Mercury 2022

Current and future science of the innermost planet

Orléans, France, 7-10 June 2022

ABSTRACT BOOK AND PARTICIPANT LIST

Web access:

https://mercury2020.ias.u-psud.fr/

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Program at a glance

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9:50	André
10:10	Zender
10:30	Coffee break (posters)
11:15	Murakami G. *(invited)*
11:45	Griton
12:05	Pump
12:25	Livi
12:45	Lunch break
14:15	Rothery *(invited)*
14:45	Galiano
15:05	Hirata
15:25	Barraud
15:45	Coffee break (posters)
16:30	Van Hoolst *(invited)*
17:00	Cappuccio
17:20	Charlier
17:40	Head
18:00	End of the day

Wednesday June 8	
9:00	Imber (invited)
9:30	Lavorenti
9:50	Glass
10:10	Schmid
10:30	Coffee break (posters)
11:15	Caminiti
11:35	Jozwiak
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14:15	Iess *(invited)*
14:45	Di Stefano
15:05	Fraenz
15:25	Tenthoff
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16:30	Wright
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17:30	Hood
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	PUBLIC OUTREACH EVENT MUSEUM OF FINE ARTS

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	CONFERENCE COCKTAIL MUSEUM OF NATURAL HISTORY

Friday June 10	
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16:00	END OF CONFERENCE

Theme 1 : Exosphere and magnetosphere dynamics
Theme 2 : Surface geology and composition
Theme 3 : Deep interior and planetary evolution
Theme 4 : Fundamental physics
Theme 5 : Miscellaneous

TUESDAY JUNE 7, 2022

8:30 : Opening
9:00-9:20 : Welcome

(Conveners : Delcourt D., Leblanc F.)

Theme 5 : Miscellaneous

9:20-9:50 : Benkhoff J. (invited) : “BepiColombo - comprehensive exploration of Mercury: first results and mission status”

9:50-10:10 : André N. : “Overview of low-energy electron observations from the Mercury Electron Analyzers onboard Mio/BepiColombo during cruise phase and planetary flybys”

10:10-10:30 : Zender J. : “BepiColombo Mercury Swing-by-2 on 23 June 2022 - An Overview”

10:30-11:15 : coffee break (poster setup)

11:15-11:45 : Murakami G. (invited) : “Updated status and results of BepiColombo/Mio during interplanetary cruise phase”

Theme 1 : Exosphere and magnetosphere dynamics

11:45-12:05 : Griton L. : “Global 3D numerical simulations of the magnetosphere of Mercury in a dynamic solar wind"

12:05-12:25 : Pump K. : “Revised Modular Model of Mercury’s Magnetospheric Magnetic Field"

12:25-12:45 : Livi S. : “Strofio Status and Measurements Outlook"

12:45-14:15 : lunch break

(Conveners : Chabot, N., Denevi B.)

Theme 2 : Surface geology and composition

14:15-14:45 : Rothery D. (invited) : “BepiColombo surface science objectives"

14:45-15:05 : Galiano A. : “Principal Component Analysis and Spectral Angle Mapper on MASCS/MESSENGER data for the spectral characterization of Mercury surface"

15:05-15:25 : Hirata K. : "Comparison of magma eruption fluxes in the Rembrandt and Caloris interior plains: implications for the north-south smooth plains asymmetry"

15:25-15:45 : Barraud O. : "The lack of hollows in the Mercury's high-reflectance red plains"

15:45-16:30 : coffee break (poster viewing)

Theme 3 : Deep interior geophysics and planetary evolution

16:30-17:00 : Van Hoolst T. (invited) : "Mercury's deep interior"

17:00-17:20 : Cappuccio P. : "Mercury gravity field and rotational state with the BepiColombo MORE experiment"

17:20-17:40 : Charlier B. : "A consistent model for the chemical, mineralogical, and physical characteristics of Mercury's crust"

17:40-18:00 : Head J. : "Mercury Magmatic, Tectonic and Geodynamic History: A Comparative Planetology Analysis"

WEDNESDAY JUNE 8, 2022

(Conveners : Murakami G., Langevin Y.)

Theme 1 : Exosphere and magnetosphere dynamics

9:00-9:30 : Imber S. (invited) : "Mercury's Magnetospheric Dynamics"

9:30-9:50 : Lavorenti F. : "Electron dynamics at Mercury: acceleration, circulation and precipitation processes using a global fully-kinetic model"

9:50-10:10 : Glass A. : "Mercury's Plasma Sheet Horn from MESSENGER Data"

10:10-10:30 : Schmid D. : "Magnetic evidence for an extended hydrogen exosphere at Mercury"

10:30-11:15 : coffee break (poster viewing)

Theme 2 : Surface geology and composition

11:15-11:35 : Caminiti E. : "Evolution of Mercury's crust: A common process for the formation of smooth plains associated with impact basins"

11:35-11:55 : Jozwiak L. : “Understanding the Age and Distribution of Explosive Volcanism on Mercury: Insights from Pyroclastic Deposits"

11:55-12:15 : Man B. : “Newly discovered widespread extensional grabens on Mercury’s compressional structures"

12:15-12:35 : Conway S. : “Landforms caused by downslope mass wasting on Mercury"

12:35-14:15 : lunch break

(Conveners : Zender J., Vincendon M.)

Theme 4 : Fundamental physics with Bepi-Colombo

14:15-14:45 : Iess L. (invited) : “Tests or relativistic gravity with the MORE investigation on BepiColombo"

14:45-15:05 : Di Stefano I. : "The MORE fundamental physics test at Mercury"

15:05-15:25 : Fraenz M. : "Effects of spacecraft outgassing and potential at Mercury"

Theme 2 : Surface geology and composition

15:25-15:45 : Tenthoff M. : “Accurate 3D Reconstruction of Mercury with Shape from Shading"

15:45-16:30 : coffee break (poster viewing)

16:30-16:50 : Wright J. : “Georeferenced M-CAM images from BepiColombo’s first Mercury swingby"

16:50-17:10 : Hyodo R. : “Late accretion onto Mercury"

17:10-17:30 : Blance A. : “Prevalence and Significance of Ejecta Flows on Mercury: A Global Survey"

17:30-17:50 : Hood L. : “Magnetic Anomalies Aligned Radial to the Caloris Impact Basin: Further Evidence for Ejecta Deposit Sources"

19:00-20:30 : Public outreach event at Orléans Museum of Fine Arts

THURSDAY JUNE 9, 2022

(Conveners : Henri P., Millilo A.)

Theme 1 : Exosphere and magnetosphere dynamics

9:00-9:20 : Robidel R. : “Observations of Mercury’s Exosphere during BepiColombo First Mercury Flyby with PHEBUS’ visible channels"

9:20-9:40 : Milillo A. : “BepiColombo First Mercury Fly-by: first taste of the mission results on investigation of the environment around the planet"

9:40-10:00 : Mangano V. : “Coordinated campaign of ground-based observations of Mercury’s exosphere in 2021"

Theme 4 : Fundamental physics with Bepi-Colombo

10:00-10:30 : Will C. (invited) : “Zombie alert! Solar system tests of GR are still alive”

10:30-11:15 : coffee break (poster viewing)

Theme 2 : Surface geology and composition

11:15-11:35 : Chabot N. : “Topography, Illumination, and Thermal Models of Mercury’s Polar Deposits"

11:35-11:55 : Bertoli S. : “Landform analysis and age determination of craters in the North pole regions of Mercury"

11:55-12:15 : Filacchione G. : “Spectral detection of ices in Mercury’s PSRs by SIMBIOSYS-VIHI on BepiColombo mission"

12:15-12:35 : Wohlfarth K. : “A Mystery solved: Wavelength-dependent Seeing changes the normalized spectral slope of Mercury"

12:35-14:00 : lunch break

14:00-18:00 : FREE (tours: Sully Castle or Radio-Telescope of Nançay)

19:00-20:30 : Conference cocktail at Museum of natural History

FRIDAY JUNE 10, 2022

(Conveners : Benkhoff J., Terada N.)

