Physical processes in planetary and cometary atmospheres derived from narrowband imaging of gaseous fragment species

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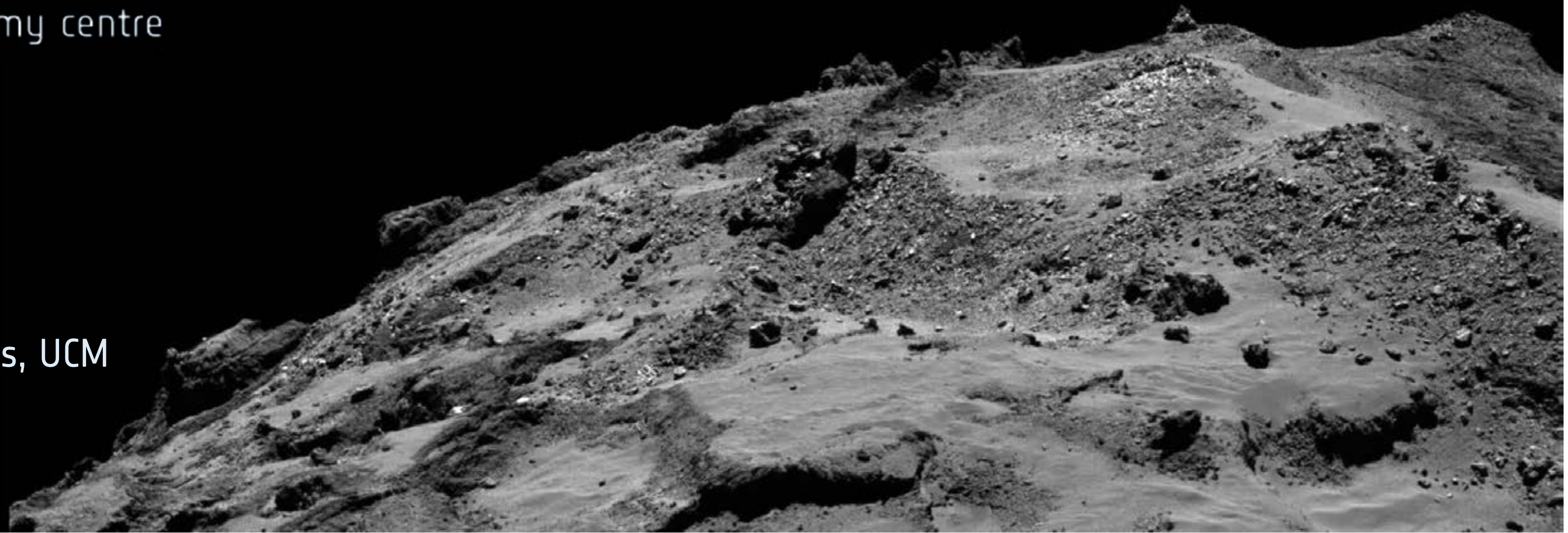

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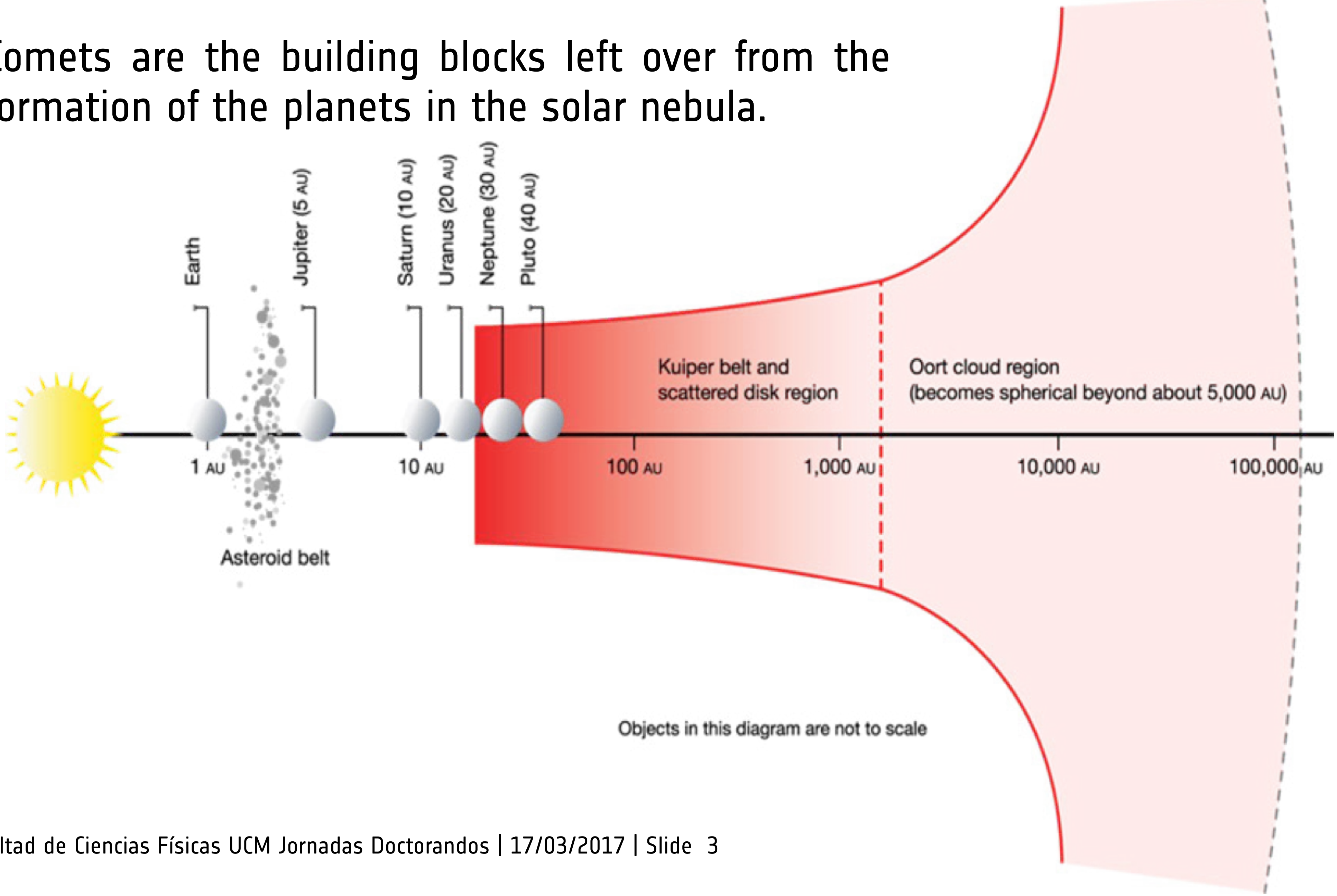
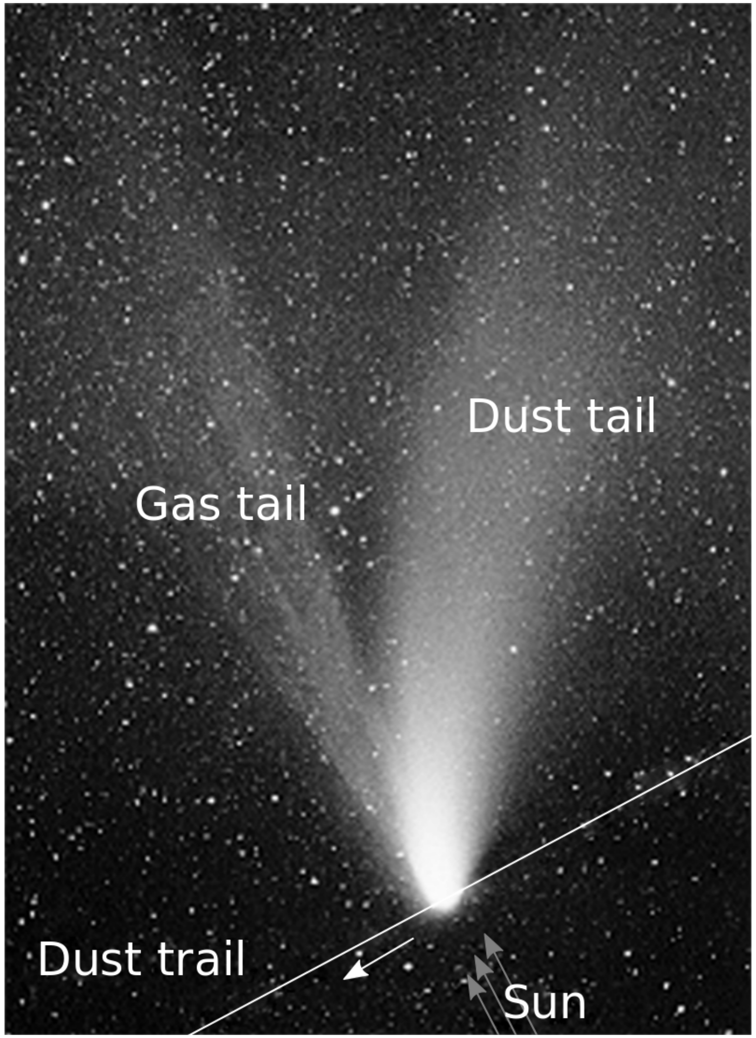
  - OSIRIS Team

Cometary Science Concepts

- Comets are the building blocks left over from the formation of the planets in the solar nebula.



