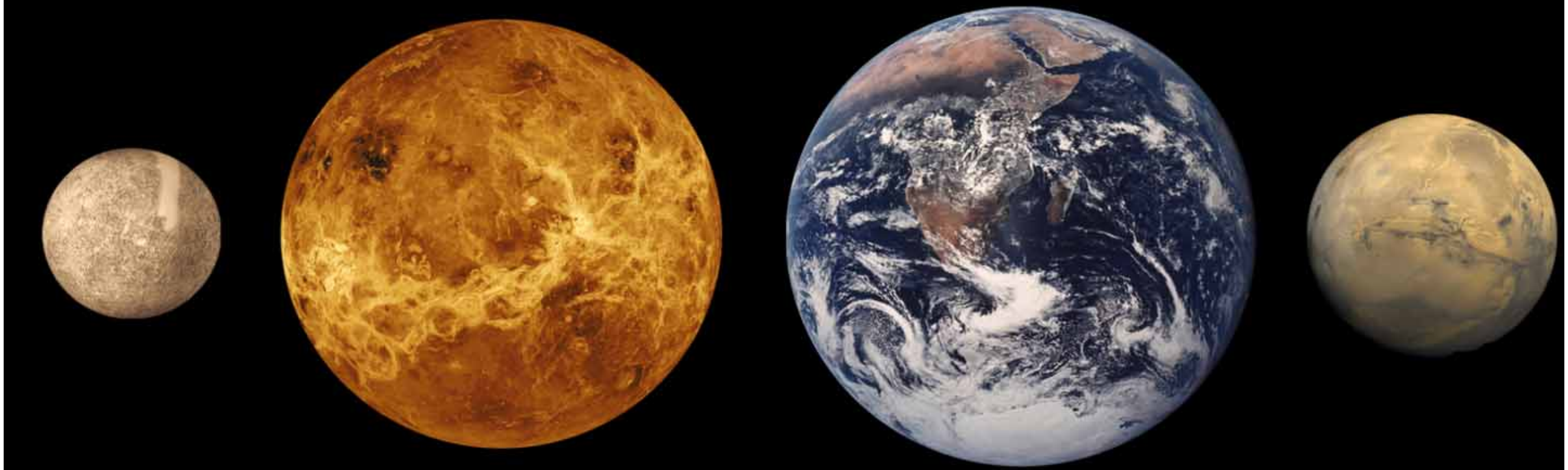

VIS/IR- Spectroscopy of terrestrial planets -

toward the unknown Mercury

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Moscow, Space Week, IKI, Planetary Session

October 2007

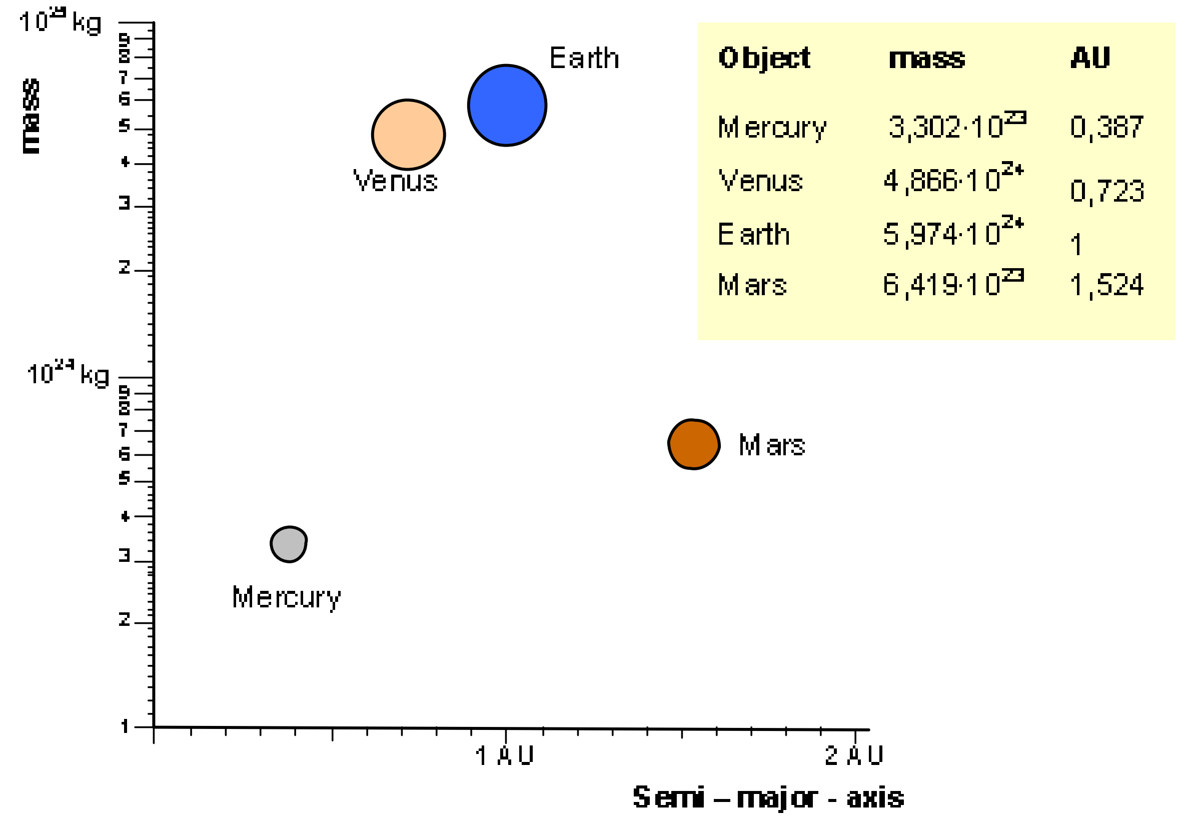
Comparative planetology of the terrestrial planets

Goals

- Studies of origin, evolution and state of terrestrial planetary bodies in the Solar system starting from the Solar nebula
- Accretion processes (interior, core, crust, magnetic field and atmospheres) - initial processes, time lines, formation constrains
- Comparative analysis!
- Geology, chemical and physical properties of terrestrial planets
- Study of evolution prospects

Comparison

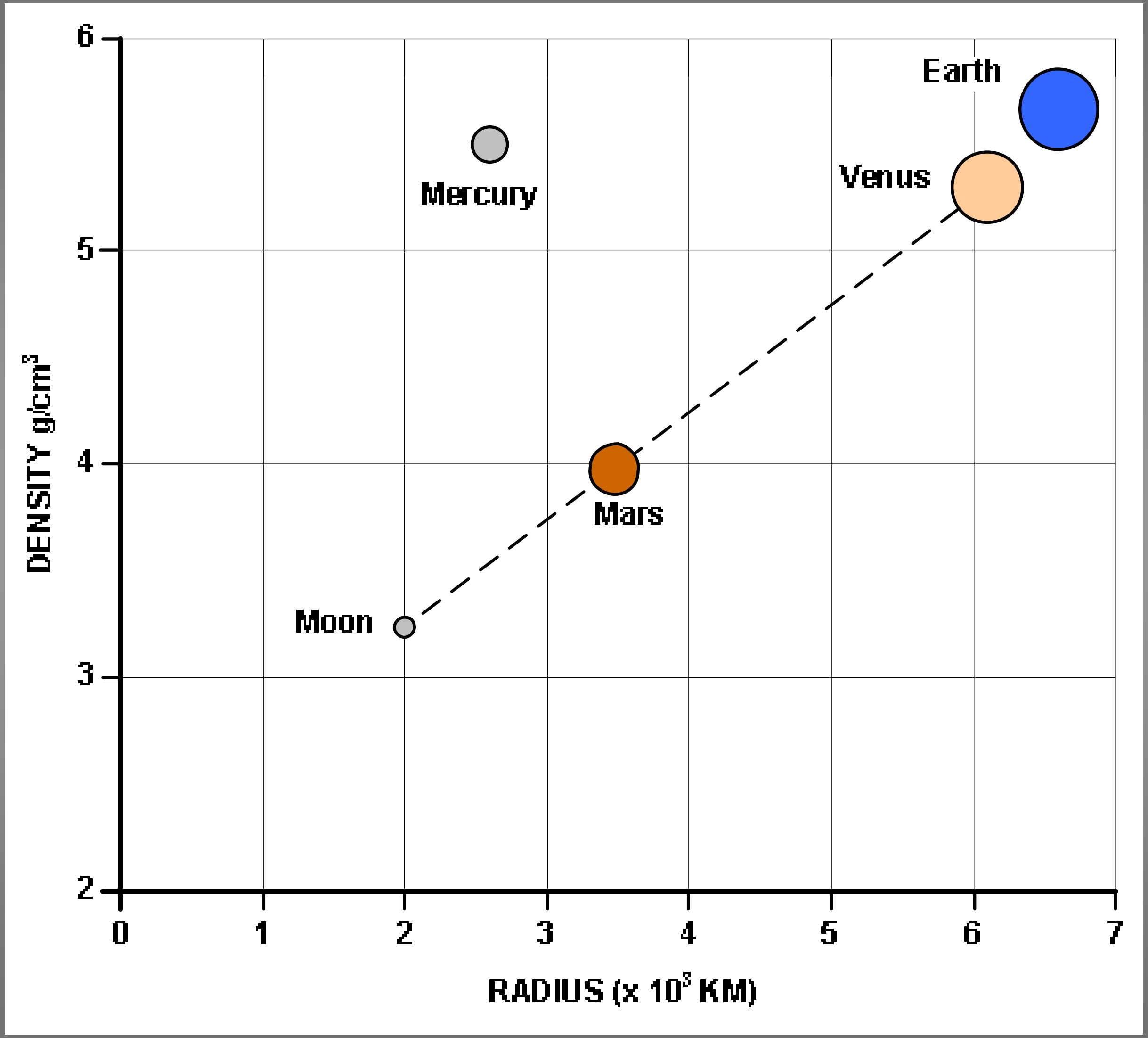
- **Masses**
- Density
- Structure and composition
- Atmospheres
- Evolution paths



Object	**mass**	**AU**
Mercury	$3{,}302 \cdot 10^{23}$	0,387
Venus	$4{,}866 \cdot 10^{24}$	0,723
Earth	$5{,}974 \cdot 10^{24}$	1
Mars	$6{,}419 \cdot 10^{23}$	1,524

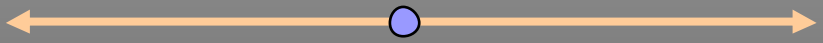
Comparison

- **Masses**
- **Density**
- **Structure and composition**
- **Atmospheres**
- **Evolution paths**



Comparison

- Masses
- Density
- Structure and composition
- **Atmospheres**
- Evolution paths



	runaway greenhouse		freezing
T_{mean}:	737 K	288 K	210 K
P:	92 bar	1 bar	0.0064 bar

Evolution of terrestrial planets (formation models)

- “planetesimal accretion” in the refractory inner part of the Solar system, inward of the ice line, located at a distance of about 3 AU for Sun-like stars (Marcy et al. 2005), “rubble piles” – km – size gravitational aggregates of indestructible particles (Leinhardt 2005)

Proplyds surrounding new Borne stars in Orion nebula (NASA/C.R.O’Dell/Rice Univ.)

star onset, ice line moves inward (NASA/JPL-Caltech)

formation of planetesimals (NASA/JPL-Caltech)

runaway grow (NASA/JPL-Caltech)

Evolution of terrestrial planets (formation models)

- “planetesimal accretion” in the refractory inner part of the Solar system, inward of the ice line, located at a distance of about 3 AU for Sun-like stars (Marcy et al. 2005), “rubble piles” – km – size gravitational aggregates of indestructible particles (Leinhardt 2005)

- Mass grow of terrestrial planets with masses ranging from 0.06 up to 1 Earth mass appears to be more slowly compared to giant planets (Chambers 2001, Raymond et al. 2006, Fogg and Nelson 2006)
- “runaway grow” and formation of protoplanets with diameters of several hundred kilometers inside a time line of about 10-30 million years (Su et al. 2006), depending on mass and metallicity of the primordial disk
- “oligarchic grow” above a critical starting mass, in witch a small collection of objects accretes mass through collisions with less massive bodies (Raymond 2007)
- “late heavy bombardment” from residual debris about 700 million years after commencement of planetesimal accretion (Gomes et al. 2005)

Evolution of terrestrial planets (differentiation)

- Differentiation (nucleus, core and crust) resulting from energy sources of accretion heat, radioactive decay and tidal forces
- Endogenous processes:
  Mercury and Moon: heat lost primary by heat conduction without material movement, lithosphere grows to a single plate, surfaces characterized by high crater density

  Venus, Earth: heat lost primary by heat convection, resurfacing of the initial crust by volcanism and tectonic processes

  Mars: intermediate state
- Exogenous processes:
  Weathering, degradation, erosion, sedimentation
- Composition: primary basaltic

Open questions

Evolution:

What can we learn about thermo dynamical properties and transport of material?

