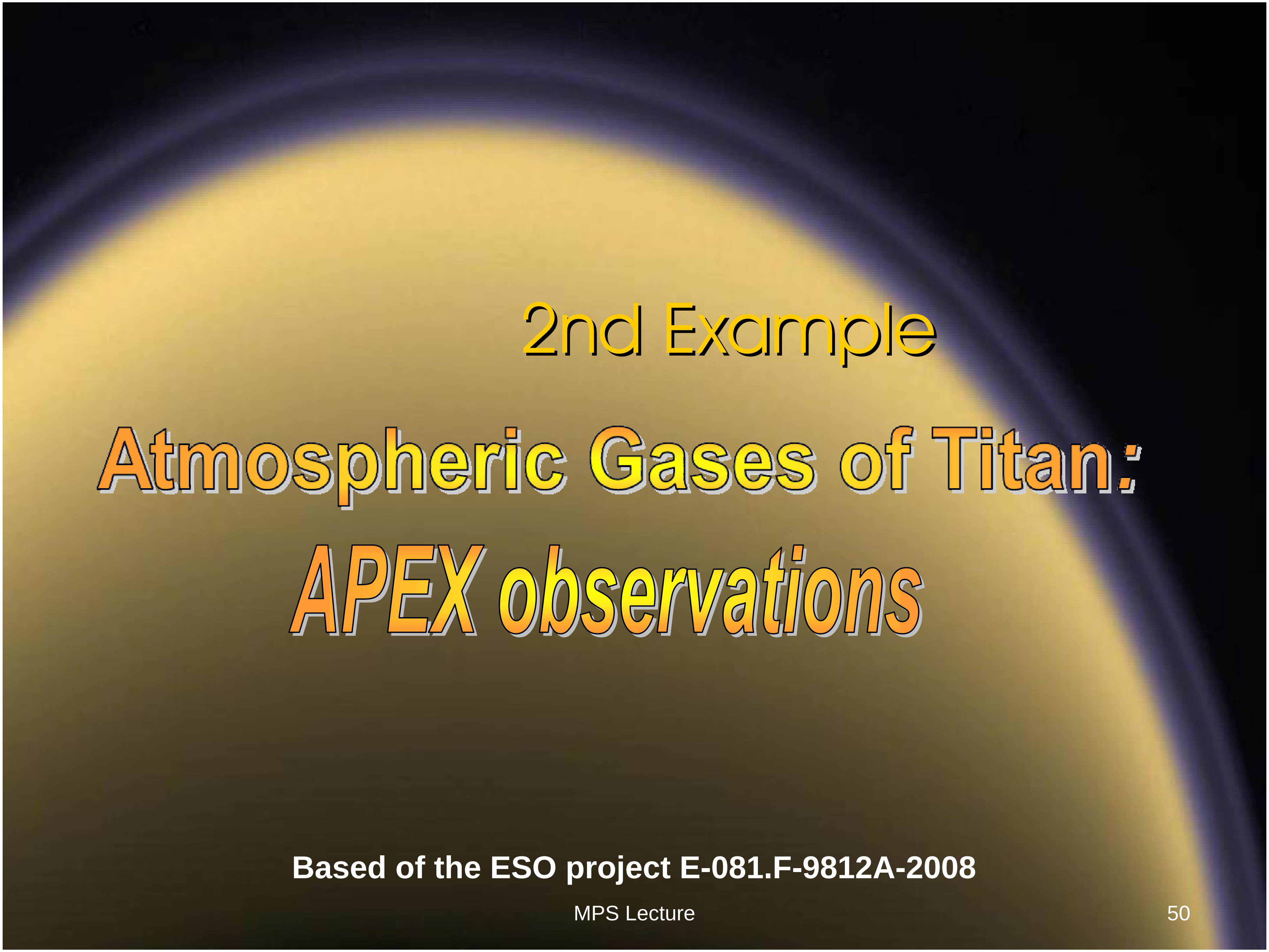
Dec. 2010 - Jan. 2011 3rd coordinated campaign

A proposed coordinated campaign in support of VEx-VCO at

VCO orbit insertion in Dec. 2010



JAXA‘s Venus Climate Orbiter



2nd Example

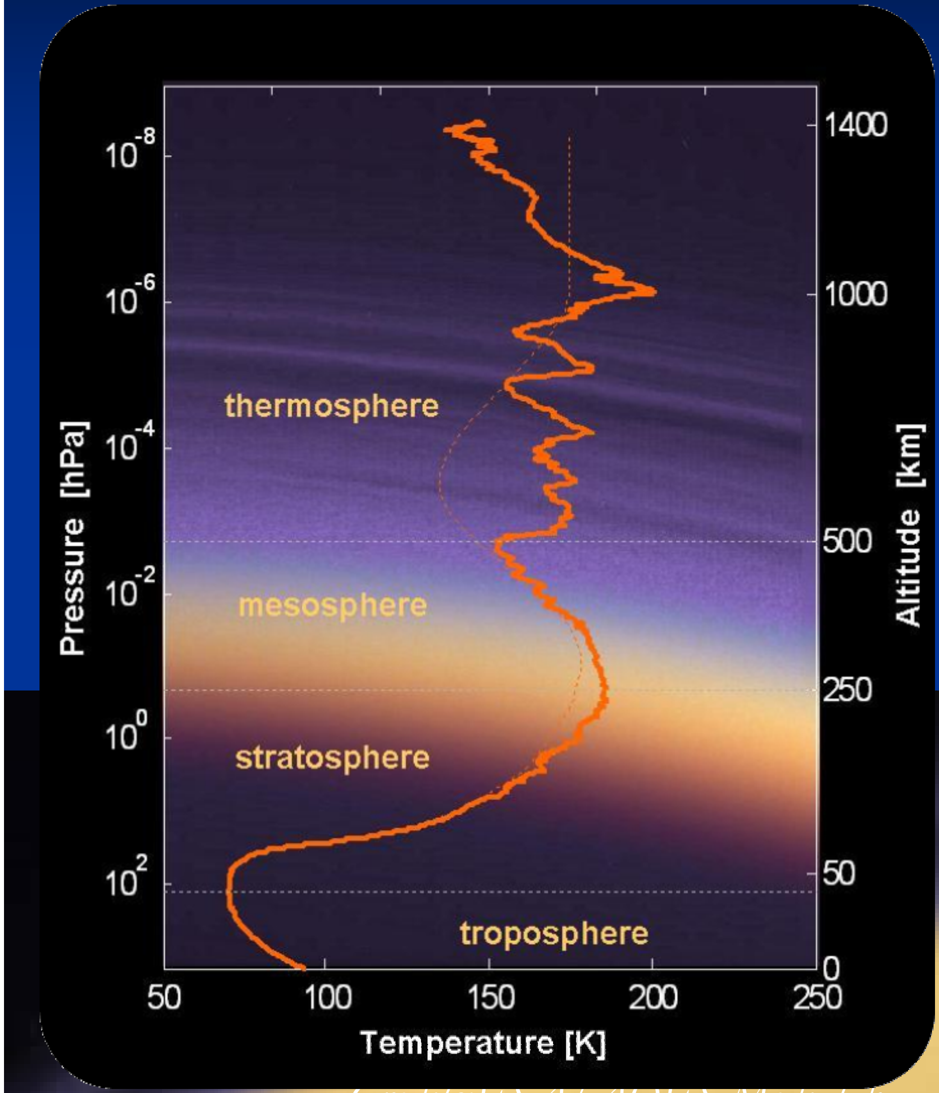
Atmospheric Gases of Titan:

APEX observations

Based of the ESO project E-081.F-9812A-2008

Example 2

Temperature profile



Credits:ESA/AOES Medialab

1655 Christiaan Huygens discovered *Mimas*

1847 John Herschel suggested the name of Titan (sisters and brothers of *Cronos*, the Greek Saturn.)

The atmosphere of Titan can be vertically split into four different dynamical regions :

(1) the ***troposphere***: below 45 km
(2) the ***stratosphere***, between z=45 and 250 km
(3) the ***mesosphere***, between z=250 and 500 km
(4) the ***thermosphere***, above z = 500 km

Example 2

Why Titan?

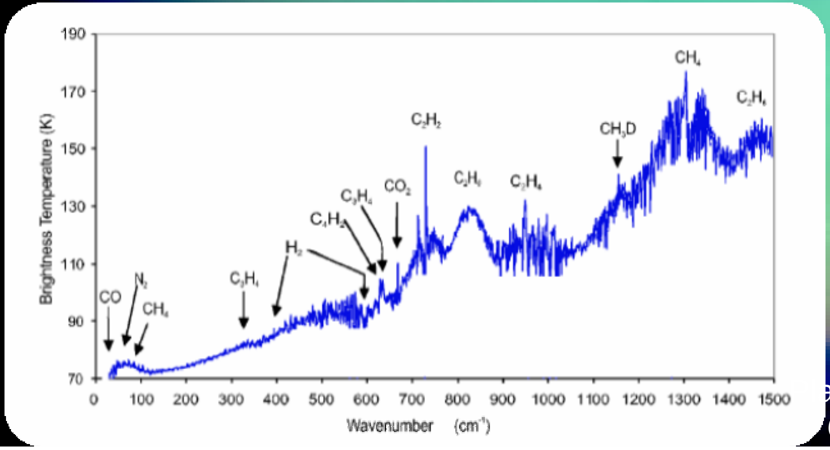
- The origin of Titan‘s atmosphere is poorly understood and its chemistry is complicated:

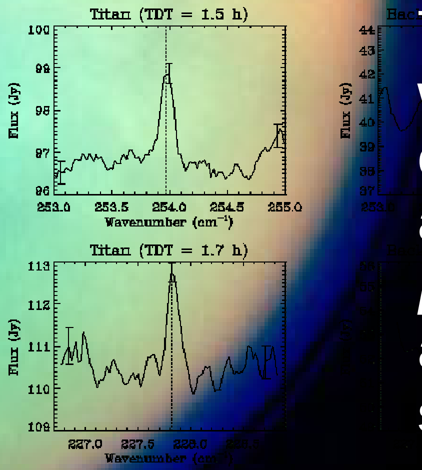
* CH_4 is the second most abundant specie detected

*HCN is the most abundant nitrile on Titan

*CO origin is not well understood

Water, CO, nitriles, and hydrocarbons have been detected by spacecrafts and from Earth.





Titan observations with SWS/Grating of two water lines at 43.9 and 39.4 μm respectively, along with the off-source spectra.

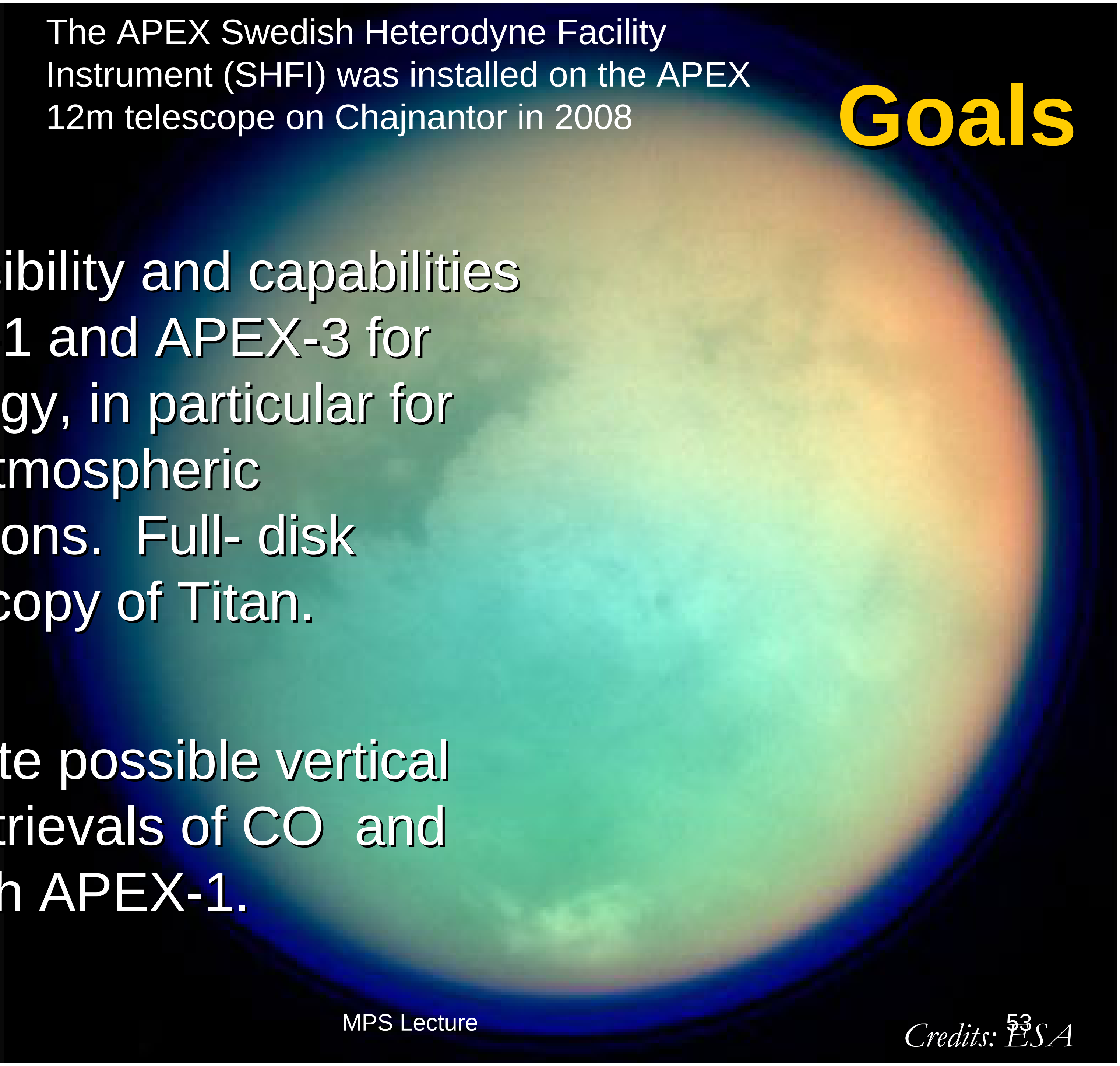
Coustenis et al. A&A. 336, L85-L89 (1998)

Coustenis et al .

Example 2

The APEX Swedish Heterodyne Facility Instrument (SHFI) was installed on the APEX 12m telescope on Chajnantor in 2008

Goals



Credits: ESA

- Test feasibility and capabilities of APEX-1 and APEX-3 for planetology, in particular for Titan´s atmospheric observations. Full- disk spectroscopy of Titan.

- Investigate possible vertical profile retrievals of CO and HCN with APEX-1.