Cometary Science Concepts



A comet typically consists of a nucleus, coma, and tail.

- The nucleus is embedded in the coma and they together form the **head** of a comet.
  - The **Nucleus** is composed of ice and dust. Far away from the Sun (more than 5 AU) the comet only consists of the nucleus which is around several km in size (a few to 10s of km).
  - Most of their mass is made up by H_2O, silicates and organic refractories, in addition they also consist of some C, CO, CO_2, CH_3OH (methanol) and H_2CO (formaldehyde).

Cometary Science Concepts

Comet 17P/Holmes, 2007/11/02

- As comets get closer to the Sun, the solar radiation heats up the ice and starts the sublimation process which is incremented when comet's heliocentric distance decreases.
- The gas carries some of the solid particles (refractory grains, refractory organics, icy grains, aggregates of ice and dust) with it. The resultant material forms the cometary **coma**.
- This gives a comet a "fuzzy" appearance, like a nebulous envelope around the nucleus.
- **Dust Tail**: a long tail of dust which reflects sunlight. Often curved as the parts further from the Sun orbit slower
- **Gas Tail**: Always points away from the Sun as it is ionized by solar UV radiation and then carried away by the solar wind.

- The gases that come directly from the nucleus first flow through a region near the nucleus, named **collisional zone**, where the gas densities are sufficiently high that collisions, and thus chemical reactions, can take place.
- Once out of the collisional zone, **photochemical processes** (photolysis of parent molecules, excitation mechanisms) change the composition of the gases.

$H_2O + h\nu$	$\rightarrow$	$OH + H$	2424.6 Å
	$\rightarrow$	$OH(A^2\Sigma^+) + H$	1357.1 Å
	$\rightarrow$	$H_2 + O(^1D)$	1770 Å
	$\rightarrow$	$H_2 + O(^1S)$	1450 Å
	$\rightarrow$	$H + H + O(^3P)$	1304 Å
	$\rightarrow$	$H_2O^+ + e$	984 Å
	$\rightarrow$	$H + OH^+ + e$	684.4 Å
	$\rightarrow$	$H_2 + O^+ + e$	664.4 Å
	$\rightarrow$	$OH + H^+ + e$	662.3 Å

Many of the fragments can be further broken down:

$OH + h\nu$	$\rightarrow$	$O + H$	2823.0 Å
	$\rightarrow$	$OH^+ + e$	928 Å
$H_2 + h\nu$	$\rightarrow$	$H + H$	844.79 Å
	$\rightarrow$	$H_2^+ + e$	803.67 Å
	$\rightarrow$	$H + H^+ + e$	685.8 Å
$O + h\nu$	$\rightarrow$	$O^+ + e$	910.44 Å
$H + h\nu$	$\rightarrow$	$H^+ + e$	911.75 Å

Feldman et al. 2004, Comets II

Cometary Science Concepts

- The spectra of comets are mostly composed of emissions from gas-phase molecules superposed onto a continuum that results from sunlight reflecting off dust.

- Optical spectra of comets contain few parent species. The spectra are mostly bands of **fragment** molecules (called daughters). Thus, the parent species must be inferred using lifetimes and chemical reaction networks.

- IR and radio spectra contain a mixture of parent and daughter species. In the UV, can be seen parents and daughters, as well as a number of important atomic features, such as H, C and O.

Observations of comets by satellites

We do not observe the nucleus directly, except when observing from a spacecraft flying past or during a rendezvous mission.

1P/Halley - 16 × 8 × 8 km
Giotto, 1986

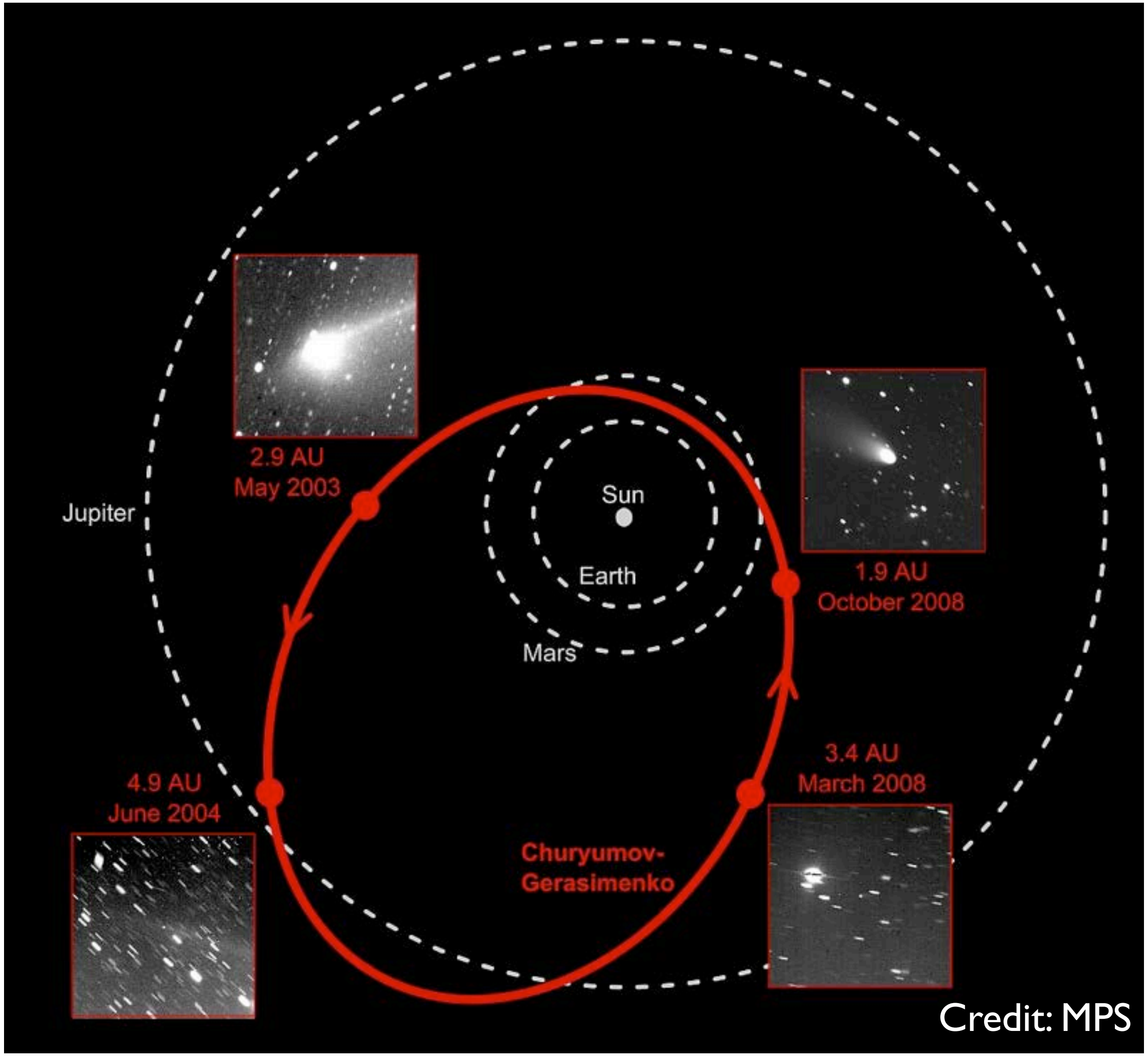
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004