Theme 3 : Deep interior geophysics and planetary evolution

9:00-9:30 : Denevi B. (invited) : “The Evolution of Mercury’s Crust"

9:30-9:50 : Lark L : “Mercury: Thermal evolution of a layered system"

9:50-10:10 : Namur O. : “Carbon partitioning under reducing conditions: implications for Mercury"

Theme 1 : Exosphere and magnetosphere dynamics

10:10-10:30 : Saito Y. : “Venus and Mercury fly-by observation by MPPE-MIA on BepiClombo/Mio"

10:30-11:15 : coffee break (poster viewing)

11:15-11:35 : Orsini S. : “Remote sensing of Mercury sodium emission and relationships with magnetospheric activity"

11:35-11:55 : Koutroumpa D. : “PHEBUS observations of the He 58.4 nm emission during BepiColombo’s first Mercury Flyby"

11:55-12:15 : Aizawa S. : “The first simultaneous observation of low energy ions and electrons at Mercury during the first BepiColombo flyby"

12:15-12:35 : Mura A. : “Yearly variability of Mercury’s exosphere: comparison of the Na and Ca cases"

12:35-14:15 : lunch break

(Conveners : Delcourt D., Leblanc F.)

Theme 2 : Surface geology and composition

14:15-14:35 : Deutsch A. : “Investigating 1064-nm Albedo along Mercury’s Hot and Cold Poles"

14:35-14:55 : Bott N. : “Simulating micrometeoroid bombardment of Mercury analog samples"

Theme 1 : Exosphere and magnetosphere dynamics

14:55-15:15 : Schmidt C. : "Impact Events Observed by MESSENGER UVVS"

15:15-15:35 : Moroni M. : "Micro-meteoroids impact vaporization (MMIV) as source for Ca and CaO exosphere along Mercury's orbit"

15:35-16:00 : Karlsson T. : "MESSENGER observations of short, large-amplitude structures (SLAMS) in the Mercury foreshock"

16:00 : end of conference

Talk list

Please refer to the conference program for the time slot of your oral presentation

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- André et al., Overview of low-energy electron observations from the Mercury Electron Analyzers onboard Mio/BepiColombo during cruise phase and planetary flybys
- Barraud O. et al., The lack of hollows in the Mercury's high-reflectance red plains
- Benkhoff, BepiColombo - comprehensive exploration of Mercury: first results and mission status
- Bertoli et al., Landform analysis and age determination of craters in the North pole regions of Mercury
- Blance et al., Prevalence and Significance of Ejecta Flows on Mercury: A Global Survey
- Bott et al., Simulating micrometeoroid bombardment of Mercury analog samples
- Cappuccio et al., Mercury gravity field and rotational state with the BepiColombo MORE experiment
- Caminiti et al., Evolution of Mercury's crust: A common process for the formation of smooth plains associated with impact basins
- Chabot et al., Topography, Illumination, and Thermal Models of Mercury's Polar Deposits
- Charlier et al., A consistent model for the chemical, mineralogical, and physical characteristics of Mercury's crut
- Conway et al., Landforms caused by downslope mass wasting on Mercury
- Denevi et al., The Evolution of Mercury's Crust
- Deutsch et al., Investigating 1064-nm Albedo along Mercury s Hot and Cold Poles
- Di Stefano et al., The MORE fundamental physics test at Mercury

- Filacchione et al., Spectral detection of ices in Mercury's PSRs by SIMBIOSYS-VIHI on BepiColombo mission
- Fraenz et al., Effects of spacecraft outgassing and potential at Mercury
- Galiano et al., Principal Component Analysis and Spectral Angle Mapper on MASCS/MESSENGER data for the spectral characterization of Mercury surface
- Glass A. et al., Mercury's Plasma Sheet Horn from MESSENGER Data
- Griton et al., Global 3D numerical simulations of the magnetosphere of Mercury in a dynamic solar wind
- Head et al., Mercury Magmatic, Tectonic and Geodynamic History: A Comparative Planetology Analysis
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- Koutroumpa et al., PHEBUS observations of the He 58.4 nm emission during BepiColombo's first Mercury Flyby
- Lark et al., Mercury: Thermal evolution of a layered system
- Lavorenti et al., Electron dynamics at Mercury: acceleration, circulation and precipitation processes using a global fully-kinetic model
- Livi et al., Strofio Status and Measurements Outlook
- Man et al., Newly discovered widespread extensional grabens on Mercury's compressional structures
- Mangano et al., Coordinated campaign of ground-based observations of Mercury's exosphere in 2021

- Milillo et al., BepiColombo First Mercury Fly-by: first taste of the mission results on investigation of the environment around the planet
- Moroni et al., Micro-meteoroids impact vaporization (MMIV) as source for Ca and CaO exosphere along Mercury's orbit
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- Namur et al., Carbon partitioning under reducing conditions: implications for Mercury
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- Pump et al., Revised Modular Model of Mercury's Magnetospheric Magnetic Field
- Robidel et al., Observations of Mercury'sExosphere during BepiColombo First Mercury Flyby with PHEBUS' visible channels
- Rothery et al., BepiColombo surface science objectives
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- Will, Zombie alert! Solar system tests of GR are still alive
- Wohlfarth et al., A Mystery solved: Wavelength-dependent Seeing changes the normalized spectral slope of Mercury
- Wright et al., Georeferenced M-CAM images from BepiColombo's first Mercury swingby
- Zender et al., BepiColombo Mercury Swing-by-2 on 23 June 2022 - An Overview

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2. André et al., SPIS simulation of Bepi Colombo interaction with the plasma environment encountered during the Venusian and Hermean flybys: influence on plasma measurements
3. Barraud et al., The BepiColombo Surface and Environment Interactions Studies Group (SEIS)
4. Bentley et al., BepiColombo science data in the Planetary Science Archive - current status and future plans
5. Besse et al., Updating the Mercury Mean Spectra using 4.7 millions MASCS Spectra
6. Cartier et al., A large proto-Mercury as the aubrite parent body
7. Chaufray et al., EUV reflectance of Mercury measured by BepiColombo/PHEBUS
8. Cornet et al., Exploring the MASCS data set through the MeSS database
9. Deborde et al., Investigating the effect of surface - exosphere interactions
10. Doressoundiram et al., A spectral study of the Caloris basin and its smooth plains' relationship
11. Futaana et al., Energetic Neutral Atom imaging at Mercury: Science objectives and the initial operation of the MPPE/ENA instrument on Mio
12. Giroud-Proeschel et al., Investigation of Hollow Locations in Craters of Different Degradation Classes
13. Glantzberg et al., Investigating the Distribution of Surface Ice in Mercury's Northernmost Craters
14. Hadid et al., Evidence of planetary Oxygen and Carbon ions in the outer flank of Venus magnetosheath

15. Ho, Suprathermal Electrons in Mercury's Magnetosphere
16. Kreslavsky et al., Ponded Melt Deposits Antipodal to Large Young Impact Craters on Mercury
17. Leblanc et al., Modelling Mercury's exospheric sodium seasonal variability
18. Lennox et al., Lobate Ejecta Deposits at Mercury's South Pole (H15)
19. Mckee et al., Investigating the Incidence Angle Effect on X-ray Fluorescence with the MIXS Ground Reference Facility
20. Milillo et al., MERCURY IMPACTOR: A mission to study below the surface
21. Morissey et al., Quantifying Mineral and Position Specific Surface Binding Energies for Multiscale Modelling of Solar Wind Sputtering on Mercury
22. Morlok et al., Mid-Infrared Reflectance Studies of Mercury Surface Regolith Analogs
23. Munaretto et al., Photometric modelling of Mercury surface features from multiangular MESSENGER/MDIS observations
24. Muñoz et al., The MeSS (Mercury Surface Spectroscopy) Database Architecture and Contents
25. Persson et al., The scenic tour of the Venusian magnetosheath by BepiColombo
26. Prado et al., Some useful orbits around Mercury for scientific missions
27. Sahraoui et al., Characterizing plasma turbulence in the Hermean environment (and beyond)
28. Sanchez-Cano et al., Space Weather monitoring with BepiColombo
29. Schriver et al., Space Weathering of Icy Volatiles within North Polar Permanently Shadowed Regions
30. Stenzel et al., Handling Cauchy Noise in Laser Altimetry of Mercury-Tests with MESSENGER Data and Prospects for BepiColombo/BELA
31. Szczech et al., Expected characterization of Mercury's surface from global to local scales by the BepiColombo Laser Altimeter (BELA)
32. Szczech et al., Mercury's basin inventory and analysis of topography and gravity field data
33. Terada et al., Collisional acceleration of Mercury's sodium exosphere in MMIV-produced clouds
34. Tognon et al., Targets definition for BepiColombo in eastern H9 Eminescu quadrangle

35. Tosi et al., Influence of insolation on Mercury's crustal thickness evolution
36. Volwerk et al., Mirror Modes in the Hermean Magnetosheath
37. Werner et al., Modeling the impact of a strong X-class solar flare on the planetary ion composition in Mercury's magnestosphere
38. Wohlfarth et al., Mercury is hot: A fractal thermal roughness Model for MERTIS spectral calibration
39. Wright et al., Combining spectral and morphostratigraphic units on Mercury: A case study of the Rachmaninoff basin area
40. Zambon et al., Spectral analysis of features of interest on Mercury northern hemisphere
41. Zomerdijk-Russell et al., Mercury's Magnetopause as a Tool for Understanding the Planet's Interior

