"Methane on Mars: Spatial & Temporal Variability"

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and

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University of Maryland

KISS – Methane on Mars   Pasadena, CA   Dec 8, 2015

"Mars – The Cutting Edge Today"

Trace Gases: CH_4, H_2O, HDO, H_2O_2, CO, O_2, O_3, etc.

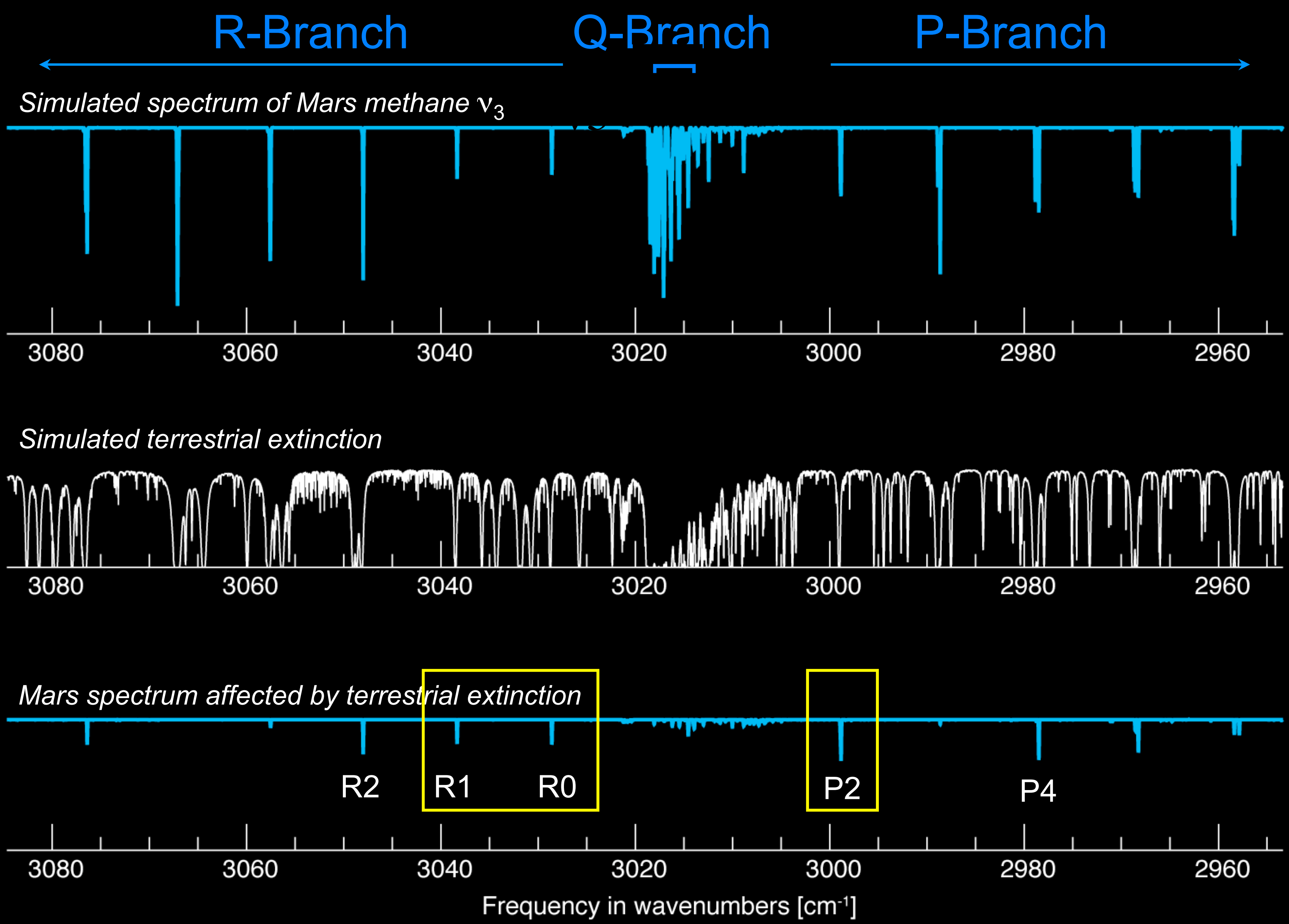
- 3-D spatial: longitude, latitude, & vertical
- 1-D temporal: (diurnal, seasonal, & inter-annual)
- High resolution (spectral & spatial)

Orbiters & Rovers

- MGS, MRO, Mars Express, Maven, *ExoMars 2016*
- Curiosity, *ExoMars 2018, Mars 2020*

Ground-based

- Keck, NASA-IRTF, VLT
- ALMA, SOFIA


R-Branch
Q-Branch
P-Branch
Simulated spectrum of Mars methane ν_3
3080
3060
3040
3020
3000
2980
2960
Simulated terrestrial extinction
3080
3060
3040
3020
3000
2980
2960
Mars spectrum affected by terrestrial extinction
R2
R1
R0
P2
P4
3080
3060
3040
3020
3000
2980
2960
Frequency in wavenumbers [cm-1]

CH_4 :

3 nuclear spin species,

A, E, F

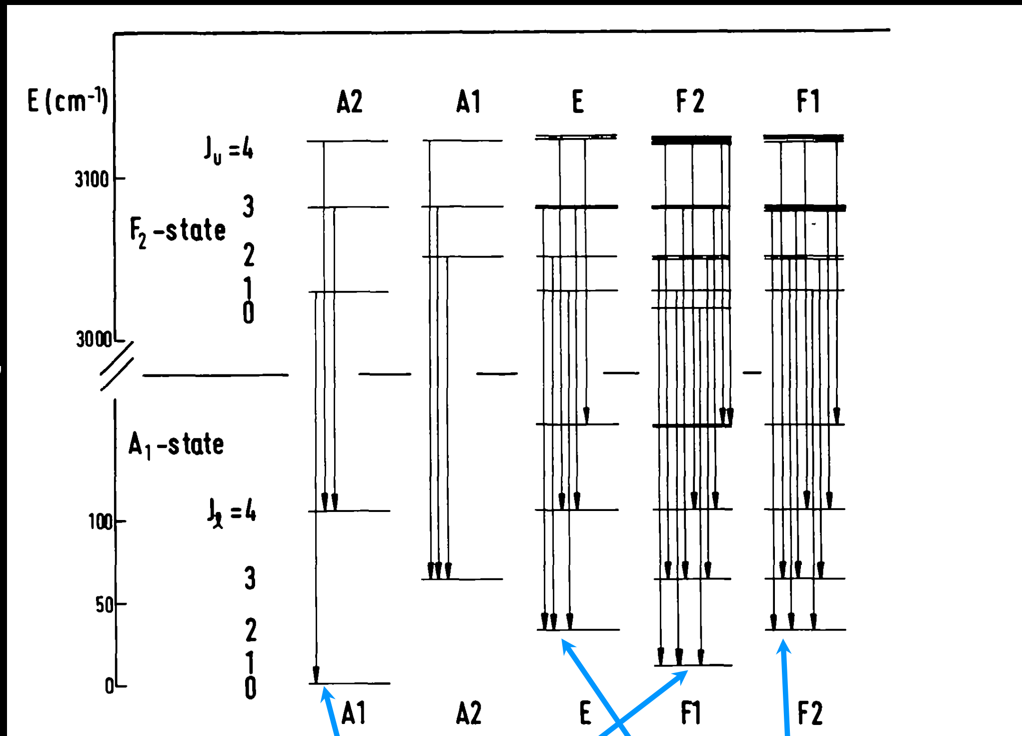
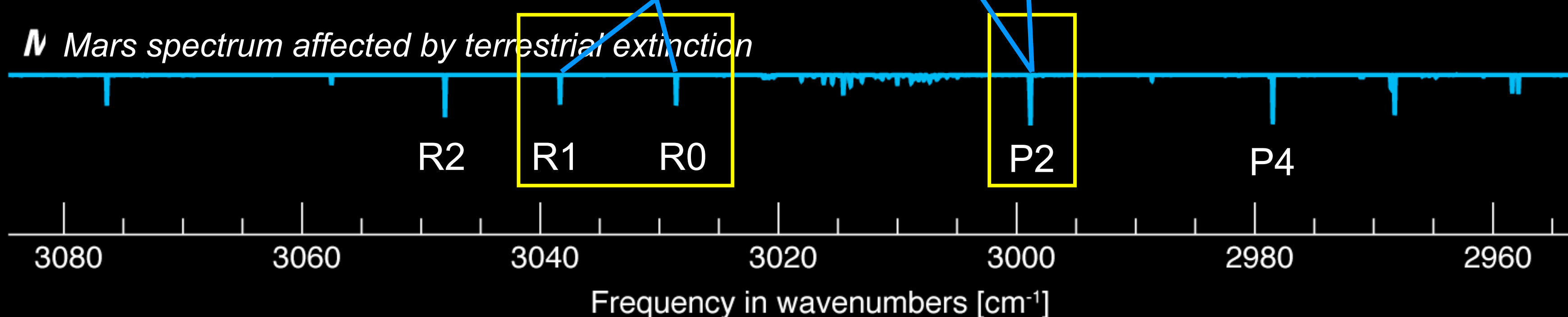
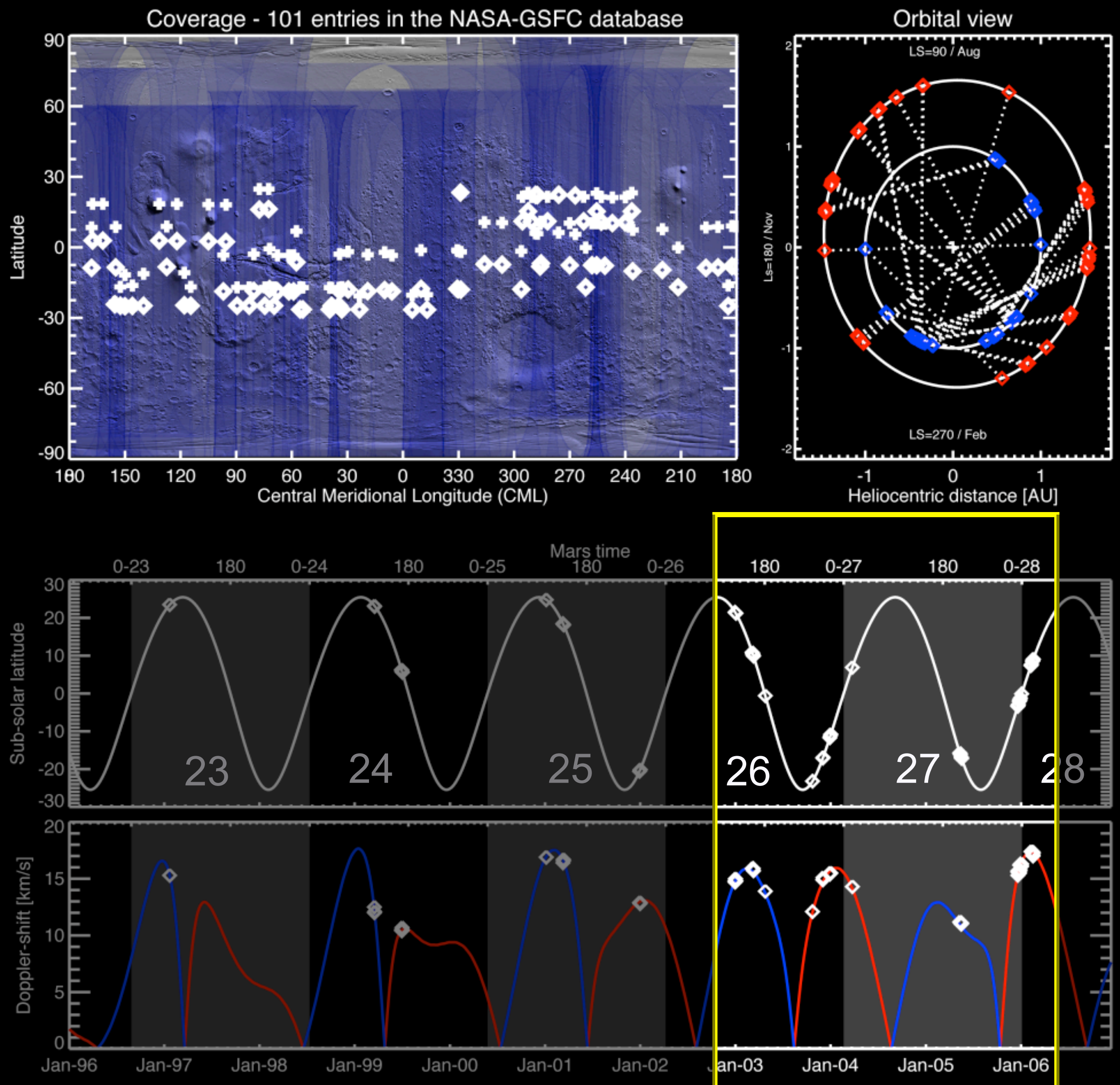


Fig. 2. Lower rotational states of the A_1 ground state and F_2 excited state of the ν_3 vibrational band of CH_4. Rotational levels of one species (A, E or F) can only combine with levels of the same species (After Drapatz et al. A&A 1987)