19P/Borrelly
8 × 4 km
Deep Space 1, 2001

9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005

103P/Hartley 2
2.2 x 0.5 km
Deep Impact, 2010

Target: 67P/Churyumov-Gerasimenko



Discovery	1969
Perihelion	1.2458 AU
Aphelion	5.6839 AU
Semi-major axis	3.4648 AU
Eccentricity	0.64043
Inclination	7.0424°
Orbital period	6.45 yr

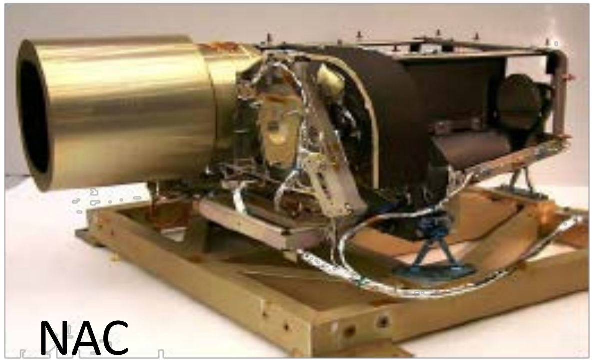
- Relatively unprocessed comet (not much time spent close to Sun),
- Short period and small orbit.
- Jupiter-family comet from the Kuiper belt

OSIRIS Cameras

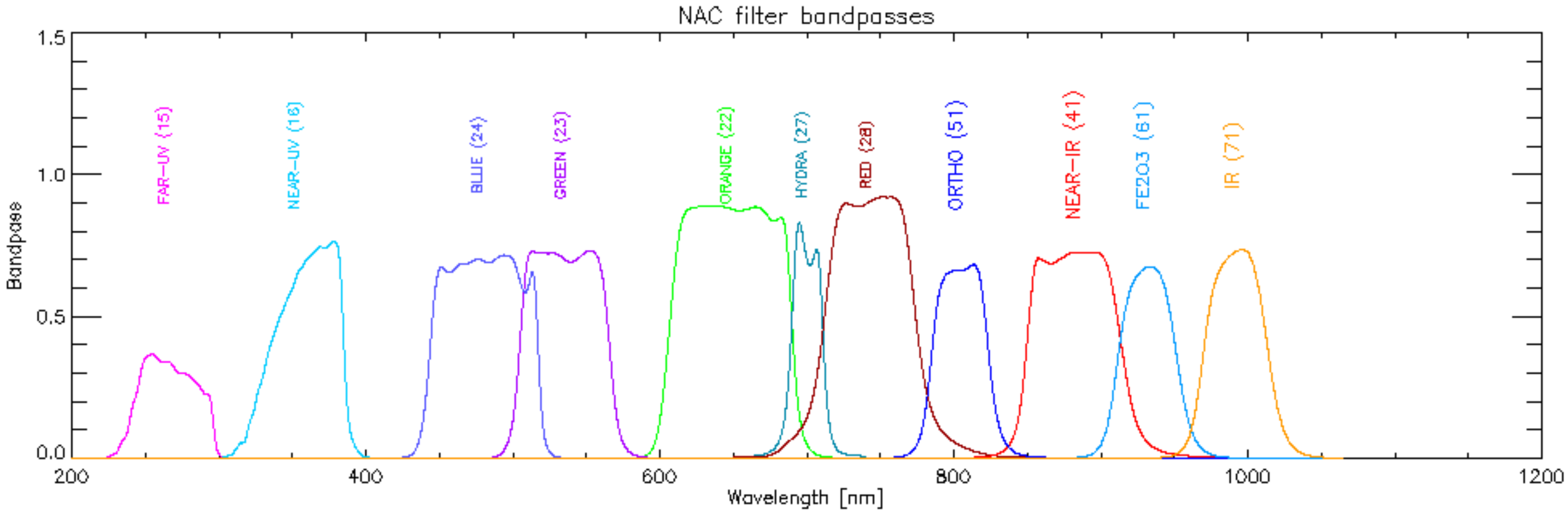
- OSIRIS is the scientific Imaging System on the Rosetta orbiter.
- Built by an European consortium (France, Italy, Spain, Sweden, ESA, Germany) lead by MPS (*Max-Planck-Institute for Solar System Research, Germany*).

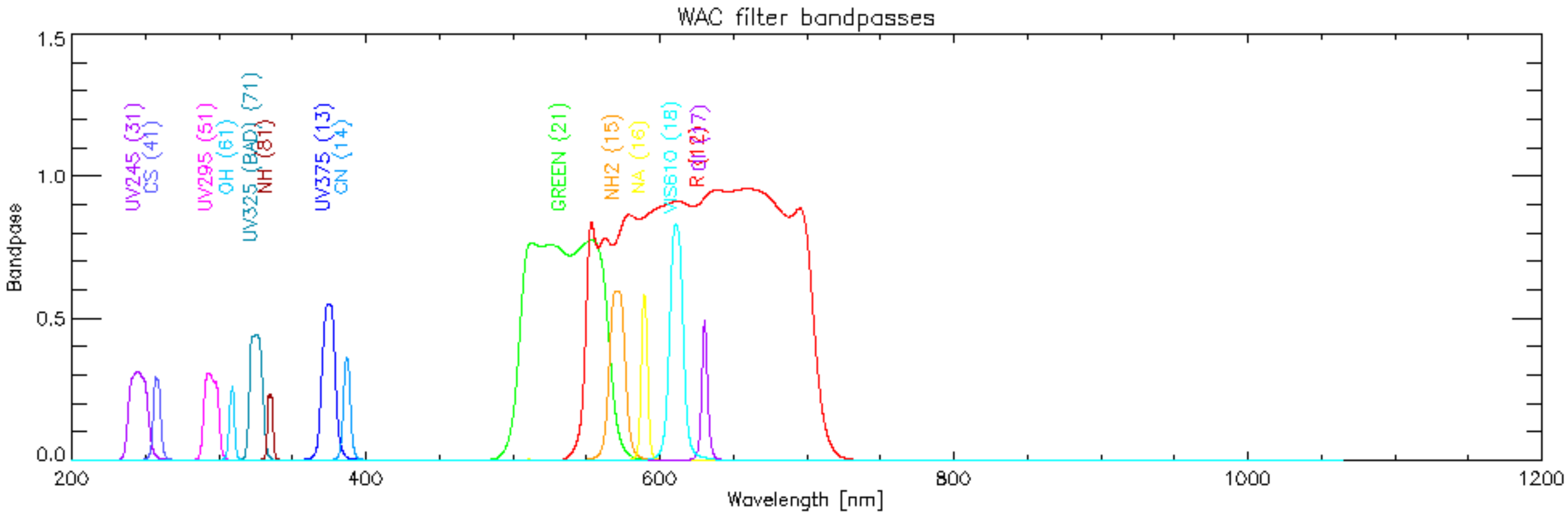
- Two units optimized for comet observations:
  - NAC (Narrow Angle Camera) designed to obtain high-resolution images of the surface of comet from more than 500 000 km down to 1 km. 12 discrete filters over the range 250–1000 nm at an angular resolution of 18.6μrad px^{-1}.

  - WAC (Wide Angle Camera) to provide images of the near nucleus environment in 14 discrete filters at an angular resolution of 101μrad px^{-1}. Seven of those filters isolate emissions from cometary gas species.



OSIRIS filters transmission curves





Thesis Objective

The main objective of this thesis will be to understand the **physical processes in the inner coma** of the comet through measurements with OSIRIS trying to address the following scientific questions:

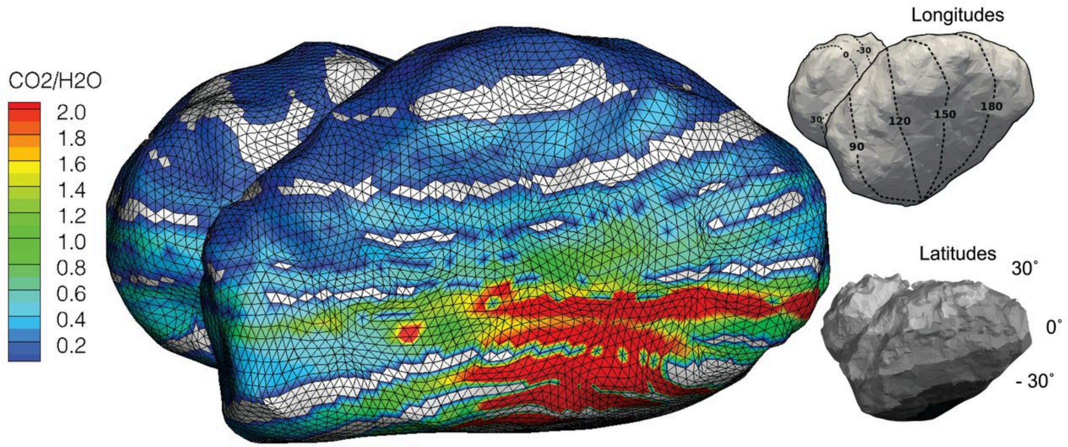
1. Distribution and evolution of source species over the nucleus and nucleus homogeneity.