Organizing committees

Science Organizing Committee (SOC)

Leblanc, François (LATMOS, Lead, France)

Benkhoff, Johannes (ESA, The Netherlands)

Byrne, Paul (NCSU, USA)

Chabot, Nancy (APL, USA)

Delcourt, Dominique (LPC2E, France)

Galluzzi, Valentina (INAF/IAPS, Italy)

Henri, Pierre (LPC2E, France)

Langevin, Yves (IAS, France)

Milillo, Anna (INAF/IAPS, Italy)

Murakami, Go (ISAS, Japan)

Peron, Roberto (INAF/IAPS, Italy)

Raines, Jim (University of Michigan, USA)

Terada, Naoki (Tohoku University, Japan)

Vander Kaaden, Kathleen (NASA Headquarters, USA)

Zender, Joe (ESA, The Netherlands)

Local Organizing Committee (LOC)

Delcourt, Dominique (LPC2E, Lead)

Chane-Yook, Martine (IAS)

Henri, Pierre (LPC2E)

Langer, Isabelle (LPC2E)

Leblanc, François (LATMOS)

Vincendon, Mathieu (IAS)

Theme 1: Exosphere and magnetosphere dynamics

Escape and precipitation of planetary ions at Mercury under different solar wind conditions

Aizawa, Sae (1,5)

André N. (1), Persson M. (1), Modolo R. (2), Raines J. (3), Leblanc F. (2), Chaufray J.-Y. (2), Nenon Q. (4)

(1) IRAP/CNRS/OMP (2) LATMOS/CNRS, Sorbonne Université (3) University of Michigan (4) ESA/ESTEC (5) ISAS/JAXA, University of Pisa

The escape and precipitation of planetary ions from Mercury's environment under different solar wind conditions have been examined using a global hybrid simulation. The combination of Mercury's weak intrinsic magnetic field and solar wind conditions at Mercury's location results in the formation of a relatively small magnetosphere compared to that of Earth. Its magnetosphere is strongly compressed and may disappear when solar wind conditions are extreme. Under these circumstances, the solar wind can directly interact with its exosphere and surface and the escape of planetary ions is expected to be enhanced. By focusing on the dynamic pressure and interplanetary magnetic field dependence, three different solar wind conditions are used in this study. Under the extreme solar wind planetary protons shows the highest escape rates while planetary sodium ions show the smallest, indicating that the distribution of sodium ions around the planet is controlled by the size of the magnetosphere. As the Larmor radius of planetary sodium ions is larger than that of planetary protons, they cannot escape and instead precipitate onto surface during extreme solar wind conditions, when the dayside magnetosphere is well compressed. Precipitation maps of three components (solar wind protons, planetary protons, and planetary sodium ions) show that the flux from planetary plasmas is sometimes higher than solar wind plasmas, suggesting that the precipitation of planetary plasmas should be considered for the space weathering of Mercury's surface.

The first simultaneous observation of low energy ions and electrons at Mercury during the first BepiColombo flyby

Aizawa, Sae (1,6)

Harada Y. (2), Saito Y. (2), André N (1)., Persson M. (1), Delcourt D. (3), Hadid L. (4), Fraenz M. (5), Yokota S. (2), Fedorov A. (1), Penou E. (1), Barthe A. (1), Sauvaud J.-A. (1), Katra B. (4), Matsuda S. (2), Murakami G. (2)

(1) IRAP/CNRS/OMP (2) ISAS/JAXA (3) LPC2E/CNRS (4) LPP/CNRS-Ecole Polytechnique (5) MPI Solar System Research (6) ISAS/JAXA, University of Pisa

The first Mercury flyby by BepiColombo was successfully conducted on the 1st of October 2021 and this is the first time to have the simultaneous observation of low energy ions and electrons at Mercury. The data from Mercury Plasma Particle Experiment (MPPE) onboard Mio/BepiColombo shows (1) the compressed Mercury's magnetosphere compared to the average of MESSENGER observations, (2) boundary motions around magnetopause crossings, (3) periodic signatures in ion and electron spectra in both dawn- and dusk- night sides, which is most likely the ULF waves, and (4) high energy ions and electrons after the closest approach, which indicates the substorm related injection. Detailed analysis of these features will be addressed in the presentation, and compare them with previous MESSENGER and Mariner-10 observations.

Investigating the effect of surface - exosphere interactions

Deborde, Robin (1)

Leblanc F. (1), Tramontina P. (2), Bringa E. (2), Chaufray J.-Y. (1), Johnson R.E. (3)

(1) LATMOS/CNRS, Sorbonne Université (2) CONICET and Facultad de Ingeniería - Universidad de Mendoza, Mendoza, 5500, Argentina (3) University of Virginia, Charlottesville, USA

The surface of planetary airless bodies, also called surface bounded exosphere, like our Moon or Mercury, are directly bombarded by solar particles. The most abundant of those particles are solar wind protons. In the case of the Moon, many observations of low energy neutral atoms have shown that a significant portion of these incident protons are backscattered as neutral hydrogen. Measurements of the energy flux distribution of these neutral particles provide a clue regarding the processes occurring in the surface regolith when impacting protons collide with the surface grains.
In this work, we developed a model of the fate of protons through the regolith in order to reproduce these measurements. We combined Monte Carlo approach to reconstruct the motion of these particles with molecular dynamics to describe the interaction of an incident proton with a grain and its dependency with incident energy and angle. Using in situ measurements of the solar wind, this detailed modelling allows us to analyze accurately the measurements performed by Chandrayaan-1 CENA instrument and to highlight what could control the flux and energy properties of these backscattered neutral hydrogen particles. Predictions of the intensity and shape of the backscattered neutral hydrogen at Mercury are derived from this calculation.

Energetic Neutral Atom imaging at Mercury: Science objectives and the initial operation of the MPPE/ENA instrument on Mio

Futaana, Yoshifumi (1)

Shimoyama M. (1), Wieser M. (1), Barabash S. (1), Asamura K. (2)

(1) Swedish Institute of Space Physics (2) Institute of Space and Astronautical Science

Mercury does not possess an atmosphere. The magnetospheric plasma is thus interacting with the surface directly. The solar wind may directly access the surface when its dynamic pressure is high. The existence of the surface governs the plasma dynamics at Mercury. For example, the surface behaves as the sink of the space plasma (magnetospheric ions, electrons, and solar wind plasma). In addition, the surface is also the source of plasma (sputtered ions, reflected ions, photoelectrons) and neutral atoms (sputtered constituents, reflected atoms at various energies). The ongoing physics is a complex, interdisciplinary solar wind-magnetosphere-surface-exosphere coupling.

The energetic neutral atom (ENA) imaging, a diagnostic tool to image the plasma dynamics in a remote-sensing way, is highly suitable for characterizing the coupling. The surface is the source of ENAs via the sputtering and scattering (reflecting) processes. Therefore, the ENA measurements provide information on the plasma characteristics at the surface (at 0 km altitude). The information is highly unique by itself to characterize the plasma-surface interaction at Mercury. In addition, the ENA data includes information about physics operated on the precipitating ions between the spacecraft and the surface. This will allow complementary investigation of the plasma dynamics by combining with the in-situ plasma measurements.

This presentation will review the sciences that we aim to tackle by ENA imaging at Mercury. From the experience of the observations at the Earth's Moon, we place the sciences into a comparative context. The ENA sciences include: Precipitating ions at the surface. Imaging of open/close field regions: How much are the ions precipitating on the surface? What is the difference in flux, energy, and constituents between the open and close field lines? What are the temporal and spatial variations of ion precipitation? Physics below the spacecraft altitude. Measuring the potential drops between the spacecraft and the surface: What are the characteristic energies of ions at the surface? How much does the field-aligned potential exist? What are the temporal and spatial variations of the potential drop? Global ENA imaging: Does the solar wind reach the dayside surface globally? Under what conditions does it happen? We will also present the first-light data of the MPPE/ENA instrument onboard the BepiColombo/MMO during the Earth, Venus, and the first Mercury flybys and interplanetary cruising.