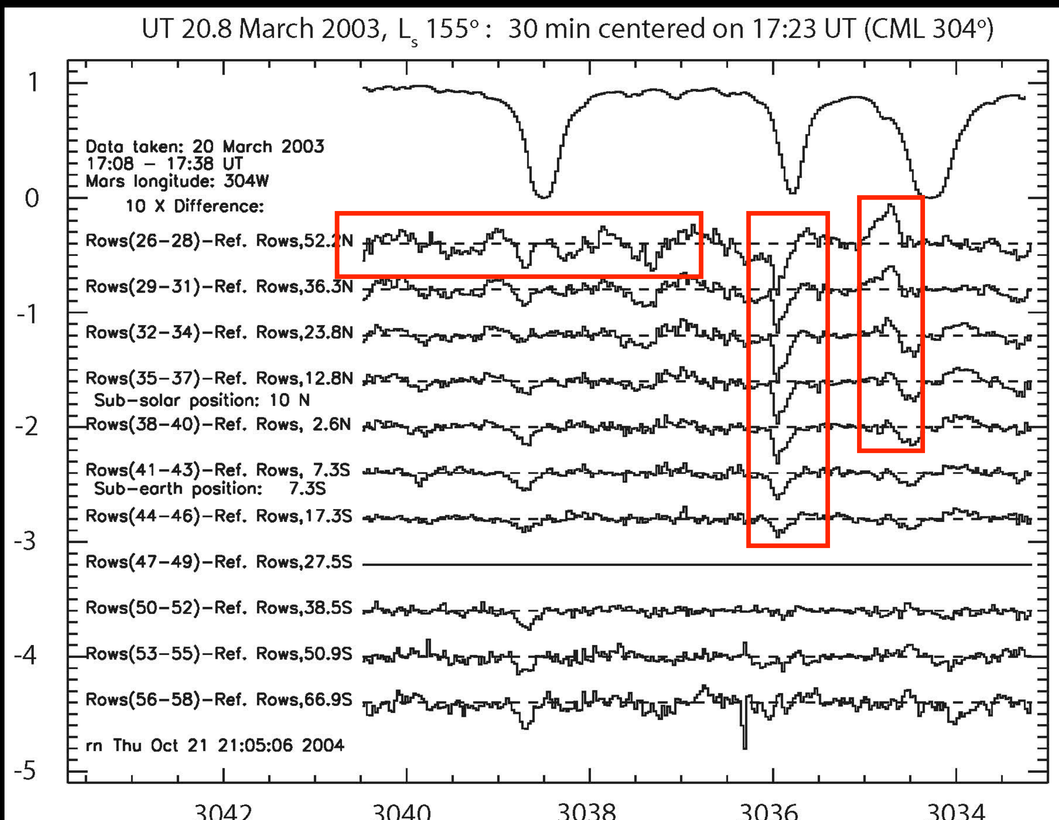

Coverage - 101 entries in the NASA-GSFC database
Latitude
Central Meridional Longitude (CML)
Orbital view
LS=90 / Aug
LS=270 / Feb
Ls=180 / Nov
Heliocentric distance [AU]
Mars time
0-23
0-24
0-25
0-26
0-27
0-28
Sub-solar latitude
Doppler-shift [km/s]
23
24
25
26
27
28
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06

Analyses after 2005
Methane and Water on Mars

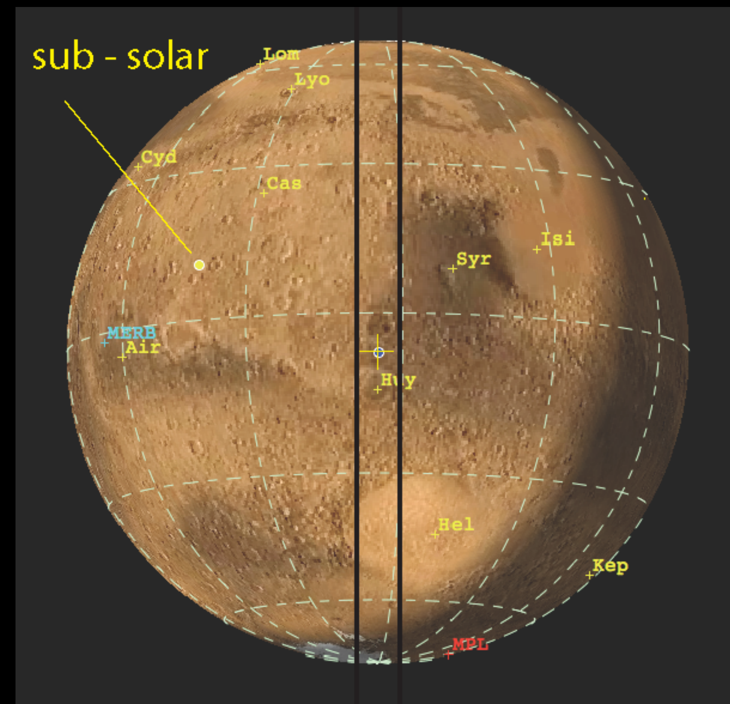
CSHELL slit position
UT 20.73 March 2003

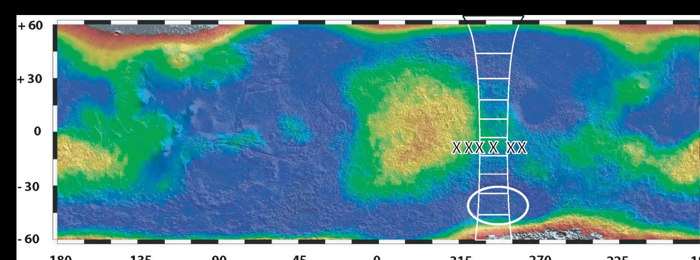
ISSUES :

CH_4 R1 | H_2O -- |-------|--



Wavenumber, cm^{-1}





mjm_080604.6

Analysis Changes Leading to Absolute Extractions (2005 Onward)

Pipeline Processing

From raw spectral-spatial frames to calibrated & registered frames

- Re-sample wavelength scale to milli - pixel accuracy (row-by-row)
- Use non-linear wavelength re-sampling (atmospheric emission)
- Remove second order fringing (Lomb periodogram analysis)
- Remove internal scattered light
- Correct residual dark current
- Correct residual terrestrial radiance

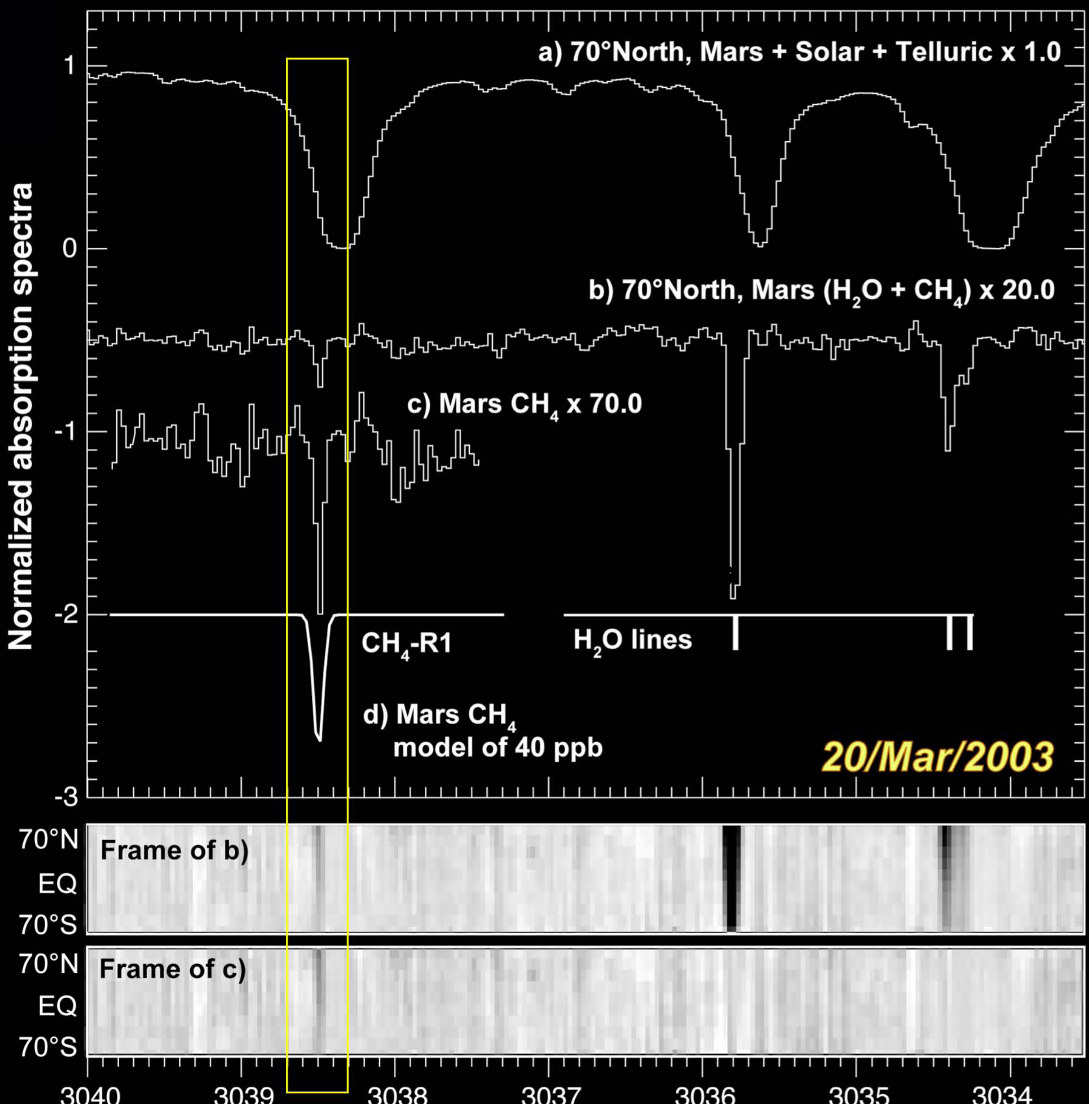
Science Analysis

Atmospheric transmittance -

- Replaced SSP with GenIn2 v4 — and corrected pressure shift code
- Upgraded molecular atlas (now HITRAN ‘04 with ‘05 upgrade)
- Model synthetic spectra using variable resolving power along the slit

Analyses after 2005

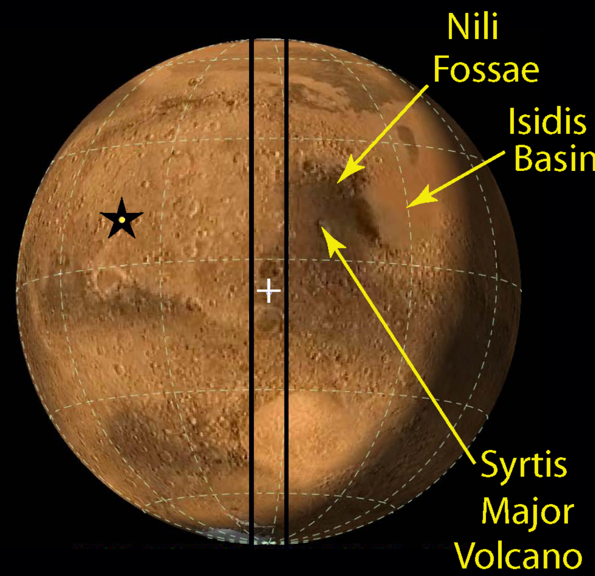
Methane and Water on Mars



CSHELL slit position
UT 20.73 March 2003

Northern late-summer

$L_s = 155°$

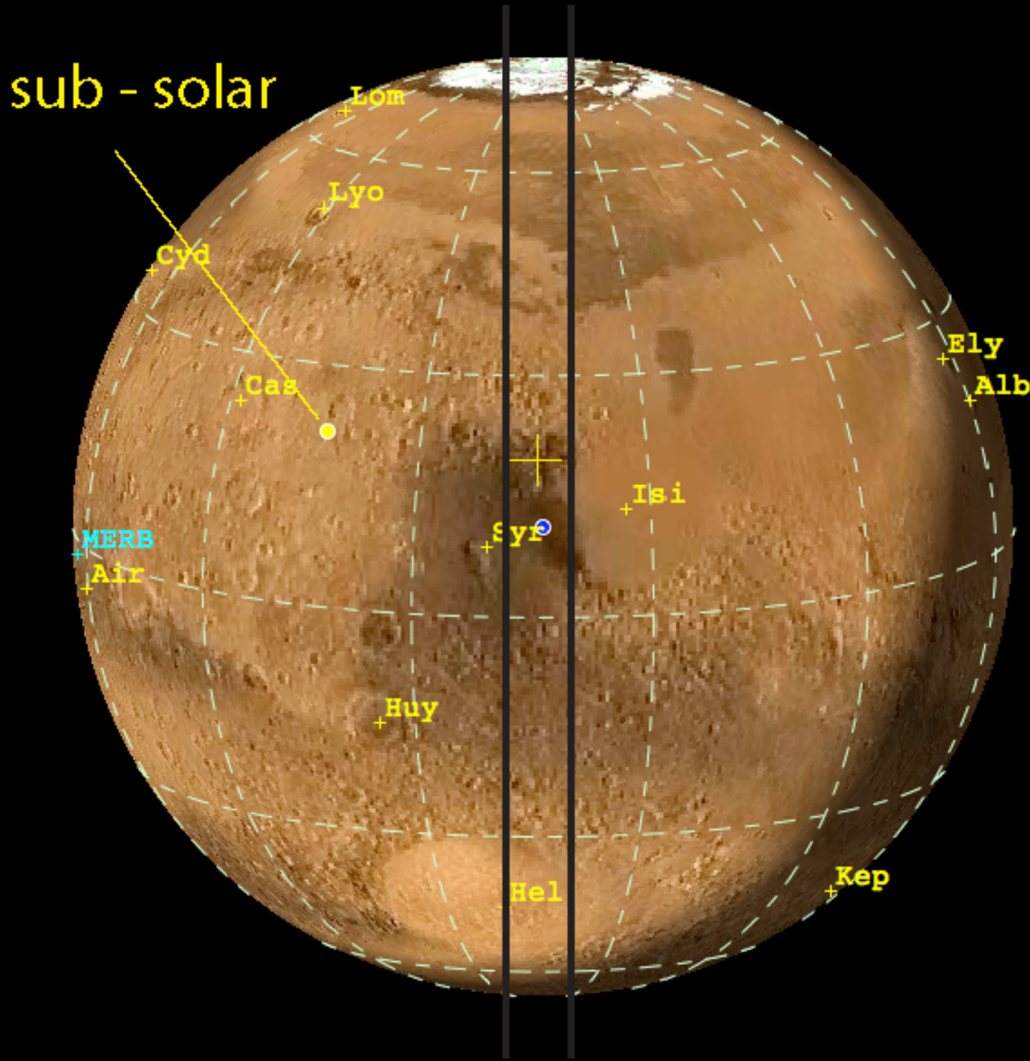


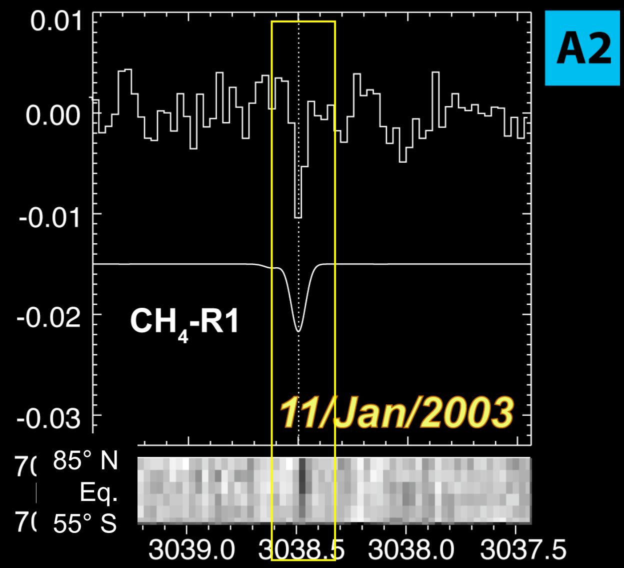
} Both gases are enhanced towards the North