2. Identification of physical and chemical processes creating the emissions close to/far from the Sun.

3. Understanding gas signal in the NAC observations.

Distribution and evolution of source species over the nucleus and nucleus homogeneity

- Nucleus heterogeneity in terms of composition of outgassing material was found



Effect of less illumination in the south and larger volatility of CO_2 vs. H_2O is not corrected in the figure

Hässig et al. 2015, Science 347, a0276

- Central Question: Is heterogeneity primordial or evolutionary?
  - It is generally difficult to get the parent molecule distribution from fragmentation products
  - However, close to the nucleus many emissions of daughter molecules come from dissociation of the parent into an excited state of the daughter and therefore track the parent distribution

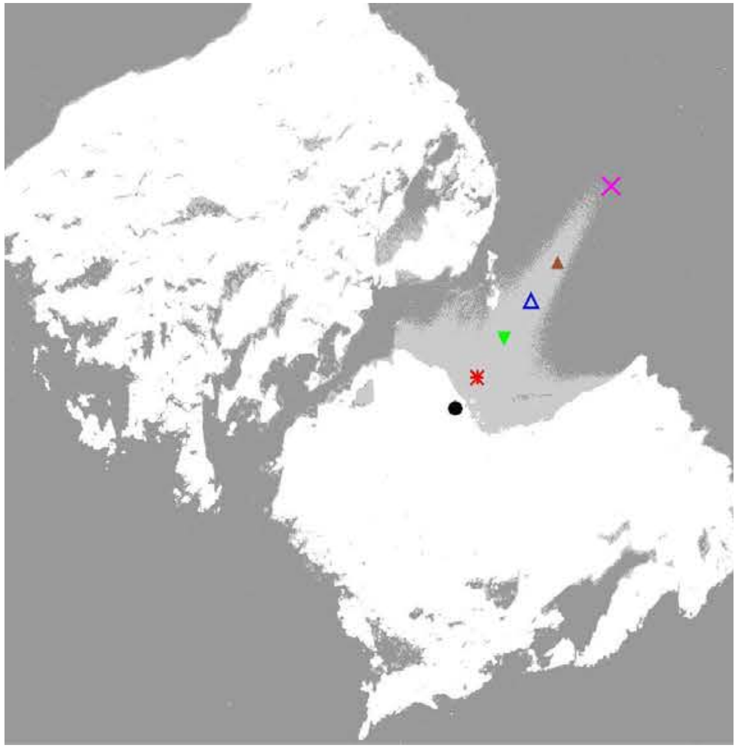
Identification of physical and chemical processes creating the emissions close to/ far from the Sun

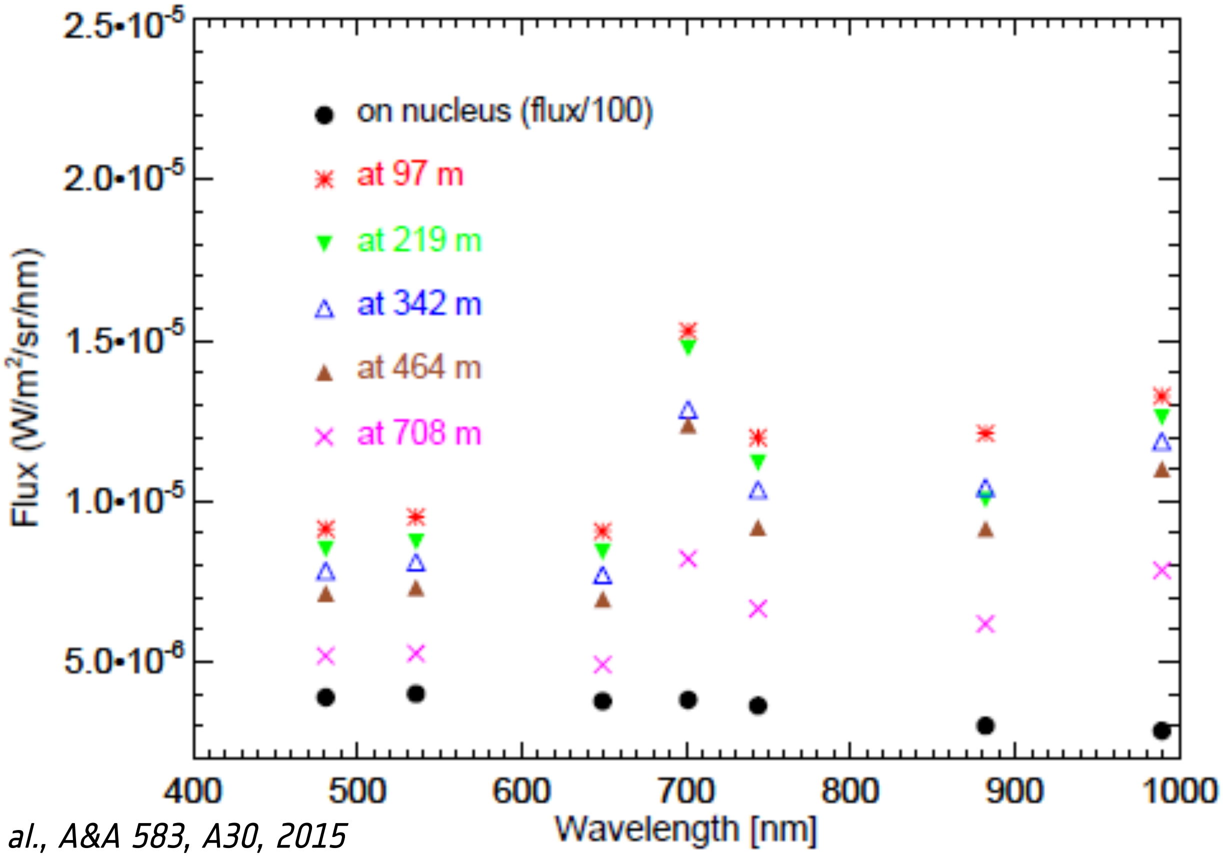
Processes responsible for the emission seen in the OSIRIS WAC gas filters:

Daughter emission	Processes known from ground based observations	Additional process found from OSIRIS data (*Bodewits et al., ApJ 152, 130, 2016*)
CS 257 nm	Fluorescence, parent CS_2	-
OH 308 nm	Fluorescence, parent H_2O Prompt emission following photo-dissociation of H_2O?	Prompt emission from electron impact dissociation of H_2O
NH 335 nm	Fluorescence, parent NH_3->NH_2->NH	Prompt emission of OH^+ following electron impact dissociation of H_2O
CN 388 nm	Fluorescence, parent HCN	Prompt emission of CO_2^+ following electron impact dissociation of CO_2
NH_2 570 nm	Fluorescence, parent NH_3	?
Na 589 nm	Resonant scattering, parent dust or Na-bearing molecule	-
O I 630 nm	Prompt emission following photo-dissociation of H_2O	Prompt emission following electron impact dissociation of H_2O Prompt emission following electron impact dissociation of CO_2

So far only part of the data are analysed. More new processes are expected to be found.

Understanding gas signal in the NAC observations





Fornasier et al., A&A 583, A30, 2015

- Emission at 700 nm (and tentatively 743 nm and 880 nm) discovered already at 3.6 AU from the sun
- Attributed to the "usual" species NH_2 and H_2O^+
  - Questionable given the results for the WAC

Thesis Steps

1. **Analysis of OSIRIS Mars flyby data**:

   - The focus will be the clouds on Mars. They are prominent in the data both towards the surface and at the limb.

   - Particular interest are the filters in the ultraviolet that provide information about the ozone content and H_2O clouds vs. CO_2 clouds

   - In collaboration with atmospheric modellers the vertical structure and physical properties of the atmosphere will be constrained from the spatial distribution and spectrum of the clouds.

