VIS/IR- Spectroscopy of terrestrial planets -
toward the unknown Mercury

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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
Comparative planetology of the terrestrial planets

Comparison

• Masses
• Density
• Structure and composition
• Atmospheres
• Evolution paths
Comparative planetology of the terrestrial planets

Comparison
- Masses
- Density
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Comparative planetology of the terrestrial planets

Comparison

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

- **runaway greenhouse**
  - $T_{\text{mean}}$: 737 K
  - $P$: 92 bar

- **freezing**
  - $T_{\text{mean}}$: 288 K
  - $P$: 1 bar
  - $P$: 0.0064 bar
Comparative planetology of the terrestrial planets

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 star onset, ice formation of runaway growth
Borne stars in Orion nebula line moves inward planetesimals (NASA/JPL-Caltech)
(NASA/C.R.O’DeII/Rice Univ.) (NASA/JPL-Caltech) (NASA/JPL-Caltech)
Evolution of terrestrial planets (formation models)

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- 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 which 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)
Comparative planetology of the terrestrial planets

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
Comparative planetology of the terrestrial planets

**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 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
Spectral remote sensing of terrestrial planets

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)
## Spectral remote sensing of terrestrial planets

### Early remote sensed deep space spectroscopy of terrestrial planets I

#### Interferometry – PMV on Venera 15 and 16

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral band</strong></td>
<td>6.25 – 38 µm V15</td>
</tr>
<tr>
<td></td>
<td>6.25 – 25 µm V16</td>
</tr>
<tr>
<td><strong>Spectral bandwidth</strong></td>
<td>5 cm(^{-1}) (apodized)</td>
</tr>
<tr>
<td></td>
<td>7.5 cm(^{-1}) (apodized, onboard FFT)</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>4° x 4° (rectangle)</td>
</tr>
<tr>
<td><strong>Recording time</strong></td>
<td>5.5 s</td>
</tr>
<tr>
<td><strong>Area of aperture</strong></td>
<td>8 cm(^{-1}) V15</td>
</tr>
<tr>
<td></td>
<td>10 cm(^{-1}) V16</td>
</tr>
<tr>
<td><strong>NER</strong></td>
<td>2.5 (10^{-8}) W cm(^{-1}) sr</td>
</tr>
<tr>
<td><strong>Orbit</strong></td>
<td>highly elliptical</td>
</tr>
<tr>
<td><strong>Apogee</strong></td>
<td>850 km</td>
</tr>
<tr>
<td><strong>Cycle time</strong></td>
<td>24 h</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>25 kg</td>
</tr>
</tbody>
</table>

Opto-mechanical part of PMV
Spectral remote sensing of terrestrial planets

Early remote sensed deep space spectroscopy of terrestrial planets

Interferometry – PMV on Venera 15 and 16

Venus mid-IR spectra
Spectral remote sensing of terrestrial planets

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.
Spectral remote sensing of terrestrial planets

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-Col-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.
<table>
<thead>
<tr>
<th>Instrument/Project</th>
<th>Planet</th>
<th>Start Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobos 2 ISM</td>
<td>Mars</td>
<td>1989</td>
</tr>
<tr>
<td>Mars Odyssey THEMIS</td>
<td>Mars</td>
<td>(since 2002)</td>
</tr>
<tr>
<td>VIRTIS Rosetta</td>
<td>Mars</td>
<td>Mars flight by</td>
</tr>
<tr>
<td>Mars Express (MEX) OMEGA</td>
<td>Mars</td>
<td>(since 2003)</td>
</tr>
<tr>
<td>Venus Express (VEX) VIRTIS</td>
<td>Venus</td>
<td>(since 2006)</td>
</tr>
<tr>
<td>Bepi Colombo (BC) MERTIS</td>
<td>Mercury</td>
<td></td>
</tr>
</tbody>
</table>
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.

Mead Crater – largest impact crater on Venus

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

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.

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.
Spectral remote sensing of terrestrial planets

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)

![Map of Venus showing topography and regions](image)

- **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 field 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
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
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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

VIRTIS Surface window radiance ratio 1.18µm/1.02µm (with stray light correction)

Radiance ratio of 1.18-µm deep atmospheric window (10 km height) to the surface window at 1.02 µm
Spectral remote sensing of terrestrial planets

Arnold et al.,
EGU 2007
Spectral remote sensing of terrestrial planets
Spectral remote sensing of terrestrial planets

**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 be able to detect volcanism (lava flows of at least 1000K covering an area of about 20 km²).

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 deviations from the altitude dependence of surface temperature exist. Disentangle of atmospheric, emittance and temperature radiance contributions from the surface and in the deeper Venusian 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 (SiO₂ – 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 TiO₂ content (Lucey et al., 1998, 2000)
5. Little evidence for nanophase FeO, but containing some Fe⁰
6. Some evidence for no-ore low-iron alkali basalts and feldspathoids (Sprague et al., 2007)
7. Structural and global dichromy (Ksanformality, 1998)
Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets III
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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
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

![Graph showing emissivity vs. wavelength for different minerals: Anorthite, Albite, and Orthoclase. Features include Christiansen feature (CF), Reststrahlen bands (RB), and Transparency feature (TF). The graph represents the spectral characteristics of feldspars with sizes less than 25 µm.](image)
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.
Spectral remote sensing of terrestrial planets

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

<table>
<thead>
<tr>
<th>Spectral coverage</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Spectral channel width</td>
<td>90 - 200 nm</td>
</tr>
<tr>
<td>SNR for spectral range 7-14 μm</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Spatial resolution for global mapping</td>
<td>500 m</td>
</tr>
<tr>
<td>Target observation with better than 500 m</td>
<td>5-10% of the surface</td>
</tr>
</tbody>
</table>

MERTIS design, dimensions: 180 x 180 x 1300 mm³, baffles: 200 x 90 x Ø 75 mm³
Spectral remote sensing of terrestrial planets

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, dense particle accretion)?
Spectral remote sensing of terrestrial planets

Remote sensed deep space spectroscopy of terrestrial planets III
Toward Mercury – MIR-Imaging spectroscopy