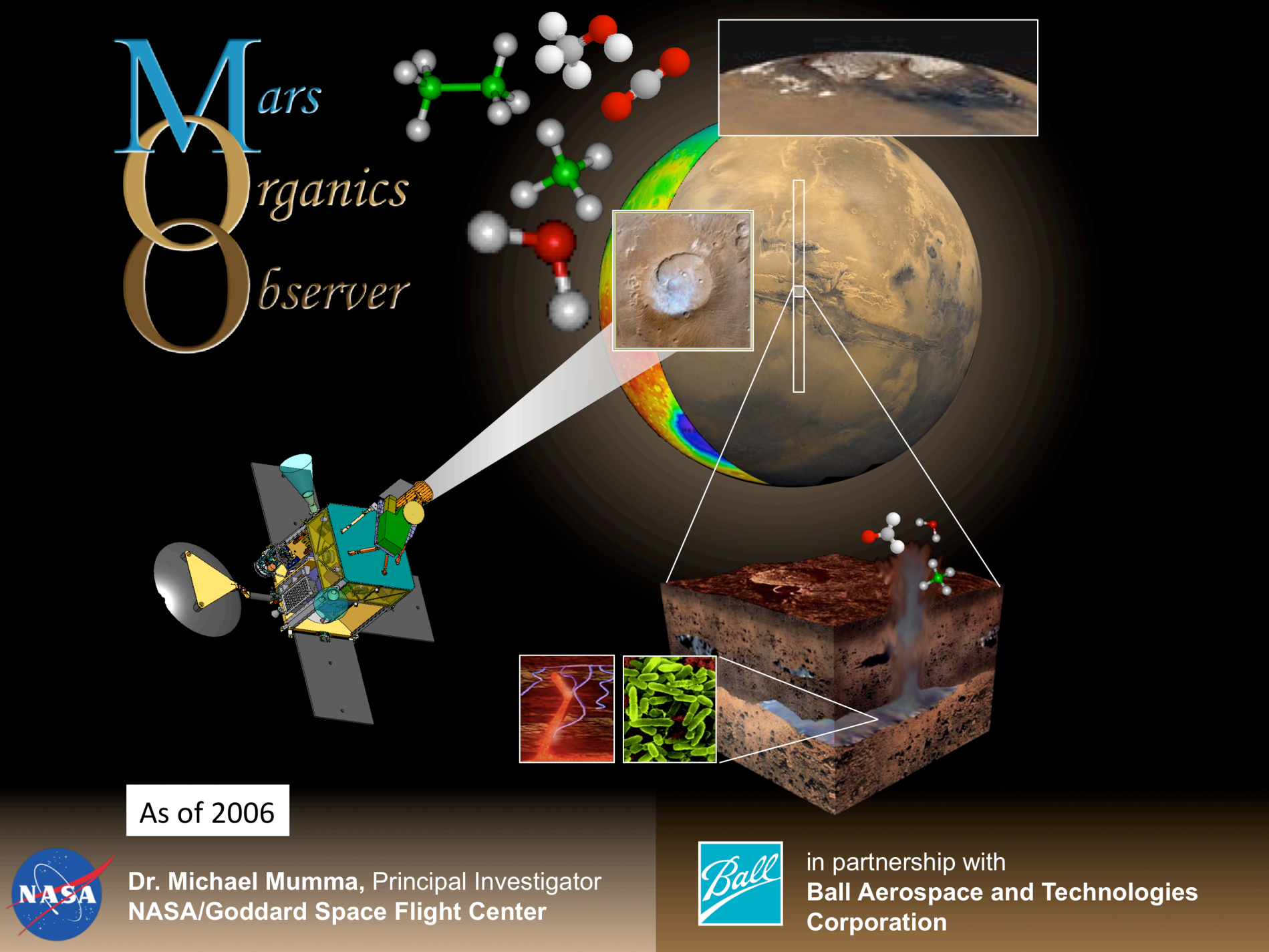
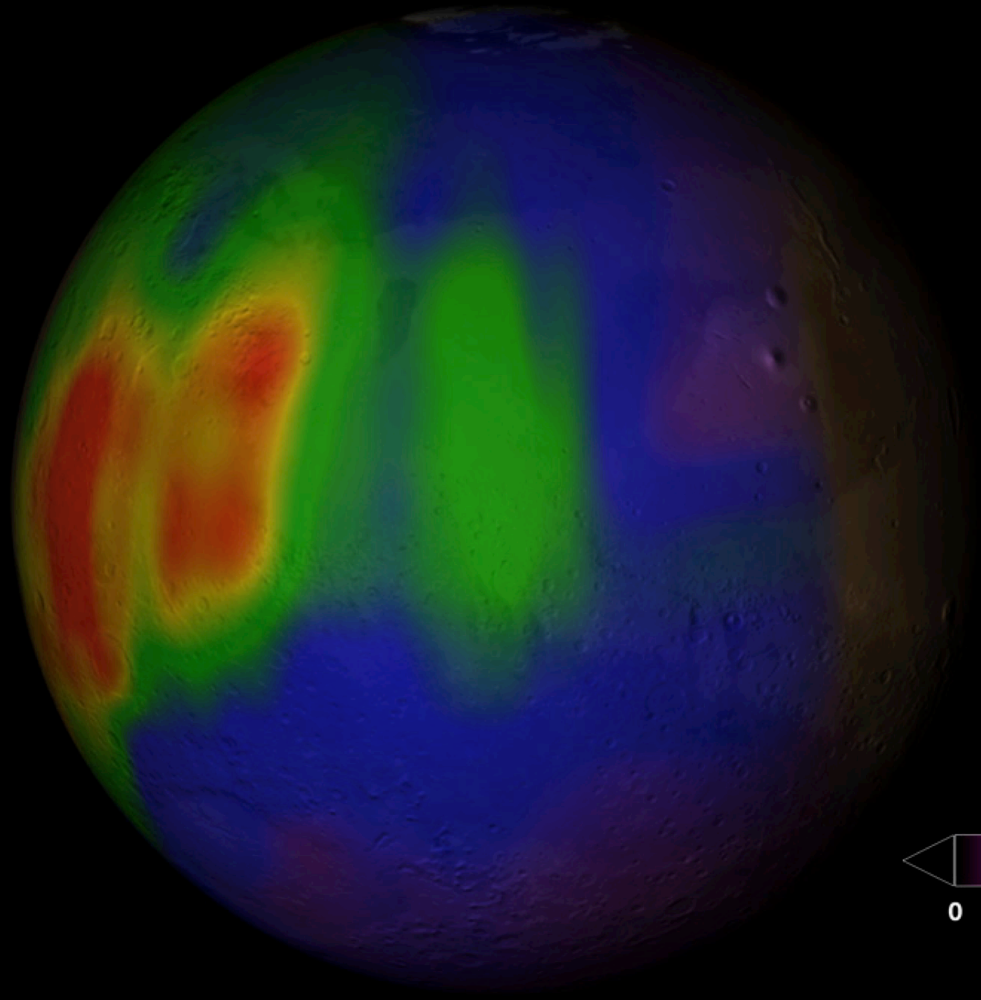
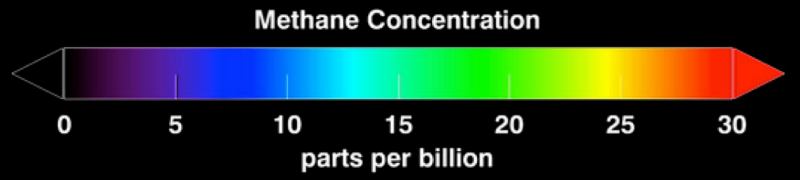

Mars
Organics
Observer
As of 2006
Dr. Michael Mumma, Principal Investigator
NASA/Goddard Space Flight Center
in partnership with
Ball Aerospace and Technologies Corporation