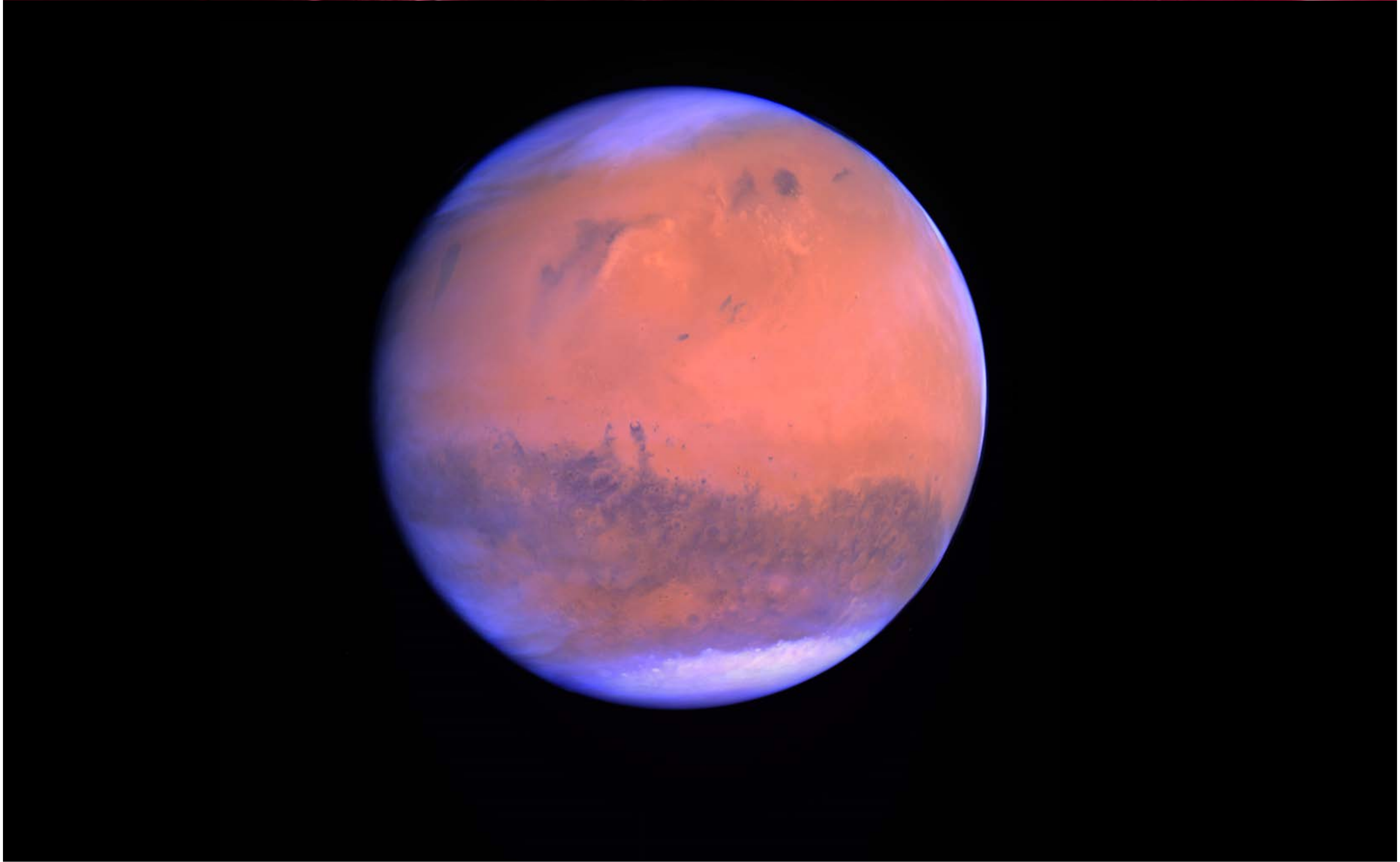
2. **Spectral analysis from the OSIRIS data of the G7P gas coma:**
   - Reduce WAC data at very heliocentric distance and NAC data closer to perihelion for the observed gas coma.
   - Revisit the calibration required for gas emission, especially removal of straylight and dust continuum
   - Extract the flux and spatial distribution of the gas emission.
   - Identify possible emission mechanism constrained by flux and spatial distribution

Where we are…

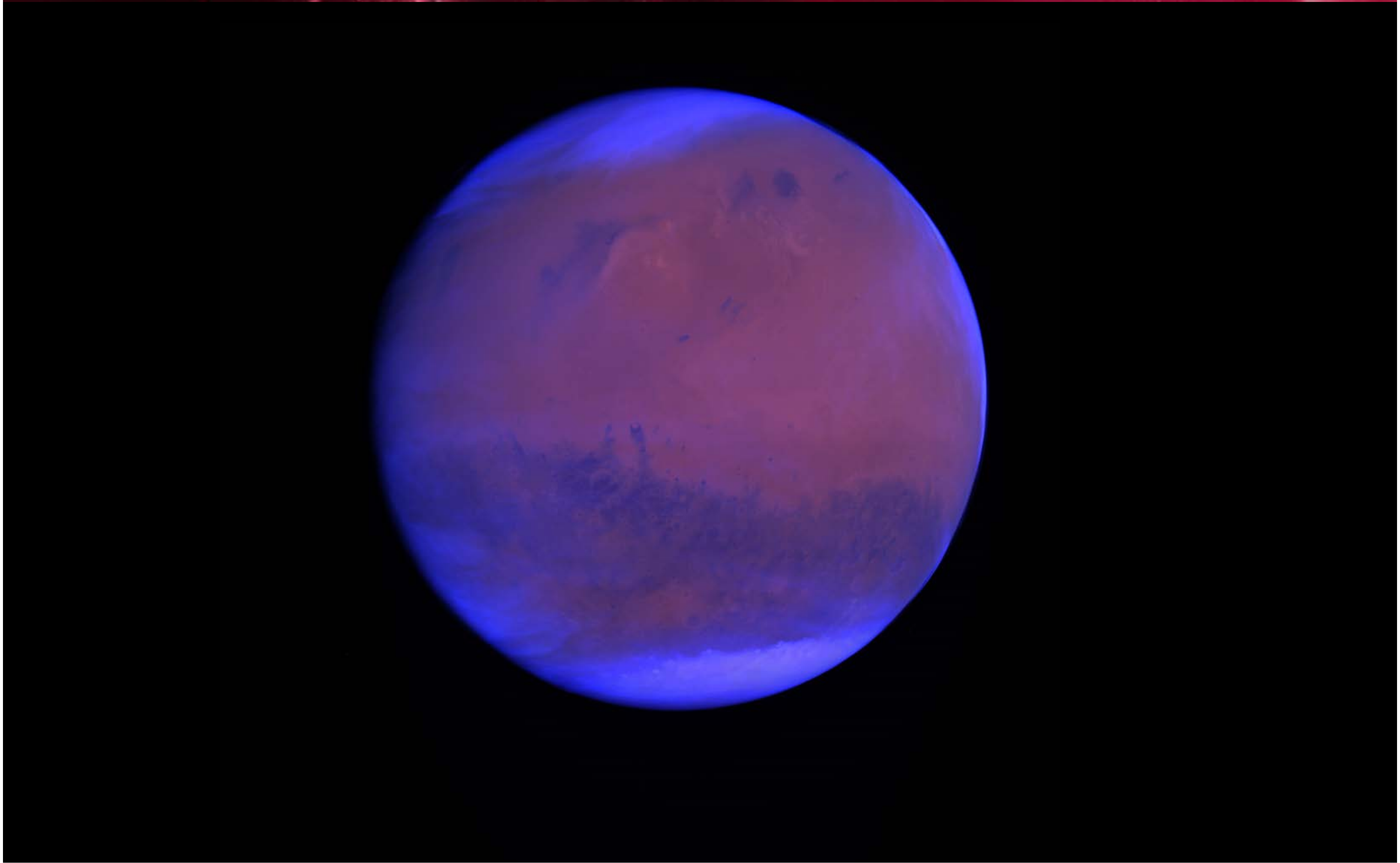
- **OSIRIS Mars flyby data: Mars Observations was used for:**
  - Mars disk illuminated and dark (nightglow)
  - Mars limb (atmosphere: dust, OH, O, Na)
  - Search for dust rings of Phobos and Deimos
  - Phobos photometry and position
  - Stray light tests of cameras
  - Cross calibration with MEX HRSC
  - Cross calibration with other Rosetta instruments
- Input data:
  - From February 24th 2007 18:00 UTC at 260.000 km
  - To February 25th 2007 04:51 UTC at 105.000 km
  - Closest approach: February 25th 01:54 UTC at 250 km
  - Martian surface and atmosphere up to resolutions of about 5 km/pixel