How do material properties and structure determine the endogenous dynamics?

What kind of mechanisms causing tectonic movements?

How planetary magnetic fields developed?

Surface formation processes:

How crater impacts effect the planetary evolution?

What teach us the surface morphology and composition about the endogenous processes?

How differ the exogenous processes for each of the terrestrial planets?

How the formation of the planetary atmospheres is determined with these processes?

Spectral remote sensing of terrestrial planets

Spectral studies in the visible and IR range

- planetary atmospheres

  Composition, temperatures, dynamics, energy balance

- planetary surfaces

  Surface composition (minerals, ices, organics)

  Surface texture

  Surface temperatures and thermal inertia

  Compositional mapping of geologic features

  Studies of regional and temporal dynamics

Early remote sensed deep space spectroscopy of terrestrial planets I

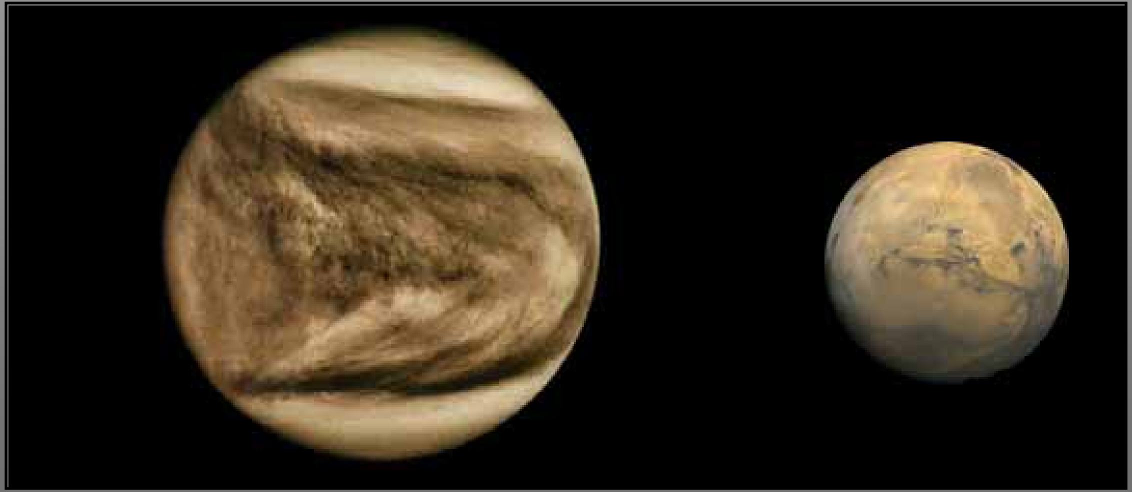
Interferometry – orbital instruments

Mariner 9, IRIS M – Mars (1972-73)

Venera 15, 16 – Venus (1983)

Mars Global Surveyor TES – Mars (1997 – 2001)

Mars Express (MEX) PFS – Mars (since 2003)



Early remote sensed deep space spectroscopy of terrestrial planets I

Interferometry – PMV on Venera 15 and 16

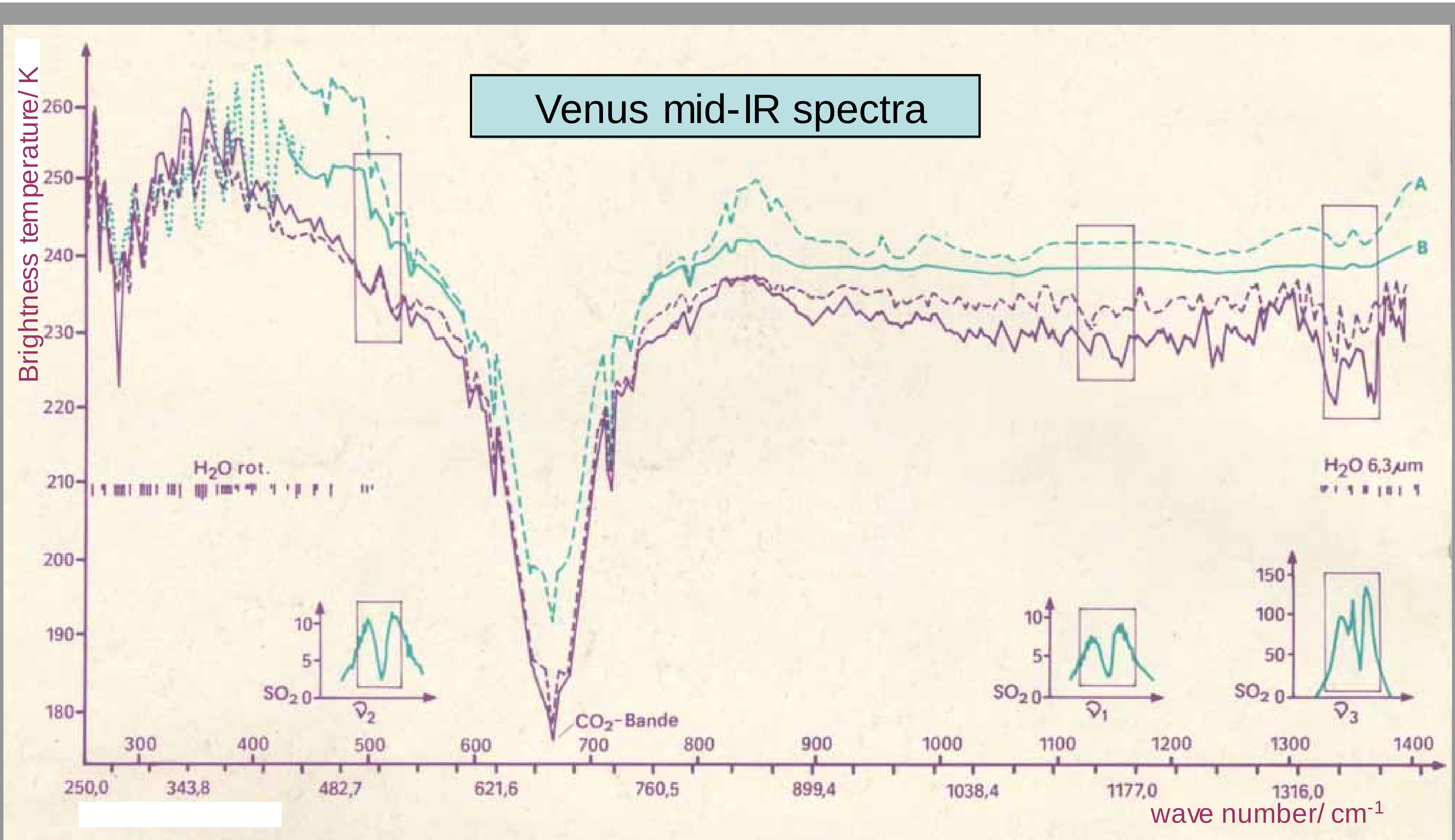
Spectral band	6.25 – 38 µm V15
	6.25 – 25 µm V16
Spectral bandwidth	5 cm^{-1} (apodized)
with	7.5 cm^{-1} (apodized, onboard FFT)
Field of view	4° x 4° (retangle)
Recording time	5.5 s
Area of aperture	8 cm^{-1} V15
	10 cm^{-1} V16
NER	2.5 10^{-8} Wcm^{-1} sr
Orbit	highly elliptical
Apogee	850 km
Cycle time	24 h
Weight	25 kg

Opto-mechanical part of PMV

Spectral remote sensing of terrestrial planets

Early remote sensed deep space spectroscopy of terrestrial planets I

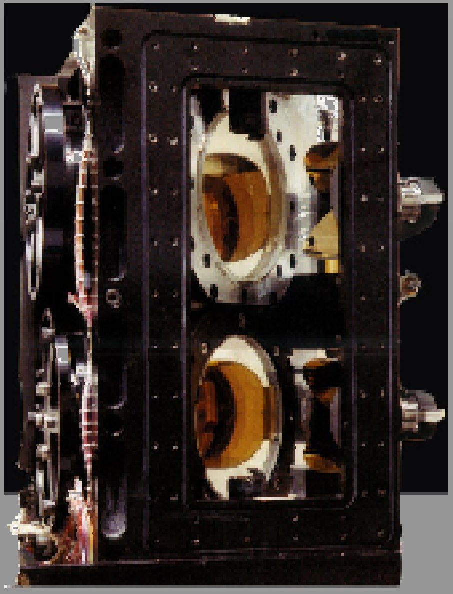
Interferometry – PMV on Venera 15 and 16



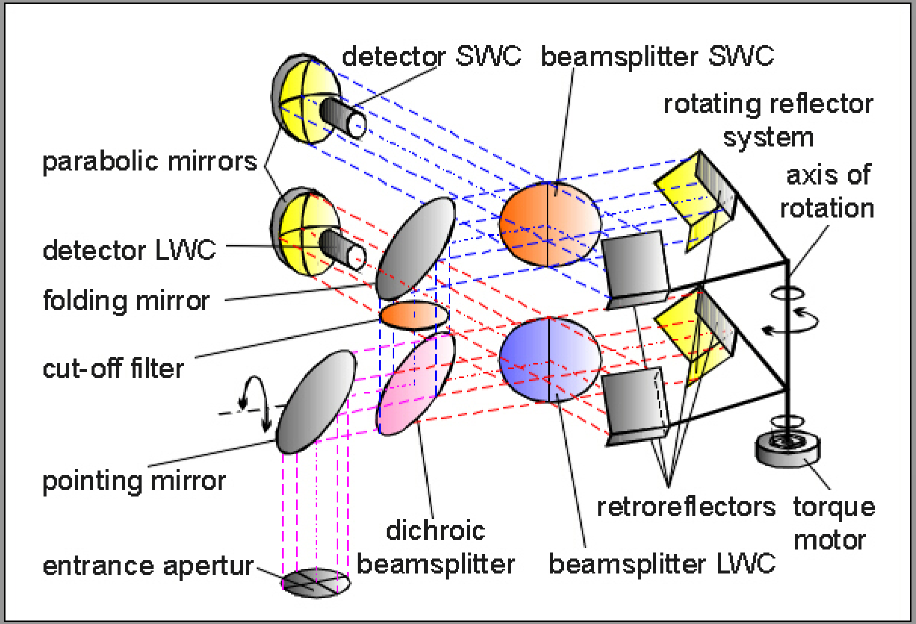
Remote sensed deep space spectroscopy of terrestrial planets I

Interferometry – Planetary Fourier Spectrometer on MEX

PFS is a two-channel Fourier transform spectrometer. Two channels indicate to spectrometers, one on top of the other one. Both are equipped with a pair of retroreflectors, i.e. three flat mirrors assembled to a corner of a cube. They are attached by brackets to an axle moved by a torque motor. This angular movement changes the path of difference.