Example 2

How? Ingredients

Observations

Deriving information from the spectra

Forward model – Inversion Algorithm

To model the expected observed emission spectra

To retrieval physical parameters as the mixing ratio

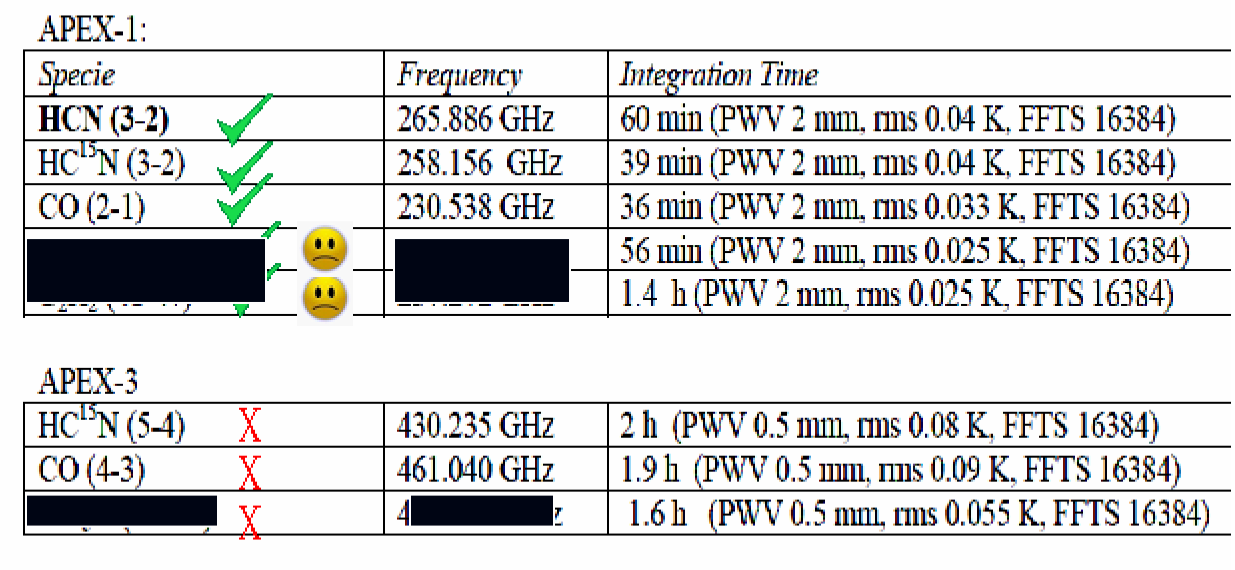
Example 2

Spectral Line Observations of Titan

Proposed lines: **Time allocated: 11.5 hrs**

(8.2 hrs observed - 2.5 hrs in very bad weather)

12-m APEX Telescope (Chile)



APEX-1:

Specie		*Frequency*	*Integration Time*
HCN (3-2)	✓	265.886 GHz	60 min (PWV 2 mm, rms 0.04 K, FFTS 16384)
HC^{15}N (3-2)	✓	258.156 GHz	39 min (PWV 2 mm, rms 0.04 K, FFTS 16384)
CO (2-1)	✓	230.538 GHz	36 min (PWV 2 mm, rms 0.033 K, FFTS 16384)
[redacted]	✓ ☹	[redacted]	56 min (PWV 2 mm, rms 0.025 K, FFTS 16384)
[redacted]	✓ ☹	[redacted]	1.4 h (PWV 2 mm, rms 0.025 K, FFTS 16384)

APEX-3

HC^{15}N (5-4)	X	430.235 GHz	2 h (PWV 0.5 mm, rms 0.08 K, FFTS 16384)
CO (4-3)	X	461.040 GHz	1.9 h (PWV 0.5 mm, rms 0.09 K, FFTS 16384)
[redacted]	X	4[redacted]z	1.6 h (PWV 0.5 mm, rms 0.055 K, FFTS 16384)

Between 21.3.08 and 27.6.08

Instrumentation used:

SHFI **Receivers**: APEX-1
[211-270] GHz

Backends:
FFTS1 (up to 122 kHz,
Bandwidth 1 GHz)

Mode: Position switching

Results:

-Improvement of the control software. After this project it was possible to properly point and track data on a moving target.

- spectral line observations of Titan with the lines

CO J=2-1 - 13 min

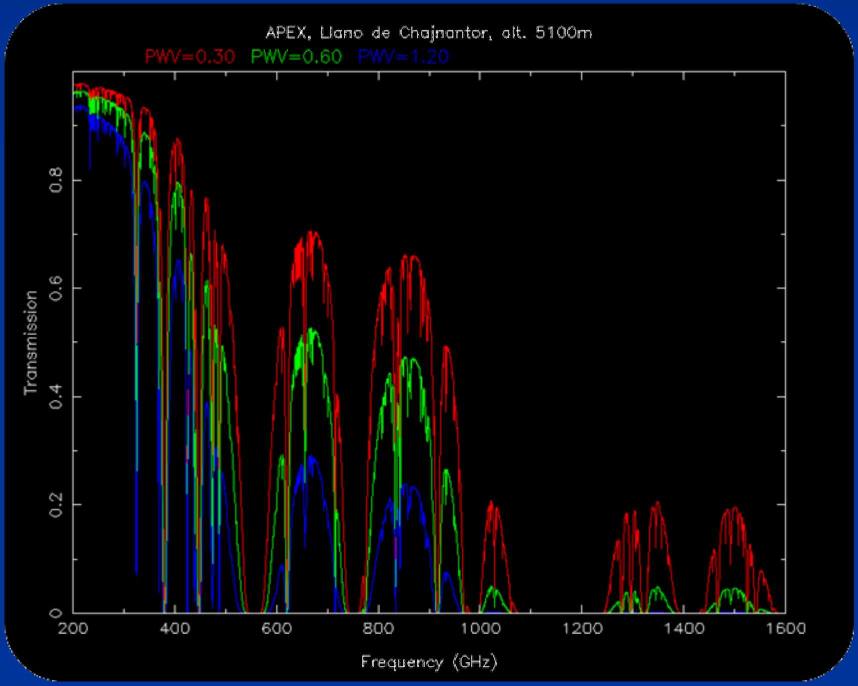
HCN J=3-2 - 19 min

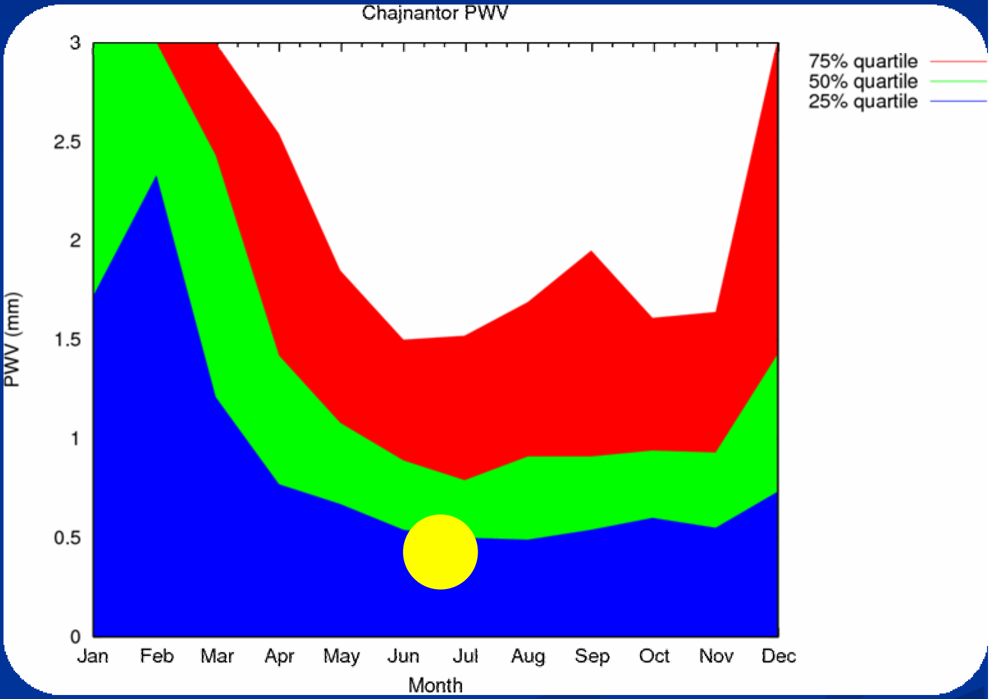
Example 2

The atmosphere above Llano de Chajnantor during these observations

Atmospheric window at Chajnantor

Annual variation of PWV at Chajnantor

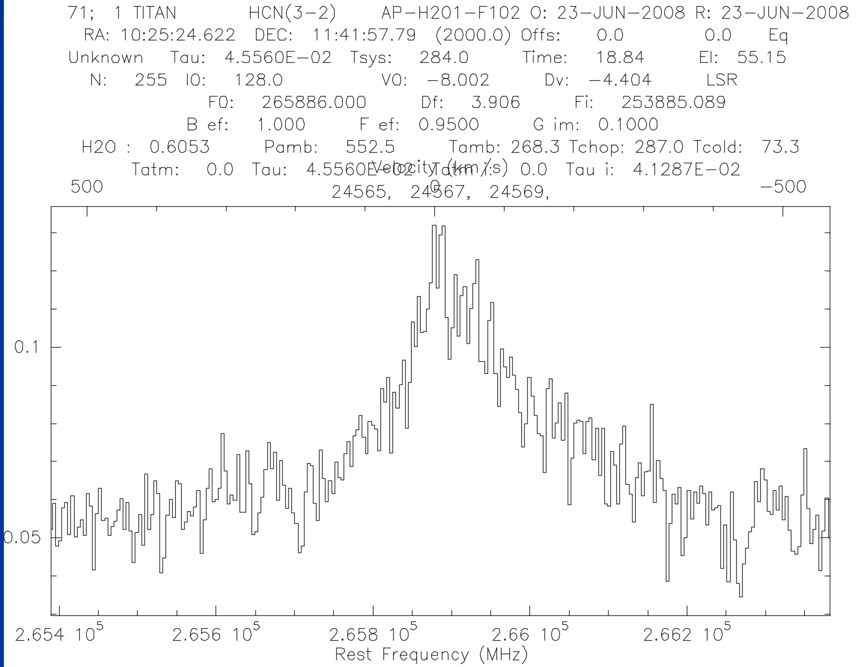




APEX-1

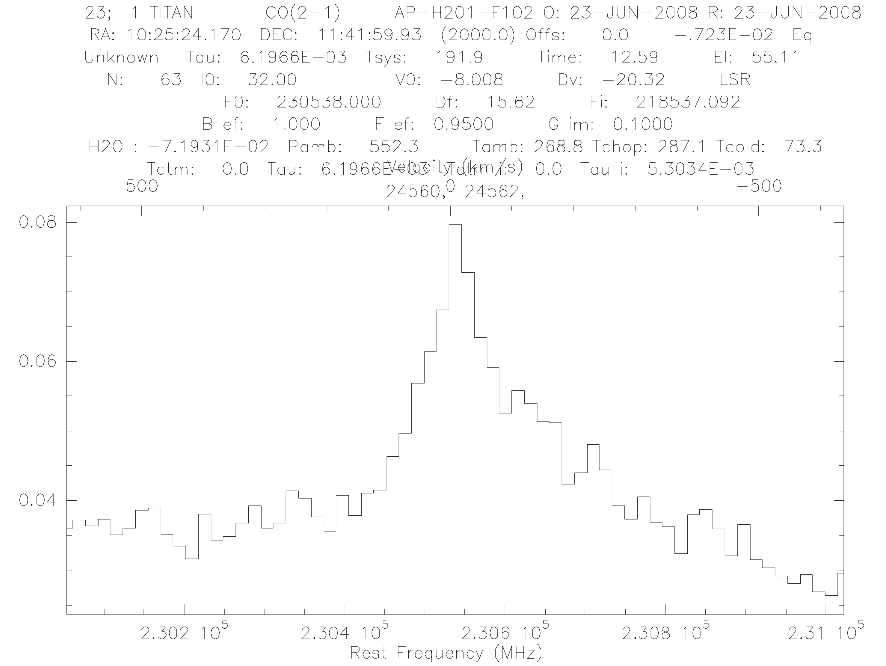
Results: Titan´s spectra

HCN(3-2)



```
71;  1 TITAN        HCN(3-2)     AP-H201-F102 O: 23-JUN-2008 R: 23-JUN-2008
 RA: 10:25:24.622  DEC:  11:41:57.79  (2000.0) Offs:     0.0         0.0     Eq
Unknown     Tau:  4.5560E-02  Tsys:    284.0         Time:    18.84       El:  55.15
   N:    255  I0:    128.0             V0:   -8.002       Dv:   -4.404        LSR
                F0:    265886.000         Df:     3.906         Fi:    253885.089
             B ef:    1.000        F ef:  0.9500        G im:   0.1000
 H2O :   0.6053          Pamb:    552.5         Tamb: 268.3 Tchop: 287.0 Tcold:   73.3
       Tatm:    0.0  Tau:  4.5560E-02  Tatm i:  0.0  Tau i:   4.1287E-02
                          24565,  24567,  24569,
```

CO(2-1)



```
23;  1 TITAN        CO(2-1)      AP-H201-F102 O: 23-JUN-2008 R: 23-JUN-2008
 RA: 10:25:24.170  DEC:  11:41:59.93  (2000.0) Offs:     0.0      -.723E-02  Eq
Unknown     Tau:  6.1966E-03  Tsys:    191.9         Time:    12.59       El:  55.11
   N:     63  I0:     32.00            V0:   -8.008       Dv:  -20.32        LSR
                F0:    230538.000         Df:    15.62          Fi:    218537.092
             B ef:    1.000        F ef:  0.9500        G im:   0.1000
 H2O :  -7.1931E-02   Pamb:    552.3         Tamb: 268.8 Tchop: 287.1 Tcold:   73.3
       Tatm:    0.0  Tau:  6.1966E-03  Tatm i:  0.0  Tau i:   5.3034E-03
                          24560,  24562,
```

Smooth 5

Smooth 7

First observations of a planet/satellite with APEX-1
But not optimal for retrievals of vertical distributions… However