# The Science Driver: Active Release of Methane

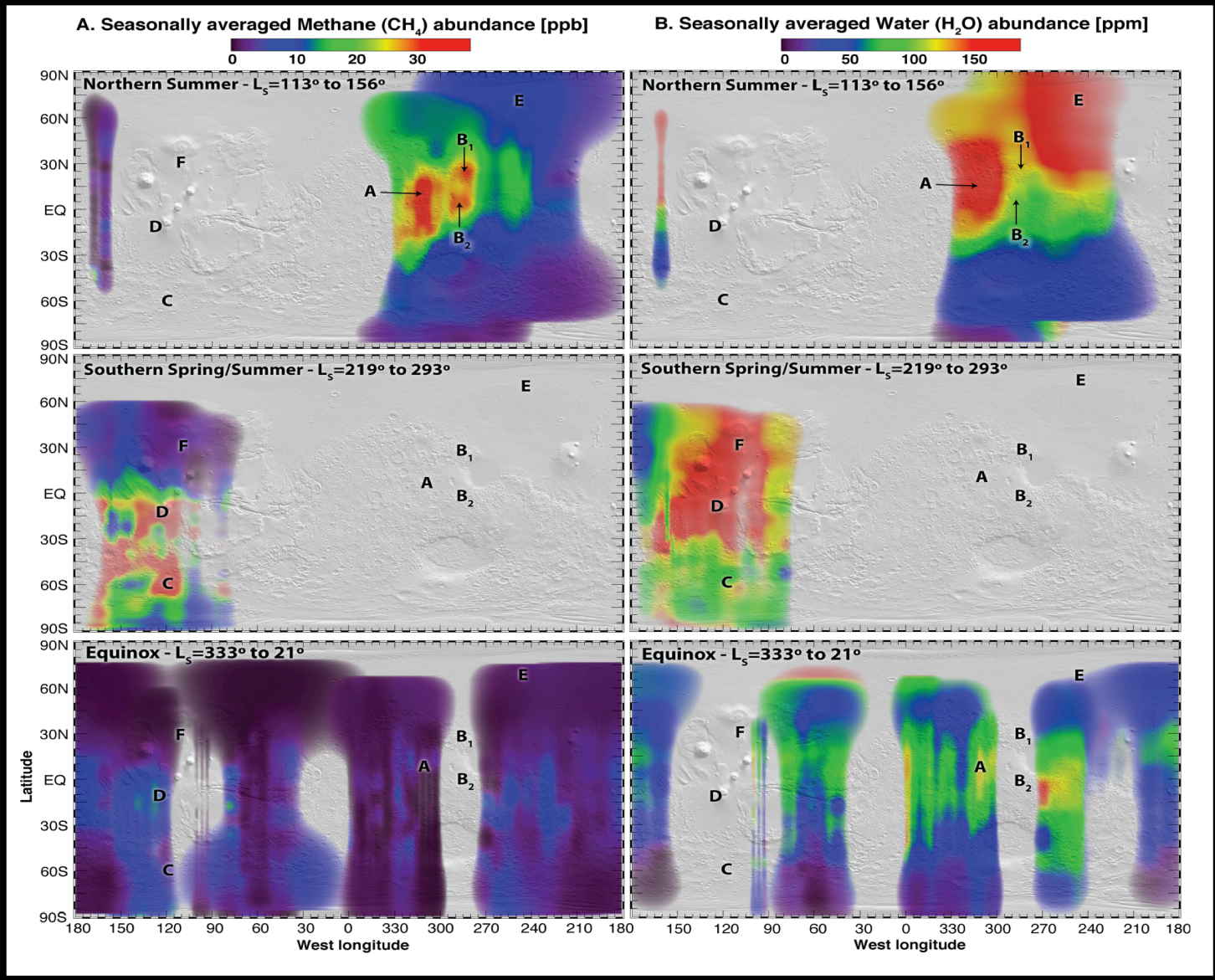


Methane release:
Northern summer




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

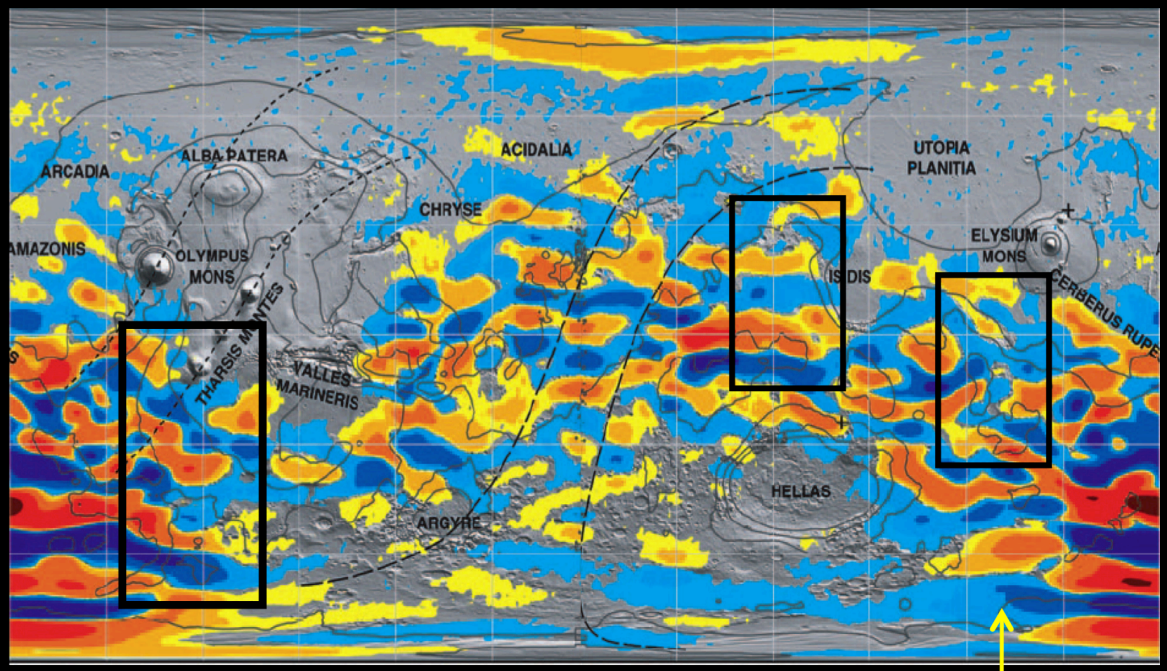
# The Science Driver: Active Release of Methane




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

# The Science Driver: Active Release of Methane

Crustal remnant magnetic field*




Latitude

Longitude

Maximum $CH_4$ abundance observed in 2005

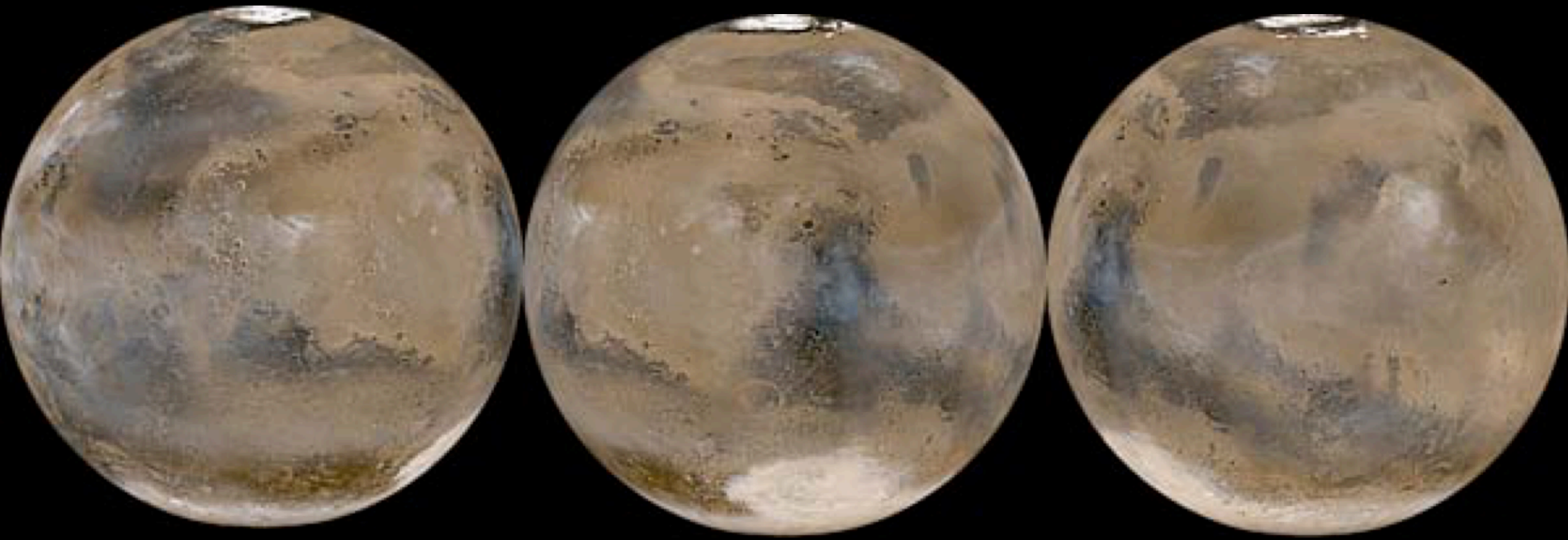
Curiosity - TLS
$CH_4$ detected 2013 - 16