Martian surface and atmosphere

Martian surface and atmosphere



Martian surface and atmosphere



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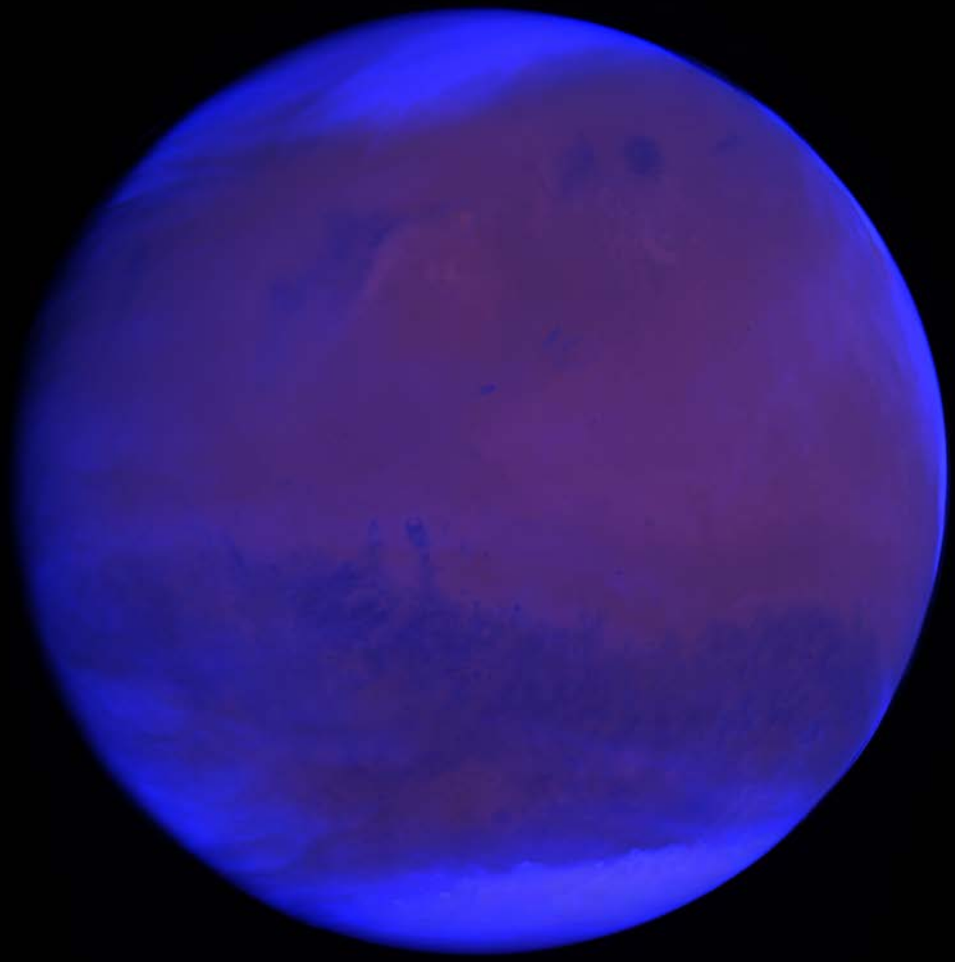

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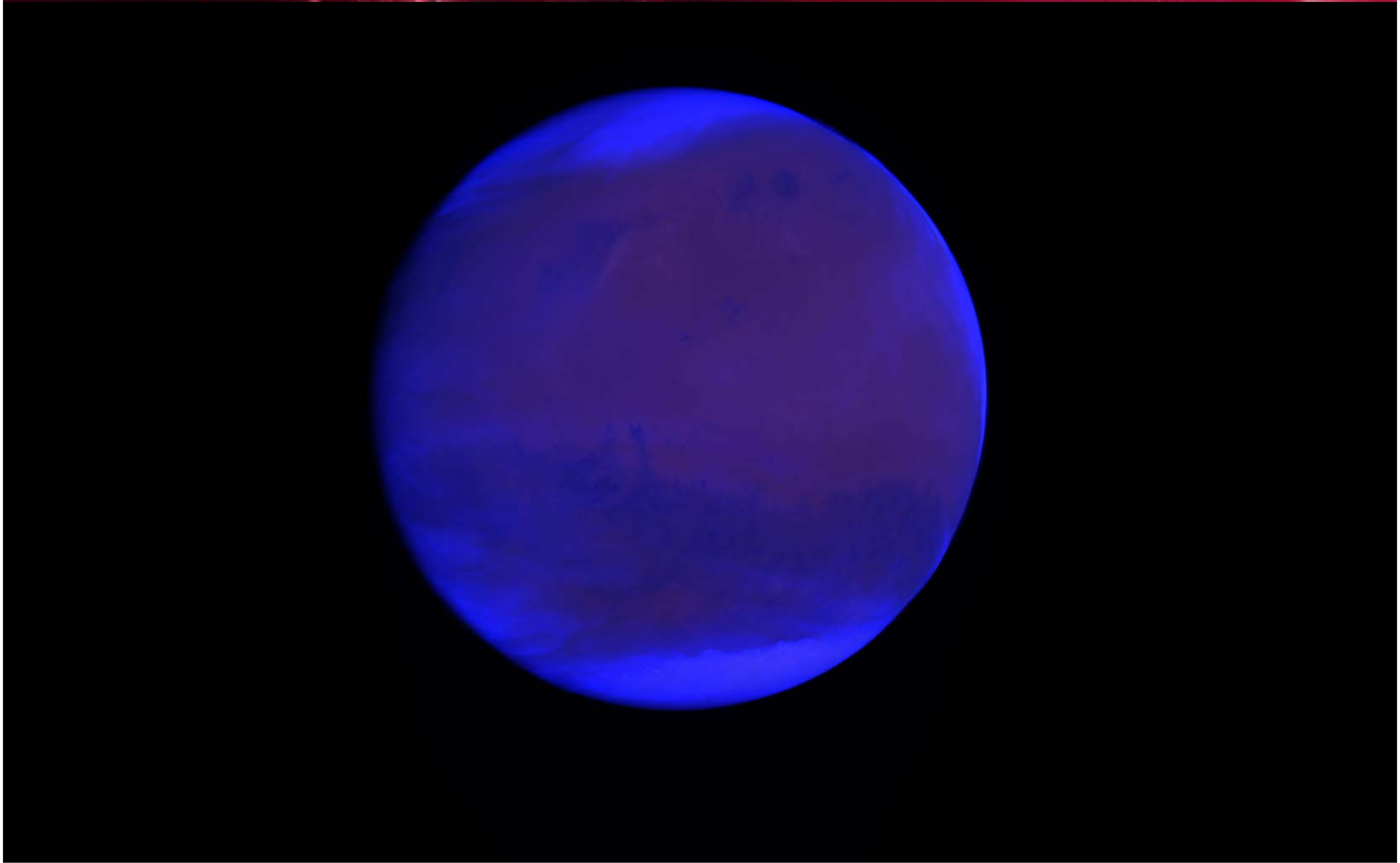
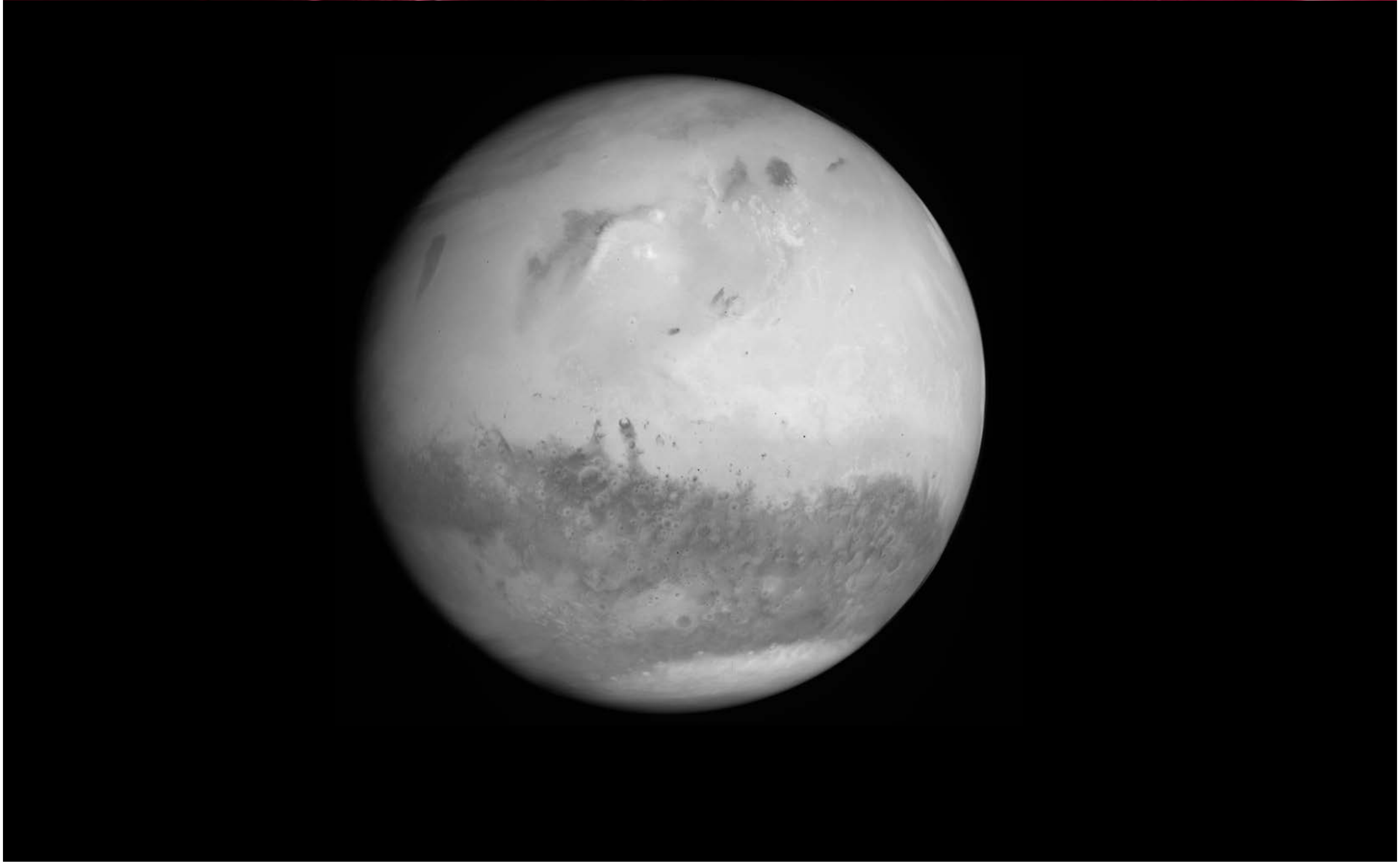