EM of PFS



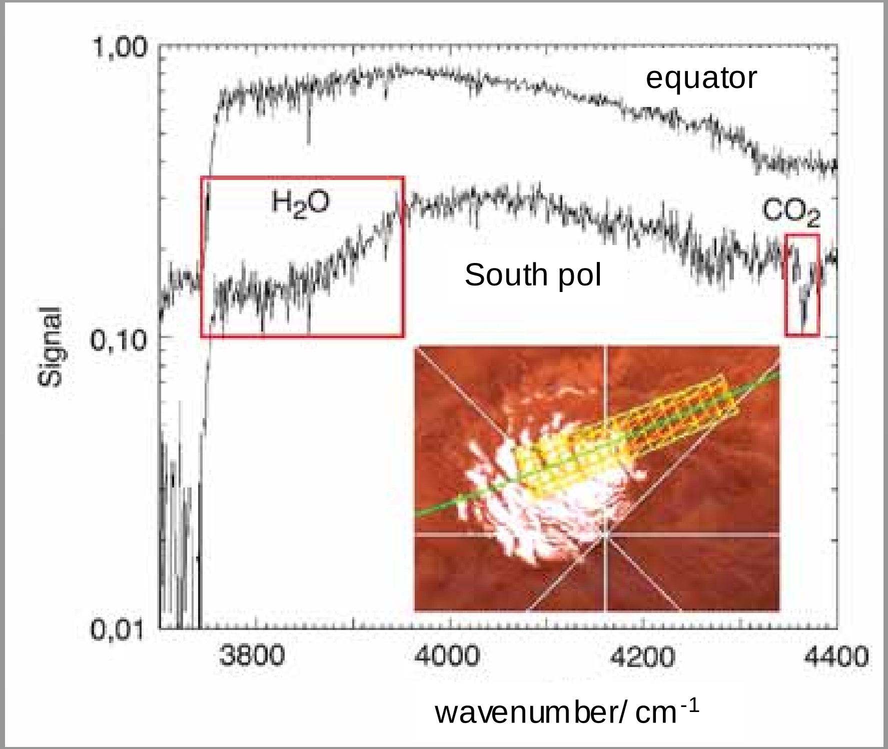
The optical performance of PFS

Remote sensed deep space spectroscopy of terrestrial planets I

Interferometry – Planetary Fourier Spectrometer on MEX

Mars:

South polar water ice observation by PFS

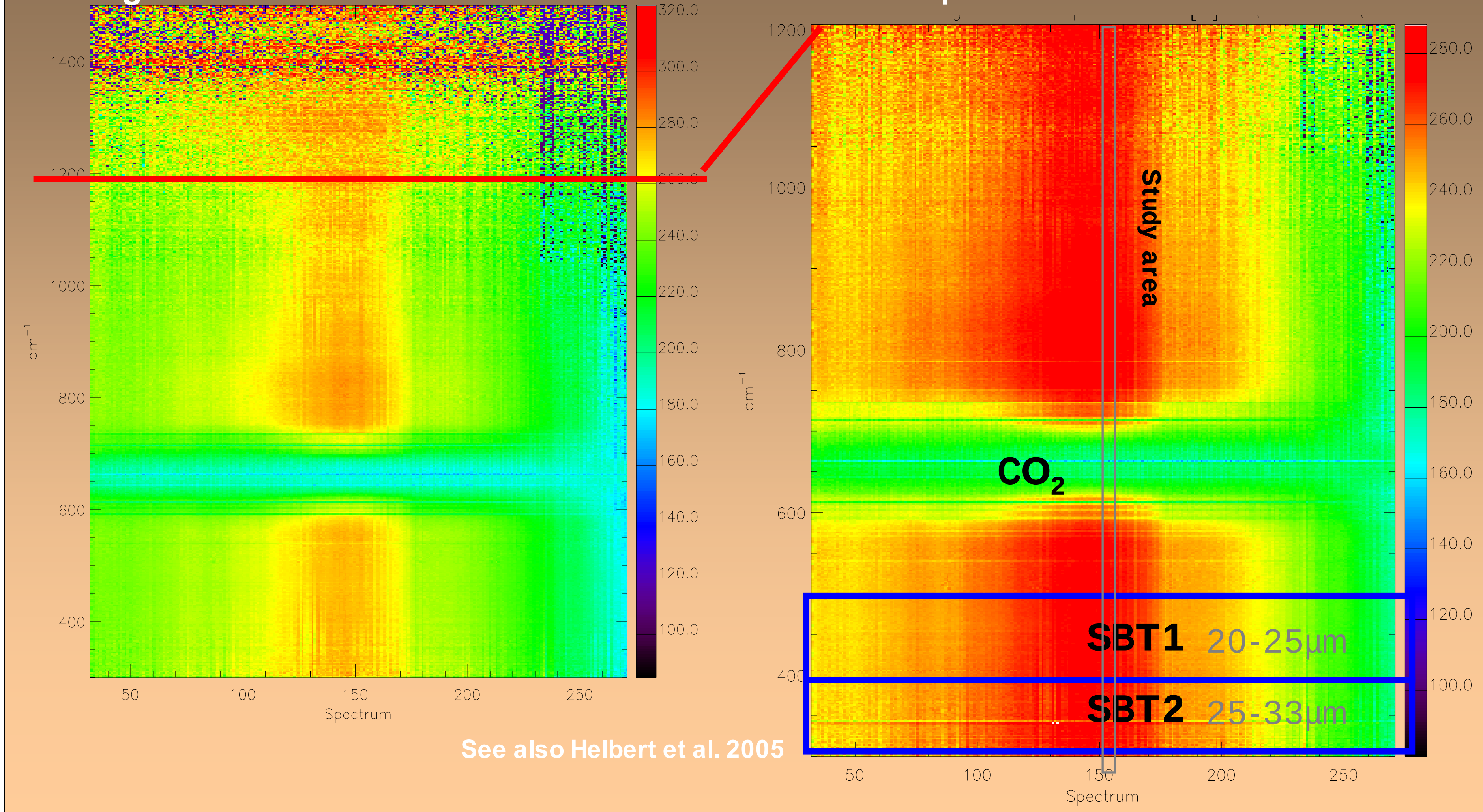


Quelle: Formisano V., PSF-CoI-Team, ESA

Spectral remote sensing of terrestrial planets

PFS-Surface temperature retrieval

- Temperatures are derived in areas showing little or no spectral contrast
- Using 2 areas allows an estimate on the error in the temperature retrieval



See also Helbert et al. 2005

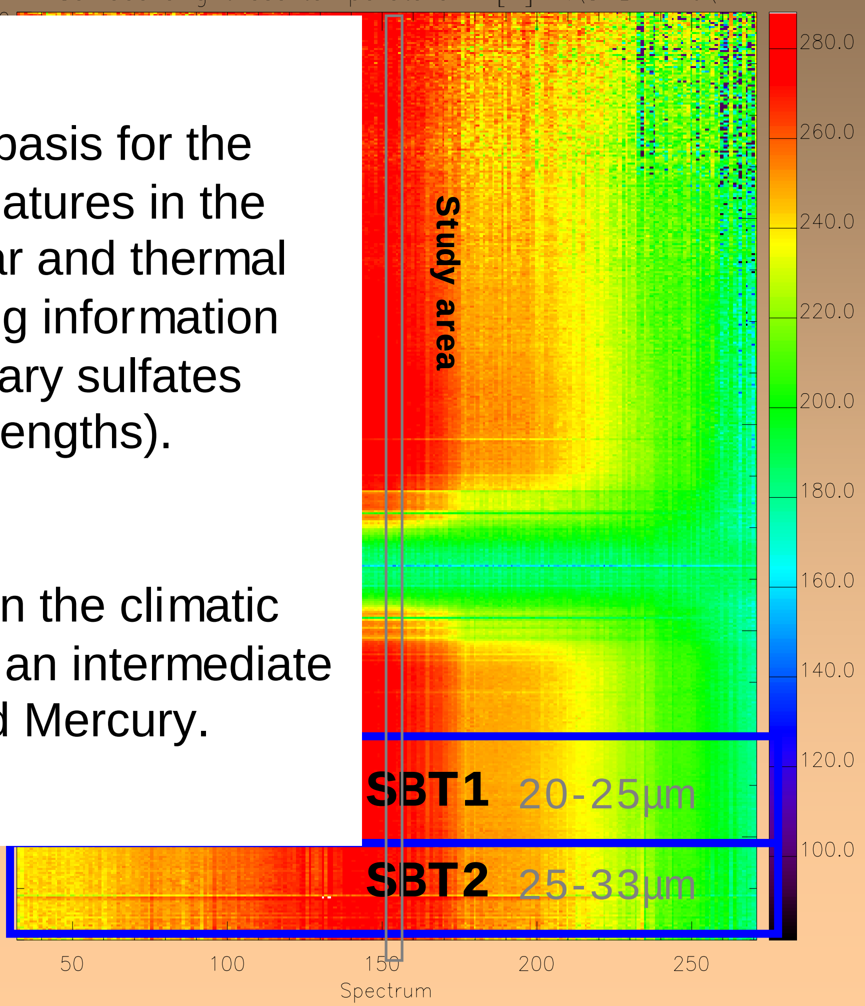
Spectral remote sensing of terrestrial planets

PFS-Surface temperature retrieval

- **Temperatures are derived in areas showing little or no spectral contrast**
- **Using 2 areas allows an estimate on the error in the temperature retrieval**

The surface temperature retrieval is the basis for the extraction of reflectance and emittance features in the transition range between the reflected solar and thermal emitted radiation of Mars (3 – 5 µm) adding information about tertiary weathering products (primary sulfates observed by Omega at shorter wavelengths).

Key information of exogenous processes in the climatic history of Mars – a terrestrial planet being in an intermediate evolution state compared to Venus and Mercury.



Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets II

Imaging spectroscopy – orbital instruments

Phobos 2 ISM – Mars (1989)

{Mars Odyssey THEMIS – Mars (since 2002)}

(VIRTIS Rosetta) – Mars flight by

Mars Express (MEX) OMEGA - Mars (since 2003)

Venus Express (VEX) VIRTIS – Venus (since 2006)

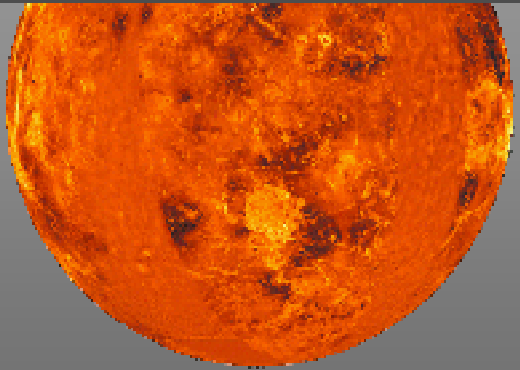
Bepi Colombo (BC) MERTIS- Mercury

Remote sensed deep space spectroscopy of terrestrial planets II

Imaging spectroscopy – orbital instruments

Venus and Earth

- Venus is only slightly smaller than Earth (95% of Earth‘s diameter, 80% of Earth‘s mass).
- Both have few craters indicating relatively young surfaces.
- Their densities and chemical composition are similar.