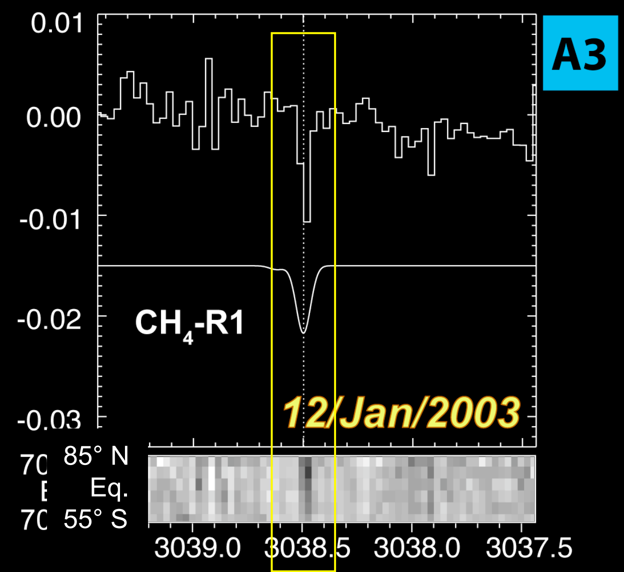
Mumma, Villanueva, Novak, et al. (Science 2009)

2003: Clear Detections of CH_4 R1 on Successive Days

Early summer (North, L_S = 121°)

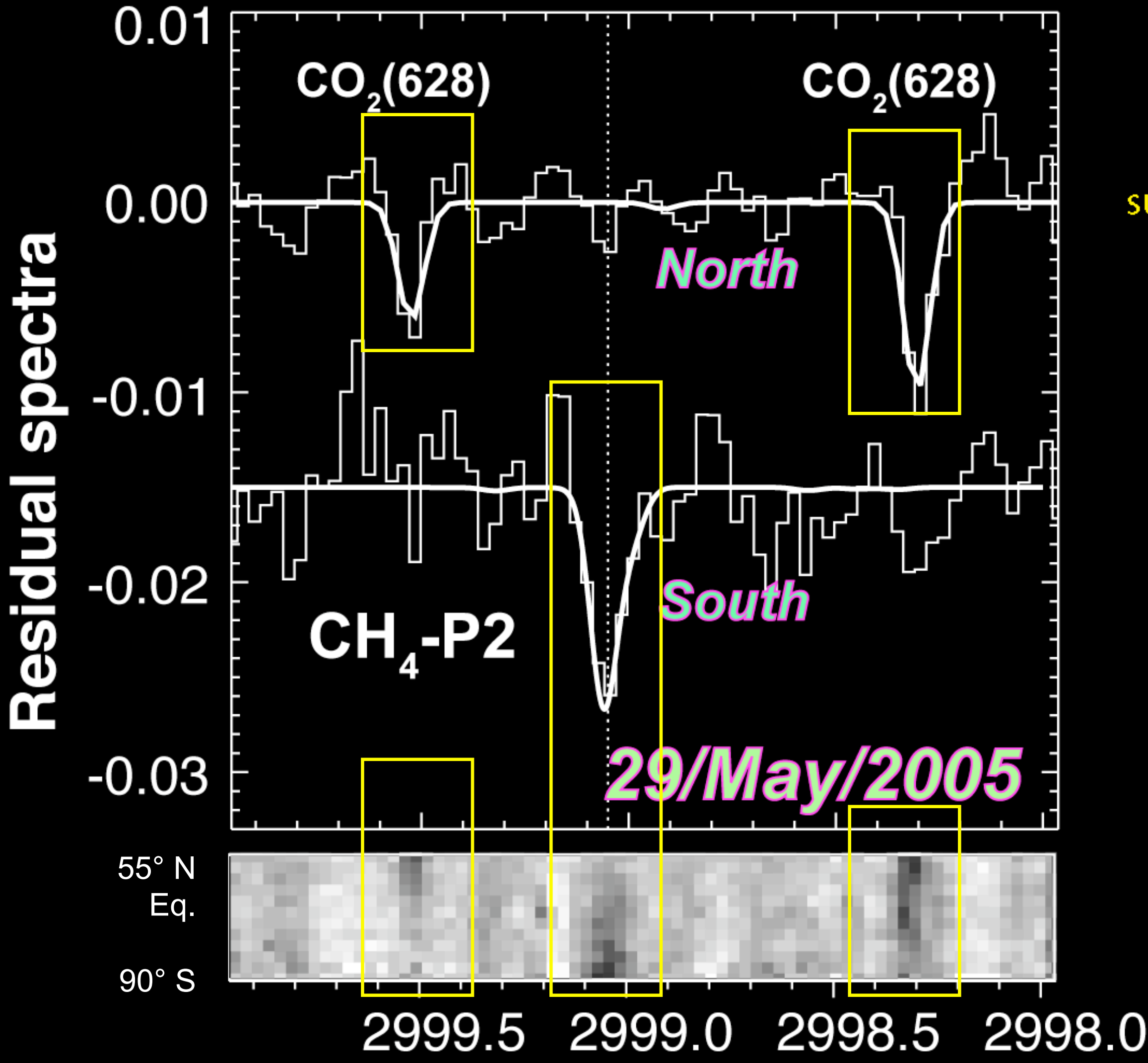




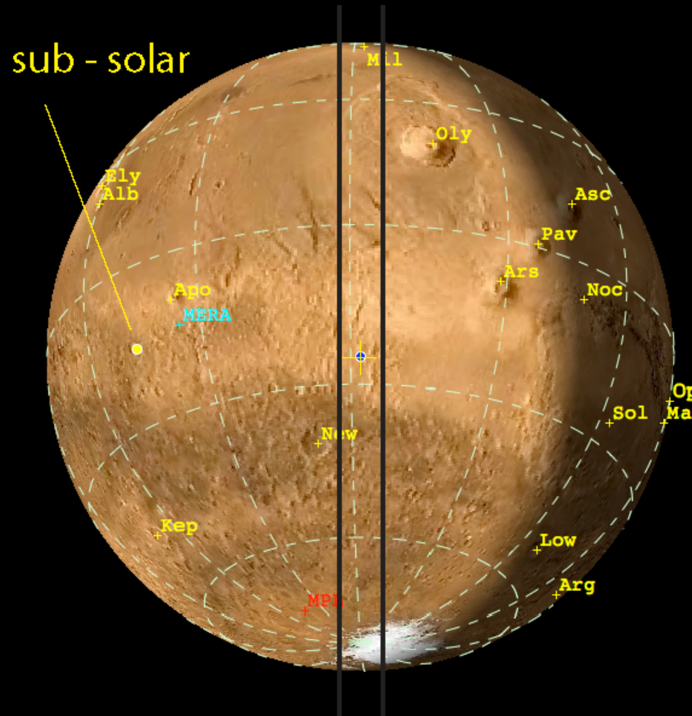


2005: CO_2 (two lines) and CH_4-P2 (two components) are detected

Mars was blue shifted -10.8 km/s

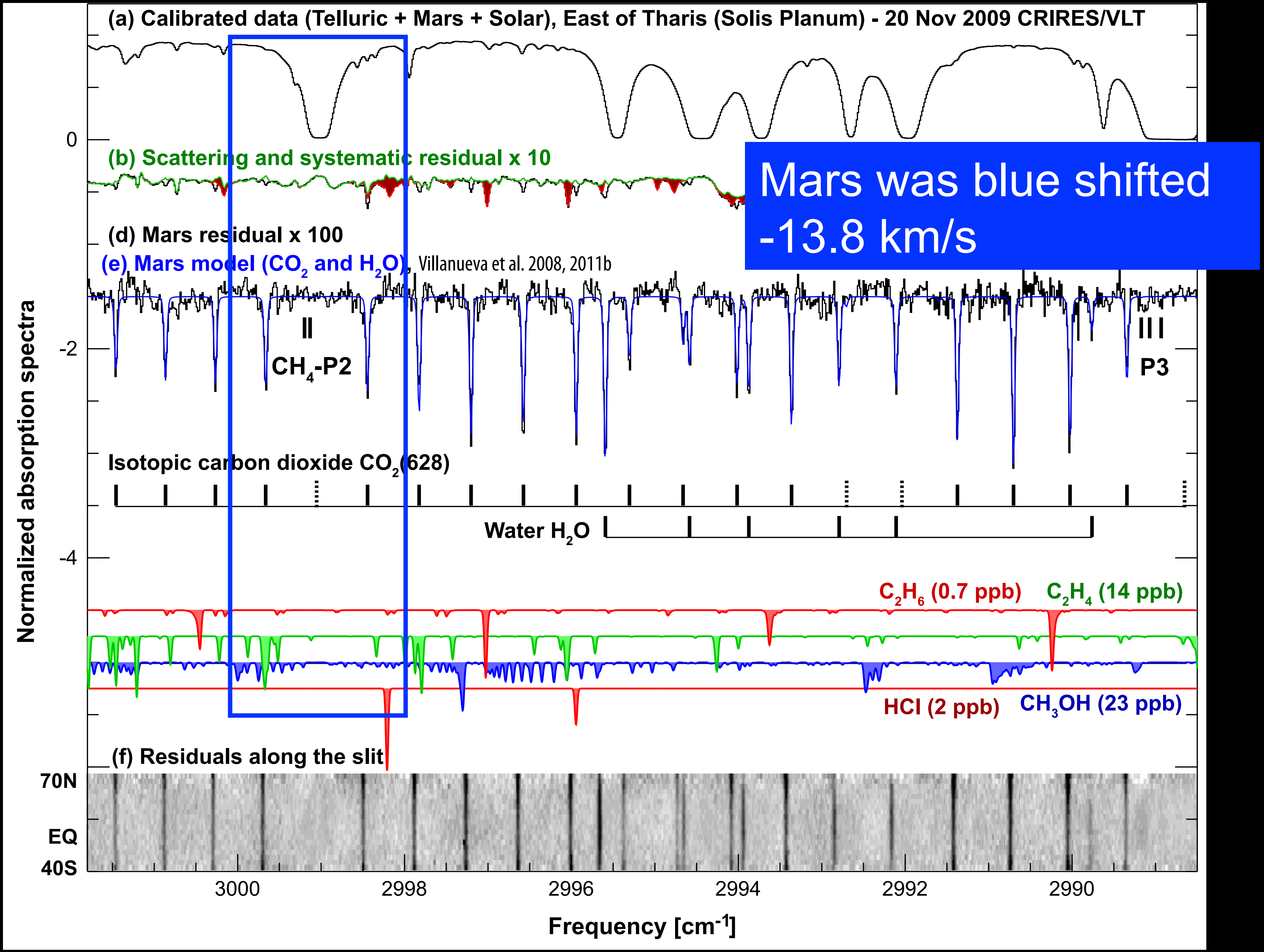


Mid-spring
(South, L_S = 220°)

