Absolute Measurements of Methane on Mars

Michael J. Mumma¹
Geronimo Villanueva¹,²
Robert E. Novak³

¹Center for Astrobiology &
Solar System Exploration Division
NASA’s Goddard Space Flight Center

²Catholic University of America

³Iona College

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The Search for Mars methane

- The measurement approach
- Improvements in Analysis
- Our spectral detections
- The current campaign
Simulated spectrum of Mars methane $\nu_3$

Simulated terrestrial extinction

Mars spectrum affected by terrestrial extinction

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 $\nu_3$ 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)

Mars spectrum affected by terrestrial extinction
How did we search for methane?

NASA IRTF - 3m
Hawaii - USA

Keck II - 10m
Hawaii - USA

Gemini South - 8m
Cerro Pachon - Chile
IRTF - CSHELL : shaded boxes (lots of observing time!)

Keck - NIRSPEC : Large Spectral & Spatial Grasp

Data taken on 06 January 2006 09:00 UT (L_s = 352°)

Frequencies between 2700-3400 cm^{-1} (3.7-2.9µm)
Resolution-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?

Mumma, Villanueva, Novak, et al. (Science 2009)
Maximum abundance observed at $L_s$ 220° (mid-spring in South)

Maximum abundance observed at $L_s$ 155° (late summer in North)
Methane Issues

✓ Origin —

When was it produced? (recent vs. ancient)

How was it produced? (abiotic vs. biotic)

reduce carbon in mantle \((\text{CO}_2, \text{H}_2\text{O}, \text{heat})\)

release \(\text{H}_2\): serpentinization, pyrite production, \(\text{H}_2\text{O}\) radiolysis

microbes metabolize \(\text{H}_2\), reduce \(\text{CO}, \text{CO}_2\), or acetate

How is it released? Is it seasonal?

thermal activation of near-surface? (supra-permafrost)

by opening pores/fractures in scarps? (sub-permafrost)

✓ Sinks —

Atmospheric – triboelectric, photochemical, other?

Sub-surface (oxidants) – peroxides, perchlorates

Sequestering (adhesion, gettering)

✓ Re-charge Mechanism (if released annually)
• We want higher spectral resolution to improve detection sensitivity.
  • We want higher spatial resolution to test source properties.

✓ Spectral Resolving Power:
  CRIRES \( \lambda/\delta\lambda \approx 100,000 \) 0.2” x 30” slit
  NIRSPAO \( \lambda/\delta\lambda \approx 40,000 \) 0.036” x 2.4” slit

✓ Spatial resolution:
  CRIRES – UT1 AO, without re-imaging 0.086” pixels
  NIRSPEC – Keck 2 AO, with re-imaging 0.018” pixels
<table>
<thead>
<tr>
<th>Dates</th>
<th>Instrument</th>
<th>Mode</th>
<th>Diameter</th>
<th>Velocity</th>
<th>Season</th>
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<tbody>
<tr>
<td>19 - 24 Aug</td>
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<td>AO</td>
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<td>–</td>
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<td>-13.8</td>
<td>5.4°</td>
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<tr>
<td>10 - 11 Nov</td>
<td>NIRSPEC</td>
<td>non-AO</td>
<td>8.5”</td>
<td>-13.8</td>
<td>7.3°</td>
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<tr>
<td>18 - 21 Nov</td>
<td>CRIRES</td>
<td>AO</td>
<td>9.2”</td>
<td>-13.9</td>
<td>11.7°</td>
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<tr>
<td>23 Nov</td>
<td>CSHELL</td>
<td>–</td>
<td>9.4”</td>
<td>-13.9</td>
<td>13.6°</td>
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<tr>
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<td>-13.9</td>
<td>14.5°</td>
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<tr>
<td>1 - 2 Dec</td>
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<td>-13.5</td>
<td>17.4°</td>
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<tr>
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<tr>
<td>12 - 15 Dec</td>
<td>CSHELL</td>
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<td>11.0”</td>
<td>-12.3</td>
<td>23°</td>
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<tr>
<td>15 - 16 Dec</td>
<td>NIRSPEC</td>
<td>non-AO</td>
<td>11.1”</td>
<td>-12.2</td>
<td>24°</td>
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</tbody>
</table>
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
  [In 2008: Replaced GenIn2 with LBLRTM]
- Upgraded molecular atlas (now HITRAN ‘08 with additional upgrades)
- Model synthetic spectra using variable resolving power along the slit
Methane and Water on Mars

ISSUES:

Before 2005

CSHELL slit position
UT 20.73 March 2003

sub-solar

CH₄ R1

H₂O

Wavenumber, cm⁻¹

mjm_080604.14
Clear Detections of **Methane** and **Water** on Mars

Northern late-summer

$L_s = 155^\circ$

Both gases are enhanced towards the North
Mars 16 January 2006 05:00 UT  \(L_s = 357°\)  Velocity +16.4 km/s

**NIRSPEC**
Spectra at L-band

Frequencies between 2700-3400 cm\(^{-1}\) (3.7-2.9 \(\mu\)m)

North

South

Mars image credit: Mars24, NASA
Mars 16 January 2006 08:15 UT  L_s = 357°
Diameter 11.5’’ Velocity +16.4 km/s  NIRSPEC
Spectra at L-band

Frequencies between 2700-3400 cm⁻¹ (3.7-2.9μm)

Mars image credit: Mars24, NASA
NIRSPEC Today: Extreme Sensitivity (2 minutes on source)
Data taken on 16 January 2006 08:15 UT  \(L_S = 357^\circ\)

Villanueva et al. 2008, Icarus
CH$_4$ P2 (two components)

29 May 2005

$L_s = 220^\circ$

(Mid-spring, South)

CO$_2$ enhanced in North
CH$_4$ enhanced in South

After Mumma, Villanueva, Novak, et al. (Science 2009)
Clear Detections of \( \text{CH}_4 \text{ R1} \) on Successive Days

Early summer (North, \( L_s = 121^\circ \))
Clear Detections of **Methane** and **Water** on Mars

Northern late-summer

\[ L_s = 155^\circ \]

Both gases are enhanced towards the North
Methane on Mars

Workshop on Mars Methane – Frascati – M. J. Mumma et al.