Mercury's Plasma Sheet Horn from MESSENGER Data

Glass, Austin (1)

Raines J. (1), Jia X. (1), Sun W. (1), Imber S. (2), Slavin J. (1)

(1) Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, US (2) University of Leicester

The Mercury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) spacecraft was the first spacecraft to orbit the planet Mercury, completing over 4000 orbits of the planet from 2011 to 2015. Previous analysis of MESSENGER data has established that Mercury's magnetosphere is the most like Earth's of any in the solar system. Chief among the similarities is the dominance of the Dungey cycle in the dynamic response of the magnetosphere to solar wind forcing. Many key regions characteristic of Dungey cycle plasma flows have previously been identified at Mercury. In this work, Mercury's northern plasma sheet horn - a key plasma feature also present in Earth's magnetosphere - is identified and presented in detail for the first time. Through analysis of three different cases of horn observation, we describe the northern horn with the greatest detail possible with a single spacecraft, with special attention given to the character of the plasma contained within the northern horns and its potential effects on exosphere generation and maintenance.

Global 3D numerical simulations of the magnetosphere of Mercury in a dynamic solar wind

Griton, Léa (1)

Pantellini F. (1), Exner W. (2,3), Heyner D. (4), Jackman C.J. (5)

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Within the Solar System, planetary magnetospheres show a great diversity of responses to the variable solar wind in which they are plunged, depending on several parameters such as their size, the rotation properties of their host planet and its magnetic field strength. Among all the magnetised planets, Mercury has the magnetosphere that is the most dependent on the solar wind dynamics, for several reasons, including its proximity to the Sun and its very slow rotation. Results from the first spacecraft to orbit Mercury, NASA's MESSENGER mission (2011-2015) showed surprisingly fast-paced changes in the behaviour of magnetic fields and plasmas near Mercury. The BepiColombo (ESA/JAXA) mission has built on this knowledge, with its scientific observing strategy planned to take advantage of knowledge gained from previous exploration of this tiny but dramatic world. We present numerical simulations of the magnetosphere of Mercury under different solar wind and interplanetary magnetic field conditions, tested against data from MESSENGER and BepiColombo first flybys of the planet. We also provide identification of regions of interest to investigate with BepiColombo from 2025.

Evidence of planetary Oxygen and Carbon ions in the outer flank of Venus magnetosheath

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On August 10, 2021, the Mercury-bound BepiColombo spacecraft flew for the second time by Venus for a Gravity-Assist Maneuver. During this second flyby of Venus, a limited number of instruments were turned on, allowing unique observations of the planet and its environment. Among these instruments, the Mass Spectrum Analyzer (MSA) that is part of the particle analyzer consortium onboard the magnetospheric orbiter (Mio) was able to acquire its first plasma composition measurements in space. As a matter of fact, during a limited time interval upon approach of the planet, substantial ion populations were recorded by MSA, with characteristic energies ranging from about 20 eV up to a few hundreds of eVs. Comparison of the measured Time-Of-Flight spectra with calibration data reveals that these populations are of planetary origin, containing both Oxygen and Carbon ions. The Oxygen observations are to some extent consistent with previous in situ measurements from mass spectrometers onboard Venus Express and Pioneer Venus Orbiter. On the other hand, the MSA data provide the first ever in situ evidences of Carbon ions in the near-Venus environment at about 6 planetary radii. We show that the abundance of C^+ amounts to about $\sim 30\%$ of that of O^+. The change in the orientation of the magnetic field suggest that these planetary ions are located in the far magnetosheath flank in the immediate vicinity of the foreshock region.

Suprathermal Electrons in Mercury's Magnetosphere

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Energetic electrons at Mercury are abundant from the lowest energies (<10 keV) to energies of hundreds of keV as shown by the MESSENGER data. In particular the low-energy (1-10 keV) suprathermal electrons were present at all local times. When the measured locations of these suprathermal electrons are plotted in simplified B versus L coordinates (where B is the magnitude of the magnetic field, L defines an axisymmetric surface of those lines of magnetic force from the dipole component of Mercury's internal field that intersect the magnetic equator at a distance L RM from the dipole center, and RM is Mercury's radius), several distinct clusters of events can be seen. The majority were near the planet's magnetic equator on the nightside of the planet, and a dawn-dusk asymmetry is clearly seen in the data. We infer all of these are signatures of accelerated electrons being injected from Mercury's tail region through reconnection and/or depolarization events and then drift around the planet to form a quasi-trapped electron distribution at Mercury.

Mercury's Magnetospheric Dynamics

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During this presentation I will give an introduction to Mercury's extremely dynamic magnetosphere, and will extend this to a discussion of recent results in modelling and data analysis. I will also look at the implications of magnetospheric dynamics on the planetary surface and environment.

MESSENGER observations of short, large-amplitude magnetic structures (SLAMS) in the Mercury foreshock

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We have investigated approximately four years of MESSENGER data to identify short, large-amplitude magnetic structures (SLAMS) in the Mercury foreshock. Defining SLAMS as well-defined structures with a magnetic field strength of at least a factor of 2 higher than the background magnetic field, when MESSENGER is located in the solar wind, we find 435 SLAMS. The SLAMS are found either in regions of a general ultra-low frequency (ULF) wave field, at the boundary of such a ULF wave field, or isolated from the wave field. We present statistics on several properties of the SLAMS, such as temporal scale size, amplitude, and polarization. We find that SLAMS are mostly found during periods of low interplanetary magnetic field strength, indicating that they are more common for higher solar wind Alfvénic Mach number (MA). We use ENLIL solar wind model data to estimate solar wind parameters to verify that MA is indeed larger during SLAMS observations than otherwise. Finally, we also investigate how SLAMS observations are related to foreshock geometry.

Mercury's Exosphere - Current Knowledge and Uncertainties

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Mercury's exosphere was discovered by the Mariner 10 mission, which found the light elements H and He. Decades of ground-based spectroscopic studies since Mariner 10, and the more recent MESSENGER mission, have detected and characterized the distribution of several additional species in Mercury's exosphere. Extensive temporal and spatial studies of the species Na, K, and Ca have been performed using ground-based telescopes. During its four Earth years in orbit, the MESSENGER Ultraviolet and Visible Spectrometer (UVVS) regularly observed Na, Mg, Ca, and H. During the last few Mercury years of the MESSENGER mission, Al, Mn, and Ca^{+} (in emission) were observed by UVVS. Finally, Al and Fe have been observed using the Keck telescope on Mauna Kea. Ground-based observations of Mercury's sodium exosphere continue, with a particular focus on measurements of the sodium tail that can constrain the loss rate and spatial distribution. Despite the years of observations, there is much that remains poorly understood regarding Mercury's exosphere, particularly in terms of the physical processes that generate and maintain the exosphere. The Ca exosphere was initially reported to be of high temperature, roughly 20,000 K, from ground-based data, with values up to 70,000 K reported from models using UVVS data. Non-thermal processes may be at work instead and need to be quantified. Analyses of UVVS data have determined a dawn-centered source for Ca, but ground-based data imply extensive Ca at high northern and southern latitudes as well as anti-sunward of the planet. Apparent differences between ground-based and space-based observations are also seen in the Na data. High-latitude peaks at northern or southern latitudes, or both, are often seen in ground-based data but have not been observed in UVVS data. This is perhaps a result of differences in viewing geometry, but recent work suggests that may not be the case. The species Al, Fe, Mn, and Ca^{+} were searched for on many occasions both from the ground and with UVVS. Although Ca^{+} was detected by UVVS during the third flyby of Mercury, these species were otherwise only observed during the last few Mercury years of the MESSENGER mission and only on a few observing runs at Keck. The reasons for the sporadic nature of these elements is unknown but they may be related to comet Encke as shown for Ca. The origins of the spatial and temporal variations in Mercury's exosphere require more investigation. The causes behind the high-latitude variability of Na and its possible correlation with the magnetic cusps need to be investigated, as should those responsible for the sporadic variability in weakly emitting and/or less abundant species like Al. Finally the interaction of the plasma environment with the surface and exosphere, and the roles of dust, meteoroid streams and cometary streams in the production of exospheric species should be elucidated to provide a more complete understanding of the source processes for the exosphere.

PHEBUS observations of the He 58.4 nm emission during Bepi Colombo's first Mercury Flyby

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We present observations of the He 58.4 nm emission performed with the EUV channel of the PHEBUS spectrometer on board ESA's Mercury Planetary Orbiter during Bepi Colombo's first Mercury Flyby in October 2021. We describe the data analysis and PHEBUS EUV calibration based on interplanetary He 58.4 nm data from observations during the cruise. We discuss the results in comparison with Mariner 10 measurements at 58.4 nm and models of Mercury's exosphere.