Maximum $CH_4$ abundance observed in 2003 A & B

* Magnetic field map after Connerney et al. 2005

# The Need for Imaging Meteorology

Mars in February 2003: mid-summer in North, $L_s$ = 137.8°



CML 0° W
MOC2-326d

CML 300° W
MOC2-326e

CML 240° W
MOC2-326f

B. C. Cantor, K. S. Edgett, and M. C. Malin, MSSS 2003
http://www.msss.com/mars_images/moc/2003/04/04/globalviews/

# The Need for Imaging Meteorology

Water aerosol clouds: mid-summer in North, $L_s$ =129

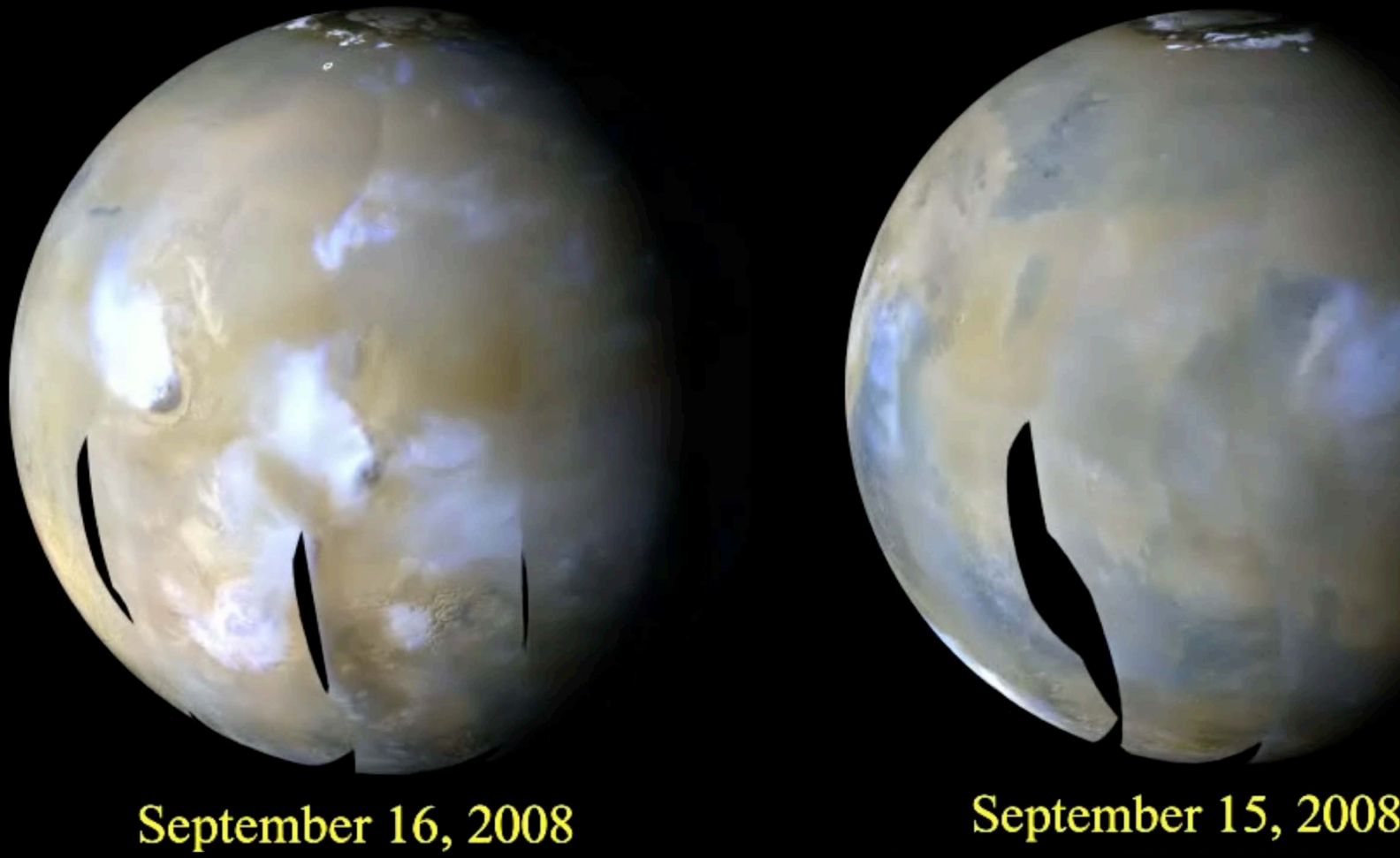
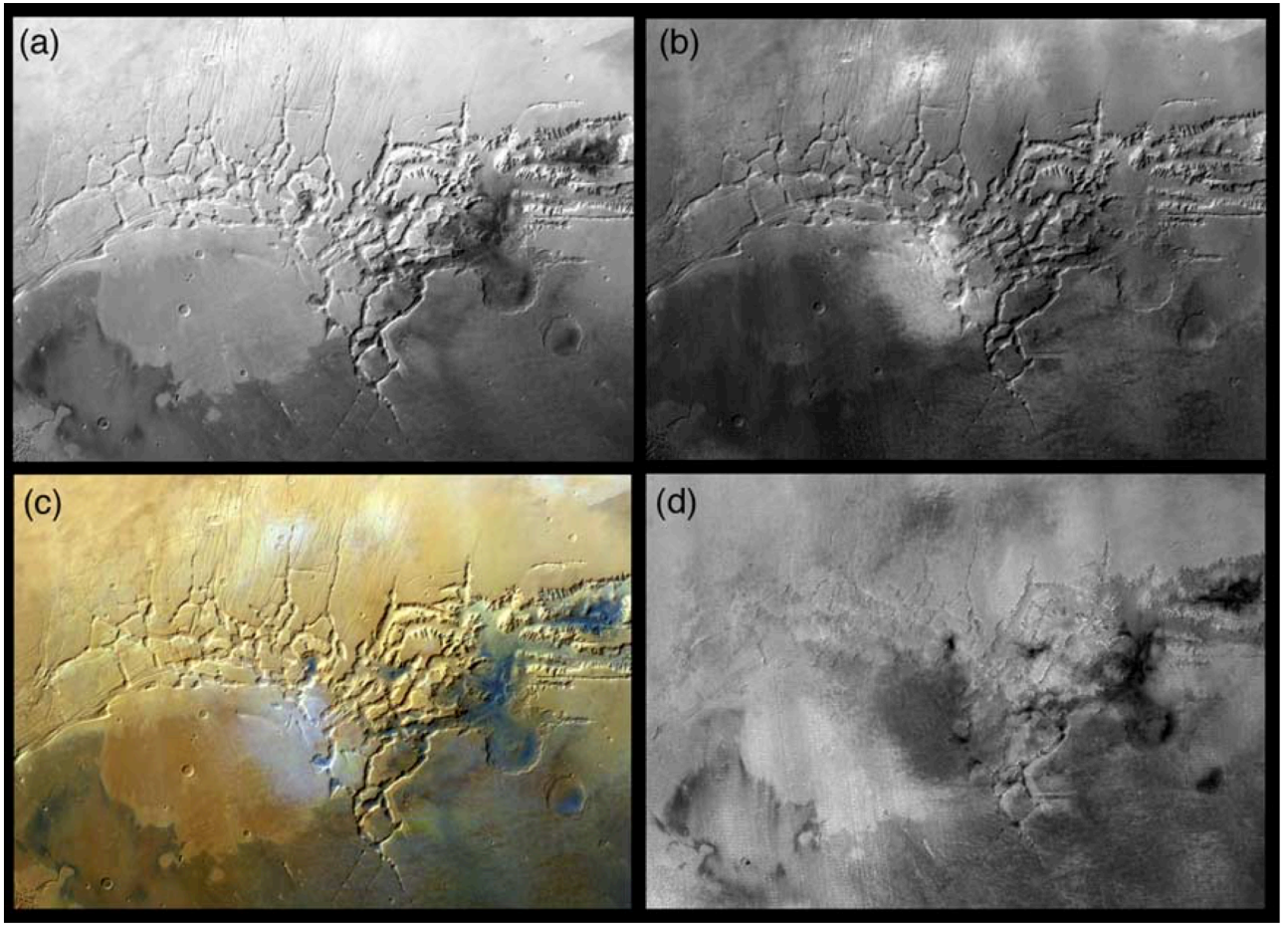



Image Credit: MARCI/MRO & NASA

# The Need for Imaging Meteorology

Water aerosol clouds: late autumn in North, $L_s$ = 240° - 270°




Bell et al. 2009

**Figure 28.** MARCI false color RGB composite mosaic of Noctis Labyrinthus (spanning 0°–15°S latitude top to bottom, and 90°E–110°E, left to right). (a) MARCI band 5 (720 nm) mosaic; (b) MARCI band 1 (440 nm) mosaic; (c) RGB composite generated from bands 5 (720 nm), 2 (540 nm), and 1 (440 nm); (d) MARCI band 5/band 1 (720 nm/440 nm) color ratio mosaic. The mosaic coverage of this region was assembled from 29 separate MARCI images acquired over an $L_s$ range from 240° to 270° (18 May 2007 to 30 June 2007).