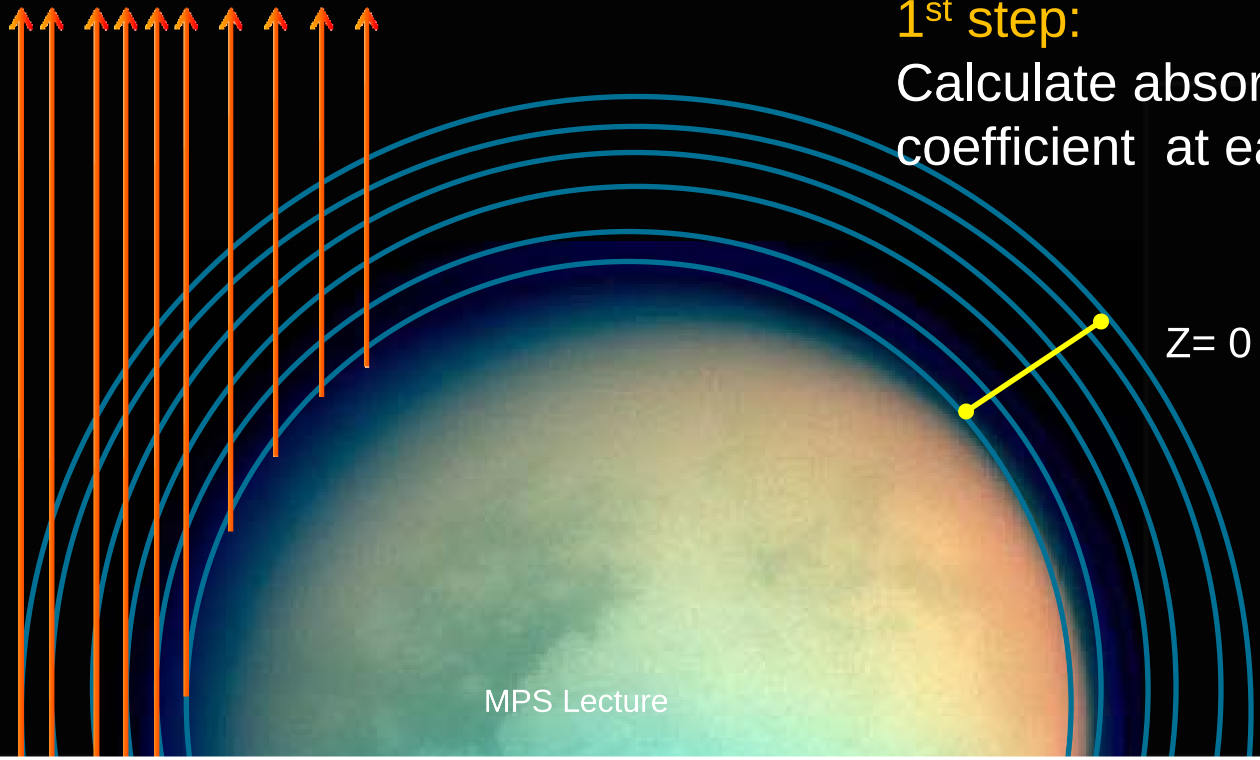
S/N = 5

Example 2

III.- Modeling procedure

3rd step:
Integrate and convolve with the antenna pattern

2nd step:
Calculate RT along each ray path



1st step:
Calculate absorption coefficient at each layer

Z= 0 – 600 km

Example 2

Adopted Titan‘s thermal and pressure profiles for the opacity calculations

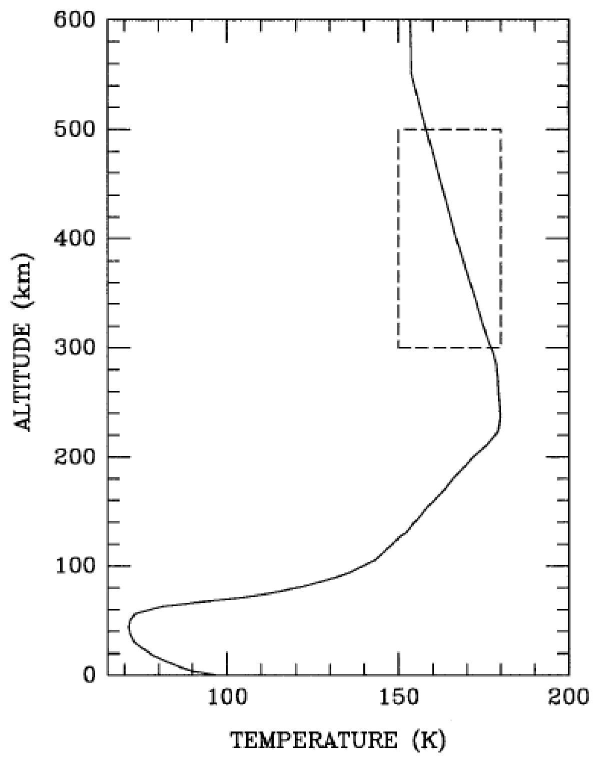
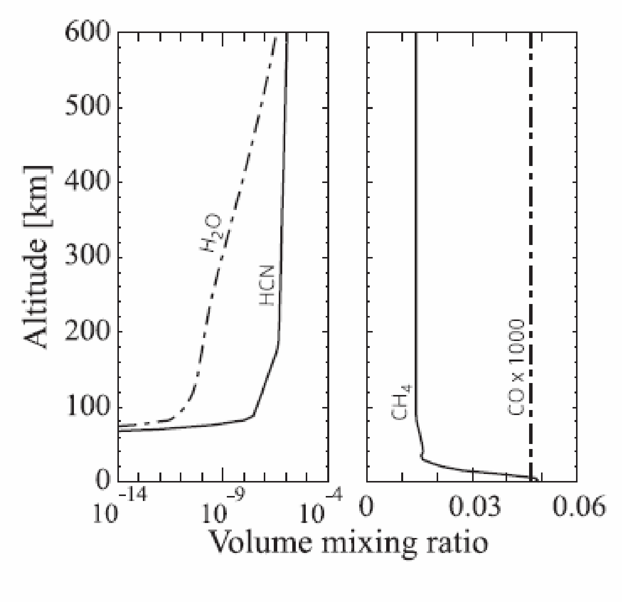


FIG. 2. Titan’s temperature profile adopted from Coustenis and Bézard (1995). The upper part (above 300 km) is from Yelle (1991). This profile is used as a “nominal” model to simulate the observed spectra.

Hidayat et al. 1998

Profile based on *Coustenis and B´ezard 1995 & Yelle et al. 1991.*

Atmospheric composition based on



Marten et al. 2002 *Kok et al. 2007*

Also used by:
Gurwell 1995, 2000 CO
Marten et al. 2002 HCN

The resulting spectra allow the retrieval of stratospheric CO and HCN profiles

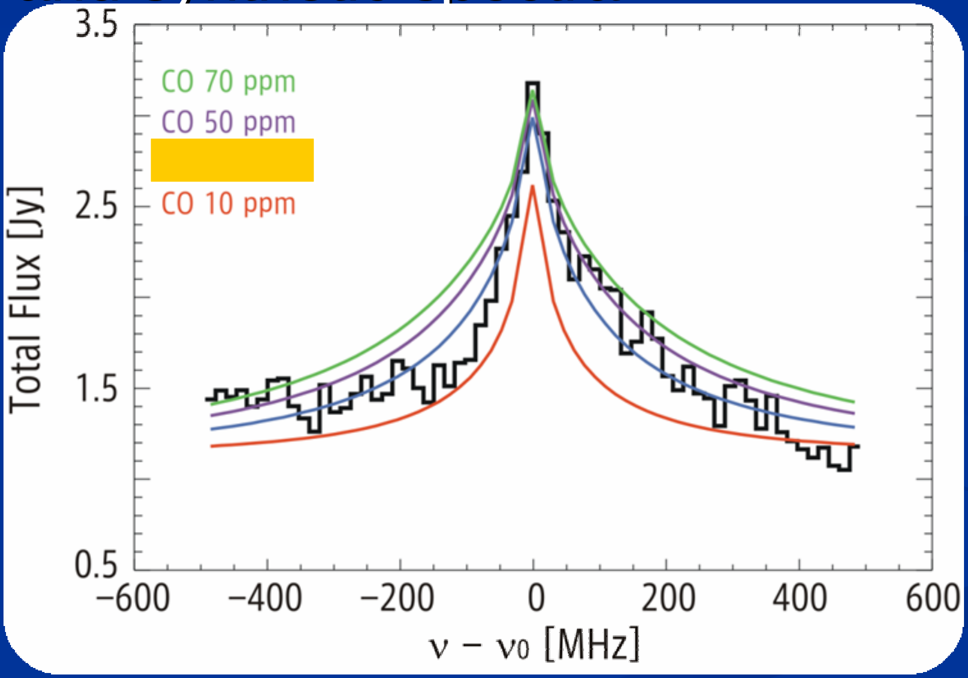
Example 2

IV.- Results

We investigate the possibility to retrieve the mixing ratio profiles of CO and HCN

- Mixing ratio of CO (2-1)

  assuming that CO is constant with altitude, we just compare observational and synthetic spectra



With 15 MHz spectral resolution: spectrally resolve the absorption line

Example 2

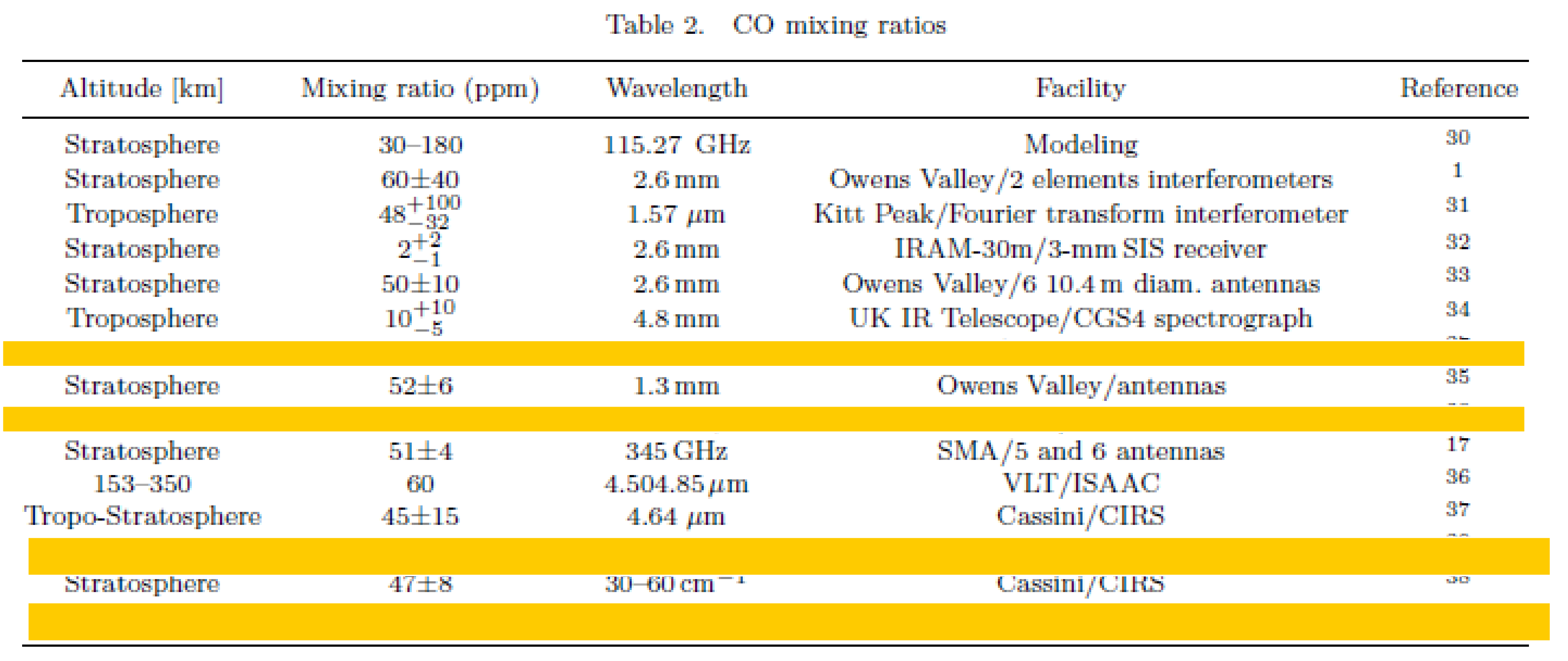


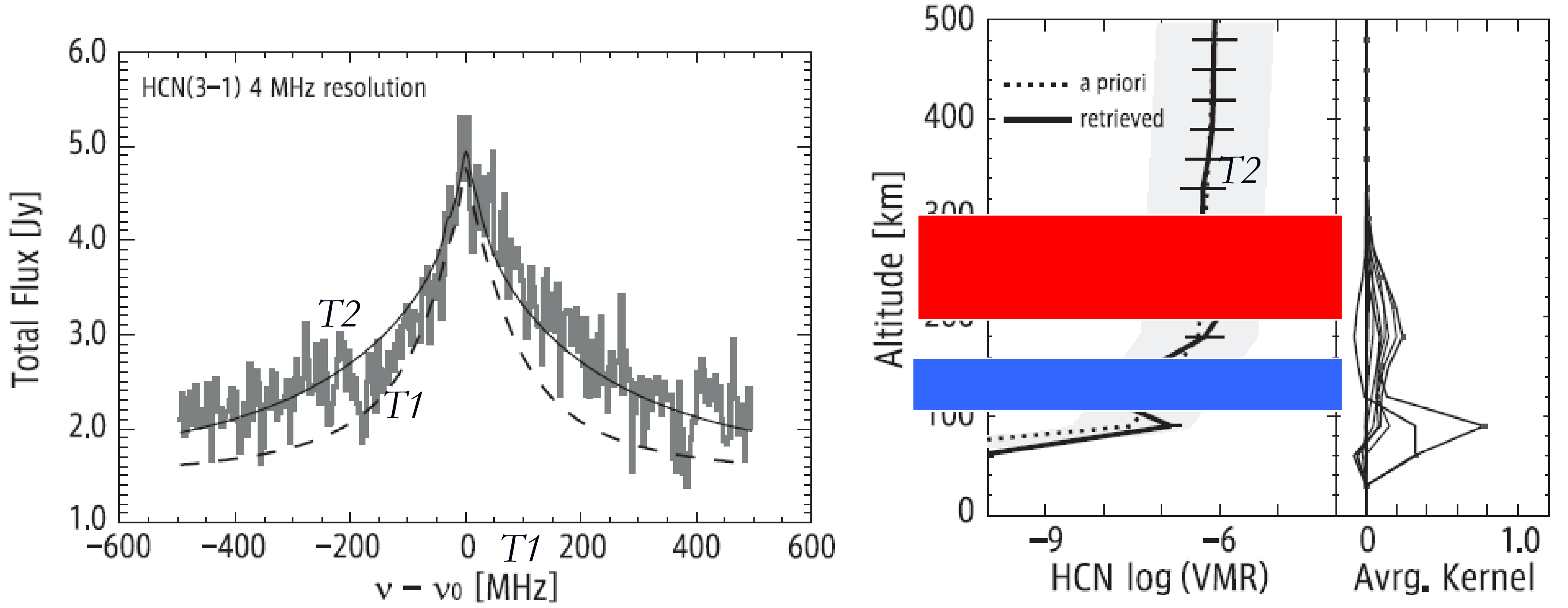
Table 2. CO mixing ratios

Altitude [km]	Mixing ratio (ppm)	Wavelength	Facility	Reference
Stratosphere	30–180	115.27 GHz	Modeling	30
Stratosphere	60±40	2.6 mm	Owens Valley/2 elements interferometers	1
Troposphere	48^{+100}_{-32}	1.57 μm	Kitt Peak/Fourier transform interferometer	31
Stratosphere	2^{+2}_{-1}	2.6 mm	IRAM-30m/3-mm SIS receiver	32
Stratosphere	50±10	2.6 mm	Owens Valley/6 10.4 m diam. antennas	33
Troposphere	10^{+10}_{-5}	4.8 mm	UK IR Telescope/CGS4 spectrograph	34
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Stratosphere	52±6	1.3 mm	Owens Valley/antennas	35
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Stratosphere	51±4	345 GHz	SMA/5 and 6 antennas	17
153–350	60	4.504.85 μm	VLT/ISAAC	36
Tropo-Stratosphere	45±15	4.64 μm	Cassini/CIRS	37
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Stratosphere	47±8	30–60 cm^{-1}	Cassini/CIRS	38
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Rengel, Sagawa, Hartogh, submitted to AdGeo