Martian surface and atmosphere

Martian surface and atmosphere



OSIRIS WAC during Mars Flyby

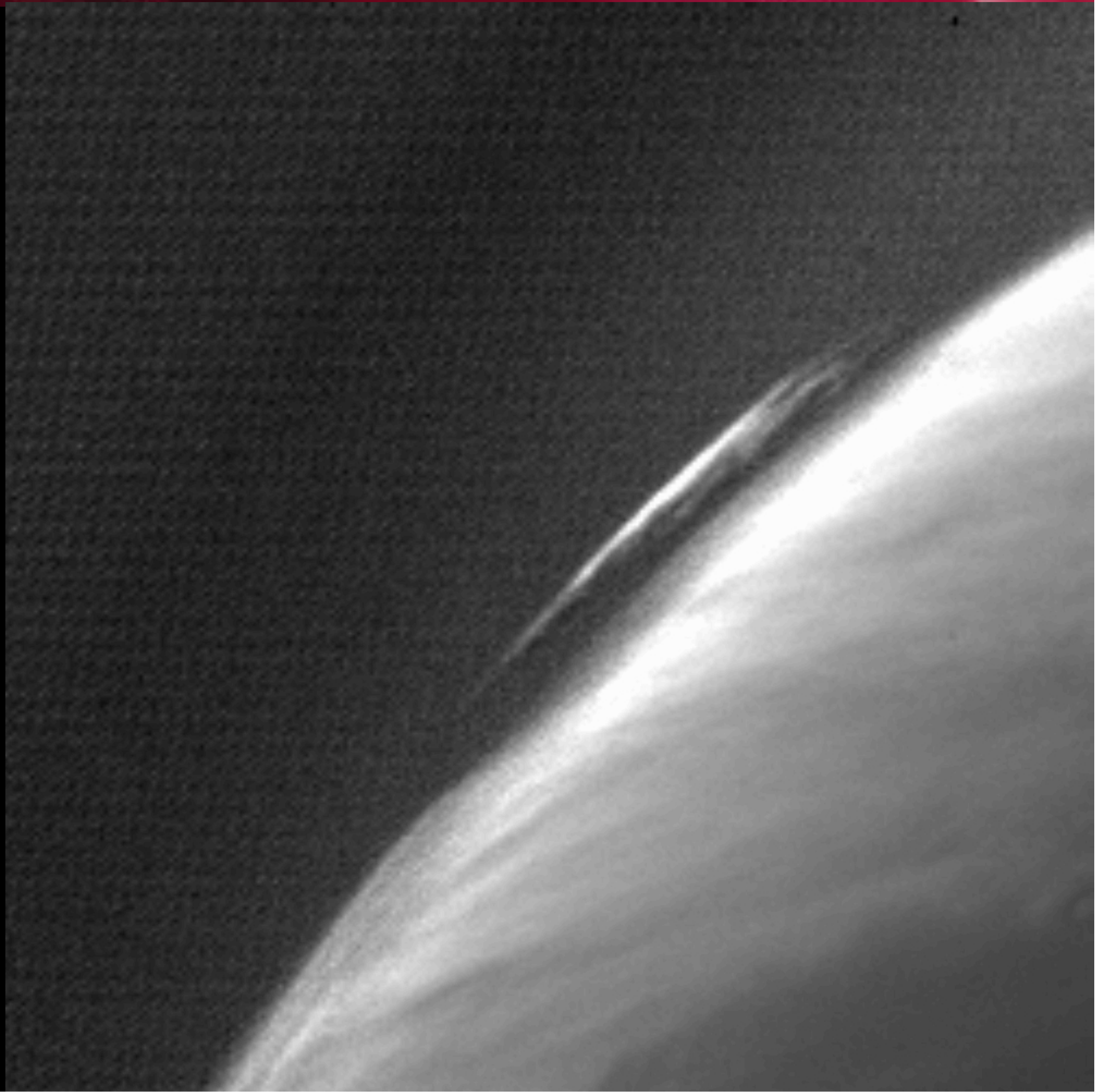
Full Mars images for RGB composition

Filter VIS610 (20 ms, as red), NH_2 (28 ms, as green), CN (1.6 sec, as blue), 800x800, bin 1x1. Corrected for geometrical distorsion.