# MOO: Science Objectives

- **Map organic source and sink regions**
  - Establish sources of methane, water, and related species
  - $CH_4$: 0.1 ppb (3-sigma), 100x100 km resolution, global coverage
    deeper integrations in selected regions (isotopes; super-resolution)
    12 x 12 km resolution on surface (sub-spacecraft region)
  - Evaluate sinks (surface, heterogeneous chemistry, etc.)
  - Measure dependence on surface temperature (season, time-of-day)
    Repeat at intervals of Mars month
- **Test factors affecting methane origin and destruction**
  - Age of water reservoir accessed: (D/H ratios in methane and water)
  - Destruction mechanisms (spatial distributions $CH_4$, $CH_3OH$, $H_2CO$)

  Biotic vs. abiotic production (homologous series: $CH_4$, $C_2H_6$, …)
- **Characterize the Climate, Meteorology, and Geology of Mars**

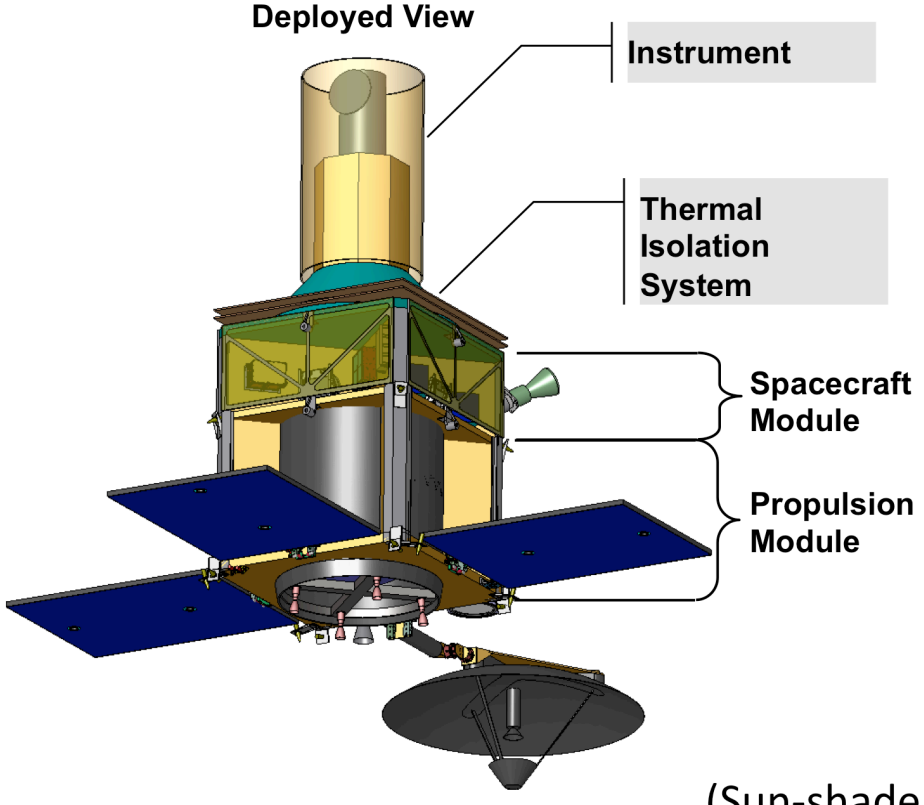
  Quantify circulation patterns on Mars; the water cycle; $HDO/H_2O$, etc.
  Characterize Mars' present climate and meteorological processes.
  Characterize Mars' ancient climate.

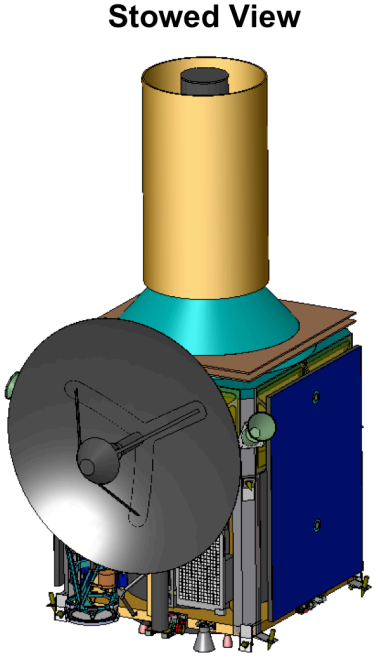
  Test presence of active geothermal processes.
  Characterize the structure, dynamics, and history of the planet's interior.
- **Mission Duration: 3 Earth-years required, 5 years goal**
  - Two full Mars years goal
  - Provide long dwell-time over specific sites
  - Provide simultaneous images (local conditions, climatology)

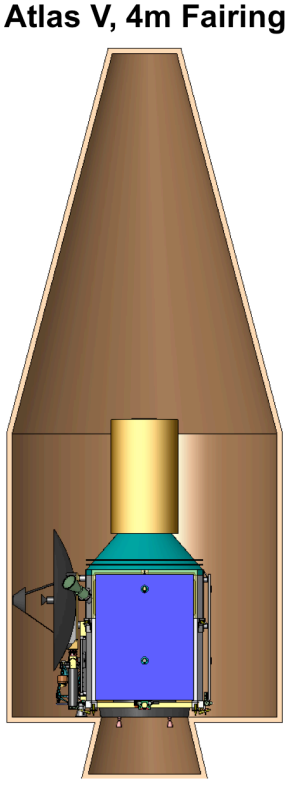
M. J. Mumma 10dec2015

# MOO Spacecraft Concept

- MOO spacecraft based on Deep Impact and Kepler Architecture
- Provide thermal isolation for instrument
- Stable and accurate pointing using camera in instrument



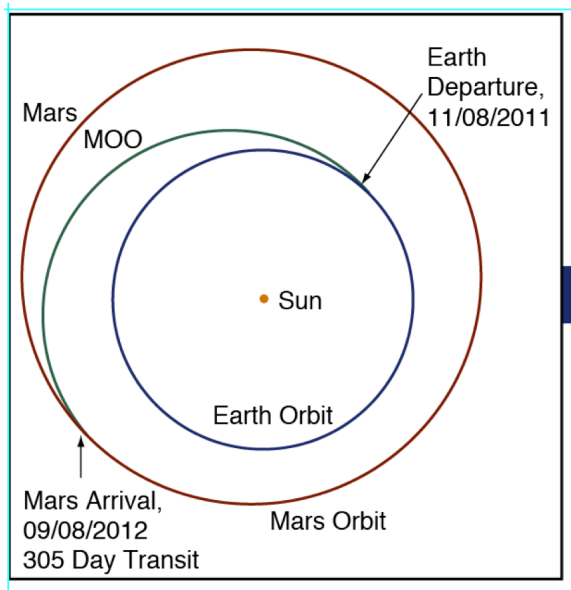



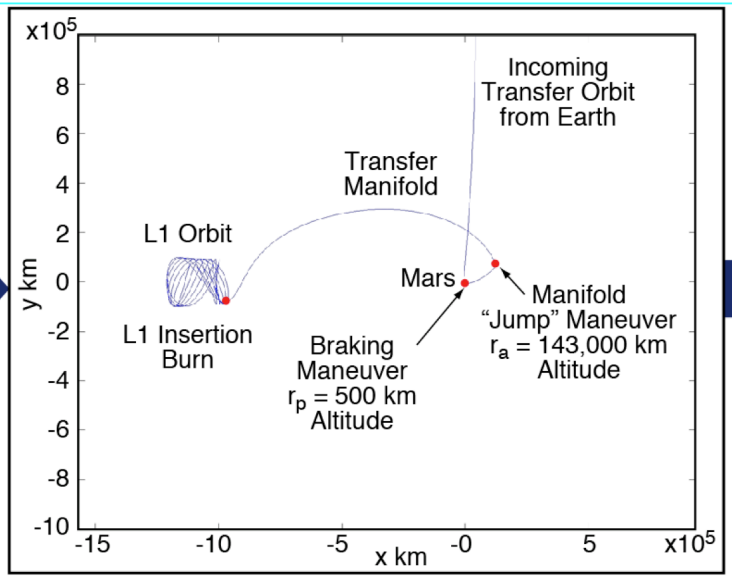

(Sun-shade not shown)