Electron dynamics at Mercury: acceleration, circulation and precipitation processes using a global fully-kinetic model

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Mercury is the only telluric planet of the solar system, other than Earth, with an intrinsic magnetic field. Thus, the Hermean surface is shielded from the impinging solar wind via an “Earth-like” magnetosphere. This magnetic cavity is however twenty times smaller than its counterpart at the Earth and Mercury occupies a large portion of this cavity. The relatively small extension of the Hermean magnetosphere enables us to model its interaction with the solar wind plasma using a global fully-kinetic model. Such modeling is crucial to interpret ongoing, and prepare future, observations of the joint ESA/JAXA BepiColombo mission.
The goal of this work is to study the global electron dynamics in the Hermean magnetosphere with a particular focus on charged particles acceleration, circulation and precipitation processes.
The model used in this work is based on three-dimensional, implicit, full-PIC simulations of the interaction between the solar wind and Mercury's dipole magnetic field. This model self-consistently includes plasma processes from the large planetary scale down to the electron scale.
As a first result, we find a plasma current flowing at the magnetospheric boundaries (bow shock and magnetopause) with amplitude the order of thousands of nA/m^2 dominated by electrons. Furthermore, in our simulations magnetic reconnection in the tail accelerates and heats electrons up to tens of keV in the case of southward interplanetary magnetic field (IMF). These electrons are ejected from the neutral line in the tail planet-ward in a substorm fashion. They start drifting dawn-ward around the planet forming a quasi-trapped population in the nightside and - eventually - a large fraction of those falls on the planet surface. We also show comparisons between our simulations and in-situ observations by Mariner10 and BepiColombo space missions We argue that these electrons have been observed in-situ by Mariner10/PLS instrument during its first Mercury flyby around and after closest approach. A similar population, although fainter, have been observed by BepiColombo/MEA instrument in the nightside magnetosphere. To conclude, we show maps of electron precipitation on Mercury's surface and discuss them in comparison with MESSENGER/XRS observations of Calcium X-ray fluorescence emission from the surface.

Modelling Mercury's exospheric sodium seasonal variability

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The sodium component is the most observed element of Mercury's exosphere. First detected from ground based observatories, it appears peaking in emission intensity at high latitudes and to be variable on hour time scale. The large set of ground based observations obtained during many consecutive years also leads to the characterization of the dependency of the emission sodium intensity with respect to its position along Mercury's orbit around the Sun. Such picture was significantly changed by MASCS/MESSENGER 4 years of observations around Mercury. Focusing on the equatorial regions, MASCS provided a different view of Mercury's sodium exosphere, highlighting a surprisingly steady radial subsolar profile of the emission intensity in contradiction with the high latitudinal variable component observed from the Earth. Moreover, MASCS observed an equatorial dawn/dusk asymmetry opposite between Mercury's inbound portion and outbound portion of its orbit. Such variation of the dawn/dusk asymmetry contradicts somehow the idea that Mercury's sodium exosphere should be partly driven by a global day to nigh sides circulation induced by the solar radiation pressure. Indeed, such circulation should lead to a systematically more intense emission at dawn than at dusk, even if variable along Mercury's orbital position. To reconcile observations and modelling, each potential driver of Mercury's sodium exosphere needs to be reviewed in order to find out what controls the fate of the sodium around Mercury.

Strofio Status and Measurements Outlook

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The mass spectrometer Strofio onboard BepiColombo will perform detailed measurements of the chemical composition of Mercury's exosphere. The time and spatial variations of the composition signal will deliver important information about the mechanisms responsible for creating and maintaining the exosphere.
The instrument suffered an unexpected high voltage problem, but we were able to identify workarounds that should be sufficient to recover most (if not all) the performances necessary for achieving the goals of the experiment.

Coordinated campaign of ground-based observations of Mercury's exosphere in 2021

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In October-November 2021 a ground-based campaign measuring the exosphere of Mercury took place with participation from four different facilities in the US and in the Canary Islands.

In daylight, the THEMIS and Dunn solar telescopes mapped sodium and potassium at high spectral resolution. In twilight, Mercury's Na tail was measured with a long-slit spectrograph at the Apache Point 3.5m telescope between 3-15 Mercury radii, and with the IoIO coronagraphic imager out to more than 100 Mercury radii.

Each of these facilities has specific capabilities and their synoptic use can provide global coverage of the morphology of the exosphere of Mercury:

- Daylight observing is a means to regularly measure the exosphere above the disk of Mercury, and the new adaptive optics system at THEMIS and Rapid Imaging Planetary Spectrograph at Dunn will help facilitate such observations.
- Measurements of the escaping Na tail constrain the budget of sources and sinks in the exosphere and help identify transient enhancements from ion sputtering or meteor impacts, as with higher energy such enhancements preferentially escape.

We will show the results obtained up to now, with a special focus on the two days in which all four facilities were observing at the same time.

BepiColombo First Mercury Fly-by: first taste of the mission results on investigation of the environment around the planet

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The ESA-JAXA BepiColombo satellite suite has passed by its target planet Mercury for the first time on 1st October 2021. The trajectory was in the southern hemisphere from nightside dusk toward dayside dawn, thus crossing the magnetosheath, the magnetotail, nightside plasma sheet and exiting in dayside dawnward magnetopause and bow shock. It explored, for the first time, regions never observed by other spacecraft in the past. All the instruments able to perform science observations in cruise configurations have been operated providing the first observations of Mercury's inner southern magnetosphere and surrounding regions. These observations include magnetic fields, solar wind and magnetospheric ions and electrons in different energy ranges, plasma waves, energetic particles and exosphere. During the pass, BepiColombo encountered a low interplanetary magnetic field and low energy solar wind. Unexpected interesting signals have been observed in the solar wind before the magnetospheric bow shock, at the magnetopause inbound as well as in the outbound solar wind. This paper will present a general overview of the observations, just as a first taste of the great results expected from this mission.

Micro-meteoroids impact vaporization (MMIV) as source for Ca and CaO exosphere along Mercury's orbit

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The study of the micro-meteoroid environment is relevant to planetary science, space weathering of airless bodies, as Mercury, and their upper atmospheric chemistry. In this case, the meteoroids hit directly the surface without any interaction with the atmospheric particles, producing impact debris and contributing to shape its thin exosphere.
The study of the generation mechanisms, the compositions and the configuration of the Hermean exosphere will provide crucial insight in the planet status and evolution.
This work is focused on study and modelling of the Mercury's exosphere formation through the process of Micro-Meteoroids Impact Vaporization (MMIV) from the planetary surface.
The MESSENGER/NASA mission visited Mercury in the period 2008-2015, providing measurements of unprecedented quality of Mercury's exosphere, which permit the study of the seasonal variations of metals like Calcium. The Ca in Mercury's exosphere exhibited very high energies, with a scale height consistent with a temperature $>$ 20,000 K, seen mainly on the dawnside of the planet. The origin of this high-energy, asymmetric source is unknown.
The generating mechanism is believed to be a combination of different processes including the release of atomic and molecular surface particles and the photodissociation of exospheric molecules.
In this paper we work on models of Mercury's impactors: we provide a detailed Ca-source extraction model simulating the expected 3-D Ca density distribution in Mercury's exosphere due to the MIV mechanism. A prototype of the Virtual Activity (VA) SPIDER (Sun-Planet Interactions Digital Environment on Request) services is used as a Monte Carlo three-dimensional model of the Hermean exosphere to simulate the bombardment of Mercury's surface by micrometeorites and to analyze particles ejected.
We study how the impact vapor varies with heliocentric distance and compare the results to the MESSENGER observations. The morphology of Mercury's Ca and CaO exosphere is in good agreement with the observed Ca along the orbit, excluding specific events like comet stream crossing.
The results presented in this work will be useful for the exosphere observations planning and for the data interpretation in the frame of the ESA/JAXA BepiColombo mission, that will study Mercury orbiting around the planet from 2025. More specifically, the resulting molecular distributions will be compared to the measurements of the SERENA-STROFIO

mass spectrometer that will be the only instrument able to identify the molecular components.

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Yearly variability of Mercury's exosphere: comparison of the Na and Ca cases

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The surface of Mercury is exposed to several processes that induce and/or modulate the release of gas into its thin atmosphere (exosphere): solar radiation, solar wind plasma and meteoroids precipitation. All these phenomena have a strong temporal and spatial variability; in some cases, there is a clear link with the true anomaly angle of Mercury, so that there is, in general, a yearly periodicity in the exosphere variability for almost all species. Here we focus on two different and quite opposite cases, the Calcium and Sodium components of the exosphere. The first is a paradigm for an exosphere that is strongly linked with the meteoroid and micrometeoroid precipitation, so that there is little need to consider or model the uppermost surface layer properties. The second, Sodium, is much more complex. For example, there is general agreement that a model of Sodium abundance is needed to explain the Na temporal variability, and that possibly more all surface processes should be accounted in a combined way. Still, recent analysis of the NASA MESSENGER mission and ground-based dataset revealed that the observed cycle of sodium has periodic afternoon enhancements that current models cannot explain. Hence, we focus this study on the improvements that an updated Na composition and surface thermal model could possibly bring to the agreement between models and data.