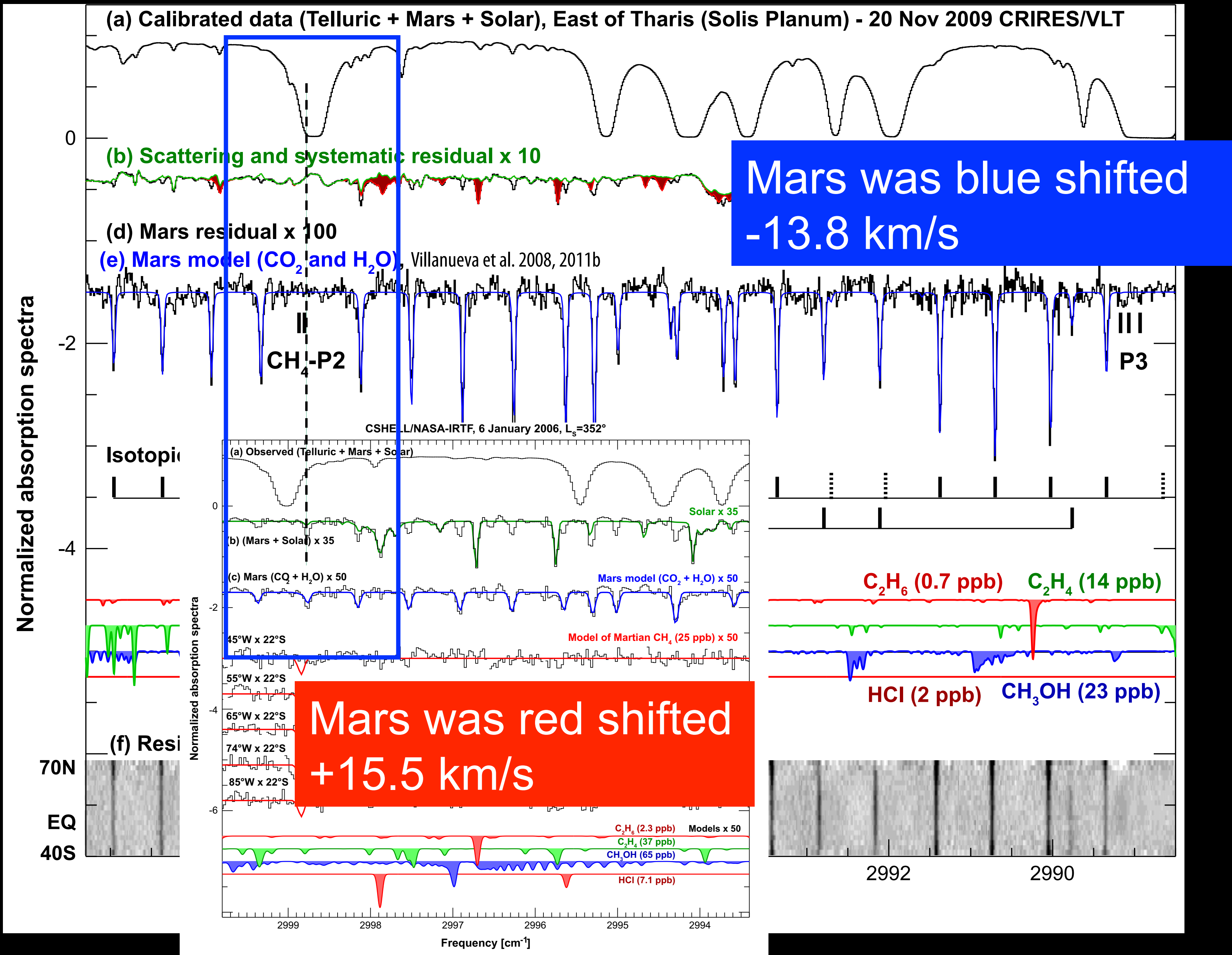


CO_2 enhanced in North
CH_4 enhanced in South

The non-mystery of the ‘missing’ R24 line of CO_2 on Mars



The non-mystery of the 'missing' R24 line of CO_2 on Mars



Additional Checks are Satisfied

A terrestrial artifact will always appear at the same rest position (wavenumber).

The blue (red) arrow marks the expected position when Mars is blue (red) shifted.

No strong residual line appears on the blue wing when Mars is red shifted.

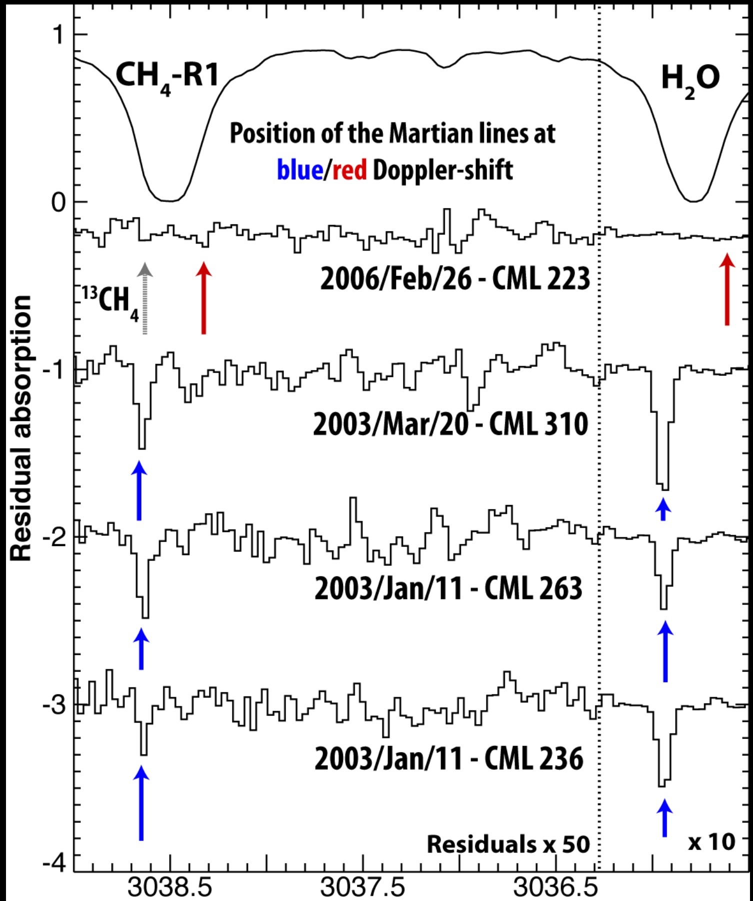
Spectrum	L_s	Doppler, km s^{-1}
'a'	17.2°	+ 17.1
'b, c'	121.9°	– 15.0
'd'	155.0°	– 15.6

'a

'b'

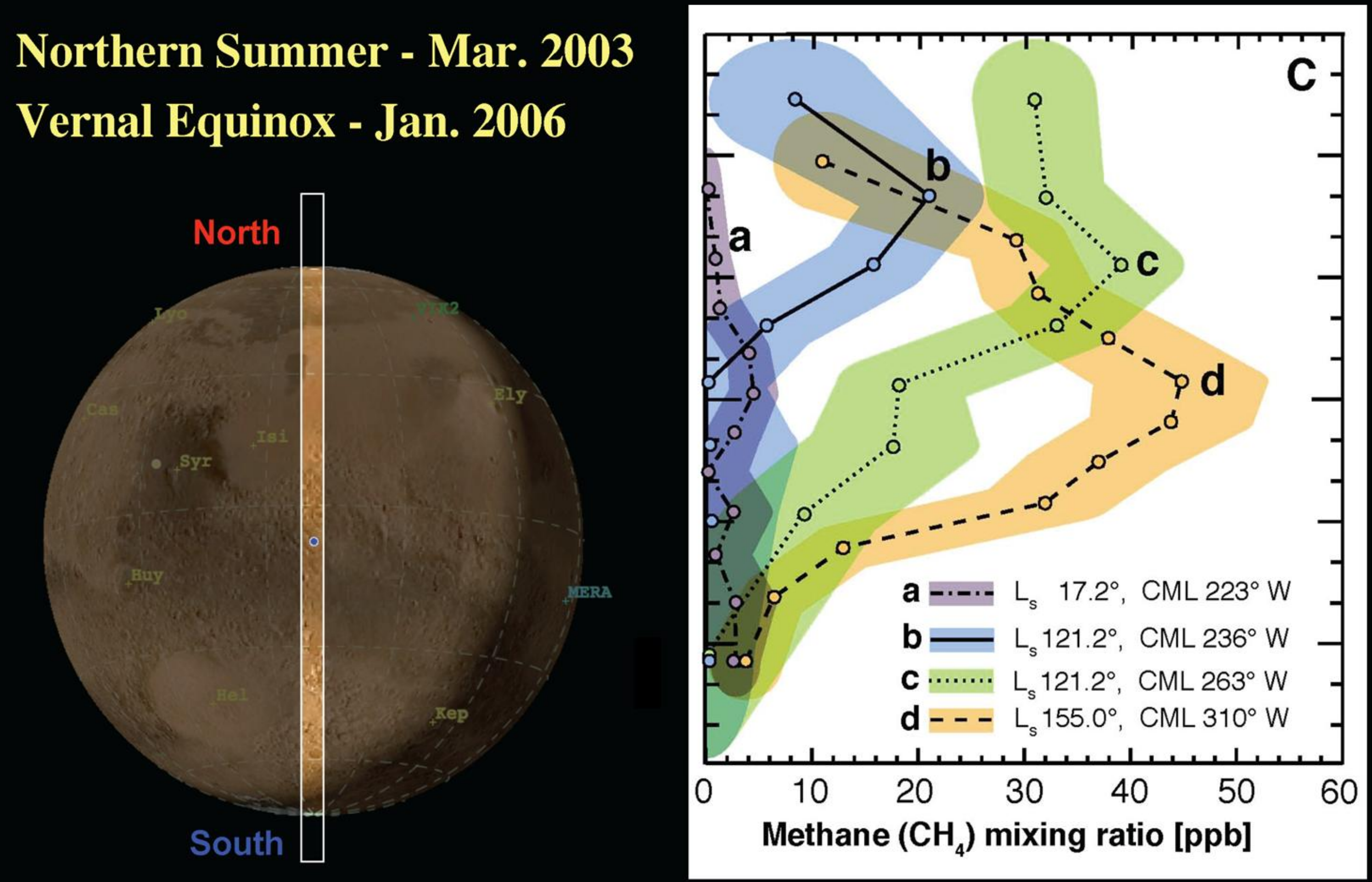
'c'

'd'



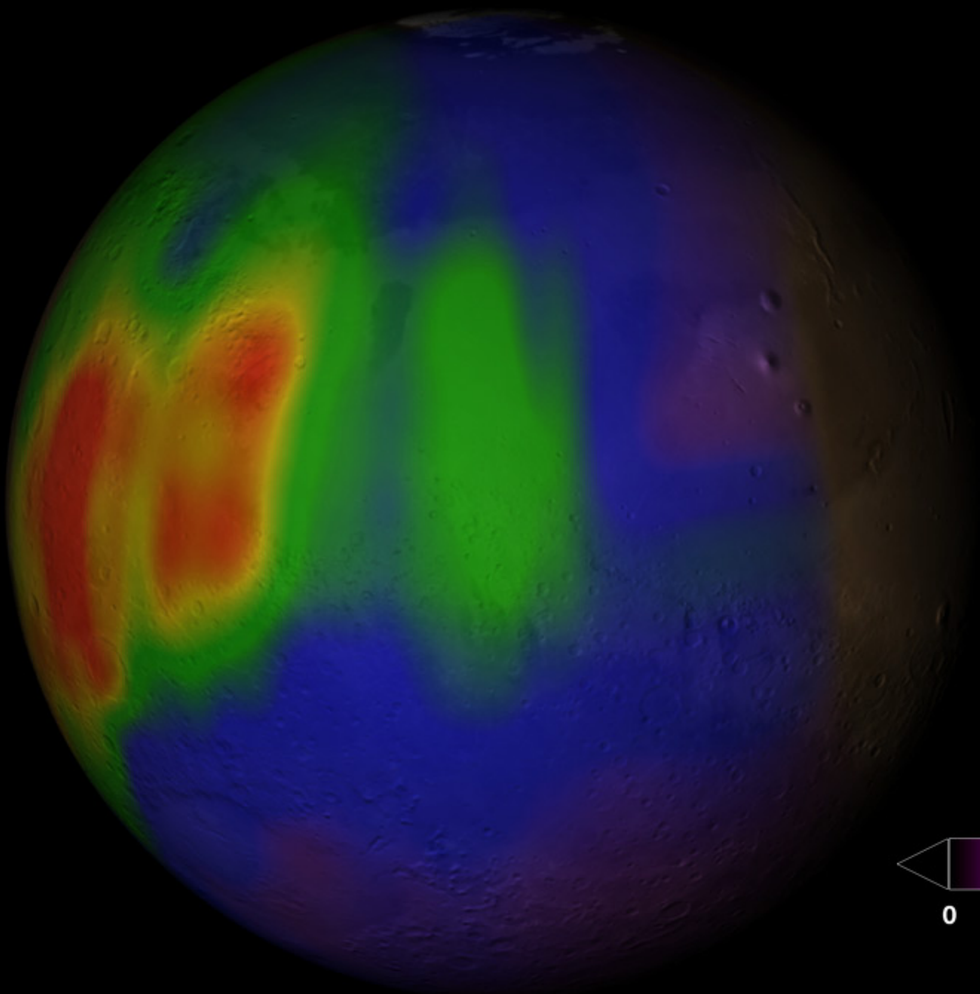
Observer's 'rest' frame

Methane varies with latitude, longitude, and season.
The maximum release moves southward with the Sun.
Methane is nearly absent at vernal equinox (after Southern winter).