M. J. Mumma 10dec2015

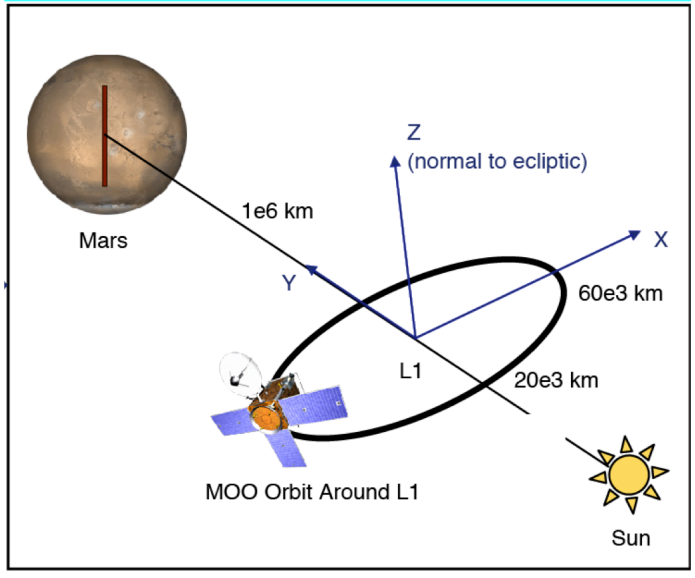
# L1 Observatory - Orbit Concept




**A1. Earth to Mars Cruise Trajectory**




**A2. Cruise to Mars L1 Trajectory**

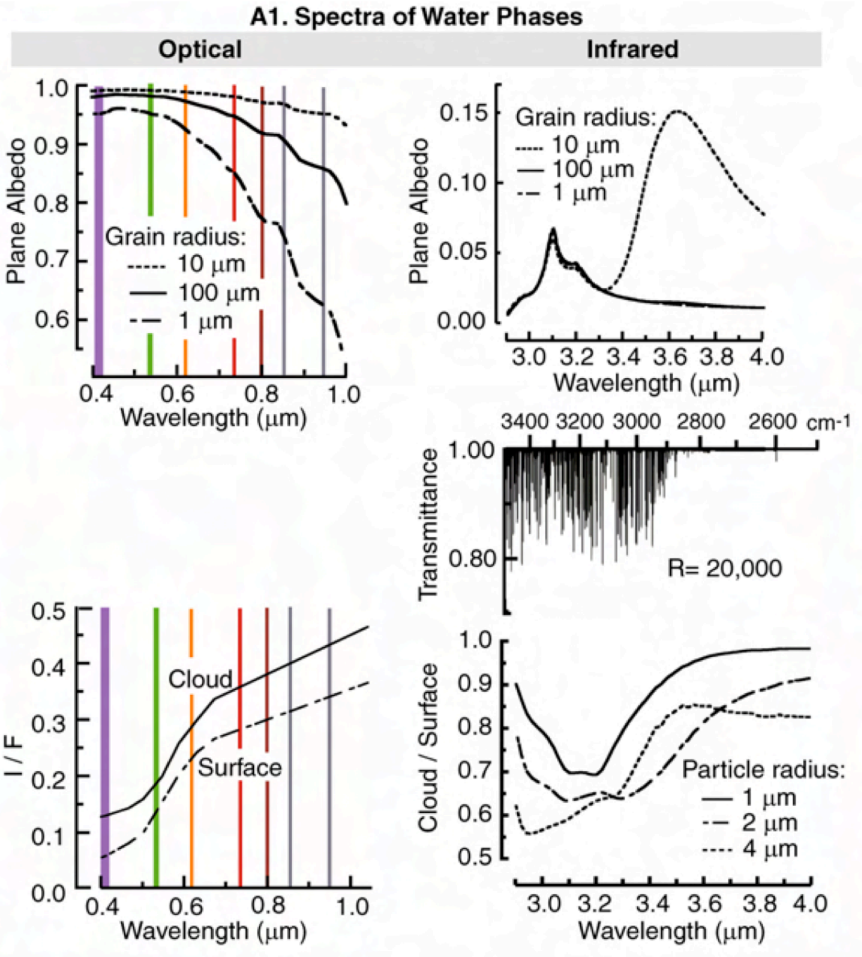


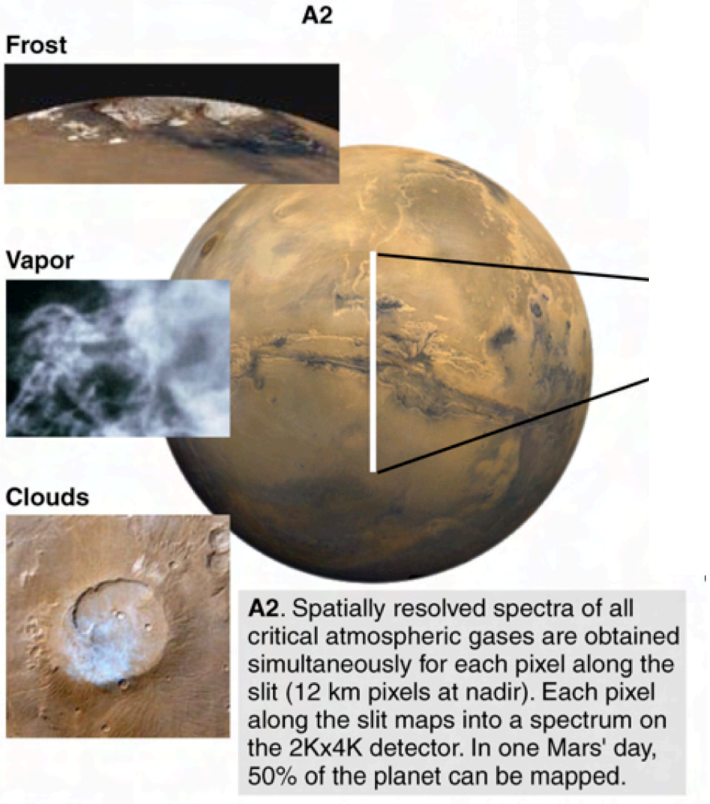

**A3. Science Operations at Mars L1**

M. J. Mumma 16jun2016

# MOO – Imaging Meteorology with SGC

7 filters for enhancing clouds, frost, dust, polar caps, fog, ...



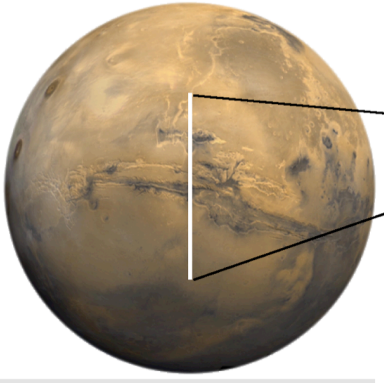



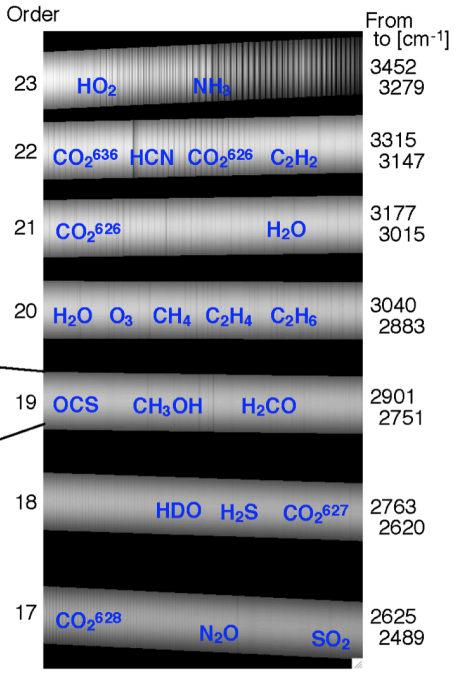

**A2**. Spatially resolved spectra of all critical atmospheric gases are obtained simultaneously for each pixel along the slit (12 km pixels at nadir). Each pixel along the slit maps into a spectrum on the 2Kx4K detector. In one Mars' day, 50% of the planet can be mapped.

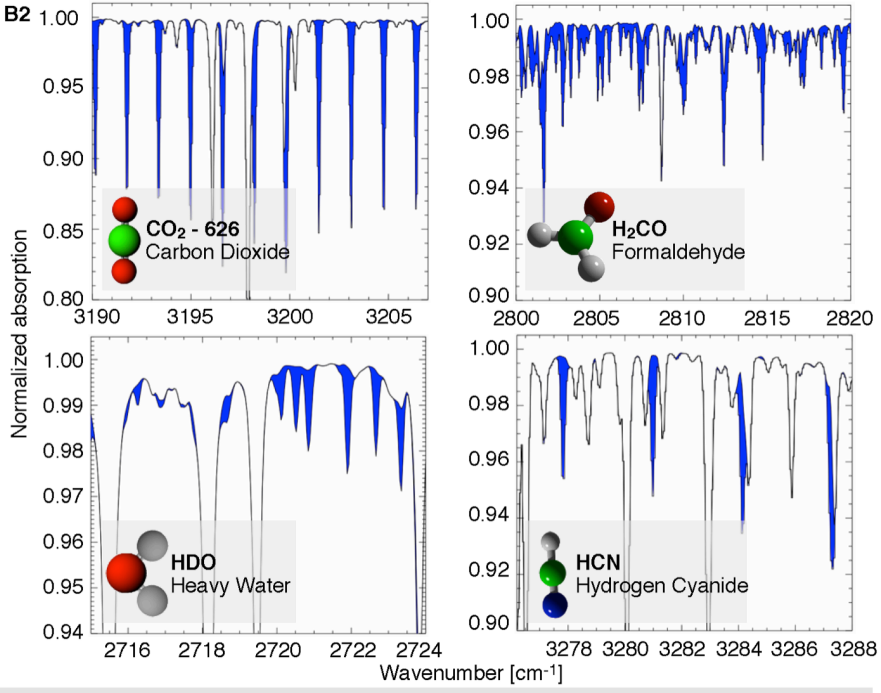
MOO features both full-disk images and high-dispersion infrared spectroscopy, and at L1 MOO can observe "All of Mars - All of the Time". **A1**. Representative spectra are shown for three phases of water on Mars. Left: optical reflectance spectra of surface frost (ice) and cloud aerosols. The wavelengths chosen for seven narrow-pass SGC (Science and Guidance Camera) filters are shown at bottom left. Center: infrared spectra of all three water phases, in the key 2.9 - 4.0 μm spectral interval. Spectrally-windowed measurements with the MOO spectrometer and multi-color full-disk maps from the SGC will be used to quantify and map water in all phases, fully accounting for the atmosphere-surface water inventory throughout the Mars year.