■ Mixing ratio profile of HCN

-Try to retrieve the HCN vertical profile with the nominal T1 profile → no fits
- Try to retrieve the HCN vertical profile with T2



Rengel, Sagawa, Hartogh, submitted to AdGeo

Simulated observations and fitted spectra, HCN distributions for the simulated observations

Example 2

Poor S/N here
Comparing these results must be considered cautiously…

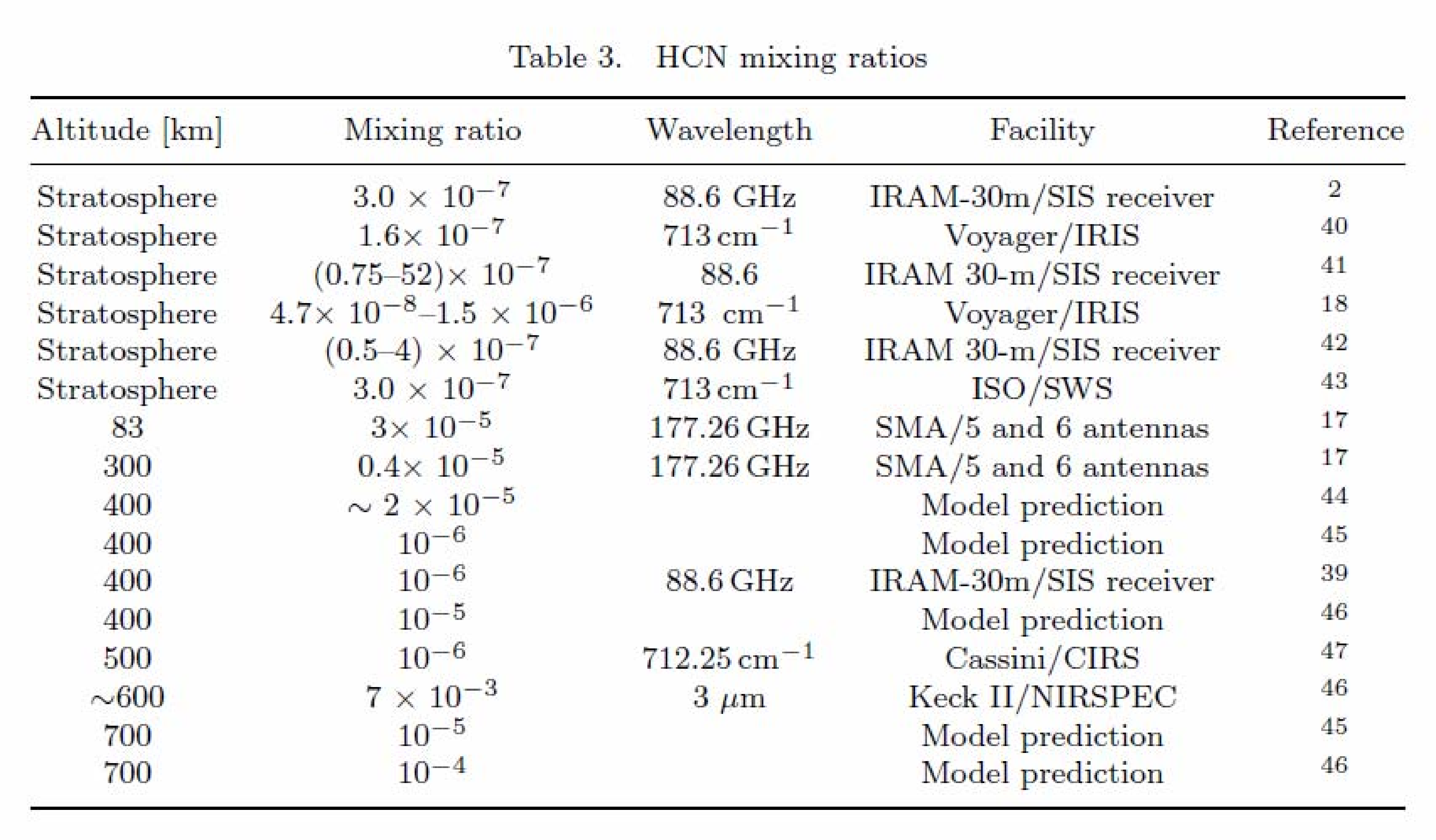


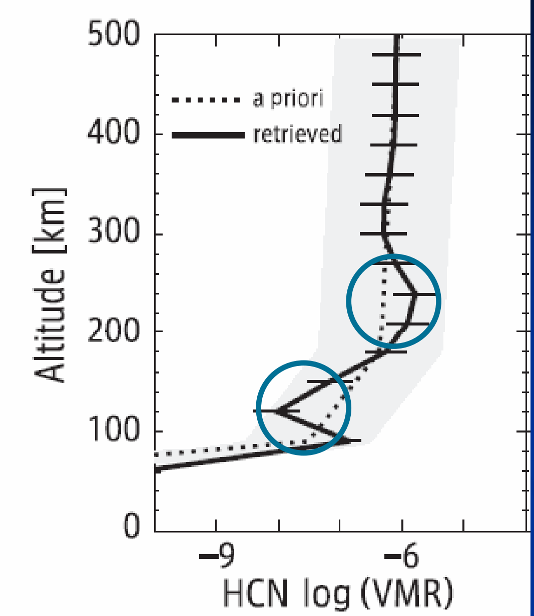
Table 3. HCN mixing ratios

Altitude [km]	Mixing ratio	Wavelength	Facility	Reference
Stratosphere	3.0×10^{-7}	88.6 GHz	IRAM-30m/SIS receiver	2
Stratosphere	1.6×10^{-7}	$713\,\mathrm{cm}^{-1}$	Voyager/IRIS	40
Stratosphere	$(0.75–52)\times 10^{-7}$	88.6	IRAM 30-m/SIS receiver	41
Stratosphere	$4.7\times 10^{-8}–1.5 \times 10^{-6}$	$713\ \mathrm{cm}^{-1}$	Voyager/IRIS	18
Stratosphere	$(0.5–4) \times 10^{-7}$	88.6 GHz	IRAM 30-m/SIS receiver	42
Stratosphere	3.0×10^{-7}	$713\,\mathrm{cm}^{-1}$	ISO/SWS	43
83	3×10^{-5}	177.26 GHz	SMA/5 and 6 antennas	17
300	0.4×10^{-5}	177.26 GHz	SMA/5 and 6 antennas	17
400	$\sim 2 \times 10^{-5}$		Model prediction	44
400	10^{-6}		Model prediction	45
400	10^{-6}	88.6 GHz	IRAM-30m/SIS receiver	39
400	10^{-5}		Model prediction	46
500	10^{-6}	$712.25\,\mathrm{cm}^{-1}$	Cassini/CIRS	47
~600	7×10^{-3}	$3\ \mu\mathrm{m}$	Keck II/NIRSPEC	46
700	10^{-5}		Model prediction	45
700	10^{-4}		Model prediction	46

Rengel, Sagawa, Hartogh, submitted to AdGeo

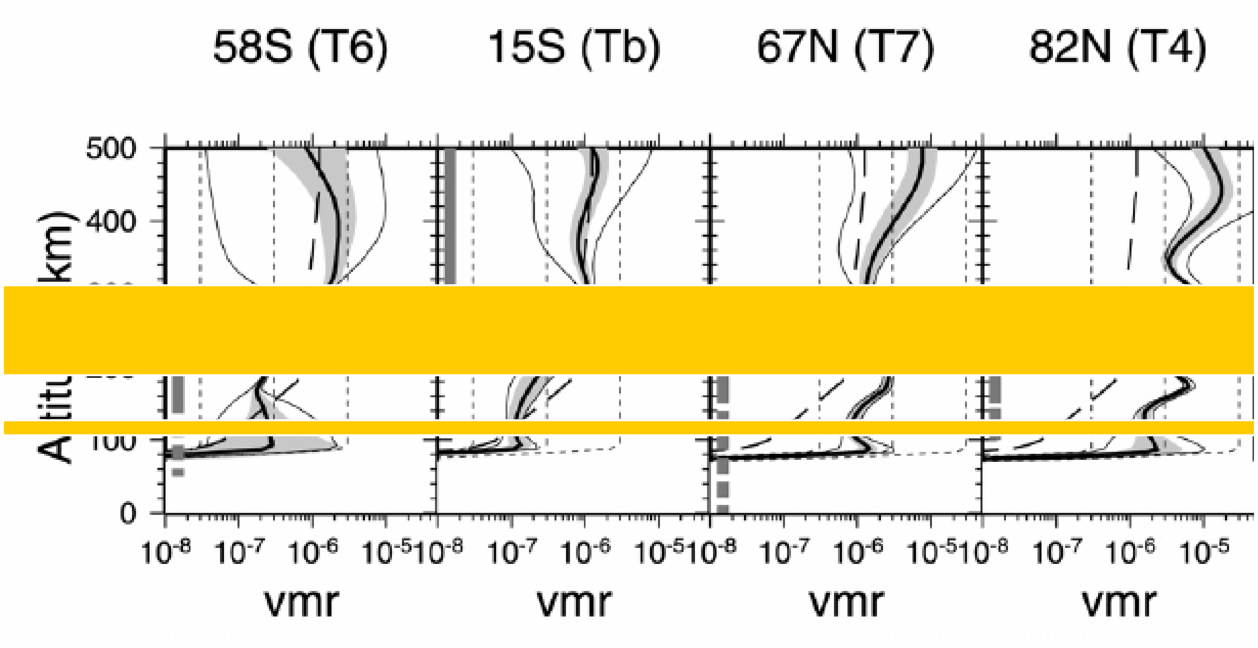
- **HCN** Although still in progress, the retrieved HCN mixing ratio suggests higher HCN abundances than Marten's result, in particularly at altitude of 200-300 km km.

Vertical profiles set up by photochemistry and condensation can be modified by atmospheric dynamics.
HCN profiles retrieved from CIRS data:
- HCN is enriched in the north compared to the south

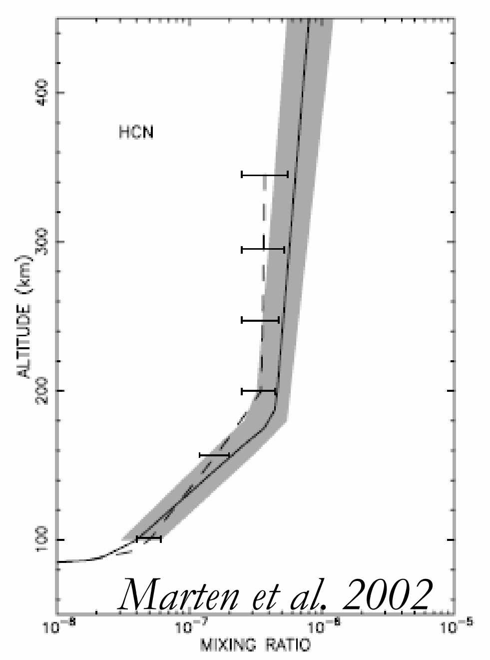


3.2 times

5 times



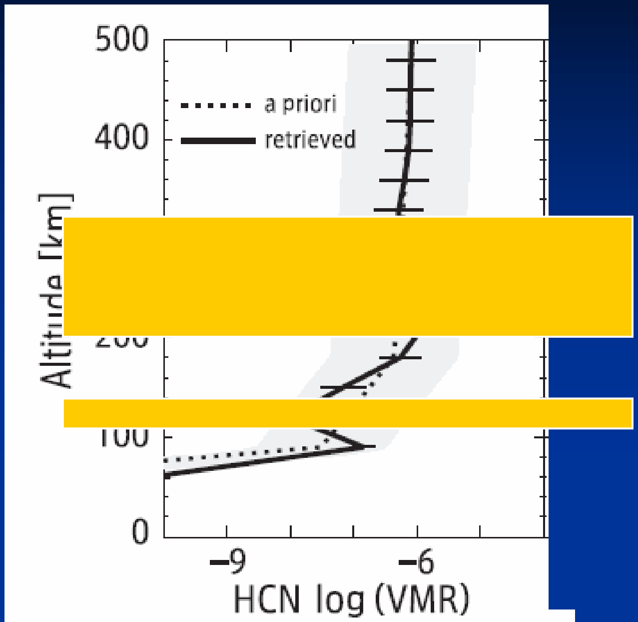
Teanby et al. 2006



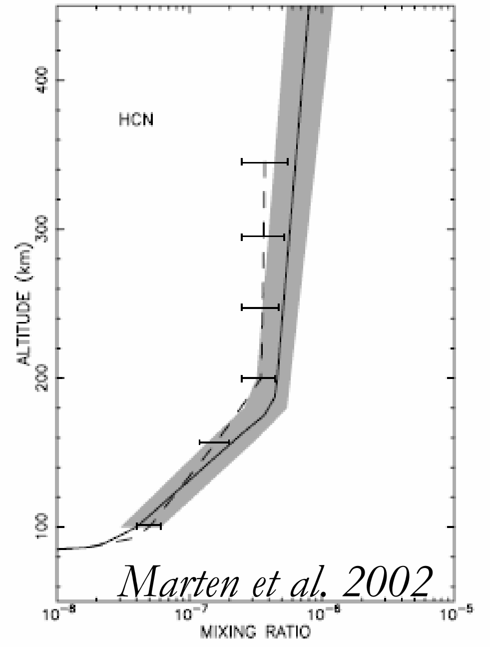
Marten et al. 2002

- **HCN** Although still in progress, the retrieved HCN mixing ratio suggests higher HCN abundances than Marten's result, in particularly at altitude of 200-300 km.