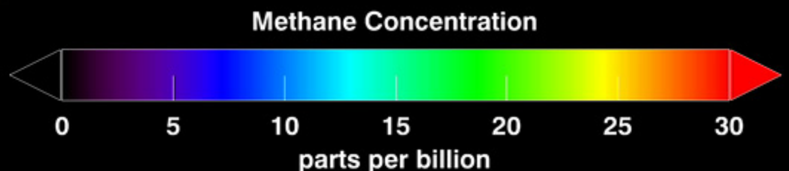


Mumma, Villanueva, Novak, et al. (Science 2009)

Mapping the Methane Plumes on Mars

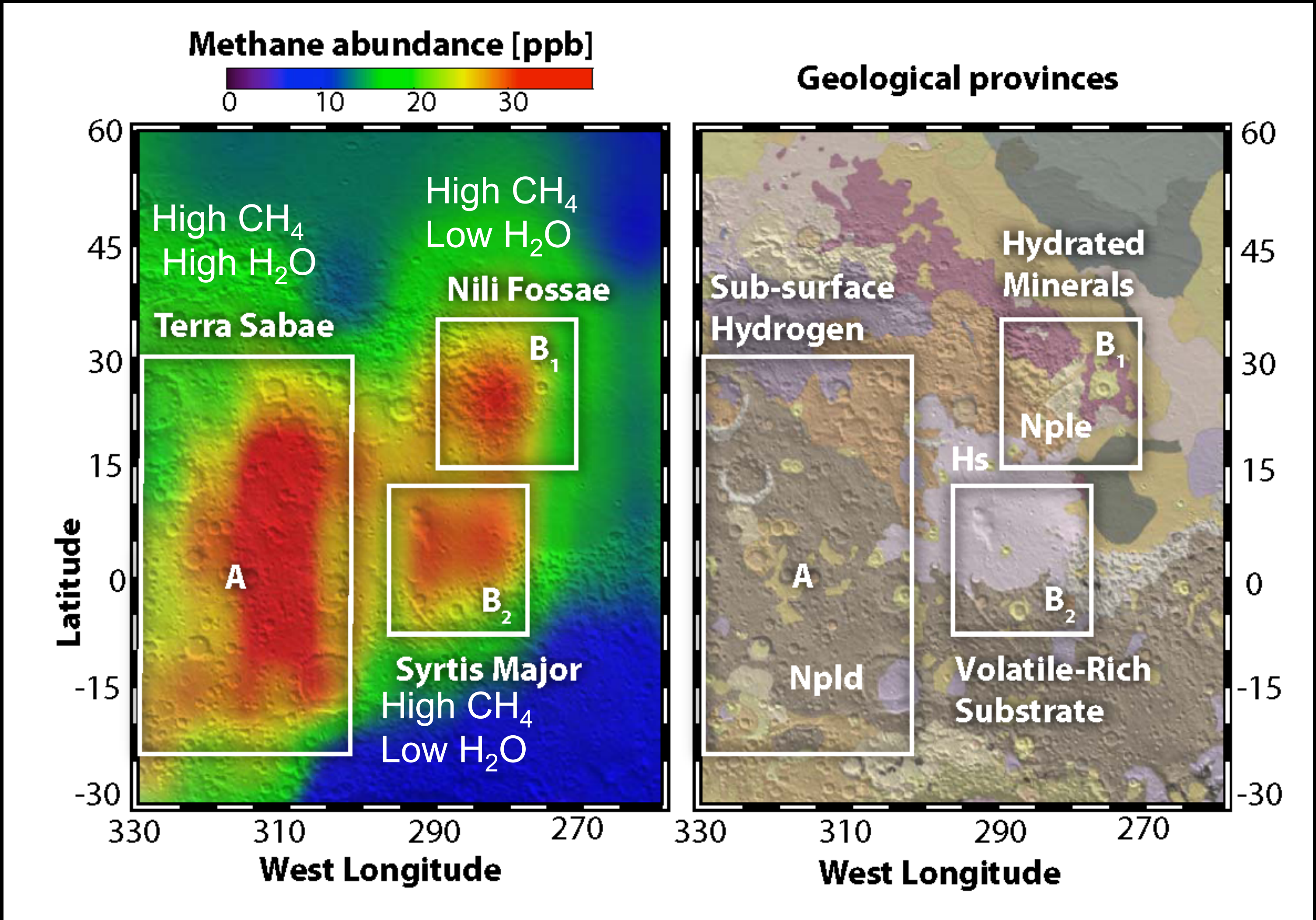


Methane release:
Northern summer



Mumma, Villanueva, Novak, et al. (Science 2009)

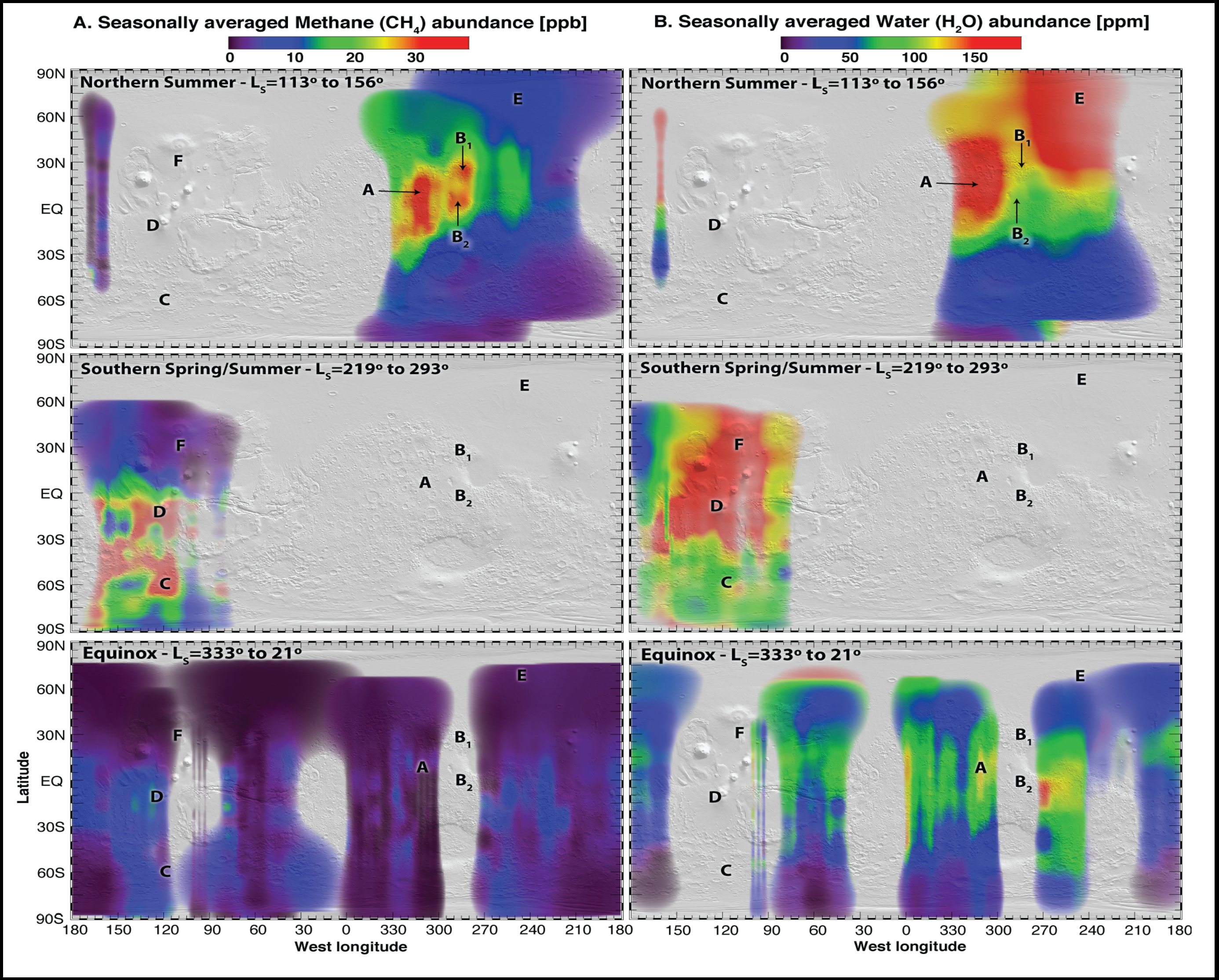
Seeing-limited Spatial Maps reveal local methane plumes on scales of 500 km. Is the release relatively uniform over these regions – or is it strongly localized?



500 km

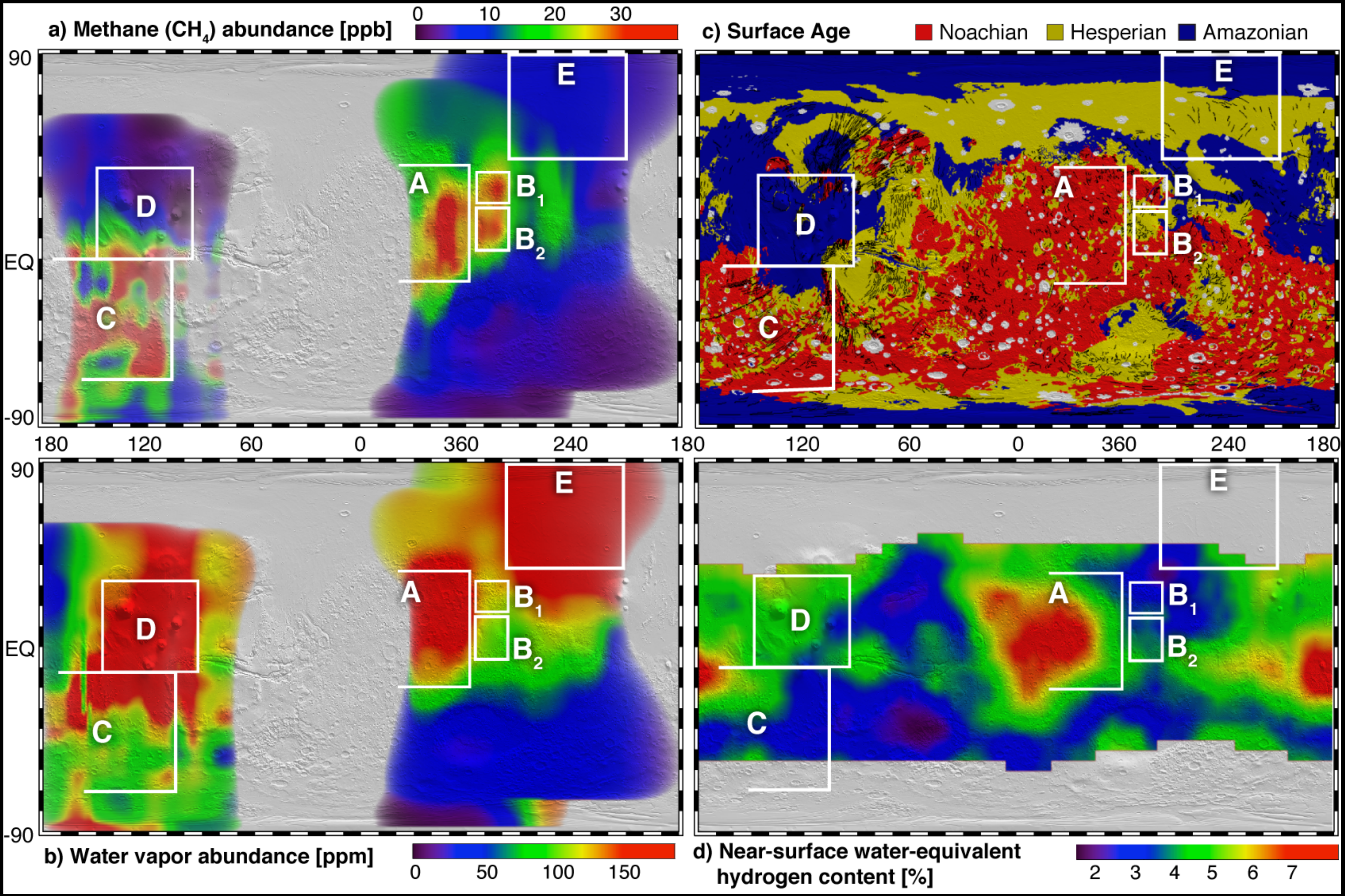
Mumma, Villanueva, Novak, et al. (Science 2009)

Water and Methane Behave Differently on Mars !



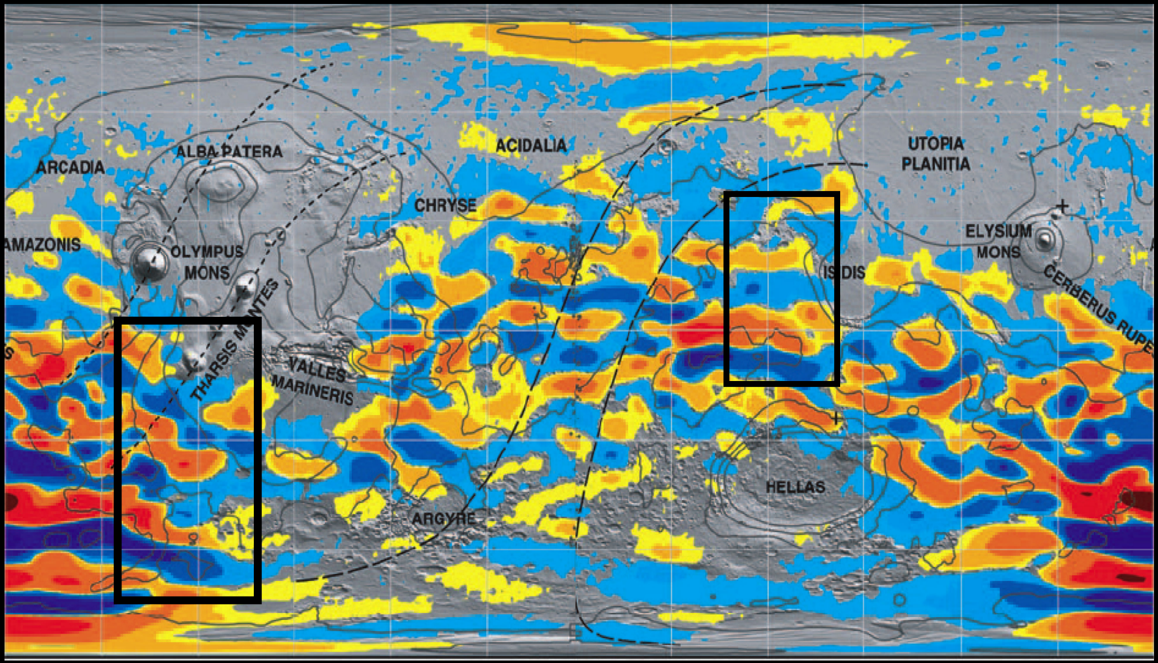
Villanueva, Mumma, Novak, et al. (in prep)