Topography map from MGS/MOLA, NASA
March 20 & 21, 2003  $L_s = 155^\circ$  Northern summer

Two independent lines of methane are detected, and they show the same latitudinal dependence.
The column abundances obtained from two independent line of methane increase strongly from South to North but agree within errors (A). The agreement improves after accounting for the surface topographies sampled on successive days (B).

The mixing ratios obtained from two independent lines of methane agree within errors (B). A pronounced maximum in mixing ratio is seen over equatorial latitudes.
The methane mixing ratios vary with longitude, latitude, and season. The maximum in mixing ratio moves southward with the Sun. Methane is nearly absent at vernal equinox (after Southern Winter).
Resolution-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?

Mumma, Villanueva, Novak, et al. (Science 2009)
Summary of Observational Evidence

• **Four lines of Methane are detected: R1, R0, P2 (doublet)**
  - R1 is detected on successive dates Jan. 11 & 12, 2003
  - R1 and R0 are detected on successive dates March 20 & 21, 2003
  - The mixing ratios derived from individual lines agree
  - P2 is detected in May 2005

• **Strong temporal changes are found**
  - Plumes are seen with peak mixing ratios up to 60 ppbv
  - At vernal equinox methane is 3 ppbv or less at locations sampled
  - The implied methane lifetime is less than one year

• **Methane varies with location**
  - The plume content in March 2003 is ~ 19,000 metric tons
  - The source strength in March 2003 is ~ 1 kg/sec
  - A strong peak is seen over Nili Fossae
  - A strong peak is seen over Syrtis Major (South-east quadrant)
  - CH₄ is detected near Arsia Mons & Terra Sabena, in Southern Spring

• **Methane and water are sometimes correlated, but not always so.**
Major Conclusions

Methane is released locally on Mars – the source strength rivals terrestrial gas seeps.
Seasonal access to sub-permafrost regions, and/or wide-spread surface activity, is implied.

Some release zones are correlated with geologically interesting features:
- Hydrated terrain, where craters show lobate ejecta associated with ice-rich soil
  - Nili Fossae, a region rich in phyllosilicates and carbonates
- Syrtis Major, a volcano whose SE quadrant shows evidence of sub-surface collapse
  - Arsia Mons, site of the largest mountain glacier on Mars, and extensive Fossae

The lifetime of atmospheric methane is less than one Mars year.
This requires a new model for its destruction, perhaps by oxidants on airborne soil particles.

The Big Question: Is this methane produced by Biology, by Geochemistry, or by both?
Much follow-on work is needed to address this fundamental question.
CRIRES on Mars - First night
UT 19 August 2009 10:20

Mars Diameter 5.6 arcsec
Geocentric velocity: −9.4 km/sec
$L_s = 325^\circ$ mid NH winter

VLT Paranal:
- airmass 1.8
- PWV 3.9 mm
- FWHM 0.7 arcsec
- AO open loop

Syrtis Major
Hellas Basin
\[ L_s = 357° \text{ vernal equinox} \]

Geocentric velocity: \(-9.4 \text{ km/sec}\)
\( L_s = 325^\circ \) mid NH winter

Geocentric velocity: \(-9.4\) km/sec

<table>
<thead>
<tr>
<th>D1</th>
<th>3041.01 - 3025.36</th>
<th>D2</th>
<th>3021.06 - 3006.25</th>
<th>D3</th>
<th>3002.36 - 2988.37</th>
<th>D4</th>
<th>2984.80 - 2971.62</th>
</tr>
</thead>
</table>

**CH\(_4\)**-P2-P3 (detector #3) - CRIRES/VLT data - 2009/Aug/19 UT

- Silt North-South centered on 285°W
- Mars + Solar + Terrestrial
- Solar x 5
- Mars x 5

Wavenumber [cm\(^{-1}\)]

- \( CO_2 \) new band (Villanueva et al. 2008)
- \( CH_4 \) P2
- \( H_2O \) (observed at water minimum on Mars)
- \( CH_4 \) P3

Heilas Basin (deepest point on Mars)

53° North
43° North
33° North
25° North
15° North
6° North
2° South
11° South
20° South
30° South
41° South
53° South
64° South
CRIRES on Mars - First night
UT 19 August 2009 10:20
Mars Diameter 5.6 arcsec
L_s = 325° mid NH winter

CRIRES 0.2” slit, 0.086” pixels
Centered on 285° W

Thermal Analysis – atmosphere and solid surface
CRIRES on Mars - First night
UT 19 August 2009 10:20

Mars Diameter 5.6 arcsec
Geocentric velocity: −9.4 km/sec
L$_s$ = 325° mid NH winter

VLT Paranal:
airmass 1.8
PWV 3.9 mm
FWHM 0.7 arcsec
AO open loop

AO closed: 10 of 12 nights
Step-maps: CH$_4$, H$_2$O, HDO

Hellas Basin

CRIRES 0.2” slit, 0.086” pixels
Centered on 285° W

Syrtis Major
Methane Issues

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When was it produced? (recent vs. ancient)
How was it produced? (abiotic vs. biotic)
  reduce carbon in mantle (CO$_2$, H$_2$O, heat)
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