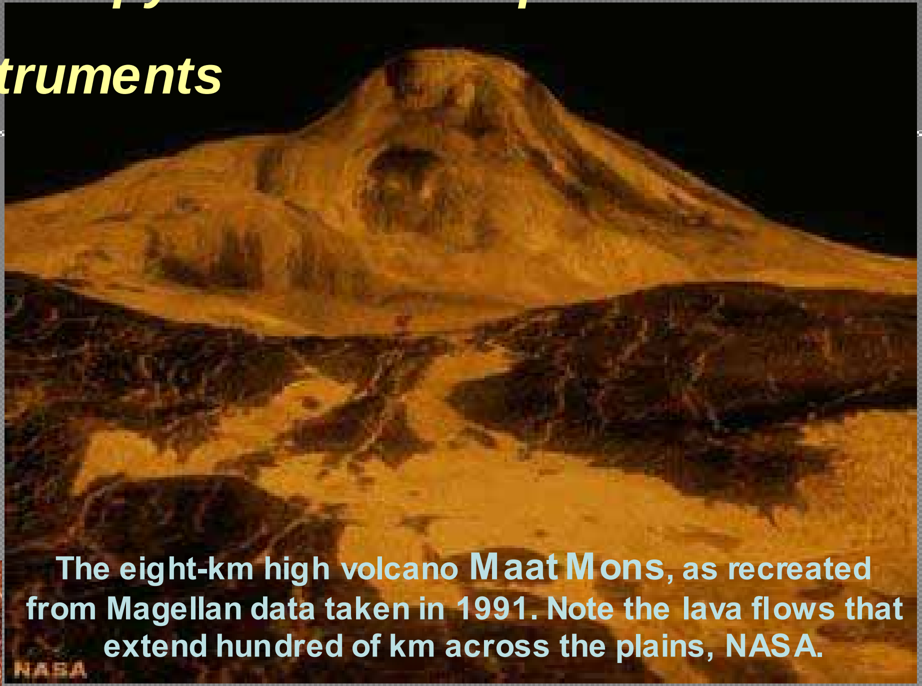


Remote sensed deep space spectroscopy of terrestrial planets II

Imaging spectroscopy – orbital instruments

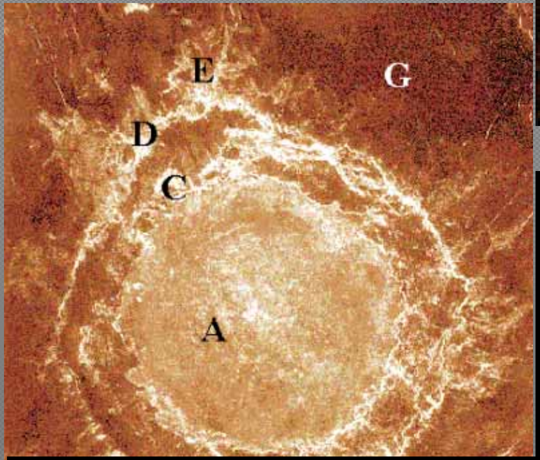
Venus surface

- The surface of Venus presents clear evidence of violent volcanic activity in the past, including shield volcanoes similar to those on Earth.



The eight-km high volcano **Maat Mons**, as recreated from Magellan data taken in 1991. Note the lava flows that extend hundred of km across the plains, NASA.

Mead Crater – largest impact crater on Venus

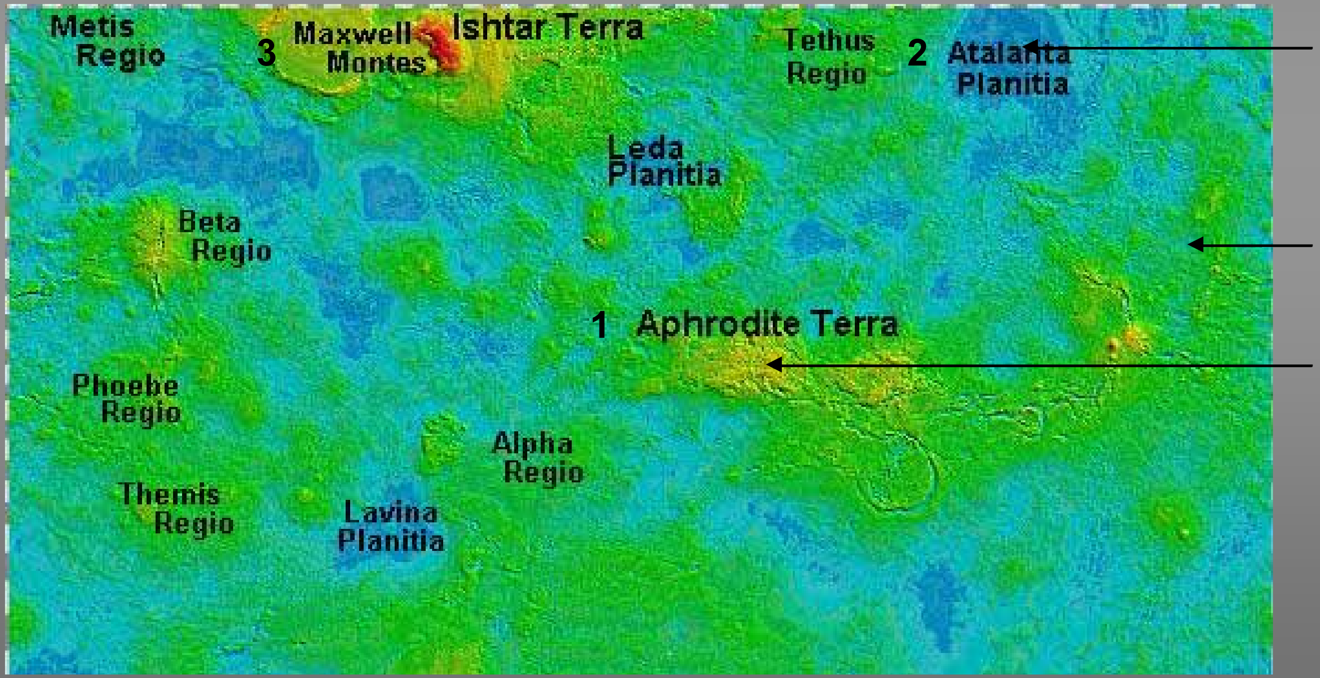


Mead Crater, 280 km in diameter, multi-ringed crater, Magellan, NASA.

Unlike Moon, Mars and Mercury, Venus have relatively few small impact craters, but does have more medium to large craters. This is the result of the planet‘s dense atmosphere burning up smaller meteorites.

Remote sensed deep space spectroscopy of terrestrial planets II - Venus

- Gently rolling plains with little relief.
- Several broad depressions: Atalanta Planitia, Guinevere Planitia, Lavina Planitia.
- Two large highlands: Ishtar Terra (northern hemisphere) and Aphrodite Terra (extends along the equator)



lowlands (20%)

deposition plains, rolling hills (70%)

highlands (10%)

altimeter topography, Magellan, red- high, blue- low

Remote sensed deep space spectroscopy of terrestrial planets II

Imaging spectroscopy – orbital instruments

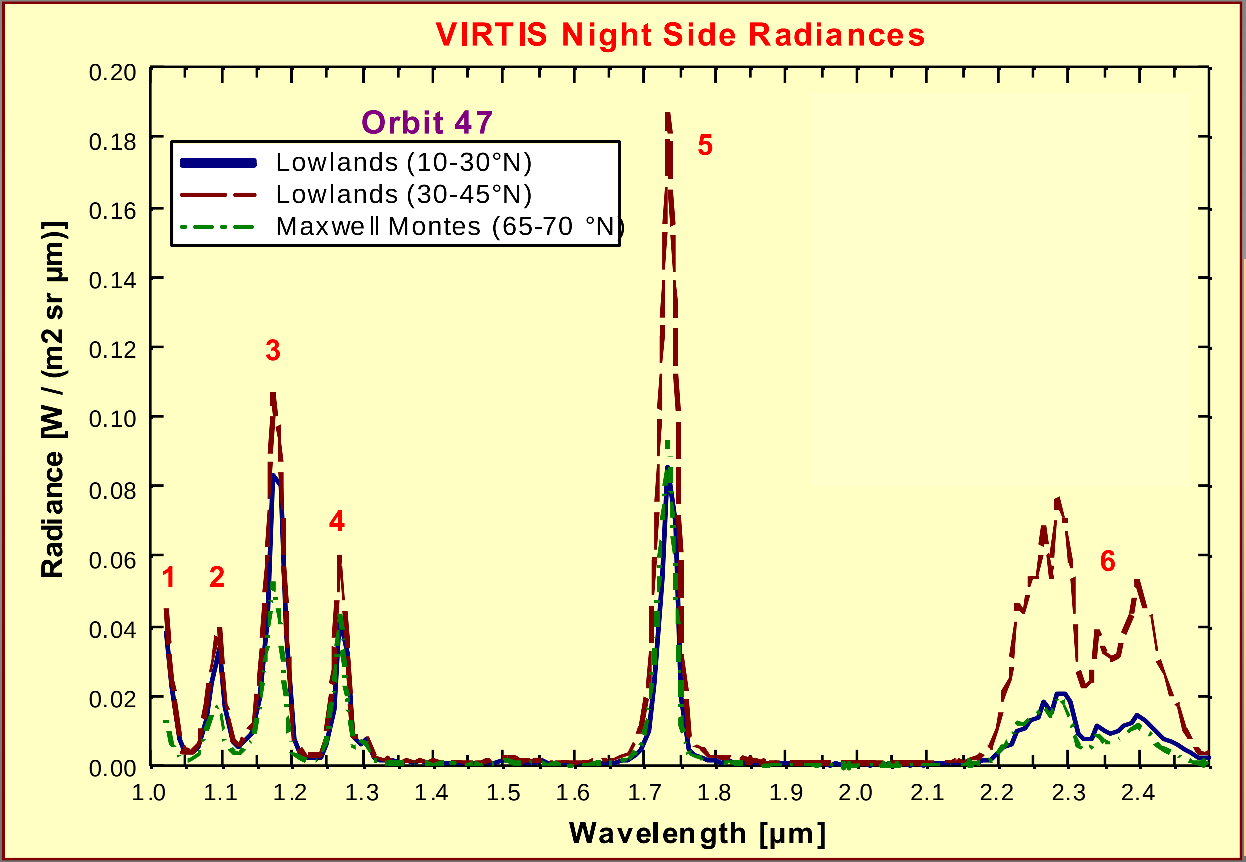
Open questions

- ***Surface composition is unknown.***
- ***Lower atmosphere – mostly unexplored, interaction of atmosphere and surface mostly unknown, alteration processes of surface material vague***
- ***Are there signs for ongoing volcanic activity? Certain regions on Venus might be younger (Beta-Atla-Themis).***
- ***Could an early magnetic filed leave signatures?***
- ***Can we learn more about the pre-resurfacing period of Venus? Probably the climate history is more sensitive to answer this question?***
- ***Did Venus exhibit habitable conditions in the pre-resurfacing phase (2 b.y ago)?***
- ***Will future Earth resemble Venus?***

Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets II

Imaging spectroscopy – orbital instruments - VIRTIS



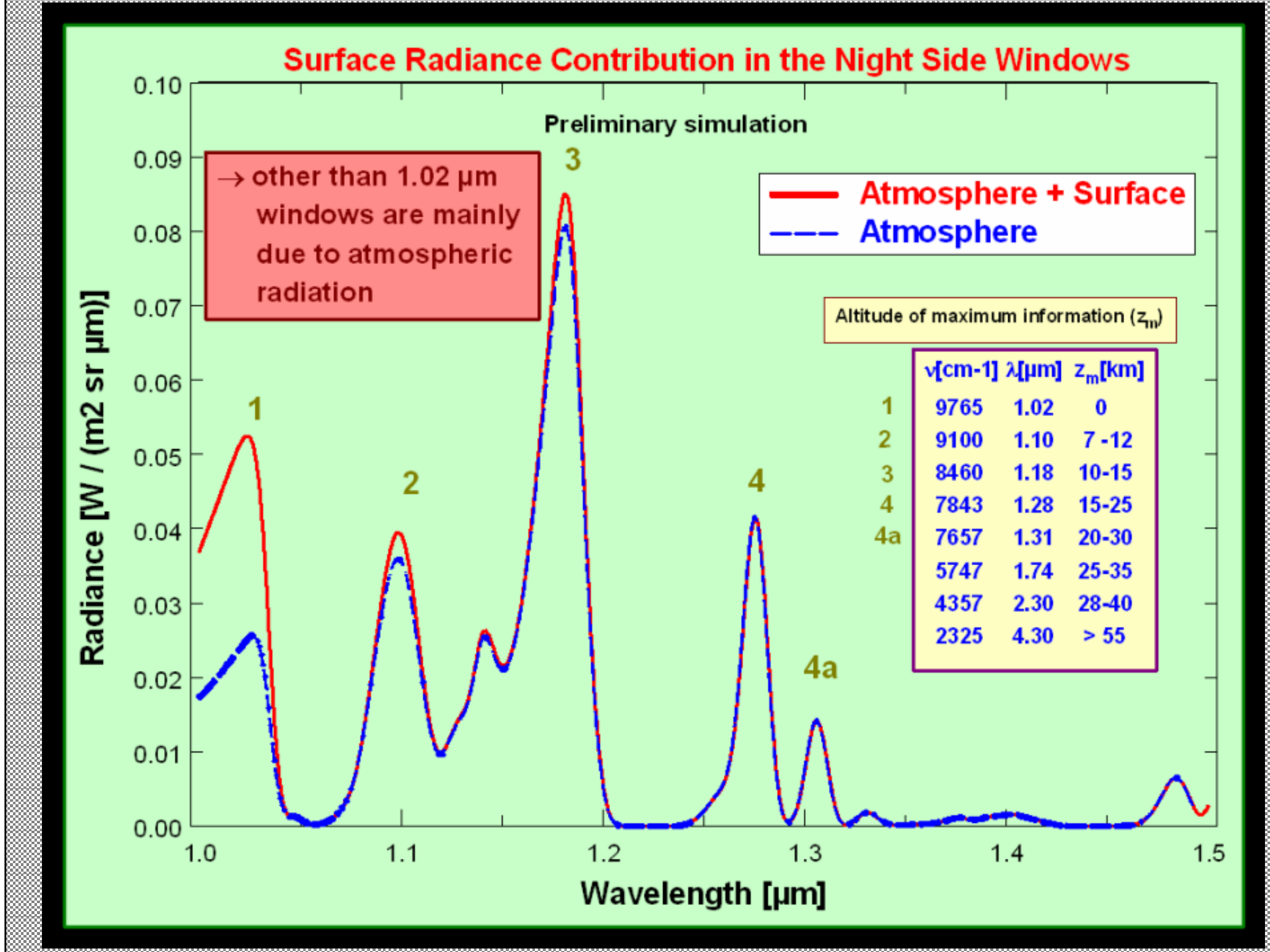
Venus night side thermal emission: a key to study surface properties

Surface window 1: radiances depend on elevation (temperature)

Surface window 2+3: evidence of surface-deep atmosphere correlation

Surface windows 4-6: latitudinal variations in the lower atmosphere

Spectral remote sensing of terrestrial planets



Surface Radiance Contribution in the Night Side Windows

Preliminary simulation

→ other than 1.02 µm windows are mainly due to atmospheric radiation

Atmosphere + Surface

Atmosphere

Altitude of maximum information (z_m)

	ν[cm-1]	λ[µm]	z_m[km]
1	9765	1.02	0
2	9100	1.10	7 -12
3	8460	1.18	10-15
4	7843	1.28	15-25
4a	7657	1.31	20-30
	5747	1.74	25-35
	4357	2.30	28-40
	2325	4.30	> 55

Venus Express VIRTIS:
RT model: first simulations

First results, application of a new RT-approach:

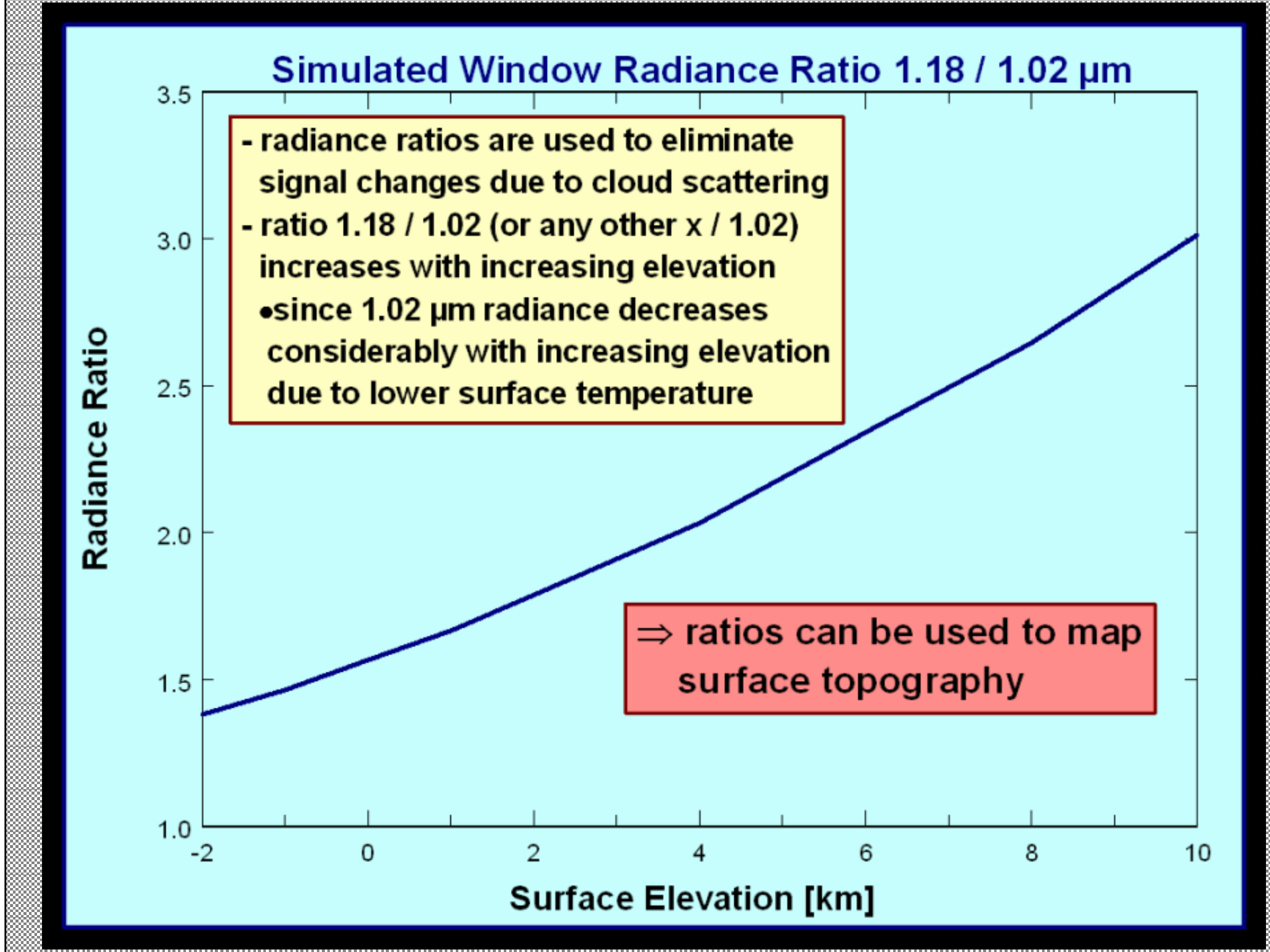
The windows at 1.02 µm can be used for surface properties extraction.

The improvement of RT models will allow to obtain quantitative information.

The windows 2 ff will give us a better understanding of the chemistry of the lower atmosphere.

Arnold et al., EGU 2007

Spectral remote sensing of terrestrial planets



- radiance ratios are used to eliminate signal changes due to cloud scattering
- ratio 1.18 / 1.02 (or any other x / 1.02) increases with increasing elevation
  - since 1.02 µm radiance decreases considerably with increasing elevation due to lower surface temperature

⇒ ratios can be used to map surface topography

Venus Express VIRTIS: RT model: first simulations

First results, application of a new RT-approach:

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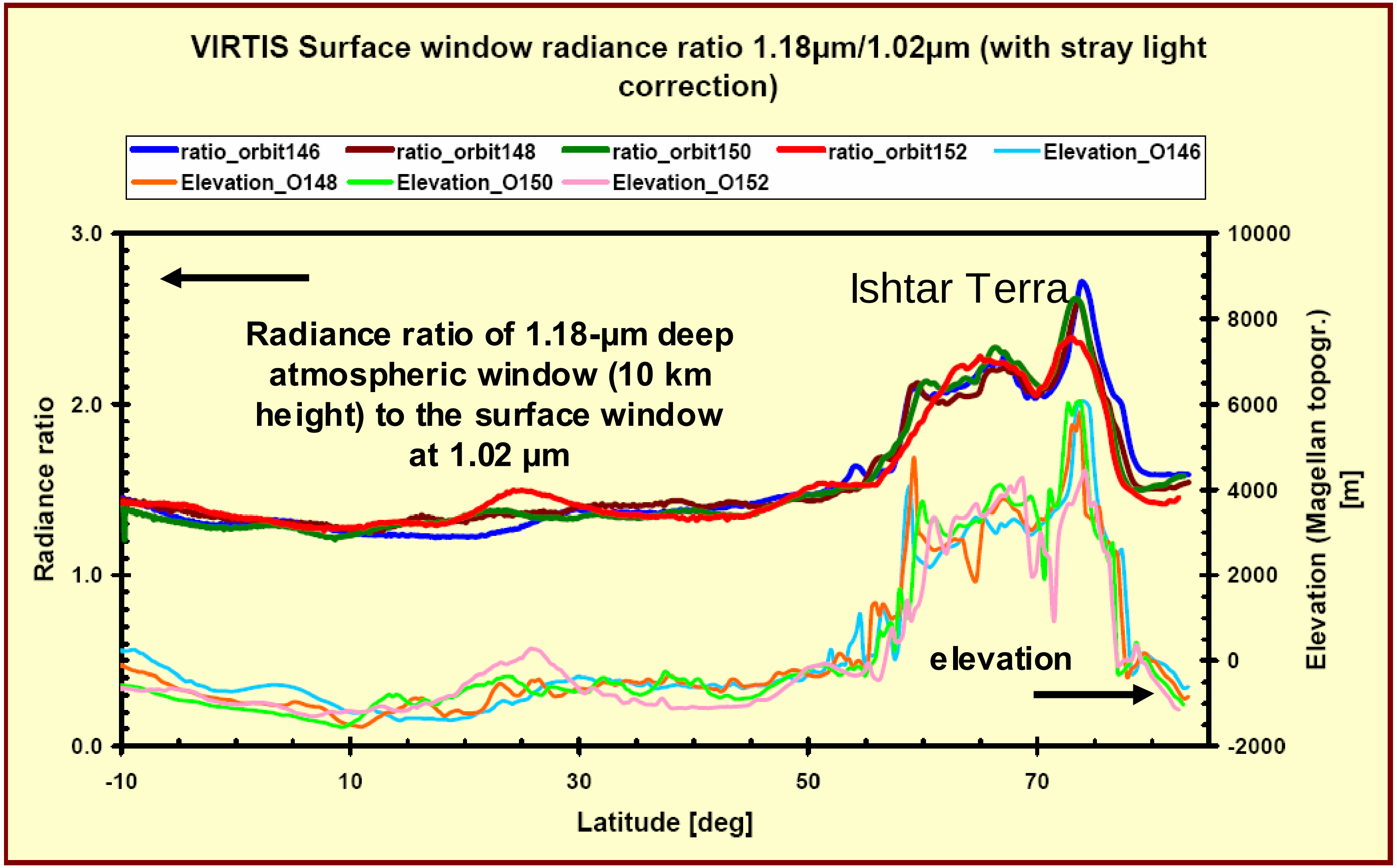
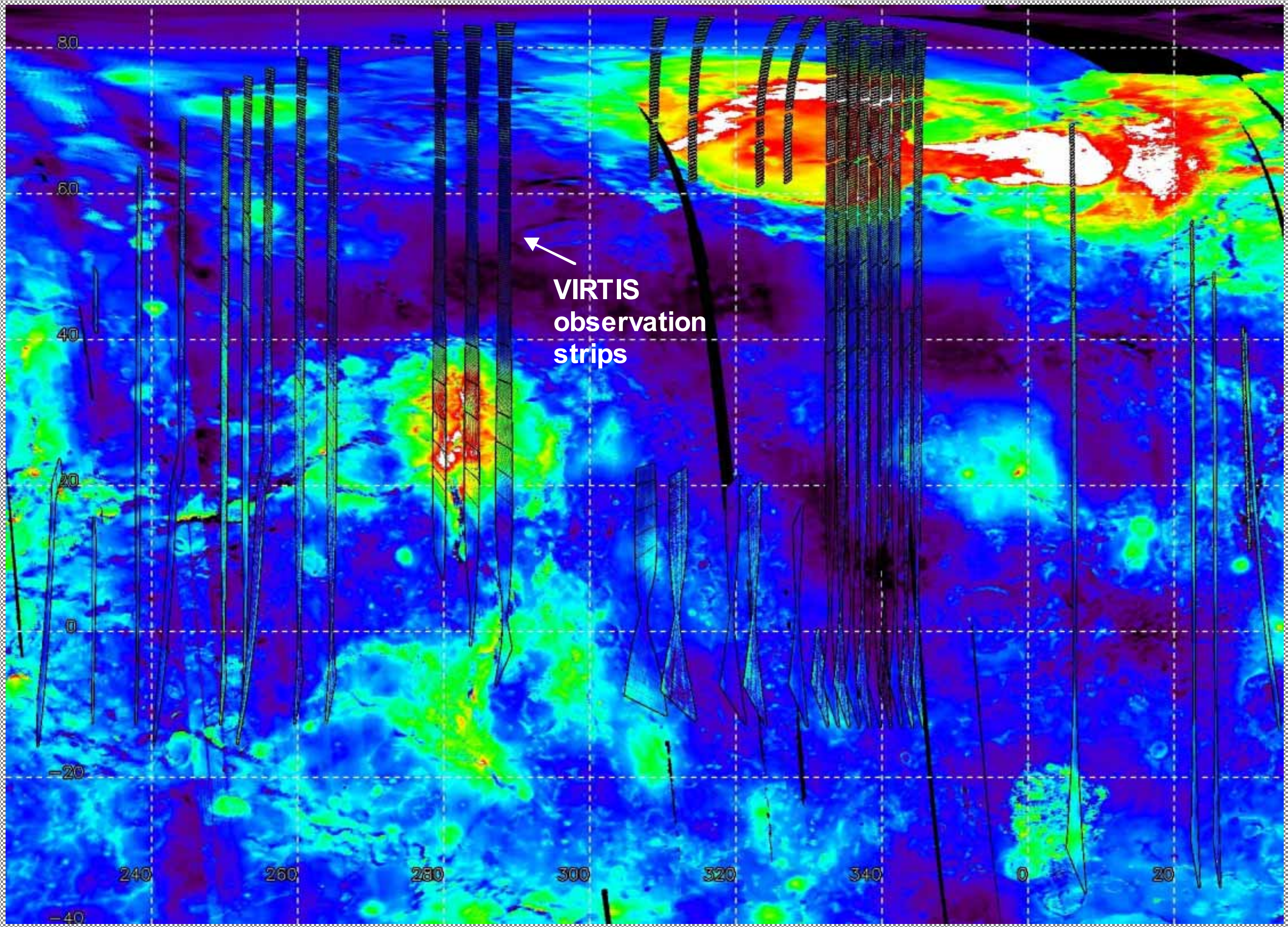
Arnold et al., EGU 2007

Spectral remote sensing of terrestrial planets

Topography analysis of northern highlands: VIRTIS-stray light correction, derivation of altitude by the 1.18/1.02 µm ratio



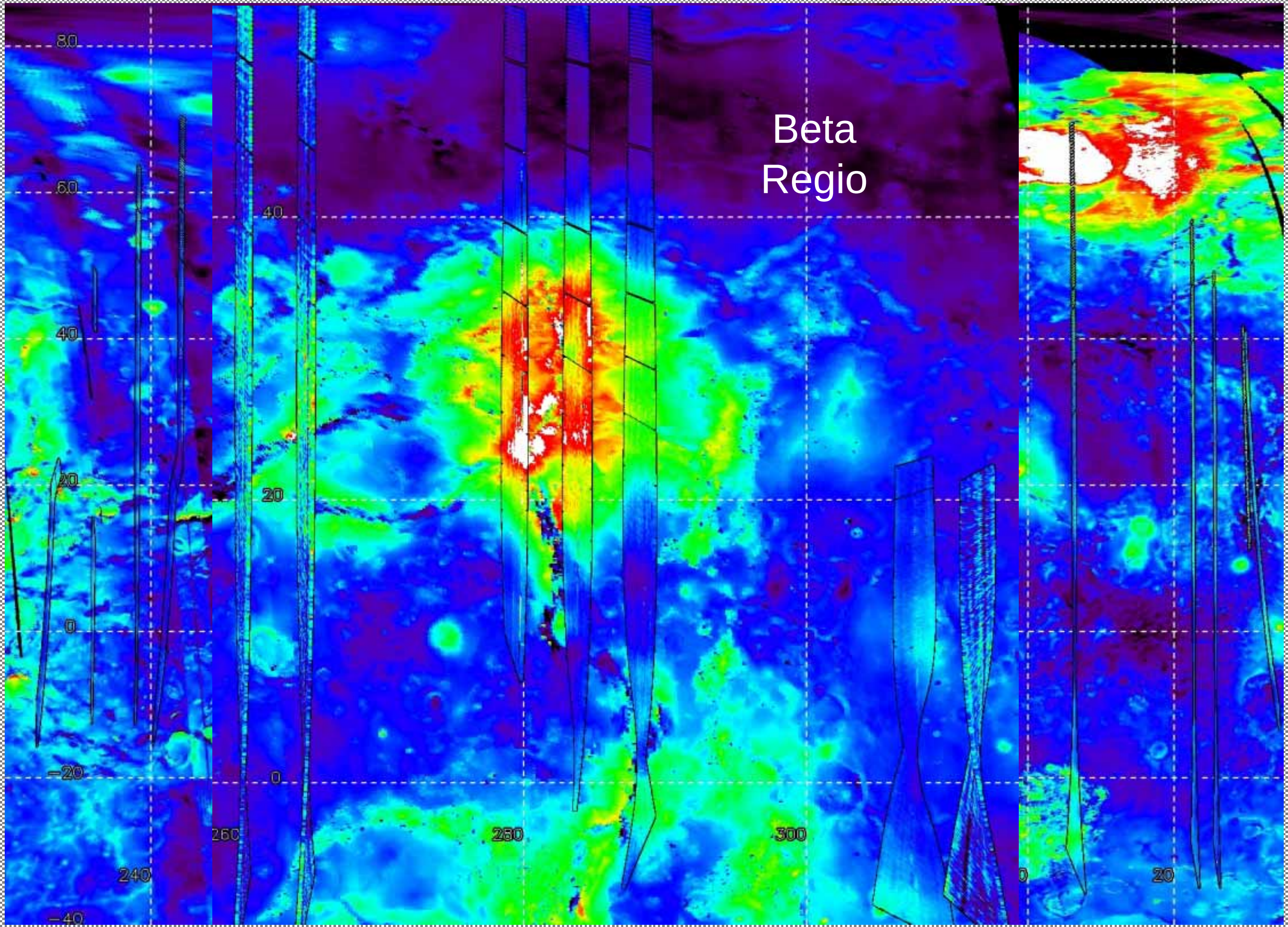
Spectral remote sensing of terrestrial planets



VIRTIS observation strips

Arnold et al., EGU 2007

Spectral remote sensing of terrestrial planets



Arnold et al., EGU 2007

Surface and deep atmosphere physics

Stray light correction.◄

Radiance ratios 1.18/1.02 µm can be used to map the surface topography. ◄

Deep atmospheric windows give us a better understanding of the chemistry of the lower atmosphere. ◄

To first order, the surface temperature is a function of altitude. ◄

VIRTIS should able to detect volcanism (lava flows of at least 1000K covering an area of about 20 km^2).