M. J. Mumma 16jun2016

# MOO – Gases: Simultaneous Detections





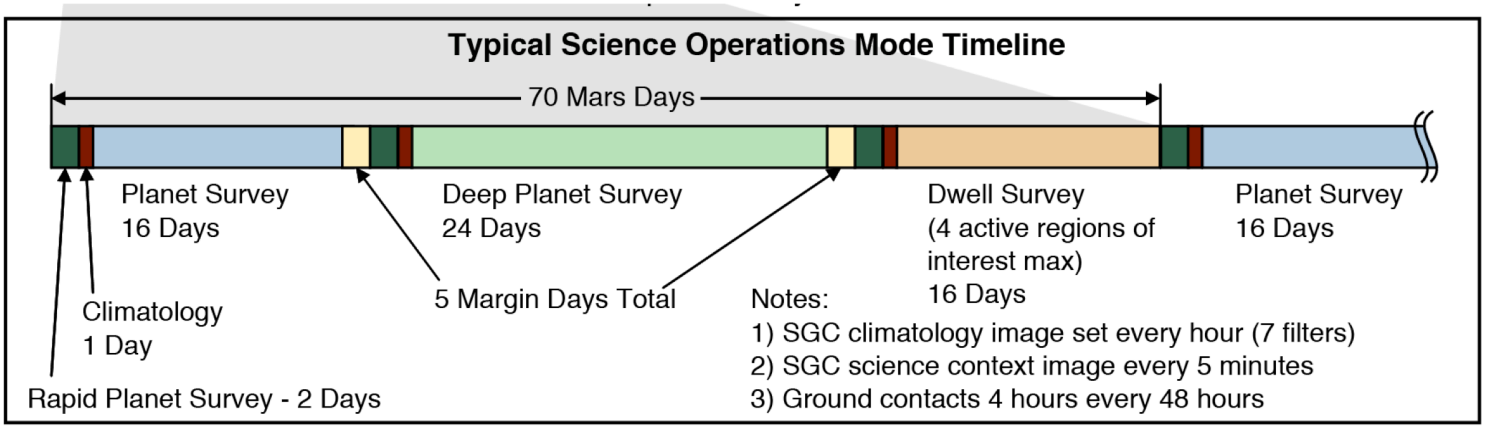



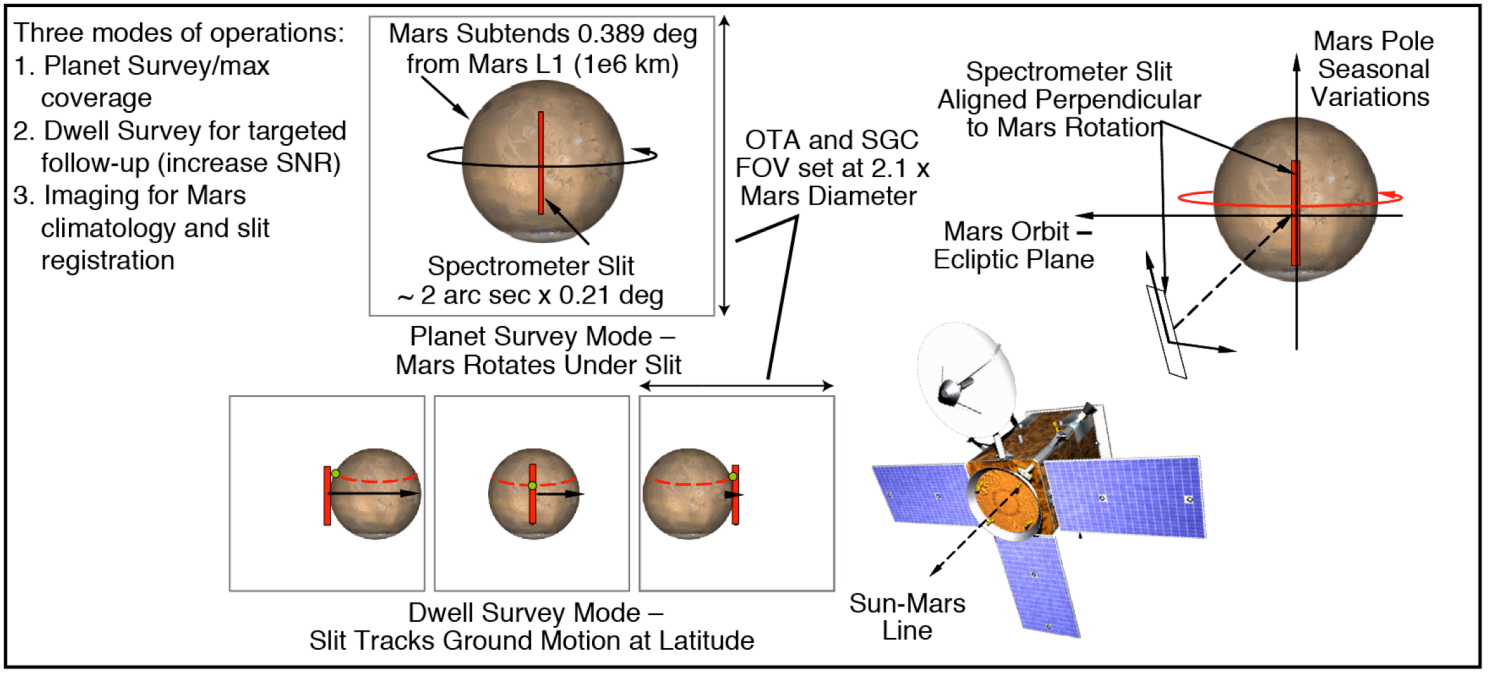

**A2**. Spatially resolved spectra of all critical atmospheric gases are obtained simultaneously for each pixel along the slit (12 km pixels at nadir). Each pixel along the slit maps into a spectrum on the 2Kx4K detector. In one Mars' day, 50% of the planet can be mapped.

Synthetic echellogram and selected spectral extracts for Mars, based on design parameters of the MOO spectrometer. **B1.** The echellogram samples the spectrum completely over the range 2.9 - 4.0 $\mu$m, in seven spectral orders. The spectrum was synthesized at a resolving power (l/dl=20,000) for Mars surface pressure of 7 mbars, standard temperature profile for mid-latitudes, and a two-way path at two air-masses. **B2**. Spectral extracts for carbon dioxide ($CO_2$, 626 isotope), formaldehyde ($H_2CO$, 50 ppb), heavy water (HDO, 10 ppb), hydrogen cyanide (HCN, 50 ppb).

M. J. Mumma 10dec2015

# MOO – Operational Modes



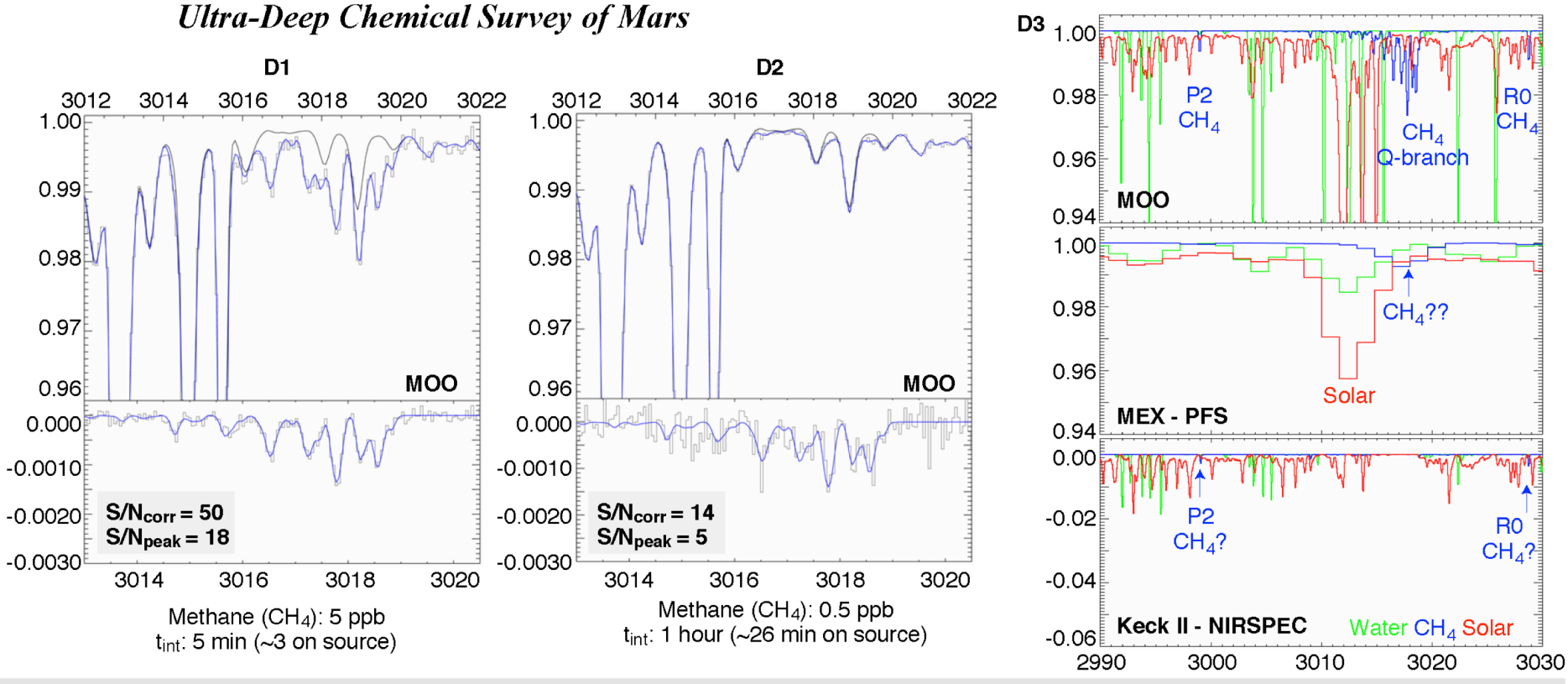

M. J. Mumma 16jun2016

| | Observing Modes | Coverage | Nadir Sampling [km x km] | Program Length [Mars days] |
|---|---|---|---|---|
| 1 | Rapid Planet Survey (RPS), Spectrally complete | Global | 96x96 | 2 |
| 2 | Planet Survey (PS), Spectrally windowed | Global | 24x24 | 16 |
| 3 | Deep Planet Survey (DPS), Spectrally windowed | Global | 48x48 | 24 |
| 4 | Dwell Survey (DS – RoI), Spectrally complete | Region of Interest 420 km x 12 km | 12x12 | 16 |