Maybe this layer is an enriched HCN layer



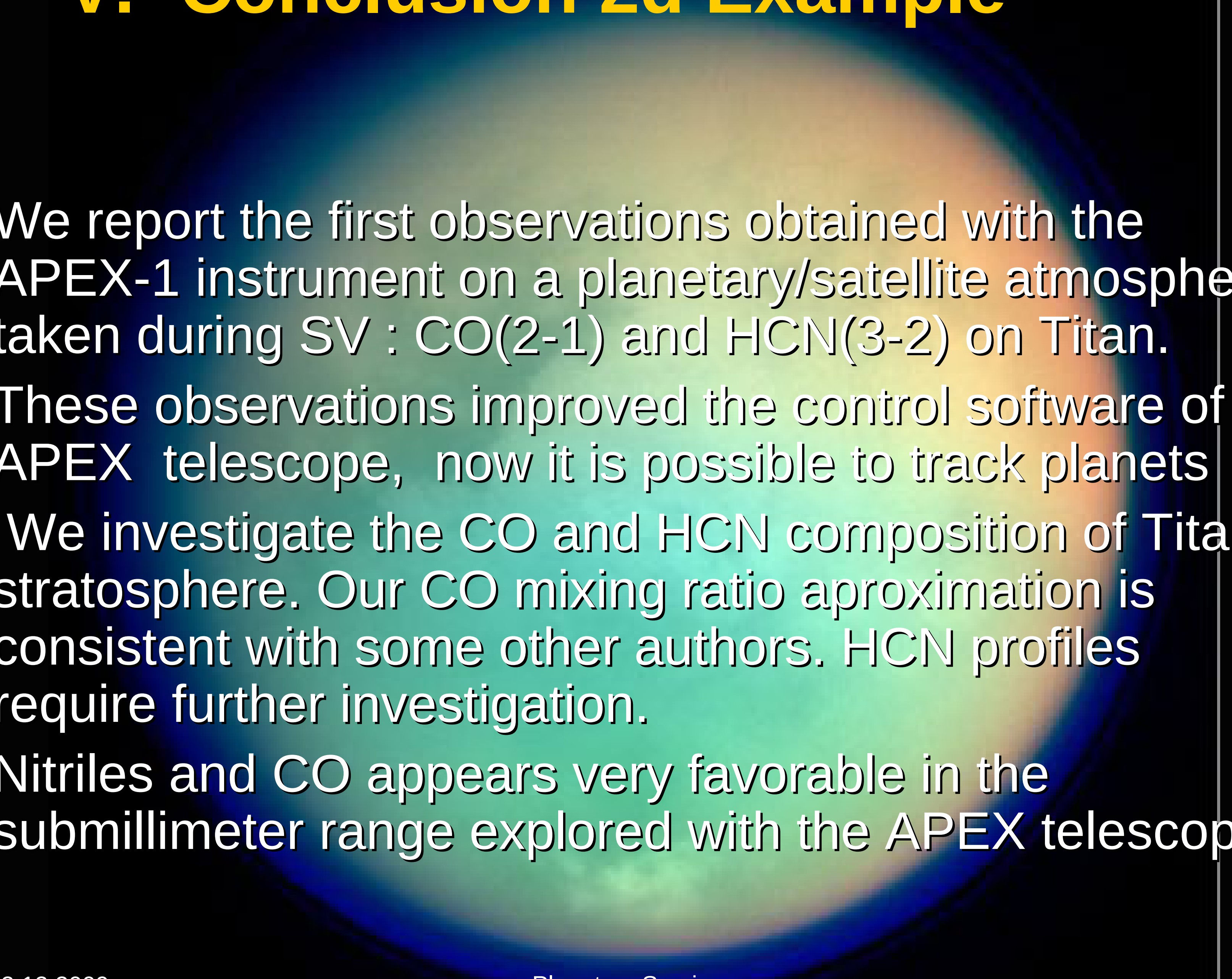
Enriched air from the north pole becomes entrained in a Hadley type circulation cell and is advected to lower latitudes



Marten et al. 2002

Example 2

V.- Conclusion 2d Example



- We report the first observations obtained with the APEX-1 instrument on a planetary/satellite atmosphere taken during SV : CO(2-1) and HCN(3-2) on Titan.
- These observations improved the control software of the APEX telescope, now it is possible to track planets
- We investigate the CO and HCN composition of Titan‘s stratosphere. Our CO mixing ratio aproximation is consistent with some other authors. HCN profiles require further investigation.
- Nitriles and CO appears very favorable in the submillimeter range explored with the APEX telescope

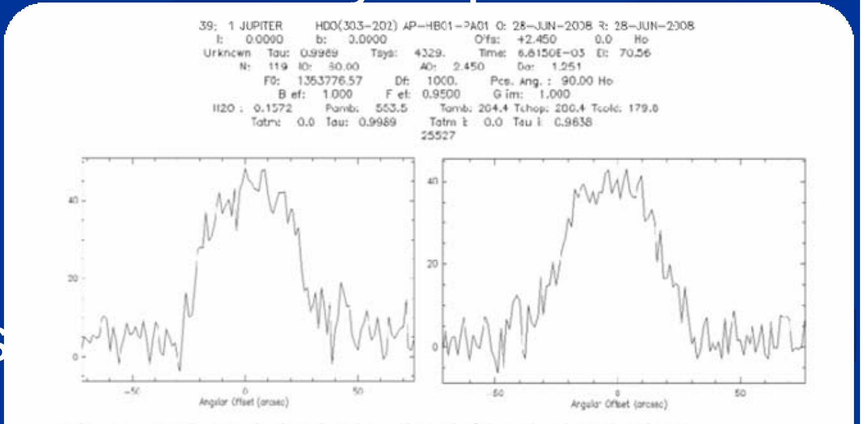
VI.- Work to do

- 1.3 THz Observations at the APEX Telescope

This receiver covers a frequency band that won’t be observed with the HIFI instrument of Herschel, and therefore both instruments could benefit from each other. The HIFI band 5 currently reaches 1271 GHz, therefore at least the **CO(11-10)** and **CS(26-25)** are observable with both receivers, which is very important for cross calibration purposes.

Increase pointing measurements

- only initial relative offsets were found between the different bands within SHFI.



```
39:  1 JUPITER      HDO(303-202) AP-HB01-PA01 O: 28-JUN-2008 R: 28-JUN-2008
 l:    0.0000      b:    0.0000                 O'fs:   +2.450       0.0    Ho
Unknown   Tau:  0.9989       Tsys:    4329.      Time:  6.6150E-03  El:  70.56
      N:   119  IO:   30.00              AO:   2.450       Da:   1.251
          F0:   1353776.57       Df:   1000.      Pos. Ang. :  90.00 Ho
            B ef:    1.000       F ef:  0.9500       G im:    1.000
 H2O :  0.1572       Pamb:   553.5        Tamb: 204.4 Tchop: 200.4 Tcold: 179.0
          Tatm:   0.0  Tau:  0.9989       Tatm I:   0.0  Tau I:  0.9638
                                25527
```

Fig. 15. Jupiter pointing in elevation (left) and azimuth (right).

Risacher et al. 2009

3rd Example

Atmospheric Gases of Titan Predictions from Herschel

Credits:ESA/AOES Medialab

Example 3

II.- Herschel-based observations/simulations

Herschel Space Observatory will observe the „cool universe“

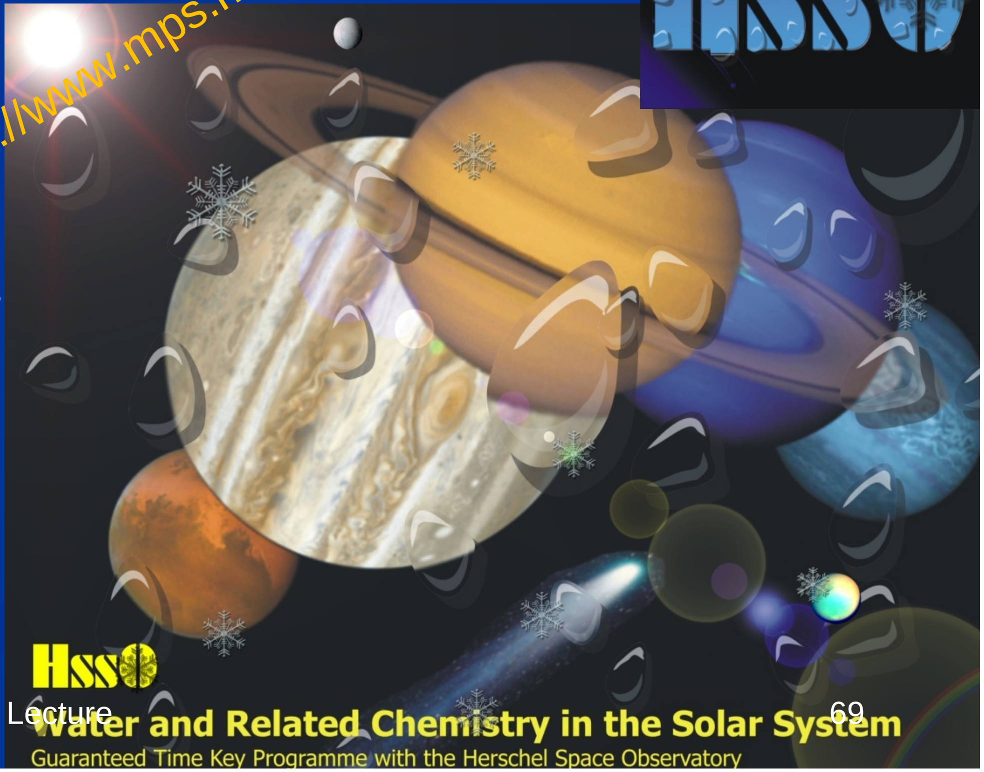
Credits:ESA/ AOES Medialab

Key Programme with guaranteed time:

"Water and Related Chemistry in the Solar System“
P.I.: Paul Hartogh (MPS Lindau)
Hartogh et al. PSS 57, Issue 13, p. 1596, 2009.

p://www.mps.mpg.de/projecs/Herschel/HssO/index.html

The HssO Program will result in a comprehensive set of sensitive and well-calibrated spectra of water, its isotopologues, and chemically related species in Solar System objects: Mars, **Outer Planets, Titan and Enceladus**, comets .



Example 3

HssO Participants

- Marek Banaszkiewicz[1],
- Frank Bensch[2]
- Edwin A. Bergin[3]
- Francoise Billebaud[4]
- Nicolas Biver[5]
- Geoffrey A. Blake[6]
- Maria I. Blecka[1]
- Joris Blommaert[20]
- Dominique Bockelée-Morvan[5]
- Thibault Cavalié, (Associate)
- José Cernicharo[7] (mission scientist)
- Régis Courtin[5]
- Jacques Crovisier[5]
- Gary Davis[8]
- Leen Decin[20]
- Pierre Encrenaz[9] (mission scientist)
- Thérese Encrenaz[5]
- Trevor Fulton
- Thijs de Graauw[10] (ex HIFI-PI)
- Armando Gonzalez (Affiliate)
- Paul Hartogh[11] (PI, coordinator)
- Damien Hutsemékers[12]
- Christopher Jarchow[11] (CoI)
- Emmanuël Jehin[12]
- Mark Kidger[22]
- Michael Küppers
- Arno de Lange
- Luisa-Maria Lara[13]

- Sarah Leeks
- Emmanuel Lellouch[5]
- Dariusz C. Lis[6]
- Rosario Lorente22
- Jean Manfroid21
- Alexander S. Medvedev[11] (CoI)
- Raphael Moreno5
- David Naylor14
- Glenn Orton15
- Ganna Portyankina
- Miriam Rengel[11] (CoI, HIFI Calibration Scientist)
- Hideo Sagawa (Associate)
- Miguel Sánches-Portal22
- Rudolf Schieder16
- Sunil Sidher17
- Daphne Stam18
- Bruce Swinyard17
- Slawomira Szutowicz1
- Gillian Thornhill22
- Nicolas Thomas19
- Miguel de Val Borro (Associate)
- Bart Vandenbussche20
- Eva Verdugo22
- Christoffel Waelkens20
- Helen Walker17

Example 3

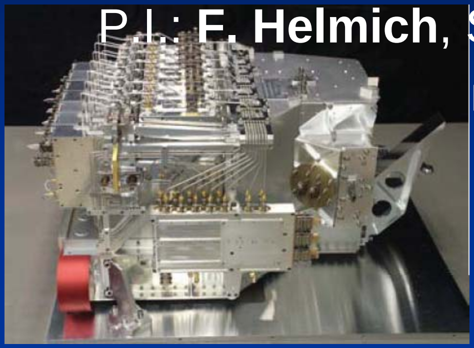
Planned Spectral Line Observations of Titan

Instruments onboard Herschel:

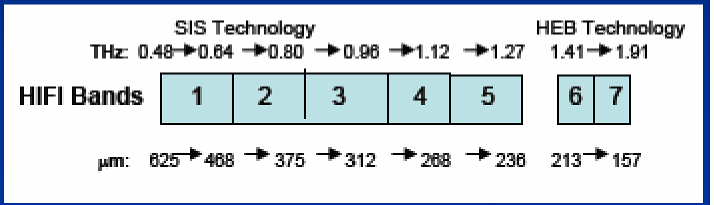
Credits: ESA

Heterodyne **I**nstrument for the **F**ar-**I**nfrared (**HIFI**).

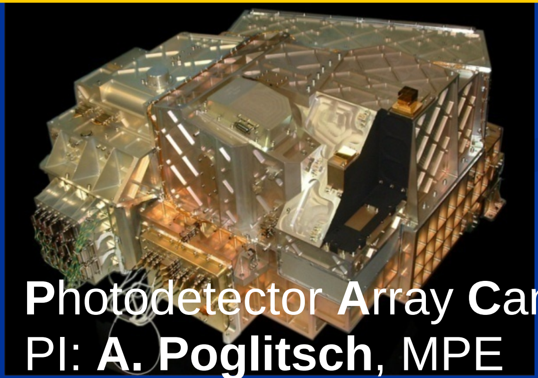
P.I.: **F. Helmich**, SRON



Resolutions: 140, 280, 560 kHz, 1.1 MHz



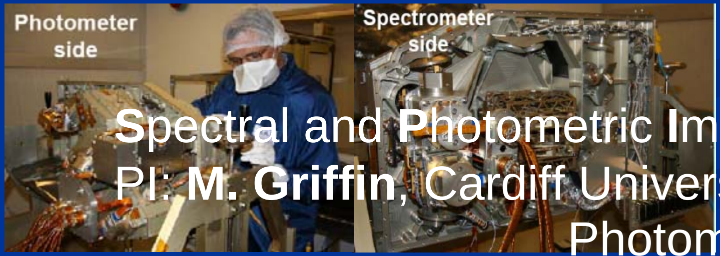
480 – 1150 GHz 1410-1910 GHz



Photodetector **A**rray **C**amera and **S**pectrometer (**PACS**).