The masking of atmospheric windows by wing absorptions of the deep atmosphere constituents requires detailed radiative transfer calculations including appropriate spectral line data basis and line profiles as well as multiple scattering effects due to the dense cloud deck.◄

Small derivations from the altitude dependence of surface temperature exist. Disentangle of atmospheric, emittance and temperature radiance contributions from the surface and in the deeper Venusians atmosphere may add new data about Venus surface material variations in global scales too?◄

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy

Mercury and Earth

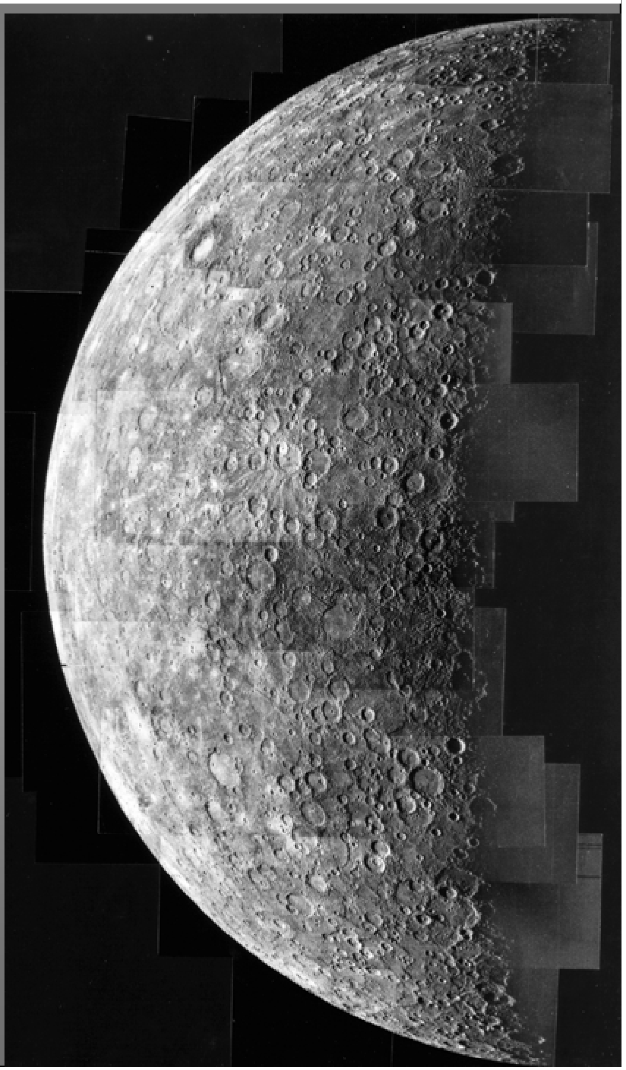
- Mercury formed closest to the sun with only 0.06 of Earth's mass.
- Mercury is characterized by high crater density indicating an old surface (45% of the surface have been imaged by Mariner 10).
- Mercury shows a density anomaly.

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy

From telescopic / spectroscopic observations

1. Space weathered silicate material (SiO_2 – content varying between 39-57%, Sprague et al. 2007), heterogeneous composition
2. Evidence for feldspatic expanses, glassy soil?, (Sprague and Roush 1998)
3. Pyroxene spectral features at four locations (clino- and orthopyroxenes, Vilas et al. 1984,85,88)
4. Low FeO and TiO_2 content (Lucey et al., 1998, 2000)
5. Little evidence for nanophase FeO, but containing some Fe^0
6. Some evidence for no- ore low-iron alkali basalts and feldspathoides (Sprague et al., 2007)
7. Structural and global dichromy (Ksanformality, 1998)



Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy

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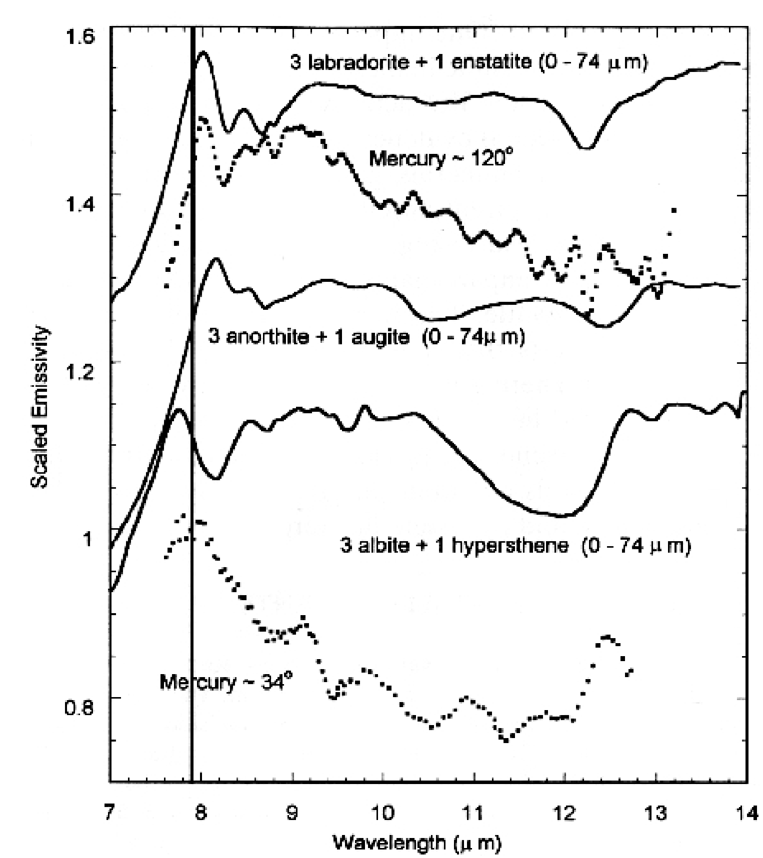