| Molecule or Isotope | | Current Knowledge | | MOO Sensitivity (10-σ) | | |
|---|---|---|---|---|---|---|
| | | Measured | Limit (3 σ) | Observing Modes | | |
| | | | | 1, 2 | 3 | 4 |
| $\delta^{13}C$ **($CO_2$)** wrt PDB | | -30±50 ‰ | | ±5 ‰ | ±2 ‰ | ±0.3 ‰ |
| $\delta^{18}O$ **($CO_2$)** wrt solar | | -130±80 ‰ | | ±2 ‰ | ±0.5 ‰ | ±0.1 ‰ |
| $\delta^{17}O$ **($CO_2$)** wrt solar | | -70±40 ‰ | | ±5 ‰ | ±2 ‰ | ±0.3 ‰ |
| **$H_2O$ (161)** water | variable: | 0-300 ppm | | 1 ppm | 0.3 ppm | 0.08 ppm |
| $\delta^{2}H$ **(HDO)** (wrt SMOW) | current: | 4200±200 ‰ | | ±15 ‰ | ±5 ‰ | ±1.0 ‰ |
| | ancient: | 900±250 ‰ | | | | |
| **$O_3$** – Ozone | variable: | 40-200 ppb | | 100 ppb | 30 ppb | 7 ppb |
| **$CH_4$** – Methane | variable? | 10-50 ppb | | 1 ppb | 0.3 ppb | 0.08 ppb |
| **$C_2H_6$** – Ethane | | | <400 ppb | 1 ppb | 0.3 ppb | 0.07 ppb |
| **$CH_3OH$** – Methanol | | | — | 2 ppb | 0.4 ppb | 0.1 ppb |
| **$H_2CO$** – Formaldehyde | | | <5 ppb | 3 ppb | 0.7 ppb | 0.2 ppb |
| **$C_2H_2$** – Acetylene | | | <2 ppb | 2 ppb | 0.7 ppb | 0.2 ppb |
| **$C_2H_4$** – Ethylene | | | <500 ppb | 10 ppb | 3 ppb | 0.6 ppb |
| **$SO_2$** – Sulfur dioxide | | | <30 ppb | 50 ppb | 15 ppb | 3 ppb |
| **OCS** – Carbonyl sulfide | | | <70 ppb | 10 ppb | 3 ppb | 0.7 ppb |
| **$H_2S$** – Hydrogen sulfide | | | <20 ppb | 1000 ppb | 300 ppb | 60 ppb |
| **$N_2O$** – Nitrous oxide | | | <100 ppb | 10 ppb | 3 ppb | 0.5 ppb |
| **$NH_3$** – Ammonia | | | <5 ppb | 15 ppb | 5 ppb | 1 ppb |
| **HCN** – Hydrogen cyanide | | | — | 2 ppb | 0.5 ppb | 0.1 ppb |
| **$CH_3Cl$** – Methyl Chloride | | | — | 15 ppb | 4 ppb | 1 ppb |
| **$HO_2$** – Hydroperoxy radical | | | — | 100 ppb | 30 ppb | 6 ppb |

‰ means “parts per thousand” relative to terrestrial values, i.e. SMOW or Pee Dee Belemnite (PDB). “ppm” means parts per million and “ppb” means parts per billion, both relative to $^{12}CO_2$ on Mars. The ***MOO*** sensitivity values are defined by stochastic noise (10-σ confidence level) and do not consider instrumentation or processing abnormalities.

# MOO – Sensitive Search for Methane

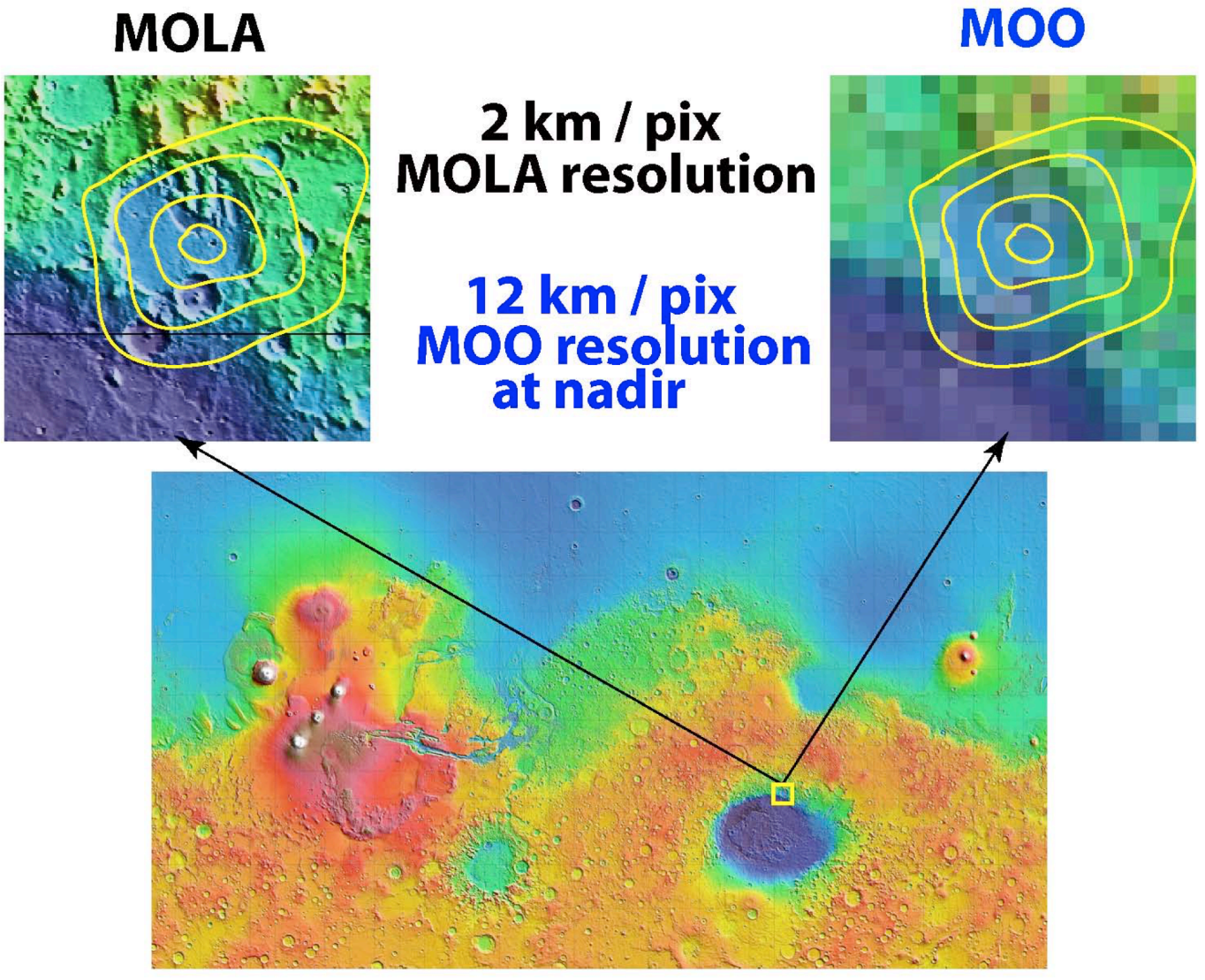



Sensitivity Estimates for Spectroscopic detection of Methane on Mars. **D1.** In the Rapid Planet survey, spectral lines in the Q-branch region are detected with high confidence in five minutes clock time, representing a 96 km x 96 km footprint (nadir) on Mars. **D2.** In the Deep Survey mode, 12 maps taken as in D1 are co-added, improving the S/N by 3.5. At 0.5 ppb, methane would be detected at the 14-sigma level (correlation mode). **D3.** The spectrum of sunlight reflected from Mars shows solar lines along with lines of $H_2O$ and $CH_4$ in the Mars atmosphere. The spectrum is shown convolved to the resolving powers of 20,000 (MOO), 1500 (MEX-PFS), and 24,000 (Keck-NIRSPEC). The significant limitation of the PFS data is demonstrated, strongly putting into question their claimed detection of methane. All ground-based searches (e.g., Keck) are severely restricted by terrestrial extinction. With a resolving power of 20,000 MOO will separate these lines cleanly and will return clear detections of methane and other targeted species.