Updated status and results of BepiColombo/Mio during interplanetary cruise phase

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The ESA-JAXA joint mission BepiColombo is now on the track to Mercury. After the successful launch of the two spacecraft for BepiColombo, Mio (Mercury Magnetospheric Orbiter: MMO) and Mercury Planetary Orbiter (MPO), commissioning operations of the spacecraft and their science payloads were completed. BepiColombo will arrive at Mercury in the end of 2025, and it has 7-years cruise with the heliocentric distance range of 0.3-1.2 AU. The long cruise phase also includes 9 planetary flybys: once at the Earth, twice at Venus, and 6 times at Mercury. Even during the interplanetary cruise phase, the BepiColombo mission can contribute to the heliospheric physics and planetary space weather in the inner solar system. In addition, NASA's Parker Solar Probe was launched in 2018 and it is orbiting around Sun (∼0.05 AU at perihelion). ESA's Solar Orbiter was launched in February 2020 and will have a highly elliptic orbit between 1.2 AU at aphelion and 0.28AU at perihelion. These multi spacecraft observations provide us great opportunities to investigate the inner heliosphere. In 2021 science observations by Mio during the second Venus flyby and the first Mercury flyby were successfully performed on 10 August 2021 and on 1 October 2021, respectively. The second Mercury flyby is planned on 23 June 2023. Here we present the updated status of BepiColombo mission, initial results of the science observations during the interplanetary cruise and planetary flybys, and the upcoming observation plans.

Remote sensing of Mercury sodium emission and relationships with magnetospheric activity

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The THEMIS ground-based solar telescope performed several Mercury sodium emission remote sensing campaigns during times when the MESSENGER spacecraft was orbiting around the planet, in between 2011-2013. By taking profit from local magnetic field measurements as taken by MESSENGER, the typical two-peaks sodium emission detected by means of one-hour scans images of the day-side planet, as performed by THEMIS, have been statistically related to the local IMF intensity and direction. In this presentation, we show how the Mercury magnetosphere structure reacts to the IMF features, in terms of reconnection and ion precipitation rates. We show that the sodium polar emission can be interpreted as a perfect tracer of such dynamics, so that in this way, ground-based remote sensing makes Mercury a permanent monitor of the solar activity in the inner heliosphere.

The scenic tour of the Venusian magnetosheath by BepiColombo

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With the 2nd Venus flyby by BepiColombo on August 10th 2021, we had the rare opportunity to make a complete tour of the Venusian magnetosheath: one of the few gas-dynamic dominated solar wind-object interaction regions in the Solar System. The flyby passed through the full magnetosheath, from the nightside flank towards the stagnation region near the subsolar point and out through a quasi-perpendicular bow shock. The flyby was made during the extremely rare opportunity when Solar Orbiter was located upstream, close to Venus, due to its Venus flyby the day before. Solar Orbiter could therefore provide complementary solar wind measurements, which showed very stable conditions during the BepiColombo flyby. The rare spacecraft configuration and the stable conditions provided new intel on the stagnation point at near solar minimum conditions, as measured by seven plasma and magnetic field instruments on BepiColombo. The measurements show a stagnation region expanded to large distances from Venus, which confirms that Venus is fully capable of withstanding the solar wind even at near solar minimum conditions.

Some useful orbits around Mercury for scientific missions

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There are many researches that should be done in the exosphere and magnetosphere of Mercury, but most of them require close observations that can be done only by a spacecraft around Mercury. Many of those observations benefit from long durations data collecting, which means to keep the spacecraft in orbit as long as we can. An important limitation for the duration of a space mission is its capability to make orbital maneuvers to correct orbit shifts due to the several perturbing forces acting in the spacecraft. In this way, the search for adequate orbits for these spacecraft is very important for a successful exploration of Mercury. An "adequate orbit" means an orbit where the natural forces acting in the spacecraft minimizes orbit shifts, therefore reducing the need of orbital maneuvers, so extending the lifetime of the mission.

In this way, the present research proposes the use of solar sails to control those orbits. It is an engine which propulsion is based in the solar radiation pressure to move the spacecraft. The main goal is to provide a large and flat reflective film with minimum structural support. The dynamics includes the non-sphericity of Mercury, the gravitational perturbation from the Sun and the solar radiation pressure. The approach is to make plot maps to search for frozen orbits (which are orbits with smaller variation of the orbital elements) with long durations around Mercury. In this way, sets of initial conditions that generate orbits that may contribute with the scientific missions that will visit the planet Mercury in the next years are found.

The dynamics considers the J2 and J3 zonal terms and the C22 sectorial term of the gravity field of Mercury, which is assumed to be orbiting the Sun in an elliptical and inclined orbit. To obtain the equations of motion of the spacecraft, it is used the double-averaged analytical model to reduce the degrees of freedom of the system by eliminating the short-period terms coming from the motion of the spacecraft and the third body.

The results identified frozen orbits that have smaller amplitudes in the variations of the orbital elements, in particular eccentricity, inclination and argument of the periapsis. One example of a set of initial conditions that generate an interesting orbit is: semi-major axis 2700 km, inclination 90 degrees, argument of periapsis 270 degrees, longitude of the ascending node 90 degrees and eccentricity 0.02159. Orbits like that may contribute to missions similar to the BepiColombo, because its orbital elements are less disturbed. We also make maps to identify important low-altitude regions around Mercury to place a spacecraft. It is observed the higher impact of the J3 term and the contribution of the C22 term to decrease the disturbing effect in the region. Frozen orbits in different altitudes are found, which give more flexibility to mission designers.

Revised Modular Model of Mercury's Magnetospheric Magnetic Field

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Mercury is the smallest an innermost planet of our solar system and has a dipole-dominated internal magnetic field that is relatively weak, very axisymmetric and significantly offset towards north. Through the interaction with the solar wind, this field leads to a magnetosphere. Compared to the magnetosphere of Earth, Mercury's magnetosphere is smaller and more dynamic. To understand the magnetospheric structures and processes we use in-situ MESSENGER data to develop a semi-empiric model, which can explain the observations and help to improve the mission planning for the BepiColombo mission en-route to Mercury.

We will present this semi-empiric KTH-model, a modular model to calculate the magnetic field inside the Hermean magnetosphere. Korth et al. (2015 and 2017) published a model, which is the basis for the KTH-Model. In this new version, the calculation of the magnetic field for the neutral current sheet is restructured based on observations rather than ad-hoc assumptions so that the description is more realistic. Furthermore, a new model is added to depict the partial ring current. An analysis of the residuals shows a better visibility of the field-aligned currents. In addition, this model offers the possibility to improve the main field determination.

Observations of Mercury's Exosphere during BepiColombo First Mercury Flyby with PHEBUS' visible channels

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During the first flyby of Mercury with BepiColombo in October 2021, the ultraviolet spectrometer PHEBUS (Probing of Hermean Environment By Ultraviolet Spectroscopy) was able to observe with the two visible channels centered at 404 nm (K line) and 422 nm (Ca line). The observation started 30 minutes before Closest Approach and lasted one hour. The results clearly depict the geometry of observation, the spacecraft moving from the nightside of Mercury to its dayside. We also see some bursts on the count rate after the exit of Mercury's shadow, and discuss possible correlations with dust particles or the crossing of magnetospheric structures. We distinctly detect Calcium at 422nm and compare these results with MESSENGER data and an exospheric model.

Characterizing plasma turbulence in the Hermean environment (and beyond)

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Turbulence is ubiquitous in astrophysical plasmas. It is thought to play a major role in accretion flows around compact objects (e.g., black holes), star formation in the ISM, solar corona heating and solar wind (SW) acceleration. In planetary magnetospheres, turbulence enhances particle energization in various key regions (cusp, magnetotail, ...) and impacts SW particle entry through magnetic reconnection at the magnetopause.
Here we review some results obtained using on Messenger data on characterizing plasma turbulence in various regions of the Hermean environment, both at large (MHD) scales and sub-ion (kinetic) scales. This includes the compressible vs. incompressible nature of the turbulence, their spectral properties and the role of ion-scale instabilities. We will confront the results to previous ones obtained in the SW and other planetary magnetospheres. A focus will be put on the range of scales where the 1/f spectrum is observed. We provide solid theoretical and observational evidence of the role of magnetic reconnection in driving sub-ion scale turbulence even in the absence of a fully developed turbulence in the inertial (MHD) range. Prospects on using the upcoming data from the BepiColombo missions in completing and extending these studies will be discussed.