Sprague et al. 1998, 2006, 2007

Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy on Bepi Colombo

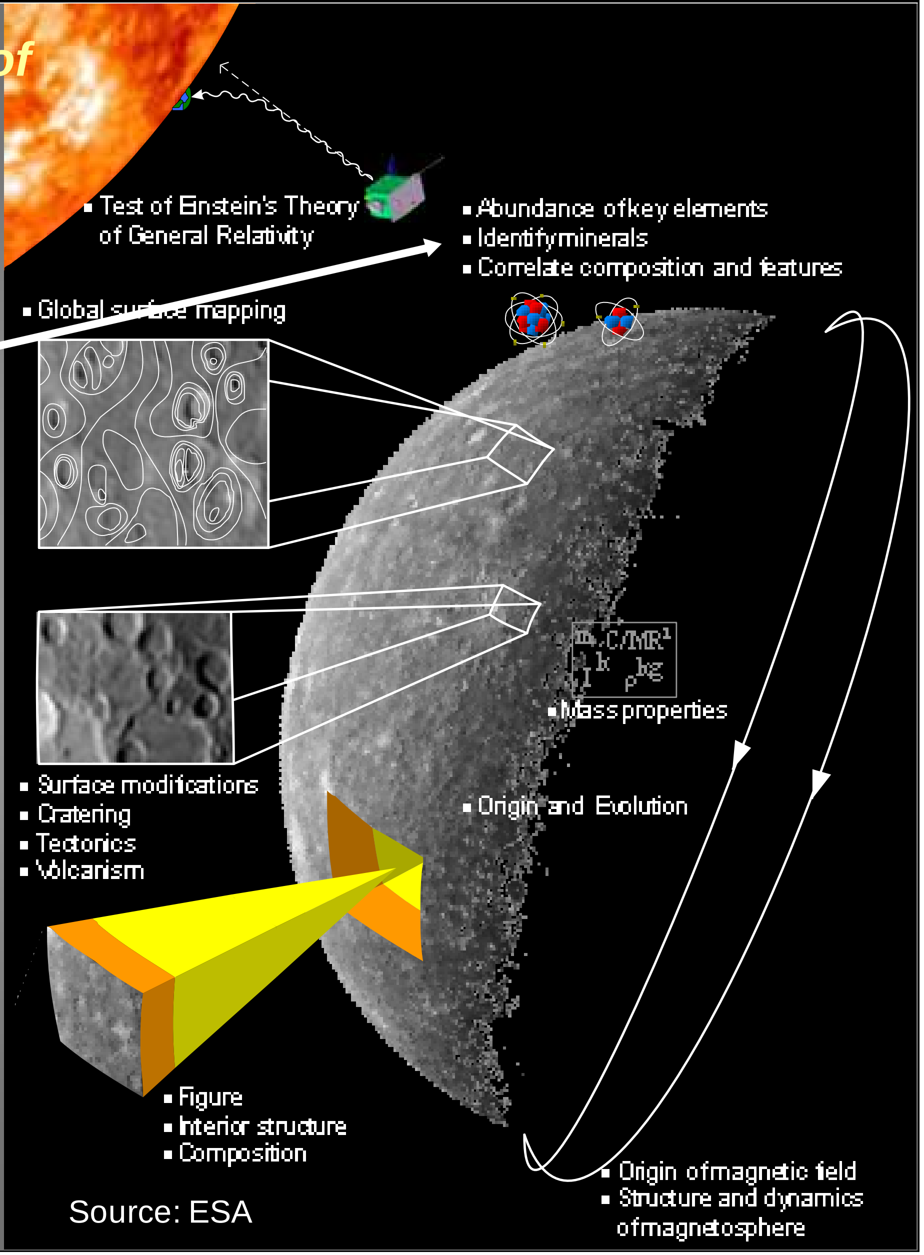
MERTIS: Identify minerals

Study of Mercury's surface composition

Identification of rock-forming minerals

Mapping of the surface mineralogy

Study of surface temperature and thermal inertia



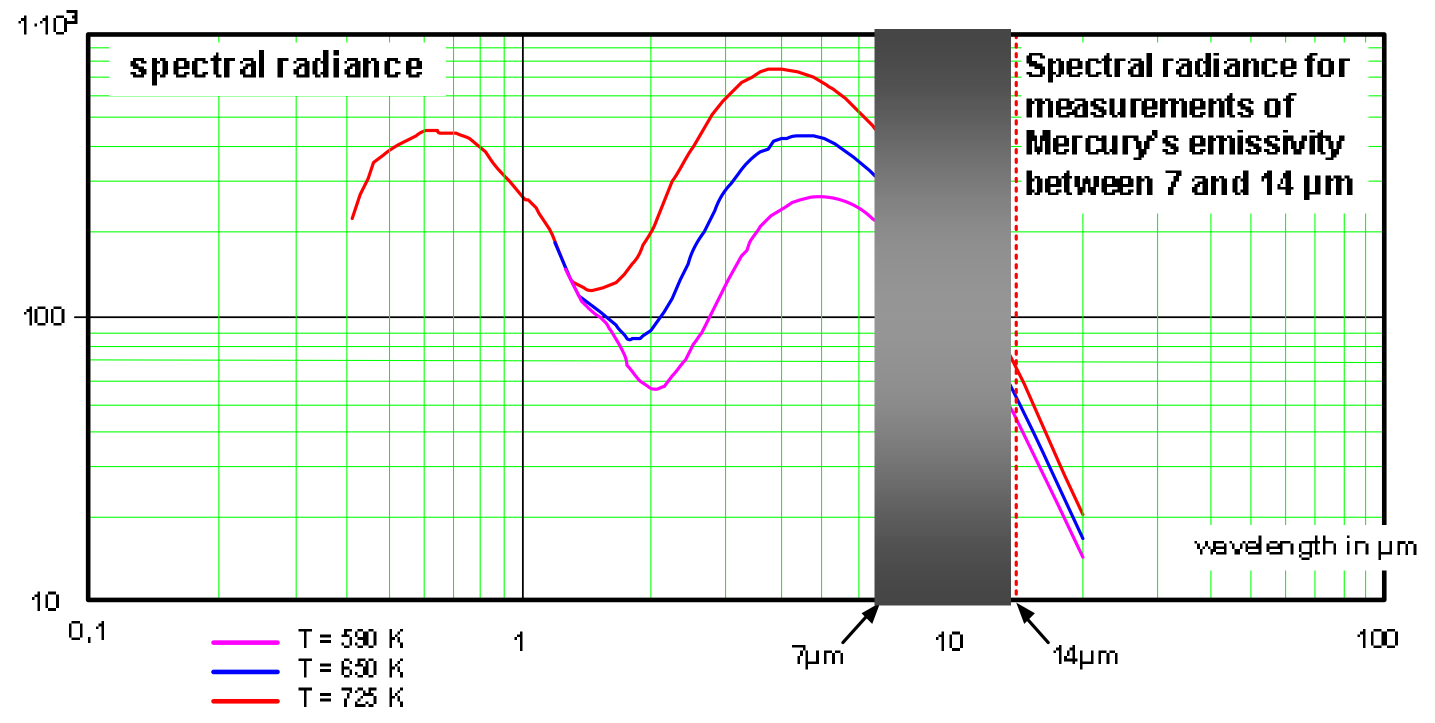
Source: ESA

Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy

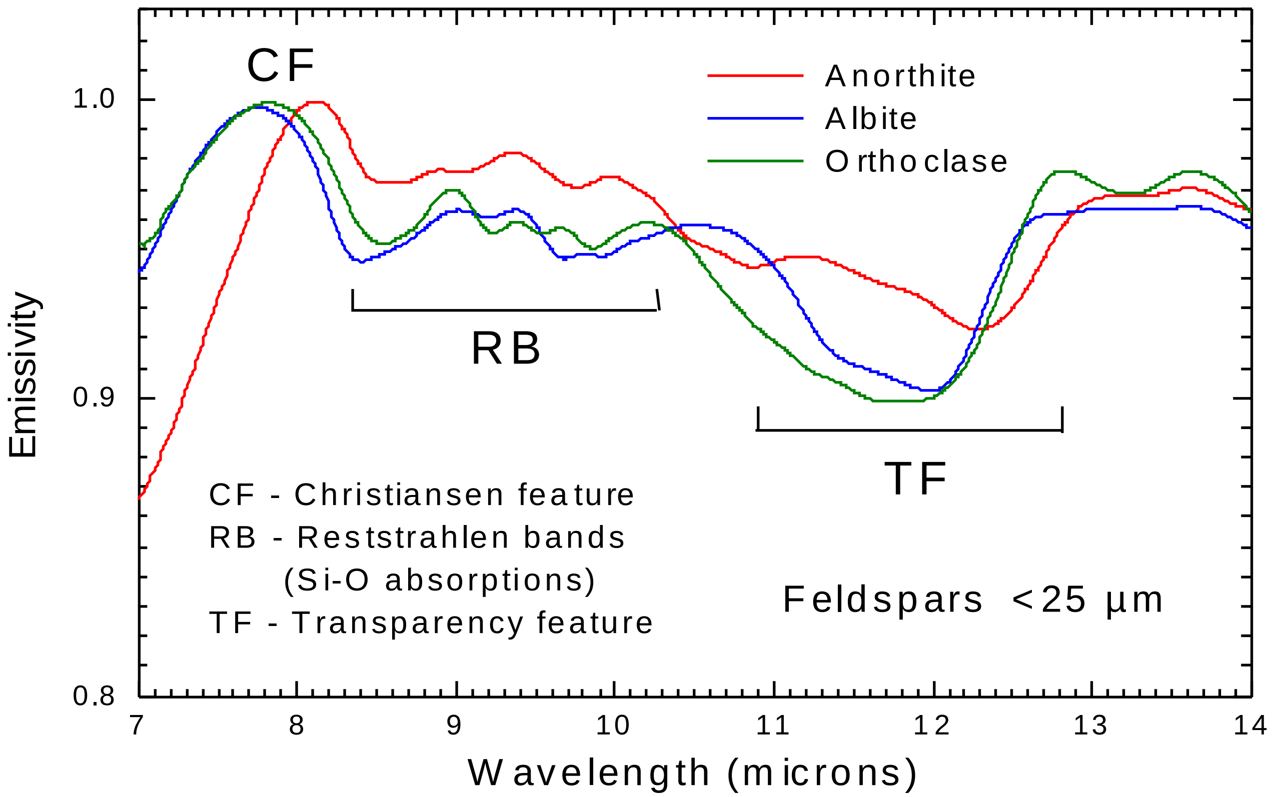
Mercury's mid infrared radiance



Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy



Main characteristics of MERTIS

MERTIS is a state the art mid-IR spectrometer based on the pushbroom principle. It uses a micro-bolometer detector which requires no cryogenic cooling.

MERTIS has an integrated instruments approach which allow including a µ-radiometer by sharing the optical entrance path, instrument electronics, and in-flight calibration components. This radiometer uses miniaturized thermopile detectors and will be placed at the slit of the spectrometer.

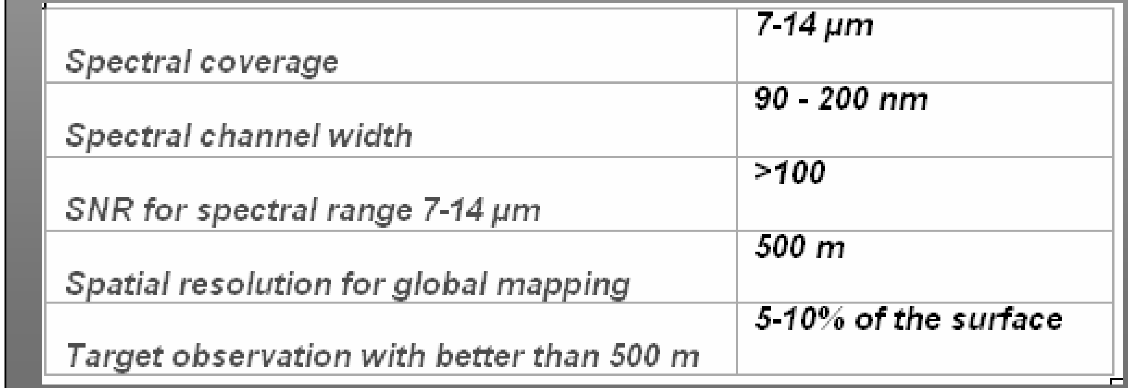
MERTIS covers the 7-14 µm range at spectral resolution better 200 nm. The resolution can be adapted to optimize the S/N.

MERTIS will globally map the planet with a spatial resolution of 500 m and a S/N of 100. For typical dayside observation the S/N ration will exceed 1000. About 5-10% of the surface will be mapped at higher spatial resolution.

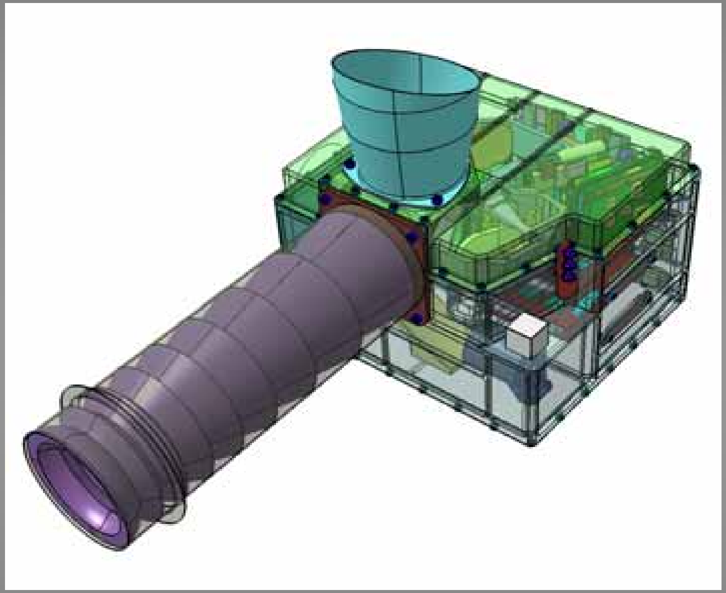
Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy – MERTIS a new state of the art spectrometer for Mercury's exploration

MERTIS: launched with Bepi Colombo in 2013 is the first push broom spectrometer to study the global mineralogical surface composition of Mercury in the thermal IR



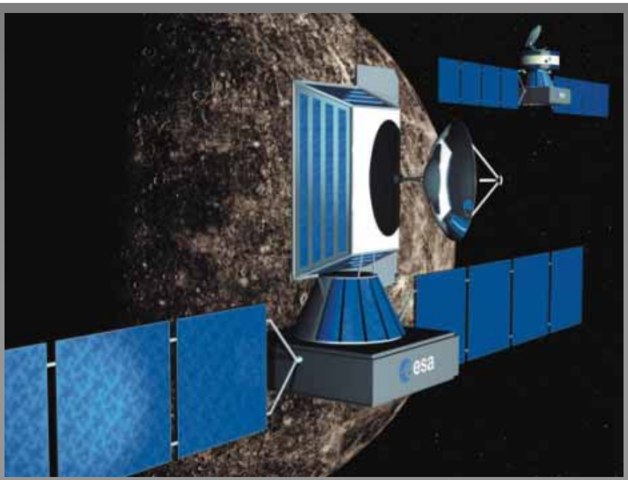
Spectral coverage	*7-14 µm*
Spectral channel width	*90 - 200 nm*
SNR for spectral range 7-14 µm	*>100*
Spatial resolution for global mapping	*500 m*
Target observation with better than 500 m	*5-10% of the surface*

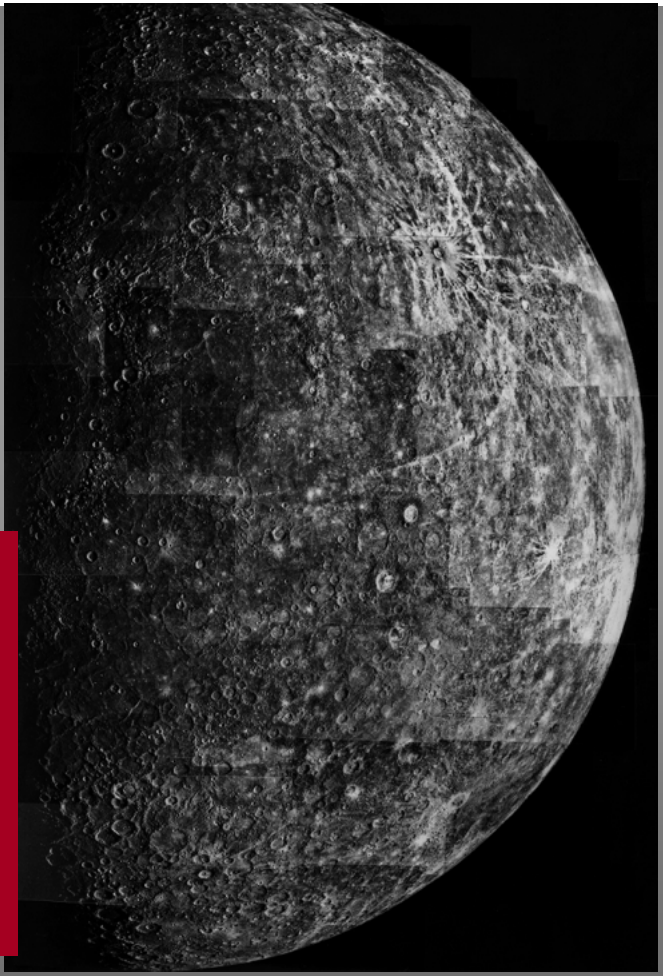


MERTIS design, dimensions: 180 x 180 x 1300 mm^3, baffles: 200 x 90 x Ø 75 mm^3

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy





Does Mercury lost a substantial part of the silicate crust by collision (Benz et al., 1988)?

Is the basin named Solitudo Criophori a sign of such a catastrophic event (Ksanformality, 1998)?

Other scenarios (hot formation, dence particle accretion)?

Remote sensed deep space spectroscopy of terrestrial planets III

Toward Mercury – MIR-Imaging spectroscopy