PI: **A. Poglitsch**, MPE

55 – 210 µm



Spectral and **P**hotometric **I**maging **Re**ceiver (**SPIRE**).

PI: **M. Griffin**, Cardiff University

Photometer: 250, 350, 500 µm

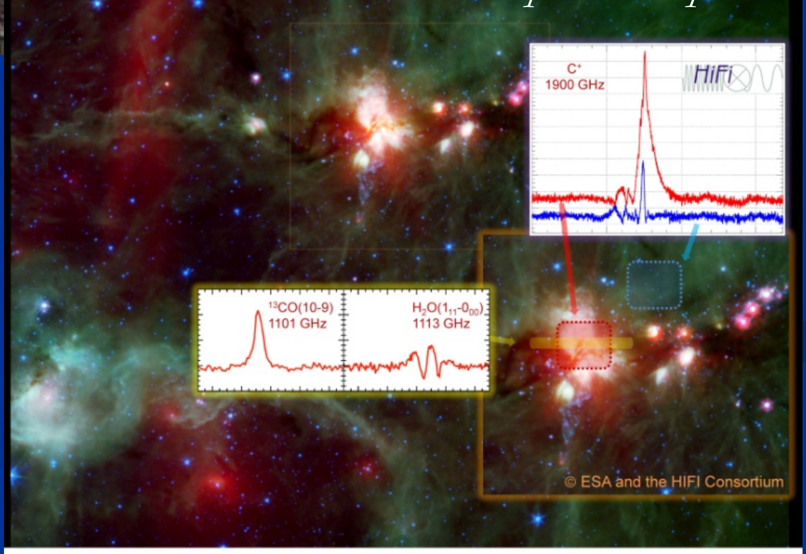
Spectrometer: 194- 672 µm.

Example 3

Herschel and Planck launch: Fantastic launch, good performance, great ground segment.

Credits: ESA,

All three instruments started up without problems



HIFI: Perfect switch on, great performance. But the LCU event

Example 3

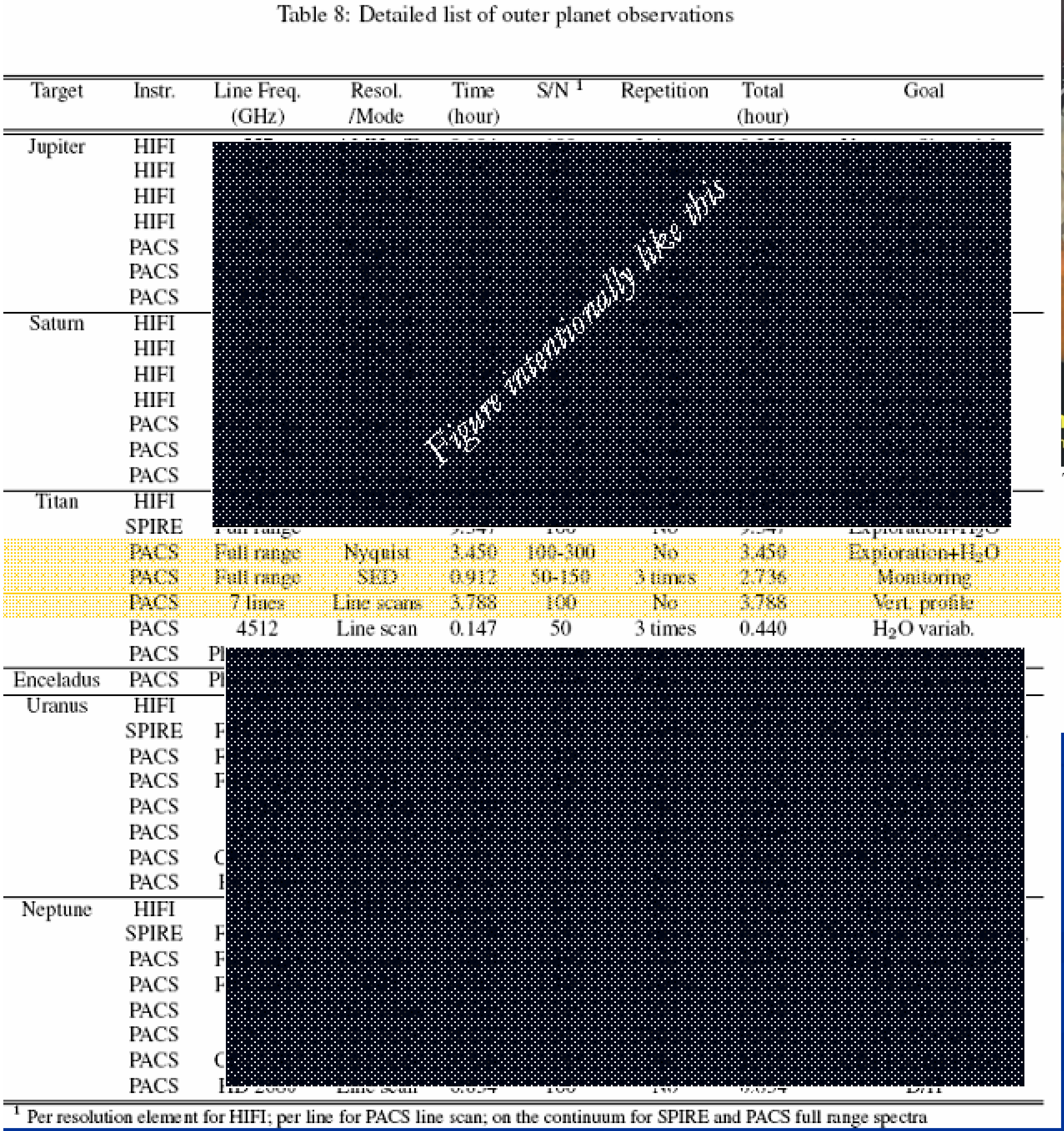


Table 8: Detailed list of outer planet observations

Target	Instr.	Line Freq. (GHz)	Resol. /Mode	Time (hour)	S/N [1]	Repetition	Total (hour)	Goal
Jupiter	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Saturn	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Titan	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	SPIRE	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	Full range	Nyquist	3.450	100-300	No	3.450	Exploration+H_2O
	PACS	Full range	SED	0.912	50-150	3 times	2.736	Monitoring
	PACS	7 lines	Line scans	3.788	100	No	3.788	Vert. profile
	PACS	4512	Line scan	0.147	50	3 times	0.440	H_2O variab.
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Enceladus	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Uranus	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	SPIRE	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Neptune	HIFI	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	SPIRE	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PACS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Figure intentionally like this

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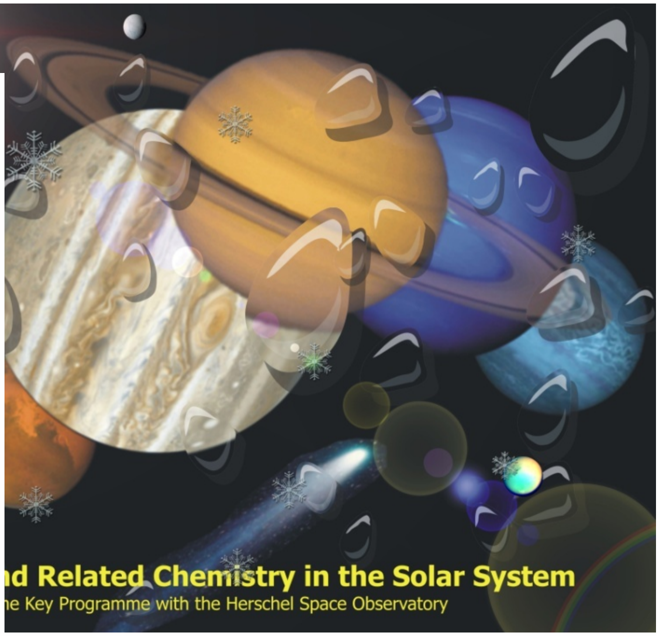
[1] Per resolution element for HIFI; per line for PACS line scan; on the continuum for SPIRE and PACS full range spectra



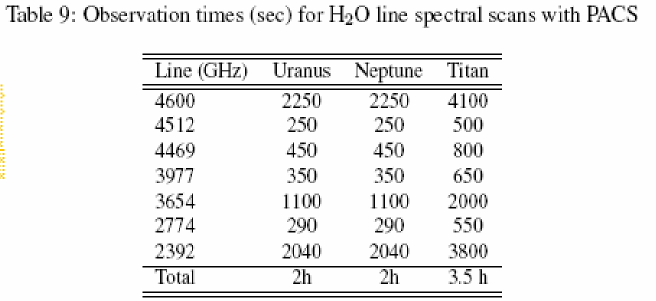


Table 9: Observation times (sec) for H_2O line spectral scans with PACS

Line (GHz)	Uranus	Neptune	Titan
4600	2250	2250	4100
4512	250	250	500
4469	450	450	800
3977	350	350	650
3654	1100	1100	2000
2774	290	290	550
2392	2040	2040	3800
Total	2h	2h	3.5 h

Investigate possible vertical profile retrievals of H_2O, HCN, and CO with HIFI and PACS for the expected signal-to-noise ratios.

Example 3

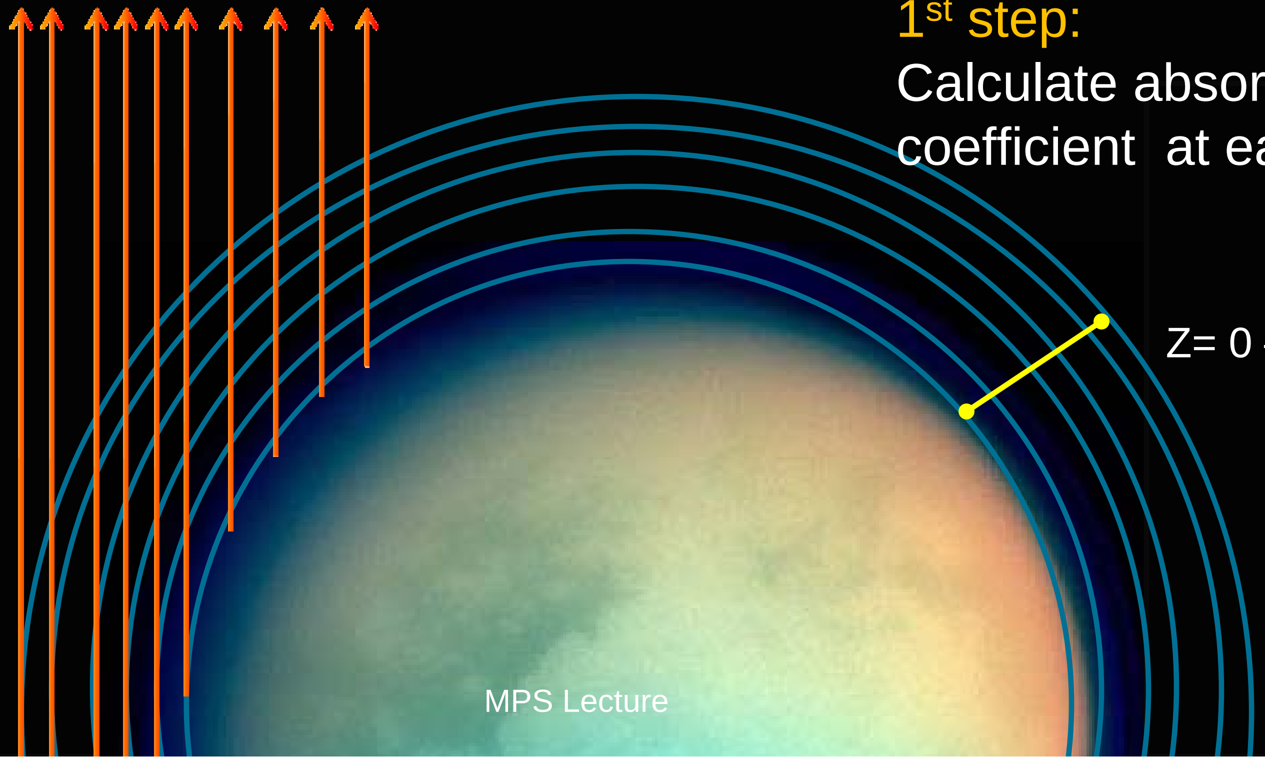
III.- Modeling procedure

3rd step:

Integrate and convolve with the antenna pattern

2nd step:

Calculate RT along each ray path

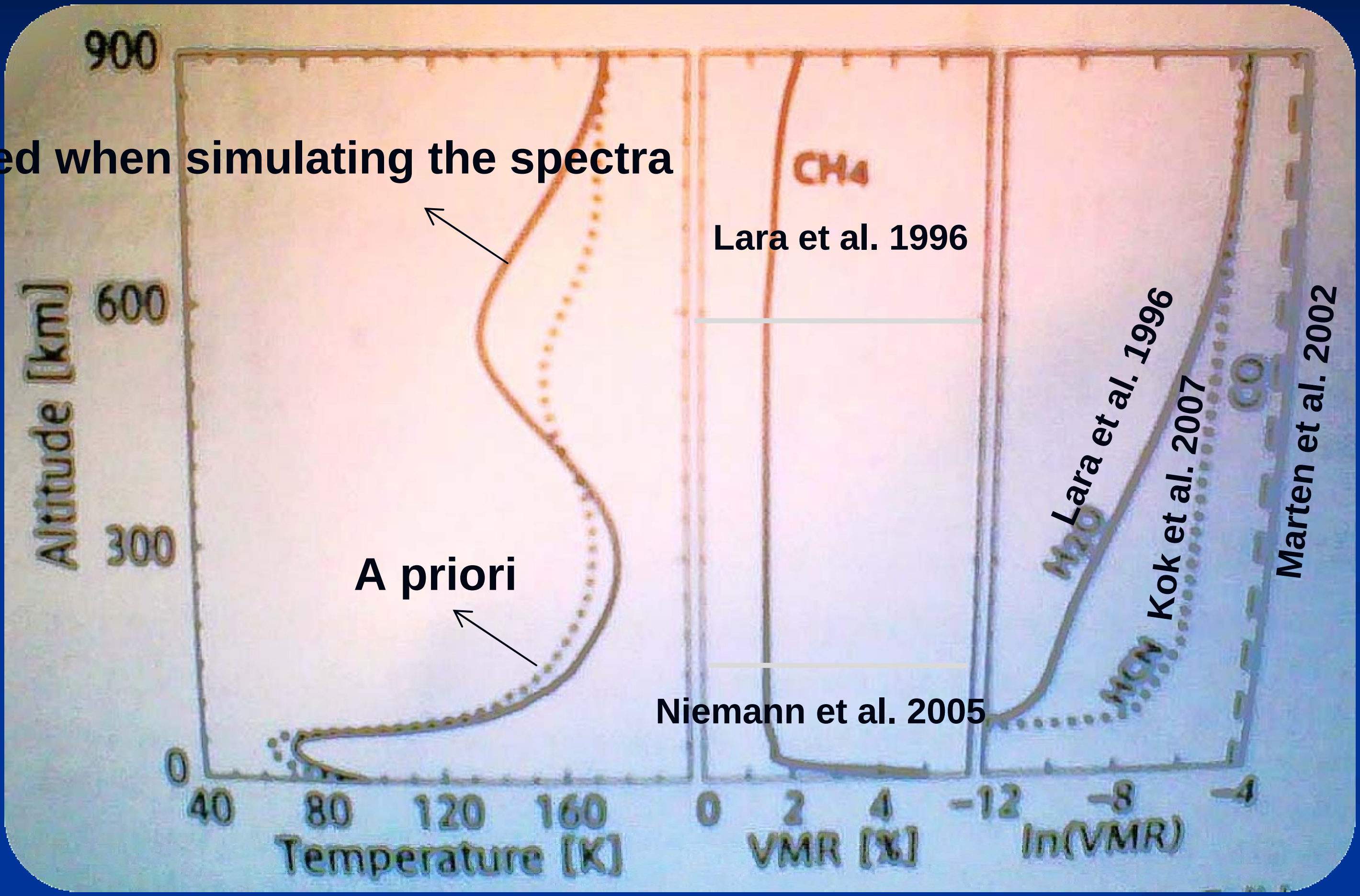


1st step:

Calculate absorption coefficient at each layer

Example 3

Adopted Titan‘s thermal and pressure profiles for the opacity calculations



Profile used when simulating the spectra

A priori

Lara et al. 1996

Niemann et al. 2005

Lara et al. 1996

Kok et al. 2007

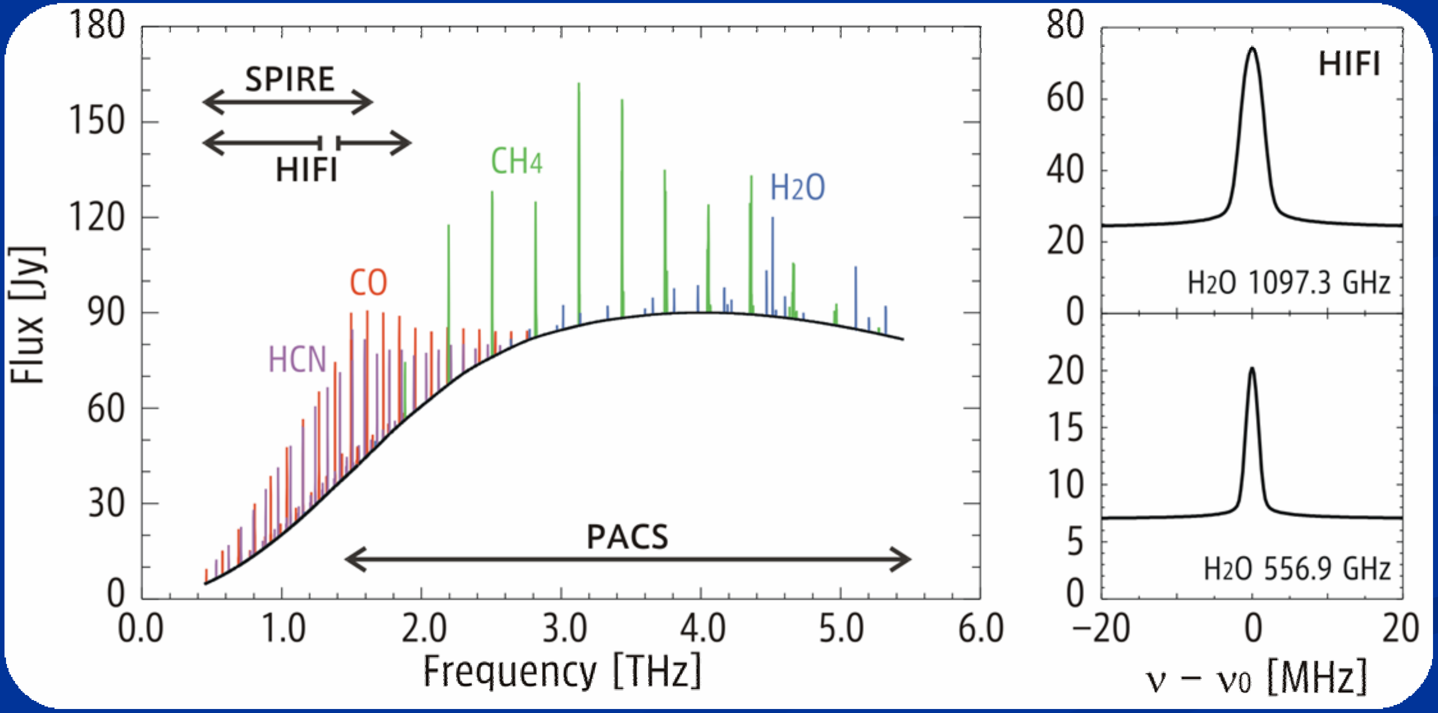
Marten et al. 2002

Example 3

IV.- Results

- Synthetic spectra of the Herschel Spectroscopic observations of Titan

- We show model calculations of the synthetic spectrum of Titan's atmosphere (CH4, H2O, HCN and CO) with the SPIRE (0.04 cm-1), PACS (1-4 GHz) and HIFI (1 MHz) spectral resolutions.

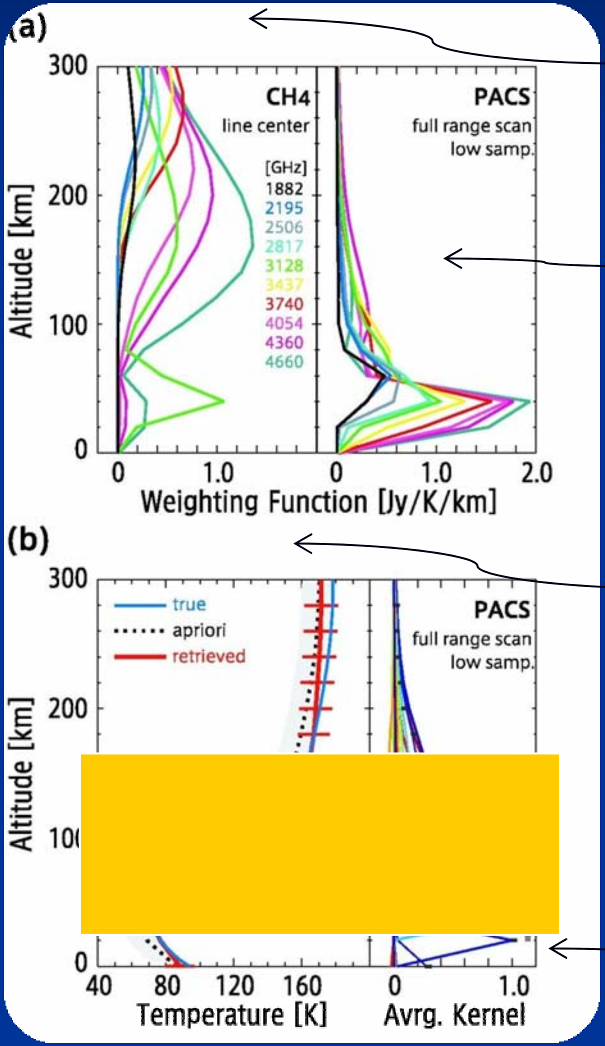


Expected Wat
spectra
observations
with HIFI

Example 3

Results - PACS

We determine a temperature profile from the emission spectra of CH4
We retrieve the mixing ratio profiles of the species



- Temperature profile

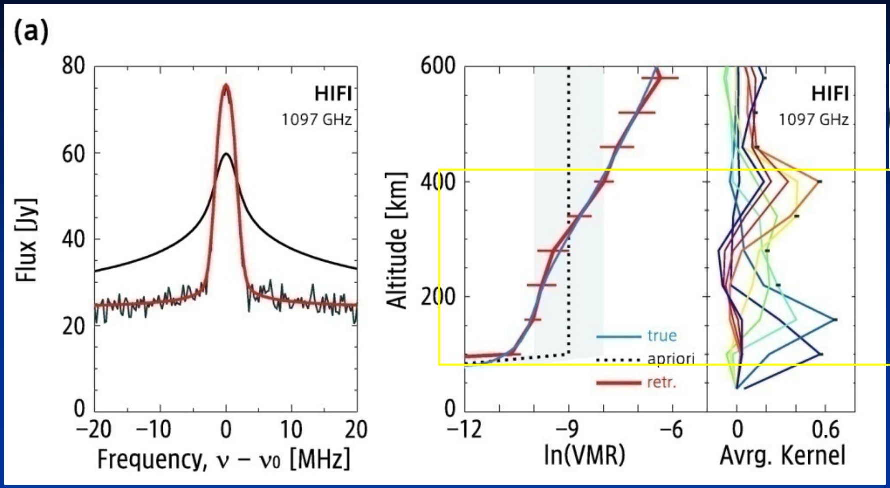
Temperature weighting functions for CH4

Results after considering PACS spectral resolution and range Scan mode.

Temperature retrieval from the PACS CH4 range scan mode (S/N 100).
Blue : used to calculate the synthetic spectra
Red: retrieved profile

Averaging kernels of the retrieved temperature

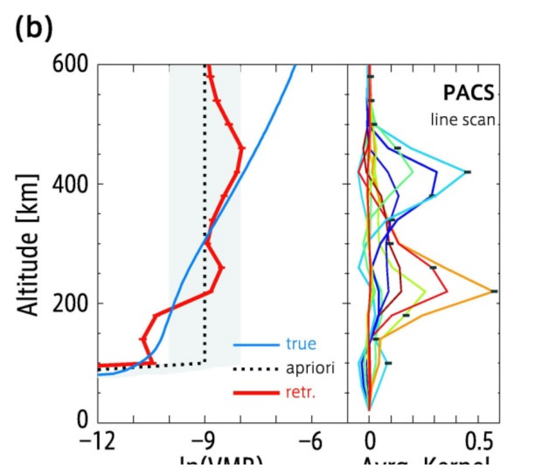
Example 3 Retrieval simulations of water mixing rations



S/N=10

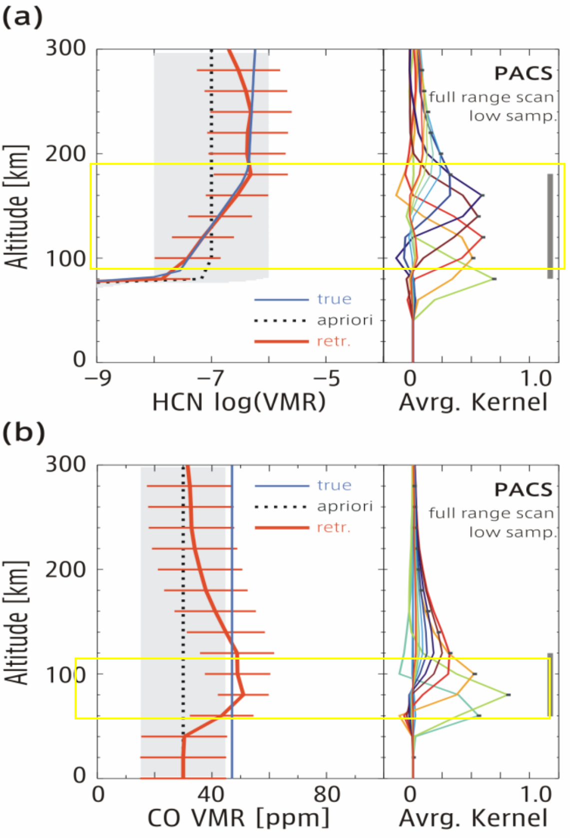
We investigate how PACS low sampling full range scan is sensitive to the HCN and CO distributions

H_2O, HCN, and CO mixing ratios



Line scan mode

Combination of 10 lines

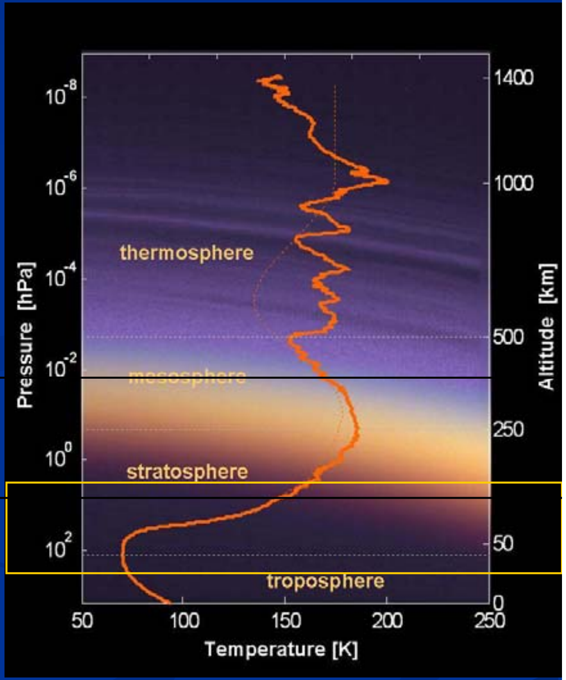


PACS mixing ratio retrievals require the use of multiple-line observations with different line opacities for each specie.

Example 3

IV.- Conclusion 3rd Example

We have calculated the expected full range spectra of Titan´s with HIFI, PACS and SPIRE.
More than 10 CH4 rotational lines are expected to be detected by PACS, but it is not able to resolve the shape lines. → A combination of lines lets to retrieve the Titan´s atmospheric temperature at 20-140 km.



High spectral resolution spectra of water is expected to be observed with HIFI, which enable us to retrieve the water mixing ratio at the altitude range of 100-400 km.

It is also expected that the line scan observations of multiple water lines with PACS will contribute to constraints the water abundances.

These results in preparation for Herschel show out technique to be a promising tool for the analysis of Titans´atmospheric data.