Geologic signatures and current regions of release



Crustal remnant magnetic field*

Latitude



Longitude

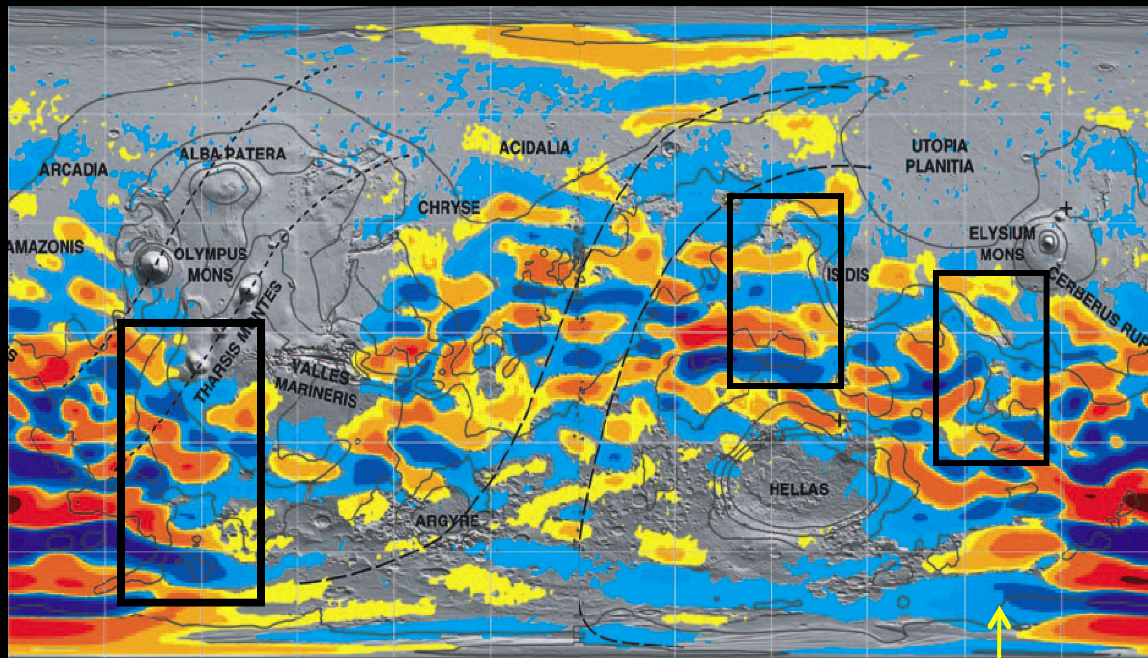
Maximum CH_4 abundance observed in 2005

Maximum CH_4 abundance observed in 2003

* Magnetic field map after Connerney et al. 2005

Crustal remnant magnetic field*

Latitude



Longitude

Curiosity - TLS
CH_4 detected 2013 - 15

Maximum CH_4 abundance observed in 2005

Maximum CH_4 abundance observed in 2003 A & B

* Magnetic field map after Connerney et al. 2005

Search for Biomarker Gases: 2006 - 2010

Table 1
Observing log and mapping coordinates of the regions sampled on Mars.

Parameter	06 January 2006			19 August 2009	20 November 2009	28 April 2010
Instrument	CSHELL	NIRSPEC KL1	NIRSPEC KL2	CRIRES	CRIRES	NIRSPEC KL2
Time (UT)	05:24	08:39	06:03	10:15	08:26	06:25
	08:16	09:21	06:46	10:30	09:11	08:05
Integration time (mins)	60	24	20	6	40	80
Doppler shift (km s^{-1})	+15.5	+15.5	+15.5	-9.4	-13.8	+15.8
L_S, Mars Year	352°	352°	352°	324°	12°	83°
	MY27	MY27	MY27	MY29	MY30	MY30
Longitude (range)	45W	93W	55W	305W	92W	48W
	85W	100W	66W	315W	99W	67W
Latitude (range)	47N	49N	49N	62N	79N	68N
	78S	80S	80S	63S	45S	30S
Main region	Valles Marineris	East of Tharsis	East of Valles Marineris	Syrtis Major	East of Tharsis	Viking 1 West of Chryse

Table 2
Abundance limits (3-σ) of trace species on Mars in parts-per-billion (ppb, 10^{-9}).

Molecule	Previous (3-σ, ppb)	06 January 2006 L_S 352° MY27	19 August 2009 L_S 324° MY29	20 November 2009 L_S 12° MY30	28 April 2010 L_S 83° MY30
Methane (CH_4)	3–50[a]	<7.8	–	<6.6	<7.2
Ethane (C_2H_6)	<0.2–0.6[b]	<0.7	<0.6	<0.2	–
Methanol (CH_3OH)	–	<19	<21	<6.9	–
Formaldehyde (H_2CO)	<4.5[c]	<3.9	–	–	<3.9
Acetylene (C_2H_2)	<3[d]	<6	–	–	<4.2
Ethylene (C_2H_4)	<750[d]	<11.2	<9	<4.1	–
Nitrous oxide (N_2O)	100[d]	<87			<65
Ammonia (NH_3)	<8[d]	<57	–	–	<45
Hydrogen cyanide (HCN)	–	<4.5	–	–	<2.1
Methyl chloride (CH_3Cl)	–	<14.3	–	–	–
Hydrogen chloride (HCl)	<0.3[e]	<2.1	<1.5	<0.6	–
Hydroperoxy radical (HO_2)	–	<198	–	–	<255

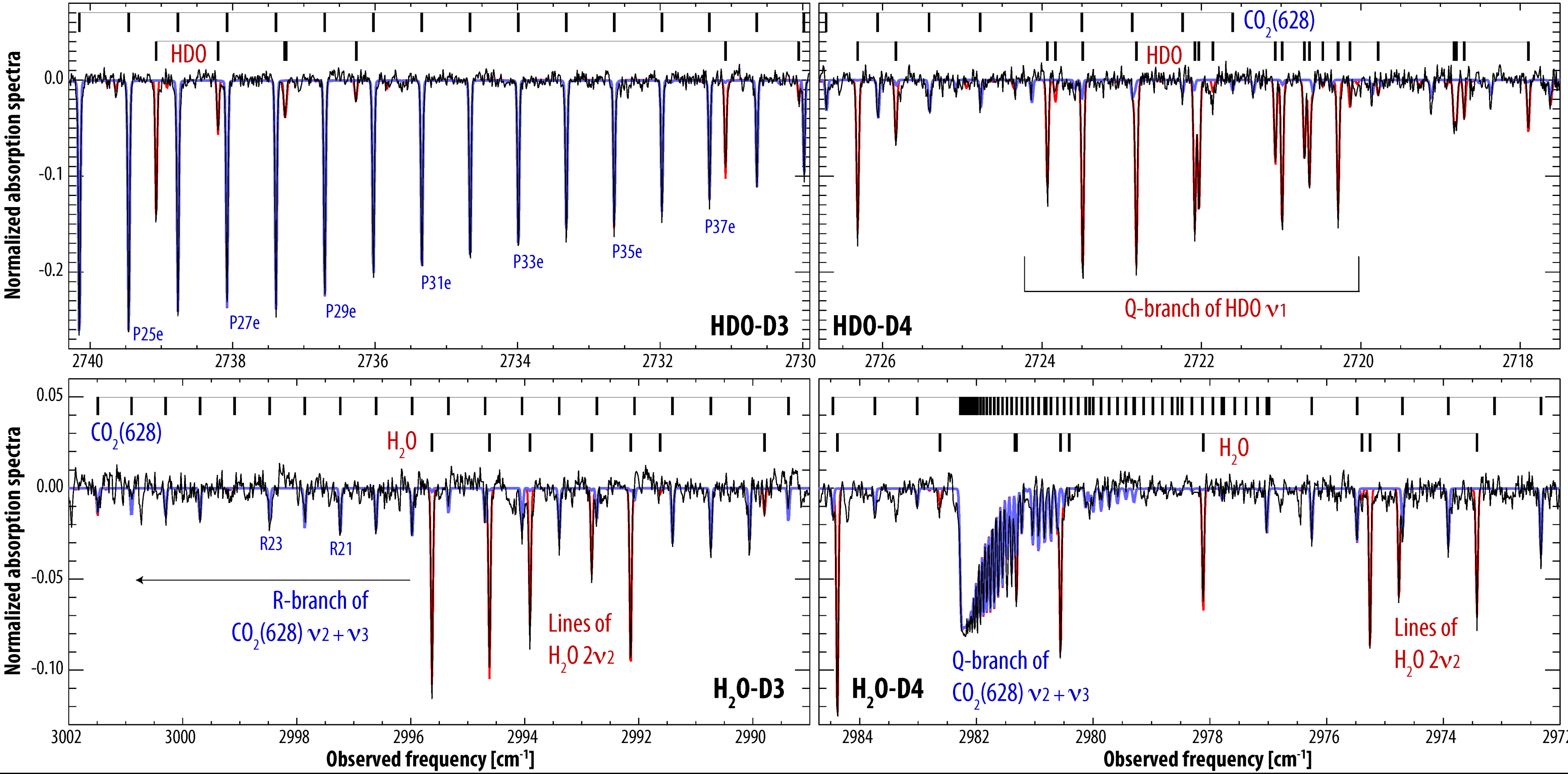
[a] Mumma et al. (2009), Krasnopolsky et al. (2004), and Formisano et al. (2005).
[b] Villanueva et al. (2011) and Krasnopolsky (2012).
[c] Krasnopolsky et al. (1997).
[d] Maguire (1977).
[e] Hartogh et al. (2010).

Villanueva, Mumma, Novak, et al. Icarus 2013

“Mars – The Cutting Edge Today”

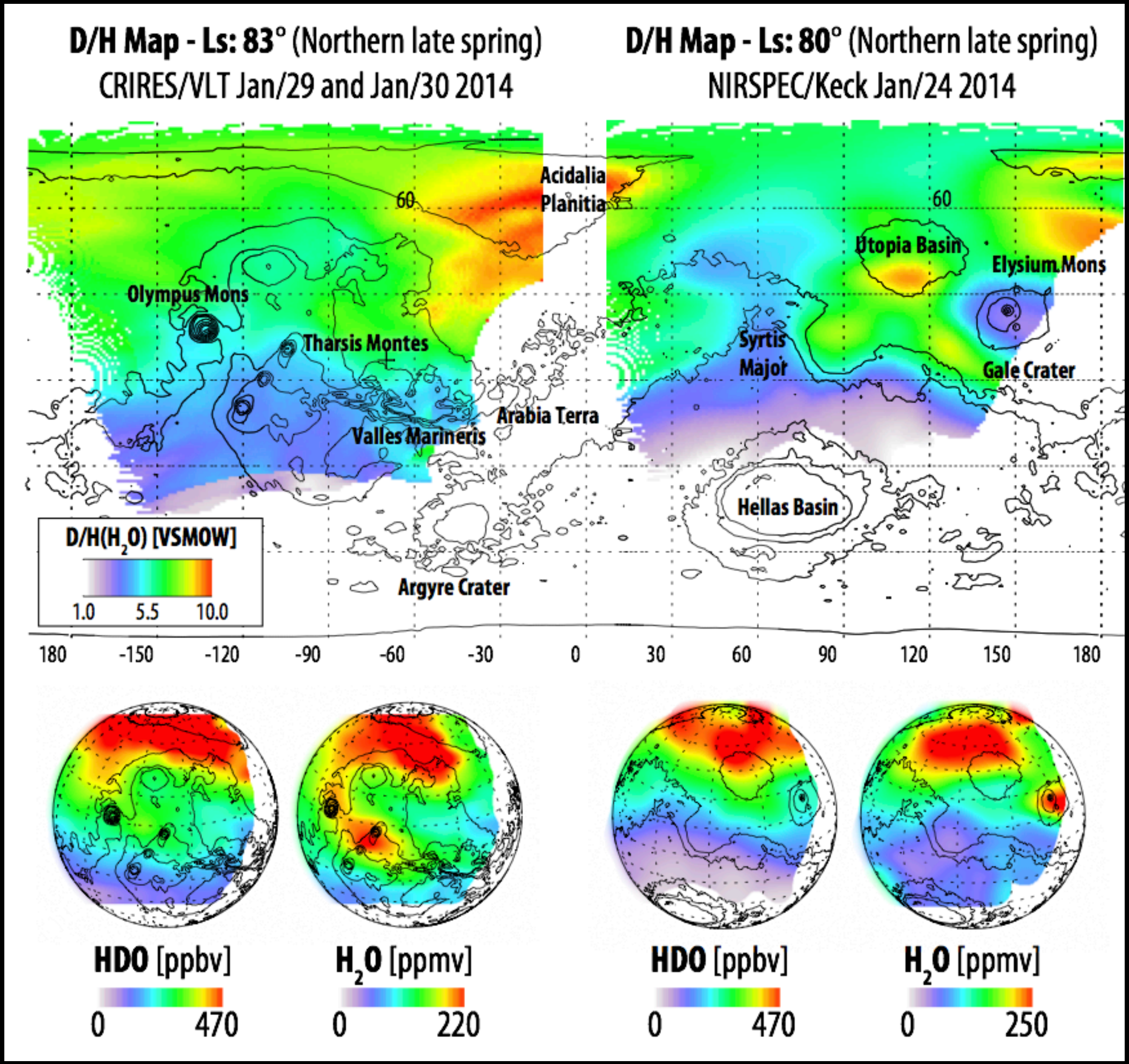
Isotopologues of Water and CO_2 Measured with CRIRES-VLT

29 Jan 2014, L_s = 83° late Northern spring



Villanueva, Mumma, Novak, et al. Science 2015

"Mars – The Cutting Edge Today"



Villanueva, Mumma, Novak, et al. Science 2015

Next:

Find & map locales of water release.
Relation to RSL?
D/H ratio in H_2O?

iSHELL at IRTF
CRIRES+ at VLT
NIRSPEC (upgraded)

HDO – ALMA
H_2O – TMT, E-ELT?

ExoMars 2016 (TGO)

"Mars – The Cutting Edge Today"

Trace Gases: CH_4, H_2O, HDO, H_2O_2, CO, O_2, O_3, etc.