Venus and Mercury fly-by observation by MPPE-MIA on BepiClombo/Mio

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The Mercury Plasma/Particle Experiment (MPPE) is a comprehensive instrument package on BepiColombo/Mio spacecraft for plasma, high-energy particle and energetic neutral atom measurements. It consists of 7 sensors: two Mercury Electron Analyzers (MEA1 and MEA2), Mercury Ion Analyzer (MIA), Mass Spectrum Analyzer (MSA), High Energy Particle instrument for electron (HEP-ele), High Energy Particle instrument for ion (HEP-ion), and Energetic Neutrals Analyzer (ENA). During the Venus and Mercury fly-bys most of the MPPE analyzers including MIA were turned on and made observation of Venus induced magnetosphere and Mercury Magnetosphere though most of the field of view of the MPPE analyzers were blocked by MOSIF (MMO Sunshield and Interface Structure) before arriving at Mercury in December 2025. MEA, MIA, MSA, HEP-ele, and ENA successfully made observations during Earth fly-by in April 2020, Venus fly-by #1 and Venus fly-by #2 in October 2020 and August 2021, respectively, and Mercury fly-by #1 in October 2021.
MIA that measures 3D phase space density of low energy ions between 15eV/q and 29keV/q was developed for understanding (1) structure of the Mercury magnetosphere, (2) plasma dynamics of the Mercury magnetosphere, (3) Mercury - solar wind interaction, (4) atmospheric abundances, structure, and generation/loss process, and (5) solar wind between 0.3 and 0.47 AU. In order to achieve these science objectives, MIA was designed to measure the three-dimensional distribution function of both solar wind ions around Mercury, and Mercury magnetospheric ions. After experiencing Earth fly-by and 1st Venus fly-by, the necessity of modifying the MIA flight software in MDP (Mission Data Processor) was identified. Although the output range of the onboard calculated ion velocity moment is limited, the definition of the output range was not optimum. The new software was successfully uploaded on 22 June 2021. MIA succeeded in observing low energy ions in the induced magnetosphere and ionosphere of Venus during Venus fly-by #2. MIA observed ∼20-second periodic low energy ion flux in the Mercury magnetosheath - magnetosphere boundary where magnetosheath ions and magnetosphere ions seem to co-exist. MIA also observed the similar ion signature that is usually observed in crossing the separatrix of the magnetic reconnection in the Earth's magnetotail.
We are planning to turn on most of the MPPE analyzers including MIA during the future Mercury fly-bys scheduled in June 2022, June 2023, September 2024, December 2024 and January 2025. The observation with full performance of MIA will start after Mio's arrival at Mercury in December 2025.

Magnetic evidence for an extended hydrogen exosphere at Mercury

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Remote observations by the Mariner10 and MESSENGER spacecraft have shown the existence of hydrogen in the exosphere of Mercury. However, to date the hydrogen number densities could only be estimated indirectly from exospheric models, based on the remotely observed Lyman-α radiances for atomic H, and the detection threshold of the Mariner10 occultation experiment for molecular H_2. Here we show the first on-site determined altitude-density profile of atomic H, derived from in-situ magnetic field observations by MESSENGER. The results reveal an extended H exosphere with densities that are $\sim 1-2$ orders of magnitude larger than previously predicted. Using an exospheric model that reproduces the H altitude-density profile, allows us to constrain the so far unknown H_2 density at the surface which is $\sim 2-3$ orders of magnitude smaller than previously assumed. These findings demonstrate the importance (1) of dissociation processes in Mercury's exosphere and (2) of in-situ measurements giving complementary evidence of processes to remote observations, that will be realized in the near future by the BepiColombo mission.

Impact Events Observed by MESSENGER UVVS

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Each species in Mercury's exosphere exhibits a different, but seasonally repeatable pattern. Episodic events that augment this behavior have been challenging to isolate within the UVVS data. Here we identify and simulate three such events: one dayside and two night side. All are consistent with ∼10 cm size impactors that ejected just a few kg of measureable vapor. Fast decay times of these vapor plumes are poorly reproduced by simulations where the atoms bounce across the surface, as expected for cold night-side surface interactions. Spectra of multiple species were obtained for one event showing Na and Mg in a ratio of 3, stoichiometric with their local ratio in the topmost soil. Both gases were enhanced several times above the nominal background, but Ca showed no deviation from the steady state exosphere. This non-response may reflect that it condenses into a molecular form within impact ejecta (e.g., CaO or CaS) since photolysis of these products is absent in shadow. Plume expansion rates indicate that the gas is surprisingly hot with ∼10,000K Na and ∼15,000K Mg best reproducing the UVVS tail sweep measurements. Overall, it is impressive that modest impact events which occur about daily in frequency can produce such strong features in the exosphere, but discerning these signatures from the background relies on observing geometry that is serendipitous in the right place and time. The findings here hold promise that PHEBUS and MSASI will encounter similar impact ejecta plumes during the BepiColombo orbital mission.

Space Weathering of Icy Volatiles within North Polar Permanently Shadowed Regions

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Mercury has an intrinsic magnetic field which generates a magnetosphere around the planet. The solar wind interacts with Mercury's magnetosphere causing the formation of large-scale structures known as magnetic cusps, which are funnel-shaped areas of focused magnetic field that converge toward the dayside planetary surface at high latitudes. Magnetospheric dynamical processes result in the cusp being filled with energetic charged particles and because Mercury lacks an atmosphere or ionosphere, these energetic ions and electrons are funneled down the cusp precipitating directly onto the surface of the planet. The latitudinal location of the cusp footprint on the planet varies with solar wind conditions, in particular with the interplanetary magnetic field (IMF) direction. Since Mercury's internal magnetic dipole is offset to the north by about 480 km, when the IMF is directed northward the northern cusp moves to very high latitudes greater 75 degrees, mapping directly onto the northern polar region. Craters near the poles contain permanently shadowed regions (PSRs) which allow frozen water ice mixed with organic molecules to exist over long timescales. The energetic precipitating particles can induce chemical radiation processing of the icy volatiles into higher-order organics and dark refractory materials overlaying the water ice. Global kinetic magnetospheric simulations in conjunction with MESSENGER spacecraft data are used to characterize the fluxes and energies of the precipitating particles in Mercury's magnetospheric cusp region and the resulting space weathering interactions with the icy volatiles in the PSRs at high northern latitudes. MESSENGER data and numerical simulation results will be presented along with a discussion of the data gaps expected to be filled by BepiColombo observations.

Collisional acceleration of Mercury's sodium exosphere in MMIV-produced clouds

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Although the tenuous atmosphere (exosphere) of Mercury is basically collisionless, it can be locally and transiently in a collisional regime in vapor clouds produced by meteoroid impact vaporization (MIV) or micro-meteoroid impact vaporization (MMIV). For the typical size and impact velocity of micro-meteoroids from Jupiter-family comets, the spatial and temporal scales of the collisional clouds are so small, on the order of meters and milliseconds, respectively, that the effect of collisions in the vapor clouds on the velocity distribution of the background exosphere has been often ignored in previous studies. In this study, we evaluate a cumulative effect of collisions in the MMIV-produced clouds on the velocity distribution of exospheric molecules using a Direct Simulation Monte-Carlo (DSMC) model. We will discuss possible modifications of the distribution of Mercury's sodium exosphere and its dependence on TAAs.

Mirror Modes in the Hermean Magnetosheath

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Mirror modes are quasi-stationary structures in the plasma frame, consisting of a train of magnetic depressions combined with plasma density enhancements. They are created by a temperature asymmetry in the plasma, where the perpendicular temperature (with respect to the magnetic field) is higher than the parallel temperature. These structures are ubiquitous in planetary magnetosheaths, and have been detected at Venus, Earth, Mars, Jupiter and even at comets. Similar structures to mirror modes are magnetic holes, usually born in the solar wind upstream of the shock and can be transported into the magnetosheath (Karlsson et al., 2021). Here we study magnetic field data during the orbital phase of the MESSENGER mission at Mercury to identify mirror mode-like structures with a magnetic-field-only method. Properties of mirror mode structures will be compared to those of isolated magnetic holes observed in the magnetosheath earlier, to investigate if they are related phenomena.