A10760_026

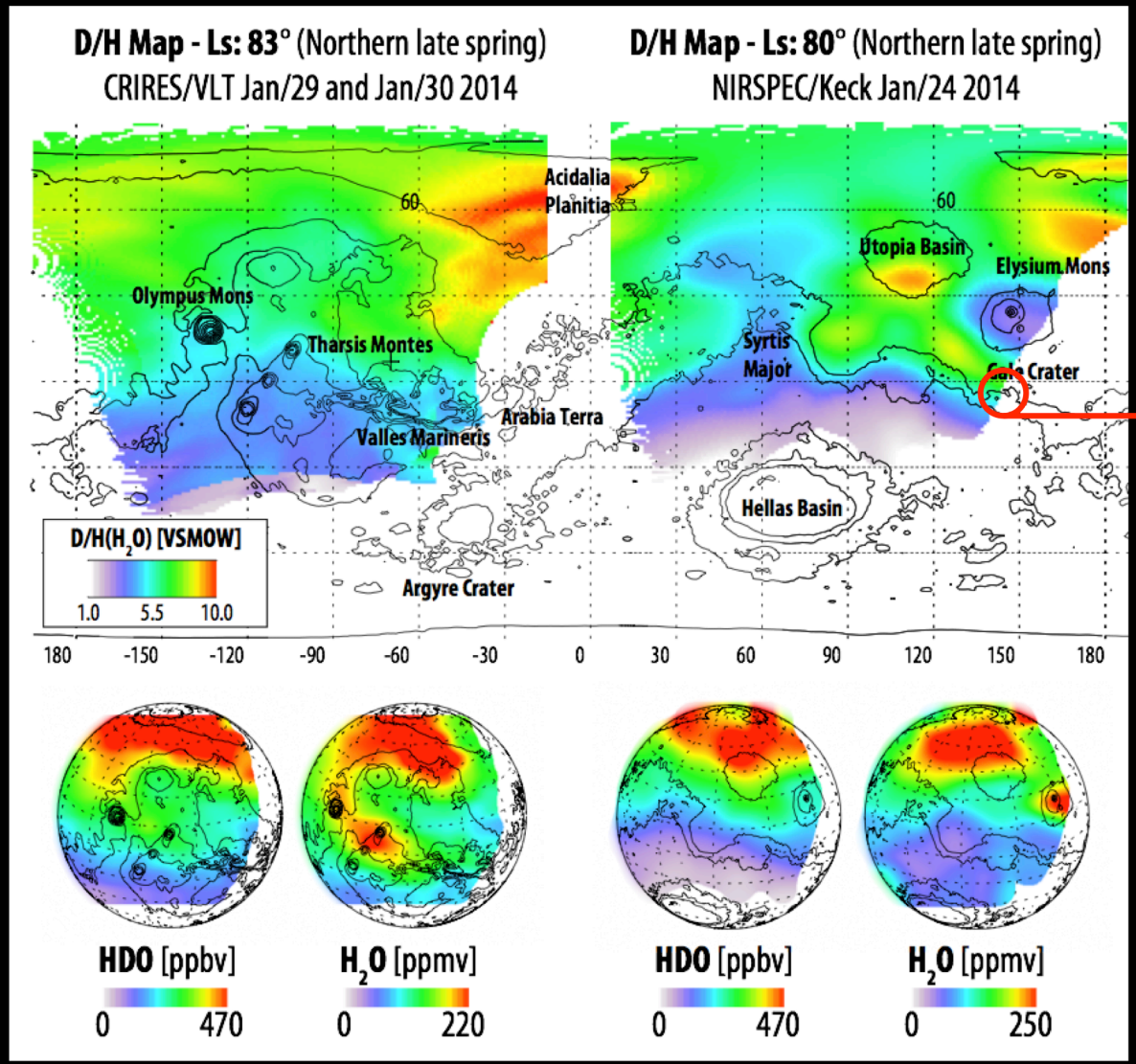
M. J. Mumma 10dec2015

# MOO – Data Products




M. J. Mumma 16jun2016

# “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 $H_2O$?

HDO – ALMA
$H_2O$ – TMT, E-ELT?

ExoMars TGO
L1 - Observatory

| | Observing Modes | Coverage | Nadir Sampling [km x km] | Program Length [Mars days] |
|---|---|---|---|---|
| 1 | Rapid Planet Survey (RPS), Spectrally complete | Global | 96x96 | 2 |
| 2 | Planet Survey (PS), Spectrally windowed | Global | 24x24 | 16 |
| 3 | Deep Planet Survey (DPS), Spectrally windowed | Global | 48x48 | 24 |
| 4 | Dwell Survey (DS – RoI), Spectrally complete | Region of Interest 420 km x 12 km | 12x12 | 16 |

| Molecule or Isotope | | Current Knowledge | | MOO Sensitivity (10-σ) | | |
|---|---|---|---|---|---|---|
| | | Measured | Limit (3 σ) | Observing Modes | | |
| | | | | 1, 2 | 3 | 4 |
| $\delta^{13}C$ **($CO_2$)** wrt PDB | | -30±50 ‰ | | ±5 ‰ | ±2 ‰ | ±0.3 ‰ |
| $\delta^{18}O$ **($CO_2$)** wrt solar | | -130±80 ‰ | | ±2 ‰ | ±0.5 ‰ | ±0.1 ‰ |
| $\delta^{17}O$ **($CO_2$)** wrt solar | | -70±40 ‰ | | ±5 ‰ | ±2 ‰ | ±0.3 ‰ |
| **$H_2O$ (161)** water | variable: | 0-300 ppm | | 1 ppm | 0.3 ppm | 0.08 ppm |
| $\delta^{2}H$ **(HDO)** (wrt SMOW) | current: | 4200±200 ‰ | | ±15 ‰ | ±5 ‰ | ±1.0 ‰ |
| | ancient: | 900±250 ‰ | | | | |
| **$O_3$** – Ozone | variable: | 40-200 ppb | | 100 ppb | 30 ppb | 7 ppb |
| **$CH_4$** – Methane | variable? | 10-50 ppb | | 1 ppb | 0.3 ppb | 0.08 ppb |
| **$C_2H_6$** – Ethane | | | <400 ppb | 1 ppb | 0.3 ppb | 0.07 ppb |
| **$CH_3OH$** – Methanol | | | — | 2 ppb | 0.4 ppb | 0.1 ppb |
| **$H_2CO$** – Formaldehyde | | | <5 ppb | 3 ppb | 0.7 ppb | 0.2 ppb |
| **$C_2H_2$** – Acetylene | | | <2 ppb | 2 ppb | 0.7 ppb | 0.2 ppb |
| **$C_2H_4$** – Ethylene | | | <500 ppb | 10 ppb | 3 ppb | 0.6 ppb |
| **$SO_2$** – Sulfur dioxide | | | <30 ppb | 50 ppb | 15 ppb | 3 ppb |
| **OCS** – Carbonyl sulfide | | | <70 ppb | 10 ppb | 3 ppb | 0.7 ppb |
| **$H_2S$** – Hydrogen sulfide | | | <20 ppb | 1000 ppb | 300 ppb | 60 ppb |
| **$N_2O$** – Nitrous oxide | | | <100 ppb | 10 ppb | 3 ppb | 0.5 ppb |
| **$NH_3$** – Ammonia | | | <5 ppb | 15 ppb | 5 ppb | 1 ppb |
| **HCN** – Hydrogen cyanide | | | — | 2 ppb | 0.5 ppb | 0.1 ppb |
| **$CH_3Cl$** – Methyl Chloride | | | — | 15 ppb | 4 ppb | 1 ppb |
| **$HO_2$** – Hydroperoxy radical | | | — | 100 ppb | 30 ppb | 6 ppb |

‰ means “parts per thousand” relative to terrestrial values, i.e. SMOW or Pee Dee Belemnite (PDB). “ppm” means parts per million and “ppb” means parts per billion, both relative to $^{12}CO_2$ on Mars. The ***MOO*** sensitivity values are defined by stochastic noise (10-σ confidence level) and do not consider instrumentation or processing abnormalities.

# "ExoMars – NOMAD: Expected Sensitivity"

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

| | | SO | LNO | | SO | |
|---|---|---|---|---|---|---|
| | | 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]<br>< 0.7 ppb [g] | 0.03 ppb | 0.02 ppb | 11 ppb | | |
| HCl | < 3 ppb [e]<br>< 0.2 ppb [f]<br>< 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]<br>< 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]<br>< 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]<br>< 3.9 ppb [g] | 0.04 ppb | 0.03 ppb | 16 ppb | 7.5 ppb | 150 ppb |
| $NH_3$ | < 5 ppb [h]<br>< 60 ppb [g] | | | | 1 ppb | - |
| $SO_2$ | < 1 ppb [i]<br>< 2 ppb [j,k] | | | | 0.5 ppb | 18 ppb |

End