- 3-D spatial: longitude, latitude, & vertical
- 1-D temporal: (diurnal, seasonal, & inter-annual)
- High resolution (spectral & spatial)

Orbiters & Rovers

- MGS, MRO, Mars Express, Maven, *ExoMars 2016*
- Curiosity, *ExoMars 2018, Mars 2020*

Ground-based

- Keck, NASA-IRTF, VLT
- ALMA, SOFIA

"ExoMars TGO – Tomorrow's Cutting Edge"

Previous ESA + NASA configuration → ESA + Roscosmos configuration

Previous ESA + NASA configuration

NOMAD
High resolution occultation and nadir spectrometers

Atmospheric composition (CH_4, O_3, trace species, isotop) dust, clouds, P&T profiles

- **UVIS** (0.20 – 0.65 μm) λ/Δλ ~ 250 — SO, Limb, Nadir
- **IR** (2.3 – 3.8 μm) λ/Δλ ~ 10,000 — SO, Limb, Nadir
- **IR** (2.3 – 4.3 μm) λ/Δλ ~ 20,000 — SO

MATMOS
High-Resolution FT spectrometer

Vertical distribution of water, methane and trace species

- **Infrared** (2.3 – 12 μm) λ/Δλ ~ 130,000 — SO

EMCS
Limb radiometer

Monitoring of atmospheric structure, water and aerosols

MAGIE
Wide-angle camera

Monitoring of clouds and ozone

HiSCI
High-resolution camera

Mapping of sources; landing site selection

ESA + Roscosmos configuration

NOMAD
High resolution occultation and nadir spectrometers

Atmospheric composition (CH_4, O_3, trace species, isotop) dust, clouds, P&T profiles

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- **IR** (2.3 – 4.3 μm) λ/Δλ ~ 20,000 — SO

CaSSIS
High-resolution camera

Mapping of sources; landing site selection

ACS
POCKOCMOC

Suite of 3 high-resolution spectrometers

Atmospheric chemistry, aerosols, surface T, structure

- **Near IR** (0.7 – 1.7 μm) λ/Δλ ~ 20,000 — SO, Limb, Nadir
- **IR** (Fourier, 2 – 25 μm) λ/Δλ ~ 4000 (SO)/500 (N) — SO, Nadir
- **Mid IR** (2.2 – 4.5 μm) λ/Δλ ~ 50,000 — SO

FREND
POCKOCMOC

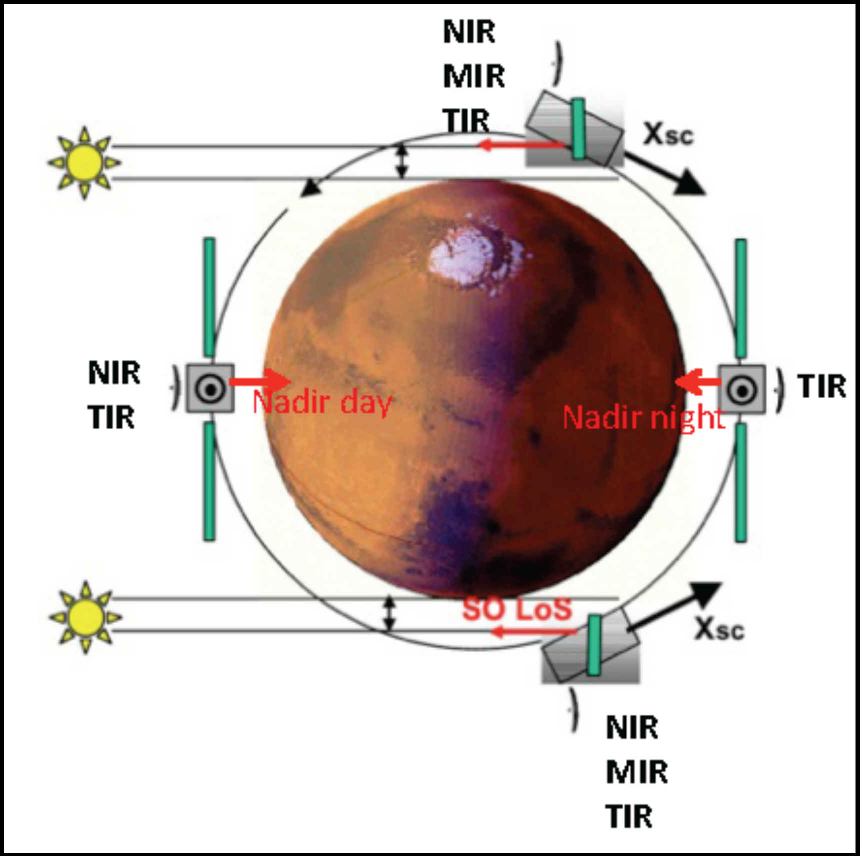
Collimated neutron detector

Mapping of subsurface water

All Power Resolution λ/Δλ calculated at mid-range

Villanueva, Sep/18/2012

"ExoMars TGO – Tomorrow's Cutting Edge"



Orbital Graphic Courtesy of Oleg Korablev

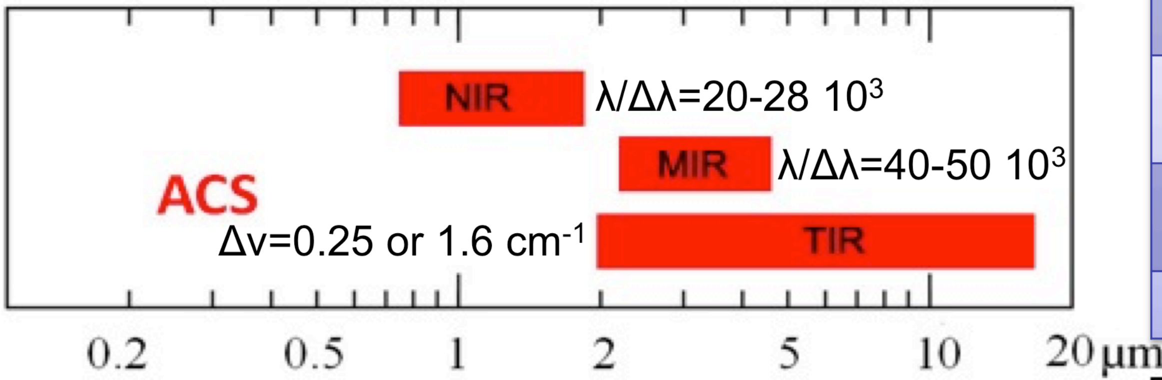
ExoMars 2016 Mission Phases Overview	
Launch Period	7-27 January 2016
EDM – Orbiter separation	16 October 2016
Orbiter insertion into Mars orbit	19 October 2016
EDM enters Martian atmosphere and lands on the target site	19 October 2016
EDM science operations	19 October - 23 October 2016 (to be confirmed)
Orbiter changes inclination to science orbit (74°)	25 October 2016
Apocentre reduction manoeuvres (from the initial 4-sol orbit to a 1-sol orbit)	27 October 2016
Aerobraking phase (Orbiter lowers its altitude)	4 November 2016 - mid 2017
Start operating the Orbiter scientific instruments	mid 2017
Superior conjunction (This is when the Sun is between Earth and Mars; Critical operations are paused.)	11 July - 11 August 2017
Start of the data relay operations to support communications for the rover mission	17 January 2019
End of mission	December 2022

Atmospheric Chemistry Suite

Oleg KORABLEV,
Franck MONTMESSIN,
Anna FEDOROVA,
Nicolay IGNATIEV,
Alexander TROKHIMOVSKY,
Alexei GRIGORIEV,
Alexei SHAKUN,
Konstantin ANUFREICHIK

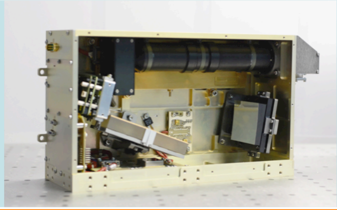
Atmospheric Chemistry Suite

ACS: Three Spectrometers



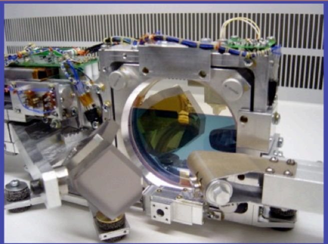
Mass:	33.5 kg
Dimensions:	600×470×520 mm^3
Power consumption:	55 W (ave)
Data rate:	1600 Mbit/day

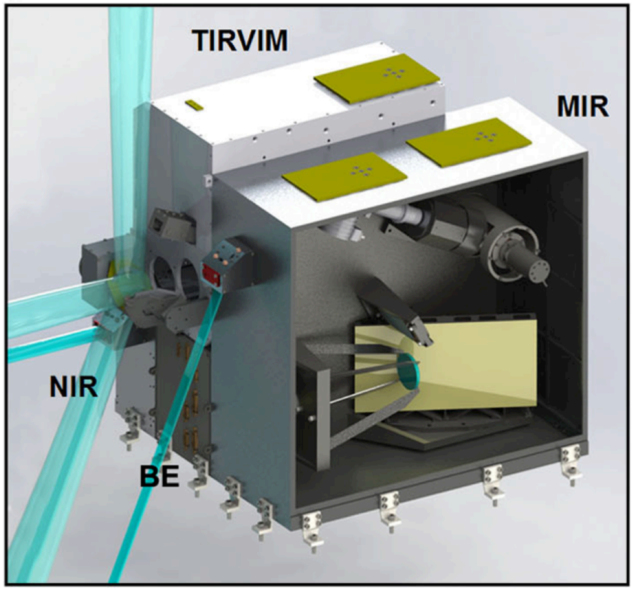
NIR: Echelle-AOTF
Nadir, Solar Occultation, Limb



MIR: Cross-dispersion
Solar Occultation
Conservative estimate to measure CH_4: 100 ppt at 20 km tangent altitude (single meas.)

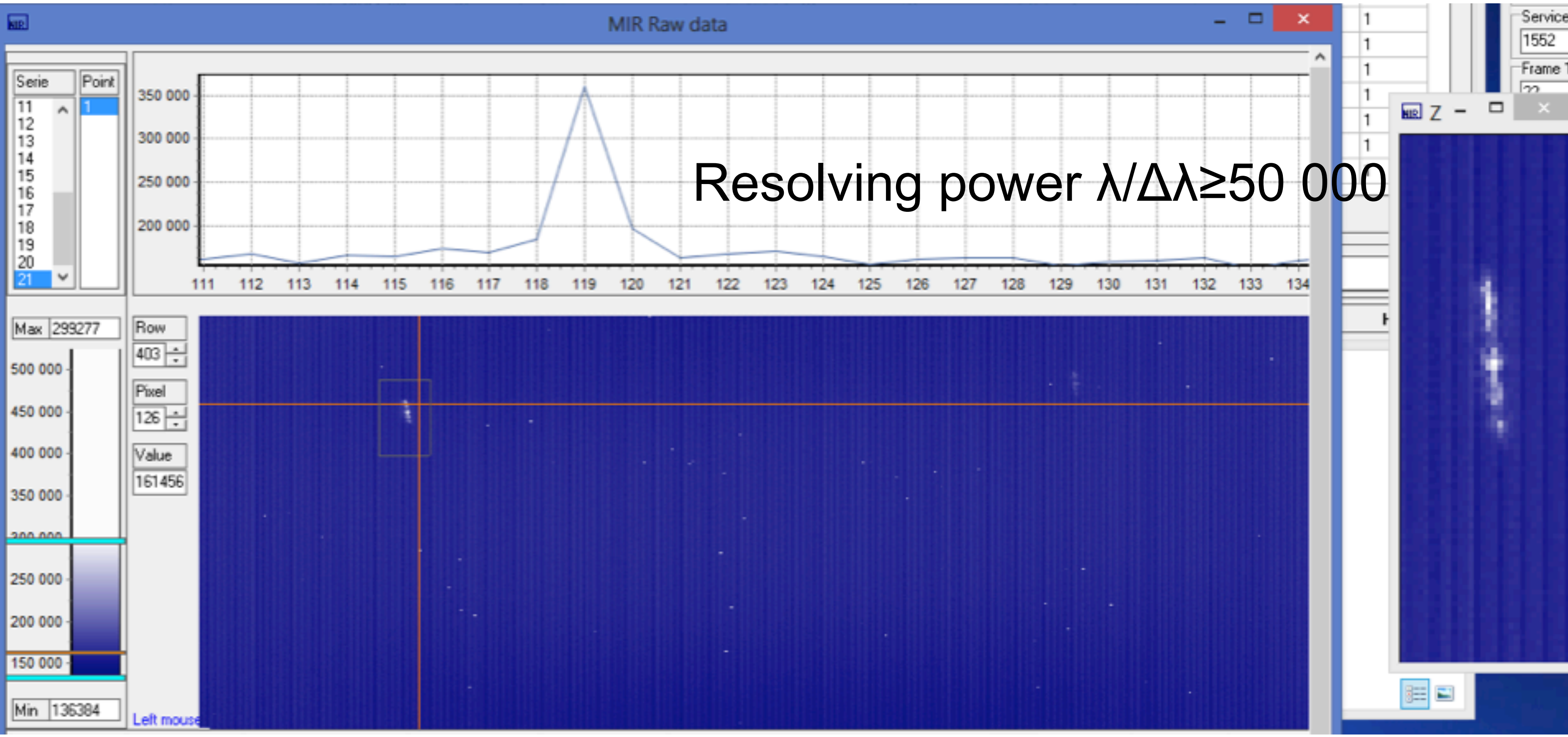
TIR: FTIR
Nadir, Solar Occultation, Limb