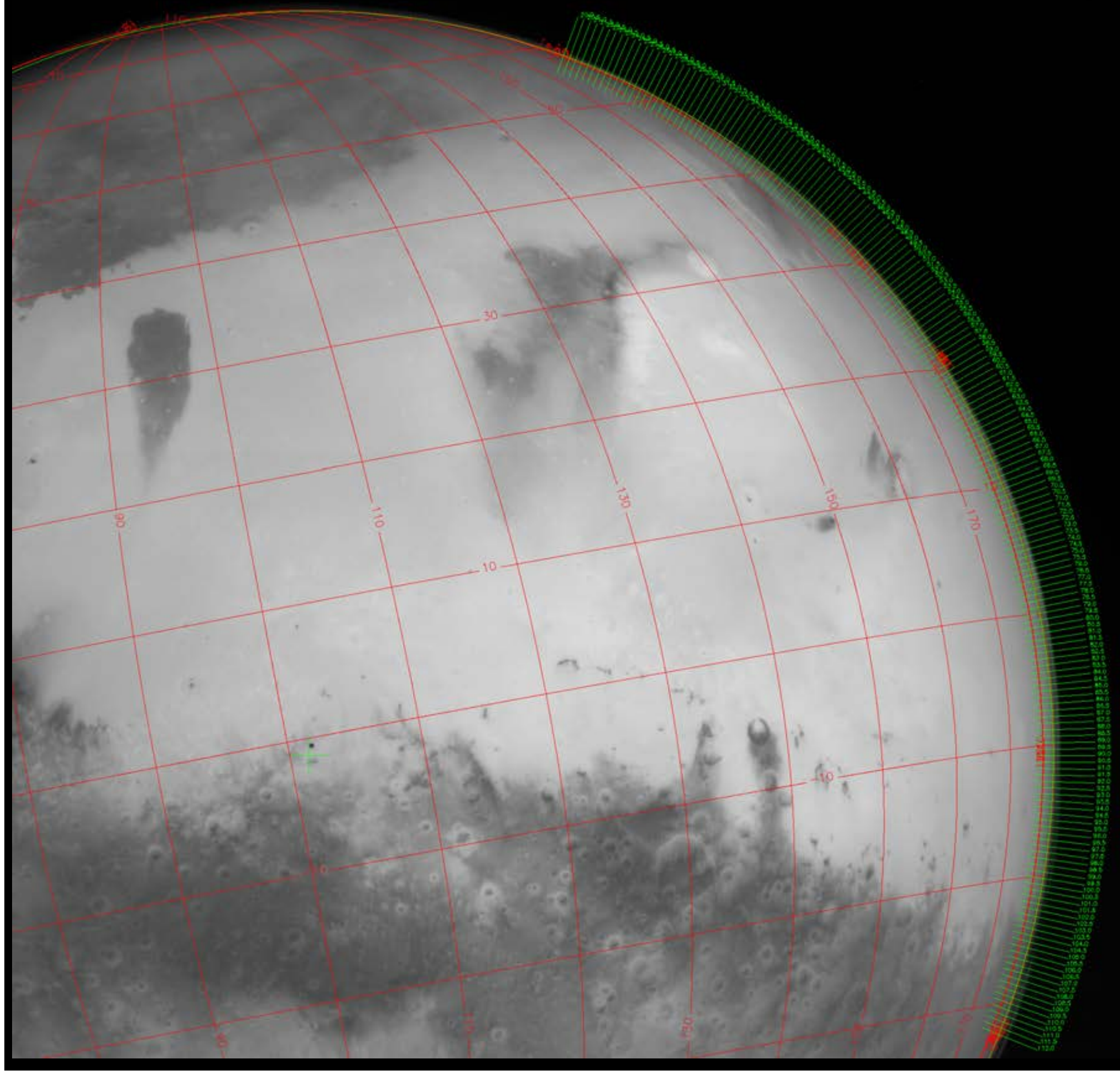
Martian limb and clouds

NAC - Near-UV – Red ratio

240 000 km

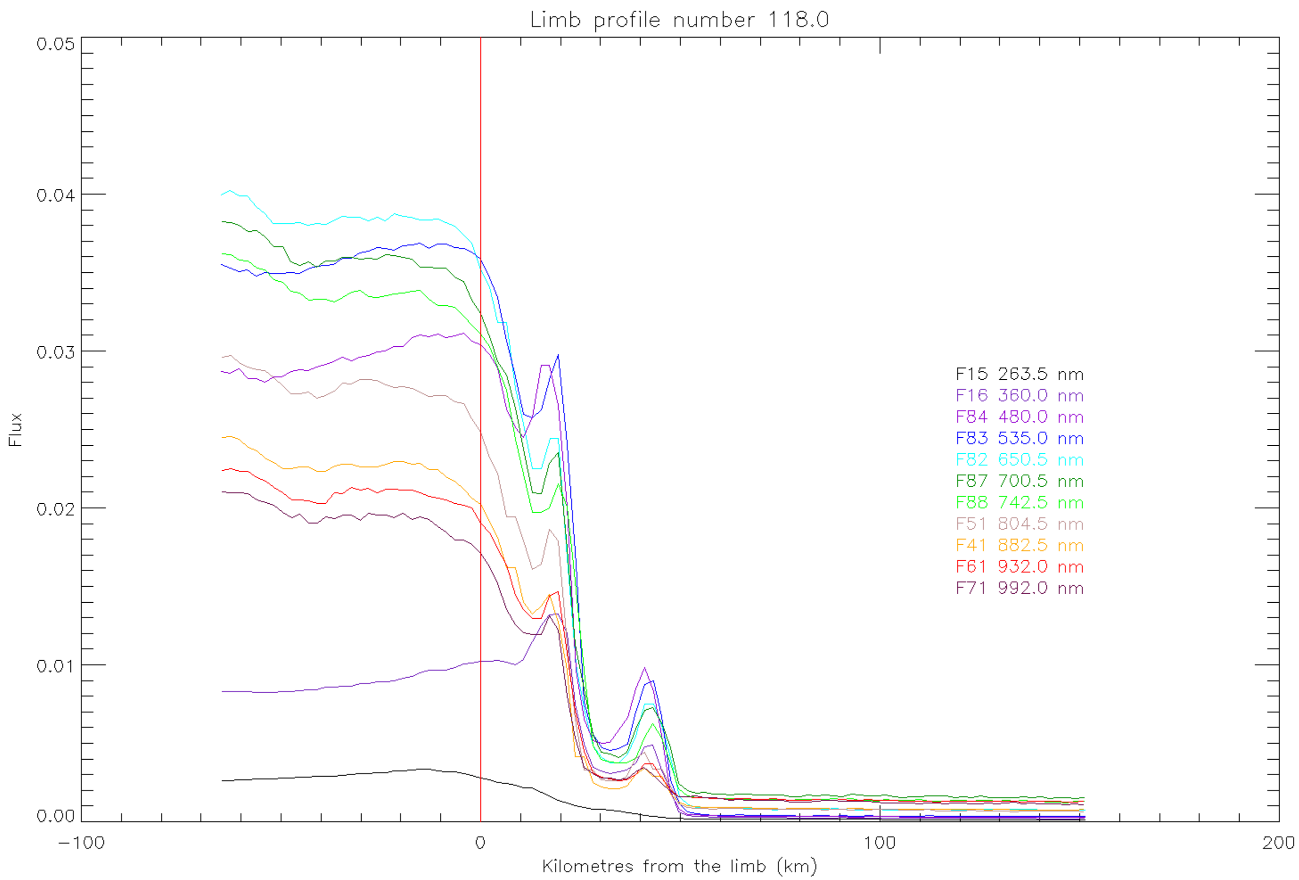


Limb Profiles



- Limb determination by Edge enhancement image filtering and detection techniques: Roberts (default), Sobel, etc.
- Analysis of Flux by latitude/longitude slides for the different wavelengths
- Results of clouds altitude at different frequencies

Altitude Profiles



- In this examples, two layers of clouds can be identified at different altitudes (between 10 and 60 km)
- Based on the spectra, cloud composition can be identified: H_2O clouds vs. CO_2 clouds and ozone
- Results can be compared with existing models and bibliography

Main Problems and workarounds

- Errors in determination of limb has high impact on altitude precision which is crucial to produce results that could be compared with existing models and bibliography

- Possible solutions:
  - Trying to use level 4 data (calibrated image data optical distortion removed) which includes: image/distance/emission angle/incidence angle/phase angle/facet index/coordinate x/coordinate y/coordinate z
  - Enhancement of Mars geometrical models
  - First definitive results are expected by mid May

References

- *Keller, H.U., Barbieri, C., Lamy, P. et al., "The scientific camera system on-board Rosetta", Space Sci Rev (2007) 128: 433. doi:10.1007/s11214-006-9128-4*
- *Feldman, P. D. et al., "Spectroscopic Investigations of Fragment Species in the Coma", Comets II; 425.*
- *Cochran, A. et al., "The Composition of Comets", Space Sci Rev (2015) 197: 9.*
- *S. Fornasier et al., "Spectrophotometric properties of the nucleus of comet 67P/Churyumov-Gerasimenko from the OSIRIS instrument on-board the ROSETTA spacecraft", A&A Volume 583 (November 2015), A30*
- *M. Hässig et al., "Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko", Science 23 Jan 2015, Vol. 347, Issue 6220.*
- *Bodewits, D., et al., "Changes in the physical environment of the inner coma of 67p/churyumov–gerasimenko with decreasing heliocentric distance", 2016 The Astronomical Journal, Volume 152, Number 5.*
- *Pajola, M., "Rosetta Mars Fly-by February 25, 2007", 2012, Mem. S.A. It. Suppl. Vol. 20, 105.*
- *Pajola, M., "Spectrophotometric investigation of Phobos with the Rosetta OSIRIS-NAC camera and implications for its collisional capture", 2012, Mon. Not. R. Astron. Soc. 427, 3230-3243.*

THANKS!