Example 3

Cassini Mission Overview

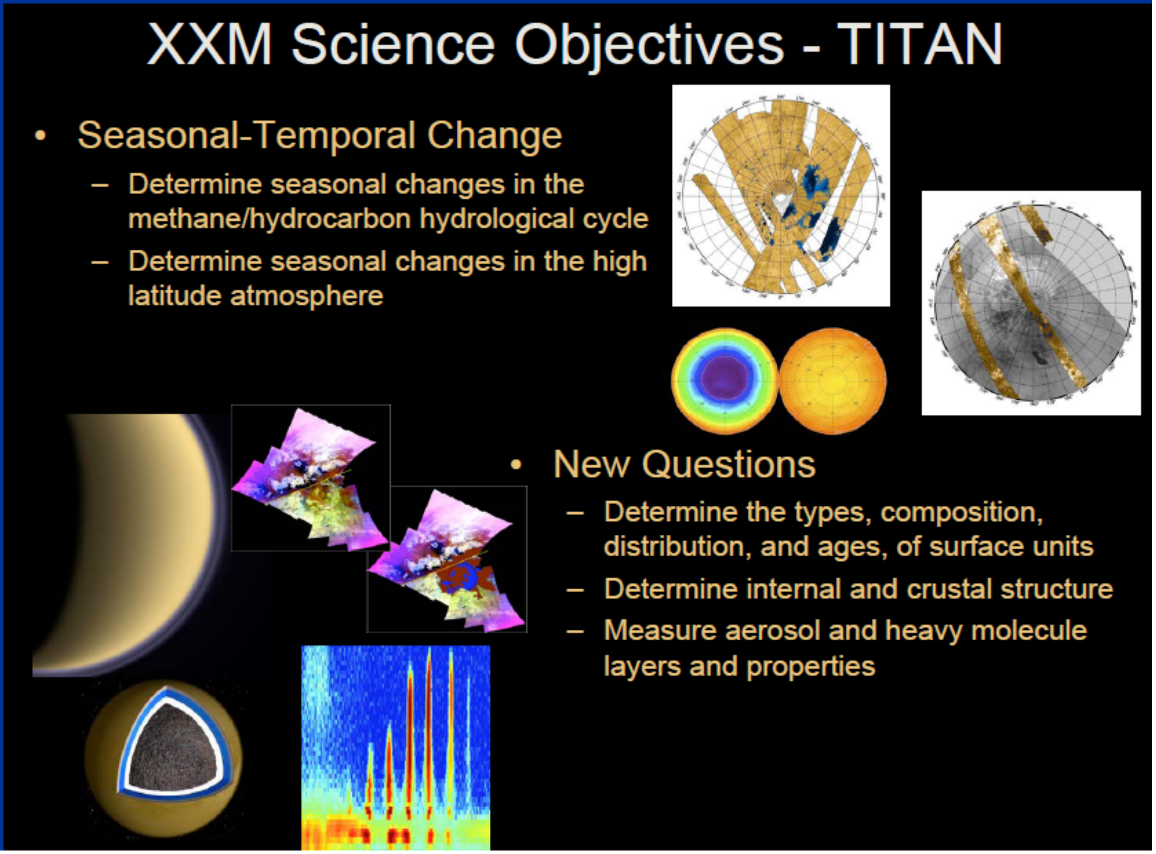
Four-Year Prime Tour + Two-Year Extended Mission (Proposed), July 2004 - July 2010

Extended Mission

Year of Tour	1	2	3	4	5	6	??
Orbits	11	15	22	27	39	21	
Titan	●●●* ●●● *Huygens	●●● ●●● ●●●	●●● ●●● ●●● ●●● ●●● ●●● ●	●●● ●●● ●●● ● ●	●●● ●●● ●●● ●●● ●	●●● ●●● ●●● ●●● ●	

26 Titan flybys

Proposed Cassini-Huygens Solstice Mission
(additional 7-year phase)



XXM Science Objectives - TITAN

- Seasonal-Temporal Change
  - Determine seasonal changes in the methane/hydrocarbon hydrological cycle
  - Determine seasonal changes in the high latitude atmosphere
- New Questions
  - Determine the types, composition, distribution, and ages, of surface units
  - Determine internal and crustal structure
  - Measure aerosol and heavy molecule layers and properties

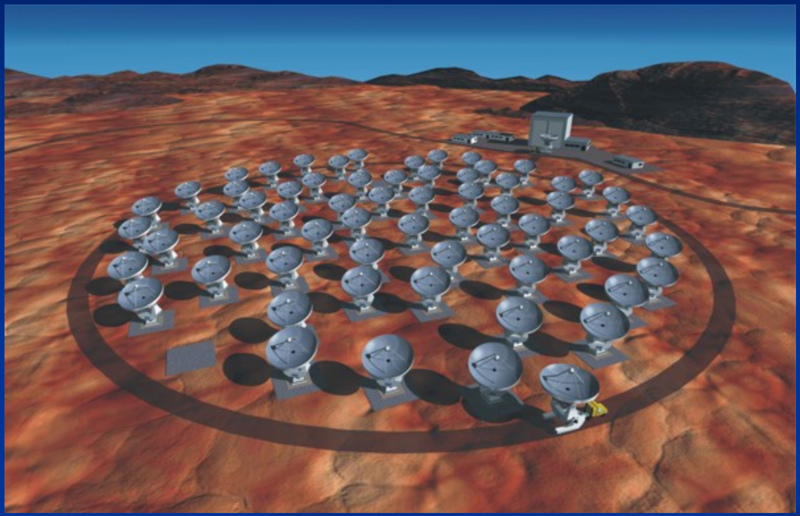
Future of planetary observations in the mm/submm

- **Atacama Large Millimeter Array Project (ALMA)**

0.3 mm – 9.6 mm

50 12m dishes

Ready in 2012

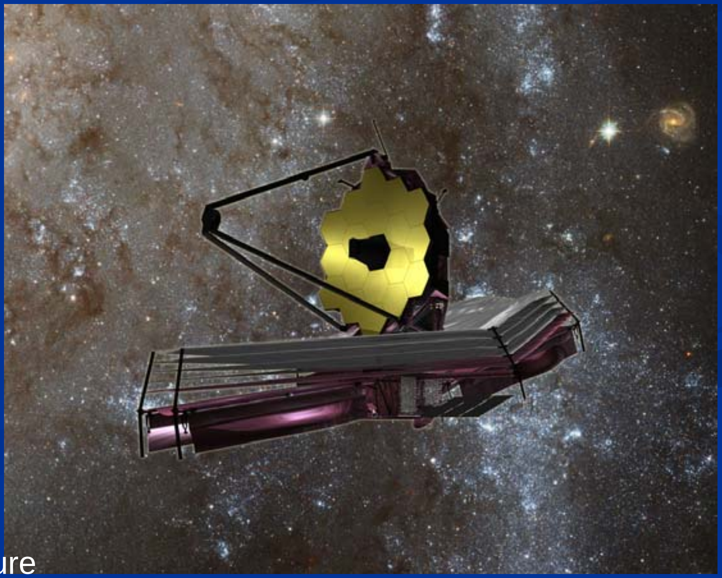


James Webb Space Telescope (JWST)

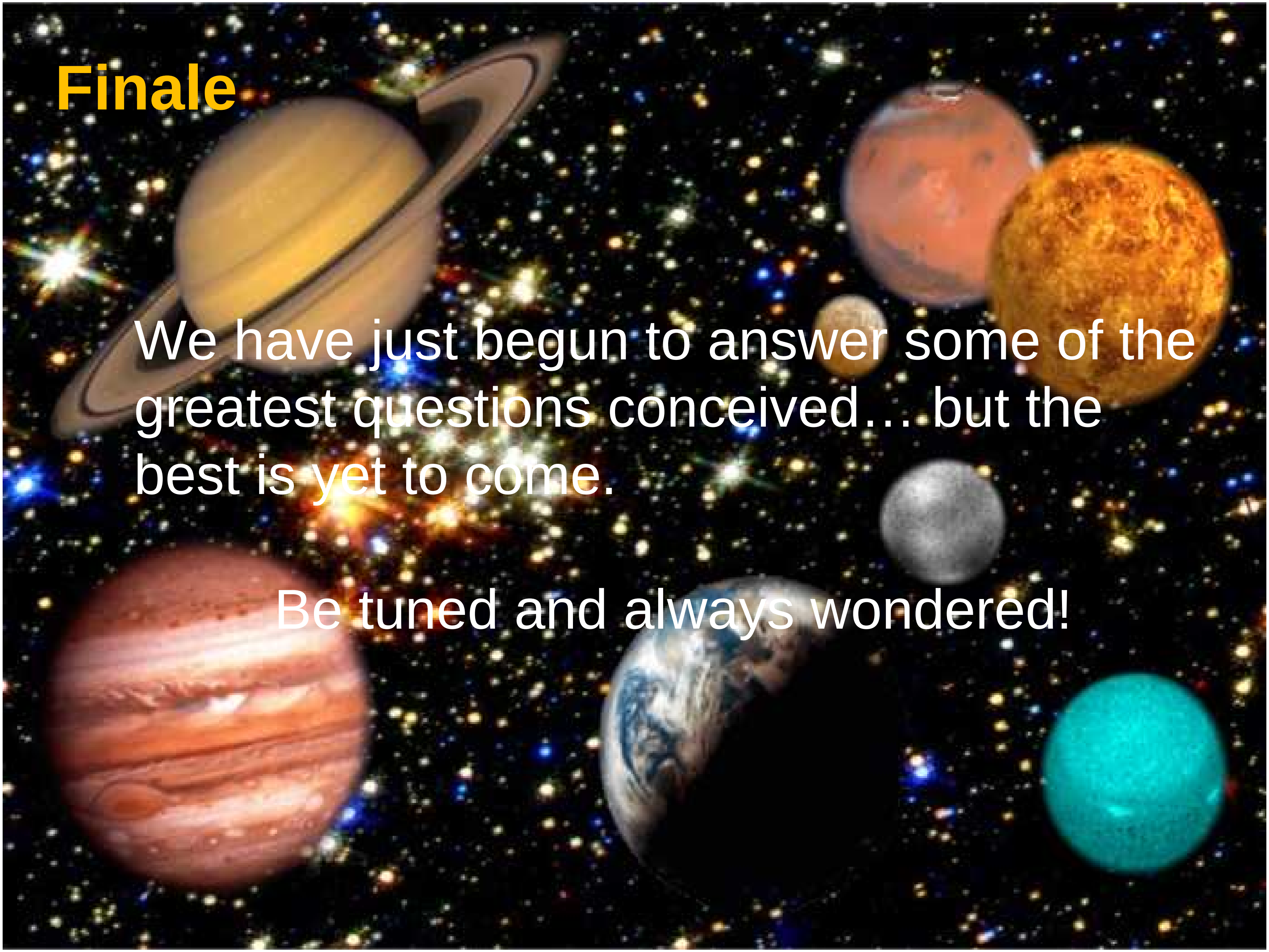
0.6 μm – 28 μm

Telescope 6.5m

Launch: 2013



Finale



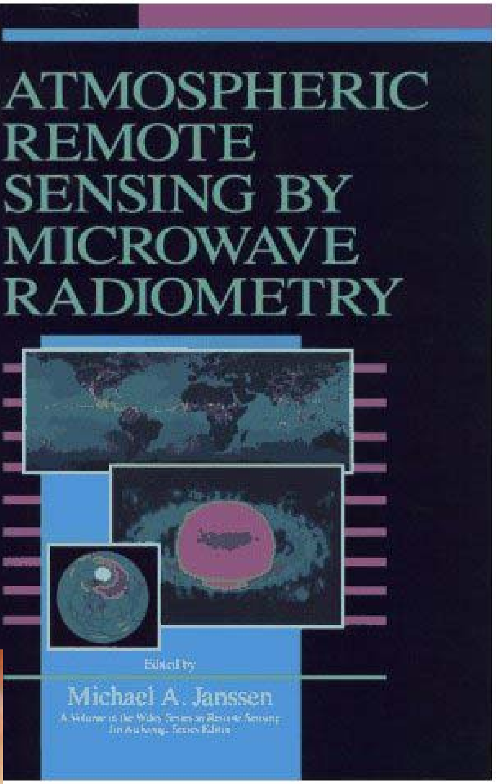
We have just begun to answer some of the greatest questions conceived… but the best is yet to come.

Be tuned and always wondered!

Where to consult?

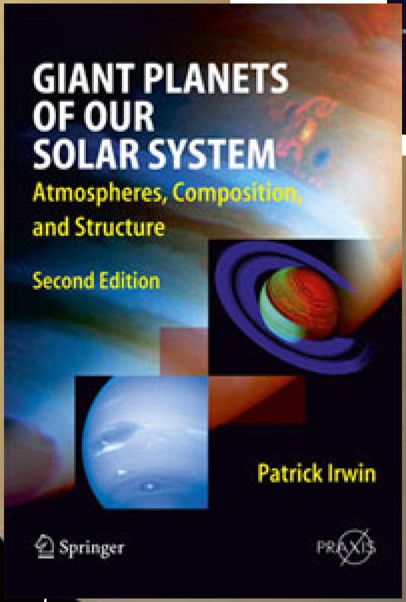
Atmospheric Remote Sensing by Microwave Radiometry
Michael A. Janssen (Editor)

Giant Planets of Our Solar System: Atmospheres, Composition, and Structure
Patrick G.J. Irwin (Author)



ATMOSPHERIC REMOTE SENSING BY MICROWAVE RADIOMETRY

Edited by
Michael A. Janssen



GIANT PLANETS OF OUR SOLAR SYSTEM
Atmospheres, Composition, and Structure
Second Edition
Patrick Irwin
Springer
PRAXIS

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Where to consult?

- Venus

M. Rengel, P. Hartogh, C. Jarchow. **"HHSMT Observations of the Venusian Mesospheric Temperature, Winds, and CO abundance around the MESSENGER Flyby"**, 2008, Planetary and Space Science, 56, 1688-1695. doi:10.1016/j.pss.2008.07.014

M. Rengel, P. Hartogh, C. Jarchow. **Mesospheric vertical thermal structure and winds on Venus from HHSMT CO spectral-line Observations "**, 2008, Planetary and Space Science, Volume 56, Issue 10, , Ground-based and Venus Express Coordinated Campaign, Ground-based and Venus Express Coordinated Campaign, August 2008, Pages 1368-1384. DOI information: 10.1016/j.pss.2008.07.004

- Titan - APEX

Rengel, Sagawa, Hartogh, Adv Geo, submitted AdvGeo

- Herschel plans/project

Hartogh P., Lellouch E., Crovisier J., and the HssO Team, "Water and related chemistry in the Solar System. A Guaranteed Time Key Program for Herschel", PSS 57, Issue 13, 2009, pags 1596-1606. doi:10.1016/j.pss.2009.07.009

- Titan : preparations for Herschel

Rengel M., Sagawa H., Hartogh P. "Retrieved Simulations of Atmospheric Gases from Herschel observations of Titan". Advance in Geosciences, in press