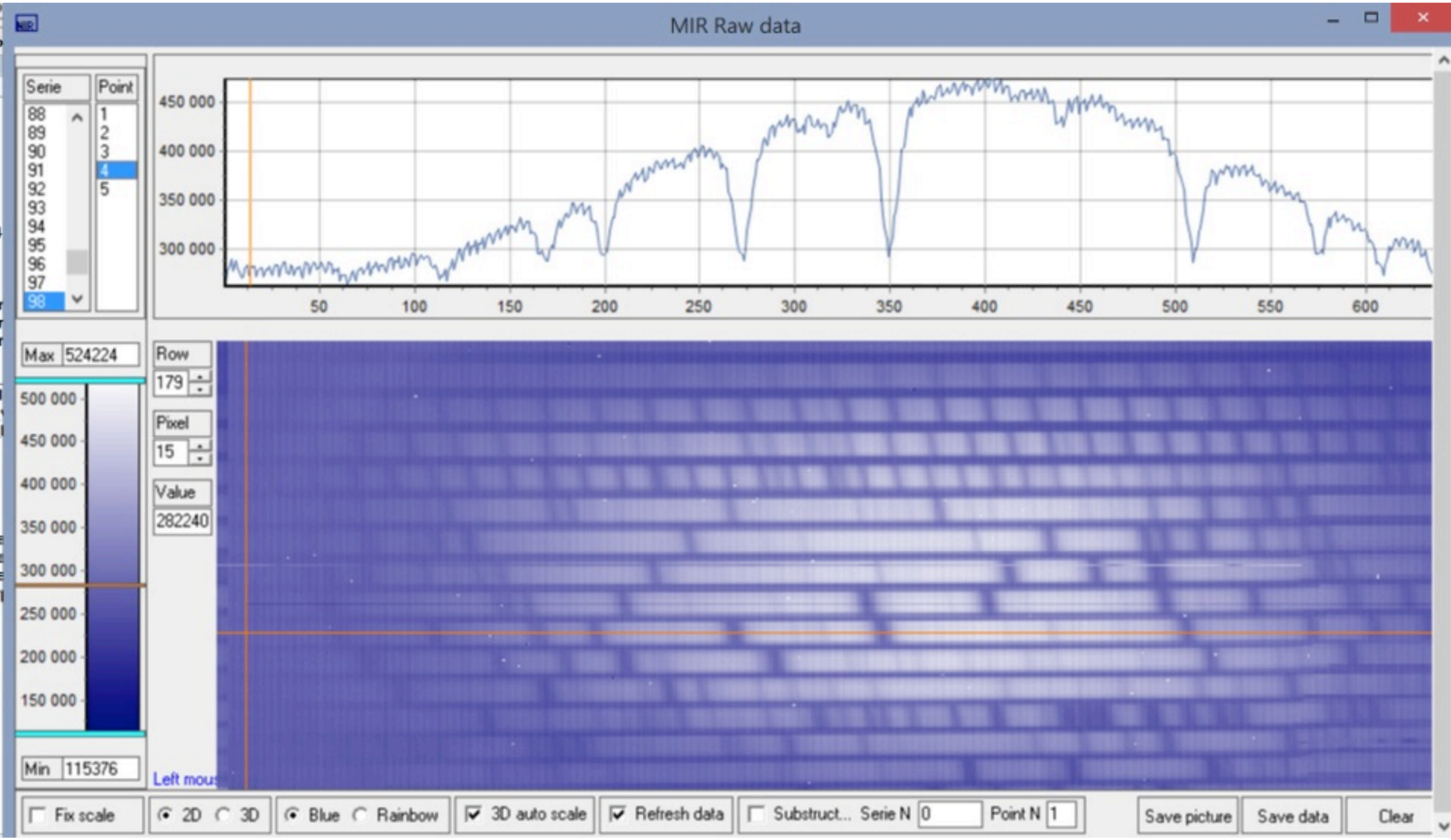
ACS PFM delivered to Thales, Cannes on June 4 2015

Adjustment: 3.39 µm HeNe



Resolving power $\lambda/\Delta\lambda \geq 50\ 000$

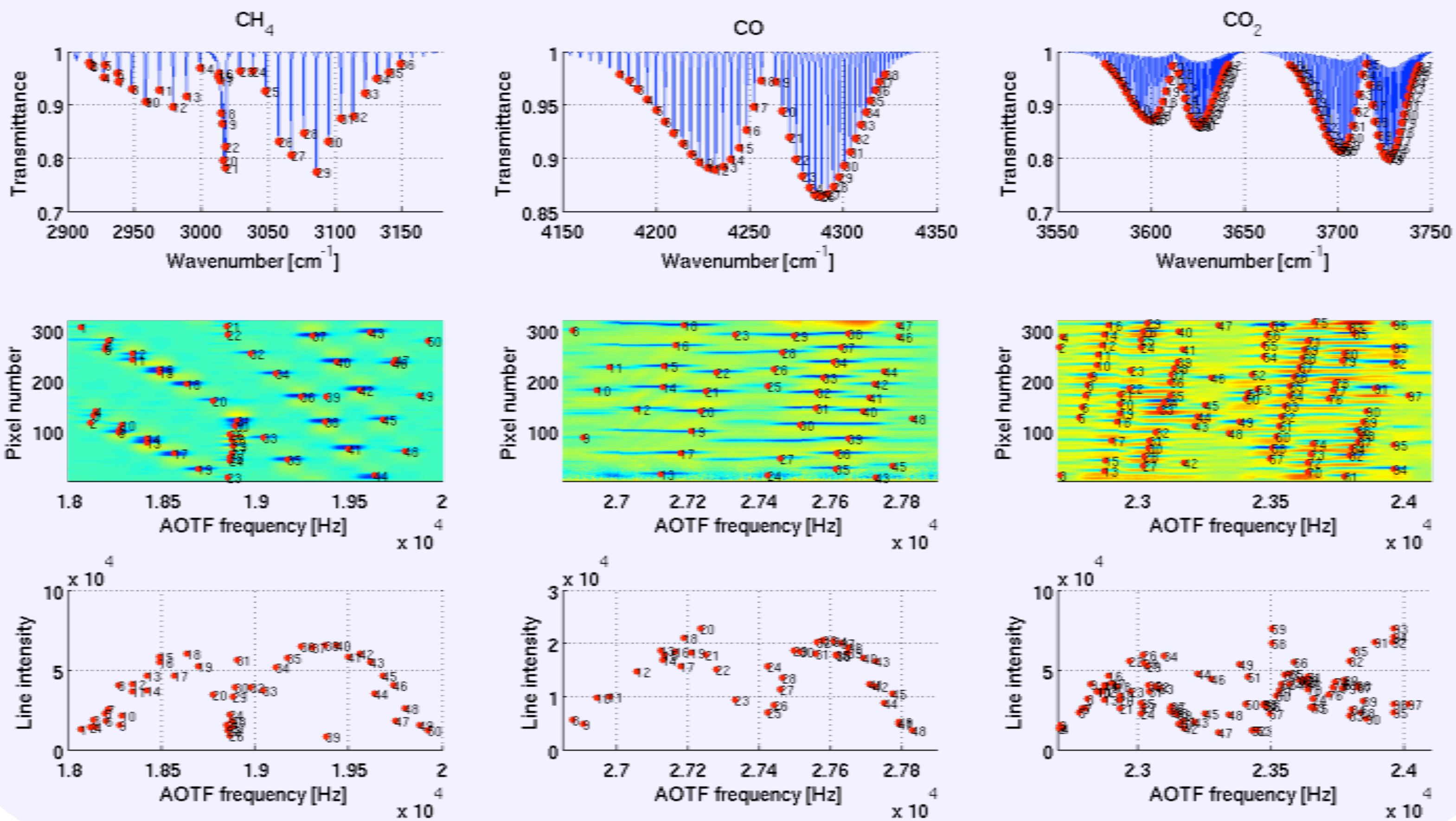
Sun calibration (terrestrial atmosphere; 3.7-4.0 μm)



SO/LNO Spectral Calibration

Courtesy: A-C Vandaele, BIRA (NOMAD Principal Investigator)

- Analysis performed by Arnaud Mahieux:
  - Match absorption lines to gas spectra
    - Determine when AOTF peak is co-incident on each line
    - And pixel number vs wavenumber relation

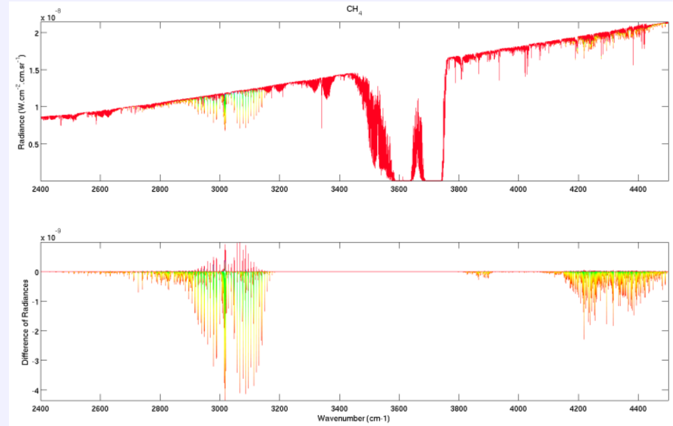


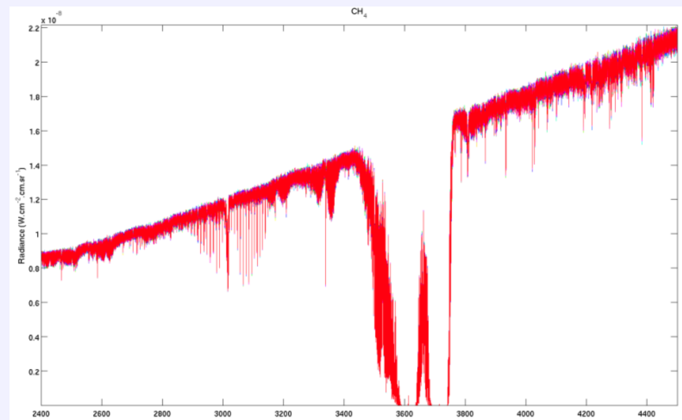
Detection Limits methodology

- Spectra are simulated considering
  - Characteristics of the channel
  - Abundances: reference value is multiplied by a series of factors covering the [100 – 0.001] interval:
    - 34 different values for all solar occultation ;
    - 50 for nadir-LNO ;
    - 16 for nadir-UVIS

- Noise was then added on all the simulated spectra. The noise level is directly related to the SNR values that were obtained in the first part of this study.

- Batch of spectra were produced :
  - 34*200 spectra in Solar Occultation (SO & LNO) per species
  - 16*200 spectra per species (UVIS, both geometries)
  - 50*100 spectra in NADIR (LNO) per species





"ExoMars – NOMAD: Expected Sensitivity"

Courtesy: A-C Vandaele, BIRA
(NOMAD Principal Investigator)

		SO	LNO		UVIS	
		Solar Occultation (SNR = 2000)	Solar Occultation (SNR = 3000)	Nadir (SNR = 100)	Solar Occultation (SNR = 500)	Nadir (SNR = 500)
CH_4	0-60 ppb [a]	25 ppt	20 ppt	11 ppb		
H_2O	< 300 ppm (variable with season)[b]	0.2 ppb	0.15 ppb	31 ppb		
HDO	D/H =5.6 SMOW[c]	0.7 ppb	0.7 ppb	0.8 ppm		
CO	700 - 800 ppm [d]	5 ppb	4 ppb	1.5 ppm		
C_2H_2	< 2 ppb [g]	0.03 ppb	0.03 ppb	20 ppb		
C_2H_4	< 4 ppb [g]	0.2 ppb	0.15 ppb	70 ppb		
C_2H_6	< 0.2 ppb [e] < 0.7 ppb [g]	0.03 ppb	0.02 ppb	11 ppb		
HCl	< 3 ppb [e] < 0.2 ppb [f] < 0.6 ppb [g]	0.03 ppb	0.025 ppb	31 ppb		
HCN	< 5 ppb [g]	0.03 ppb	0.03 ppb	15 ppb		
HO_2	0.1-6 ppb [l] < 200 ppb [g]	1 ppb	1 ppb	0.5 ppm		
H_2S	< 200 ppm [h]	4 ppb	3 ppb	1.6 ppm		
N_2O	< 100 ppb [h] < 90 ppb [g]	0.2 ppb	0.2 ppb	83 ppb		
NO_2	< 10 ppb [h]	0.14 ppb	0.1 ppb	50 ppb		
OCS	< 10 ppb [h]	0.3 ppb	0.3 ppb	122 ppb		
O_3		2.5 ppb	1.5 ppb	0.8 ppm	50 ppt	4.5 ppb
H_2CO	< 4.5 ppb [e] < 3.9 ppb [g]	0.04 ppb	0.03 ppb	16 ppb	7.5 ppb	150 ppb
NH_3	< 5 ppb [h] < 60 ppb [g]				1 ppb	-
SO_2	< 1 ppb [i] < 2 ppb [j,k]				0.5 ppb	18 ppb

“ExoMars TGO – Tomorrow’s Cutting Edge”

ExoMars 2016 Mission Phases Overview	
Launch Period	7-27 January 2016
EDM – Orbiter separation	16 October 2016
Orbiter insertion into Mars orbit	19 October 2016
EDM enters Martian atmosphere and lands on the target site	19 October 2016
EDM science operations	19 October - 23 October 2016 (to be confirmed)
Orbiter changes inclination to science orbit (74°)	25 October 2016
Apocentre reduction manoeuvres (from the initial 4-sol orbit to a 1-sol orbit)	27 October 2016
Aerobraking phase (Orbiter lowers its altitude)	4 November 2016 - mid 2017
Start operating the Orbiter scientific instruments	mid 2017
Superior conjunction (This is when the Sun is between Earth and Mars; Critical operations are paused.)	11 July - 11 August 2017
Start of the data relay operations to support communications for the rover mission	17 January 2019
End of mission	December 2022

The Critical Path for Extant Life – Follow the Methane

Firm up spatial variations - analyze additional maps, acquire additional data.
Influence landing site selection

Examine dependence on season, time-of-day, correlation with local water, etc.

Identify all local sources, characterize as bio- or geo-driven
solar occultation (e.g., ExoMars Trace Gas Orbiter)
laser absorption LMO (methane isotopologues)

Deploy High-resolution Spectral Mapper at Mars – Sun L1 (Organic Observer)
Identify & map optimum sites at high spatial & spectral resolution
All of Mars, all of the time!

Conduct *in situ* studies at most favorable sites:
Astrobiology Field Laboratories

Return critically selected samples to Earth

End