Modeling the impact of a strong X-class solar flare on the planetary ion composition in Mercury's magnestosphere

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Solar flares could potentially give rise to sudden changes in the planetary ion composition in Mercury's magnetosphere. We model the time-dependent evolution of the Mg^{+}, Na^{+}, O^{+} and He^{+} ion density distribution during the extreme X9.3-class solar flare event on 6 September 2017 with the Latmos Ionized Exosphere (LIZE) model. We find that the peak ion density in the nightside plasma sheet is delayed by $\sim 7-8$ min compared to the dayside, and that the maximum Mg^{+} density occurs ~ 4 min before He^{+} and O^{+} in the whole magnetosphere. We also find that there exist two ion energy populations on the dayside which experience different dynamical evolution during the event.

Mercury's Magnetopause as a Tool for Understanding the Planet's Interior

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An electric current is driven on the magnetopause boundary of Mercury by interactions between the dayside Hermean magnetosphere and the solar wind with the embedded interplanetary magnetic field (IMF). Electromagnetic induction processes, due to external solar wind forcing resulting in magnetopause motion or magnetopause current structure changes, have been proposed as methods to determine the interior structure of Mercury. We developed a physics-based model of the Hermean magnetopause current system and its resulting magnetic field and used it to assess the impact solar wind forcing has on the magnetopause's inducing field. The model was successfully compared to previous modelling work and observations from the MESSENGER mission. Using synthetic transient solar wind events and real solar wind conditions observed by Helios 1 and 2 as inputs to the model, we determined that the response of the magnetopause current structure and its resulting inducing field was impacted more by IMF variability than changes in the solar wind dynamic pressure. Helios data suggests solar wind conditions are highly unpredictable and there is a broad range of frequency signals in the solar wind that could be used to probe to different depths within the planet. In future, we hope to further validate this model against in situ measurements of Earth's magnetosphere. The BepiColombo mission's arrival at Mercury in 2025 will allow the response of the magnetopause's system to external solar wind forcing to be further explored as a method of determining Mercury's interior structure.

Theme 2: Surface geology and composition

The lack of hollows in the Mercury's high-reflectance red plains

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MESSENGER mission to Mercury led to the discovery of hollows. These geological landforms have no close counterpart on other airless silicate bodies. Hollow mostly occur (84.5%) within impact craters and their proximal ejecta while they are rarely found (7%) in high-reflectance red plains (HRP) (Thomas et al., 2014). Their texture and geological setting are suggestive of formation via destruction of a volatile-bearing phase through space weathering processes or sublimation by heating on contact with, or in proximity to, impact melt or volcanic materials (Blewett et al., 2013). Multispectral images and geochemical measurements suggest that hollows are formed by the loss of sulfur-bearing minerals such as CaS or MgS (Vilas et al., 2016). Reflectance spectra of hollows obtained by the Visible and Infrared Spectrograph (VIRS), component of the Mercury Atmospheric and Surface Spectrometer (MASCS) lack absorption features (Barraud et al., 2020). However, MASCS/VIRS spectra show a strong concave curvature between 300 and 600 nm, unique to hollows material (Barraud et al., 2020).

In this work, we present a comparison between reflectance spectra of hollows at high spectral resolution and laboratory spectra of Mercury's analogs: sulfides, silicates and graphite. Our main objectives are, first, to bring new constraints on the mineral phases and volatile species associated with hollows and then, to further constrain the possibility that hollows are associated with some geochemical and/or spectral units. The best candidates to reproduce the curvature of the hollows' spectra are CaS, MgS and Na2S. We conduct further work using spectral modelling to quantify the sulfide concentrations in hollows. Our results show that the concentration of sulfides in hollows material is up to two times higher than the sulfides' concentration derived from chemical measurements in Mercury's HRP. This study brings for the first time a spectral and compositional argument for the lack of hollows in the HRP of Mercury.

Landform analysis and age determination of craters in the North pole regions of Mercury

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The Earth-based radar observations performed by Goldstone-VLA 70m dish revealed high radar backscattered areas in the Mercury's North polar terrains (Butler B. et al., 1993) which correspond to the permanently shadowed regions (PSRs) of impact craters. These radar-bright materials have been interpreted as water ice deposits due to their similarity with similar features observed on Martian polar ice caps. This interpretation is also supported by thermal models developed by Paige (1992), showing that the Hermean polar environment is capable of hosting stable water-ice deposits at geologic timescales within the near-surface layers. Furthermore, multiple datasets from the MESSENGER mission measured high hydrogen concentrations in these regions, providing additional support to the water ice nature of the radar-bright materials (Chabot N. et al,2018a).
The analysis of such craters can thus provide new insights into both the behavior of water ice deposits and the surface evolution. For this reason, we have investigated fourteen craters located at latitude over 80° N with diameters ranging from 17 to 45 km. We have firstly performed a high detailed geomorphological map of each impact crater using the highest resolution MDIS (Mercury Dual Imaging System) images. In particular we identified different areas that have the same characteristics of tone, texture and structure as Geological Units. In addition, we mapped the landforms associated with gravitational and impact morphogenesis. This analysis allowed to highlight the two following morphological trends: (i) eight craters characterized by the typical complex morphology, with central peaks and flat floors and landslides extending along the inner walls, dominated by terraces and trenches, and (ii) six craters lacking both terraced walls and central peaks, but with smoothed walls and flat floors. Successively, we focused on the crater's retention age to derive the chronostratigraphic relationship between the studied impact structures. We performed crater counting with the purpose of dating both the ejecta and floor of each crater. The floor was subdivided into two areas, one corresponding to the bright radar deposits and the other without these deposits. A preliminary correlation between age and radar-bright material extent highlights that the oldest craters have more than 30% of the floor occupied by such deposit. Furthermore, the preliminary results outlined a general trend of rejuvenation of the crater floor with respect to the ejecta and, in particular, the part of the floor occupied by the radar appears to be younger. Such inhomogeneity of the floor age respect to the ejecta age could be related to morphological factors, such as resurfacing caused by landslides from the crater or thermal and illumination factors that could have led to a different deposition and persistence of water ice and, thus, different floor responses.

Updating the Mercury Mean Spectra using 4.7 millions MASCS Spectra

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Equipped with a suite of instruments looking for observing Mercury's surface, the MESSENGER mission was able to retrieve resolved reflectance spectral parameters of most of the planet during its 5 years in orbit. Of particular interest are the ultraviolet-visible to near-infrared properties, which are diagnostic of Mercury's diversity. Using the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) instrument, the MESSENGER science team was able to define the average spectral response of Mercury's surface from 300nm to 1400nm (Izenberg et al. 2014). This work makes use of more than 850 000 spectra acquired during the primary mission. Together with Mercury's average spectra, the authors also characterized the spectral properties of various geological units (e.g. pyroclastic deposits, hollows, etc.). The spectral properties of Mercury's units can also be compared to measurements derived from the Mercury Dual Imaging System (MDIS) imagers (Murchie 2018). While the absolute values may differ (for instance due to systematic differences in observing geometries and thus photometric corrections with a higher phase angle reprojection used for MASCS), the overall trends remain the same between the two instruments.

In this work, we present a revisited analysis of the Mercury Mean Spectra (MMS) together with spectral characteristics of Mercury geological and geochemical units. With respect to the previous analysis (Izenberg et al. 2014, Murchie et al. 2018), we make use of all the observations from the MASCS spectrograph from all mission phases (i.e. up to 4.7 million observations). Spectral properties are defined from 300nm to 1400nm using an improved inter-calibration of the two spectral channels (Besse et al. 2015). Analysis done after the end of the MESSENGER mission have allowed the scientific community to be more accurate in defining units on the surface of Mercury. Numerous units have been determined, for example, by geological/morphological (i.e. basins, this conference Doressoundiram et al 2022, Caminiti et al 2022) and/or geochemical boundaries (i.e. High-Mg region). Making use of the Mercury Surface Spectroscopy (MeSS) architecture (this conference, Munoz et al. 2022, Cornet et al. 2022) we can select more accurately and in greater number MASCS footprints that provide the representative spectral properties of a given unit. This methodology, by greatly increases the number of spectra used and improves significantly the signal-to-noise of the resulting average spectra.

The improved characterization of Mercury's spectral units lets us better understand the properties of Mercury's surface, and potential links to laboratory measurements. As shown in the case of hollows (this conference, Barraud et al 2022), the determination of an accurate average spectra for hollows (and other spectral units) is a necessary step in using laboratory measurements to decipher the chemical and physical properties of Mercury's surface.

Prevalence and Significance of Ejecta Flows on Mercury: A Global Survey

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Impact ejecta flows are found on rocky planets, and some icy moons. In contrast to ballistically emplaced ejecta, which thins exponentially from crater rims, ejecta flows have a layered morphology with steeper margins, often lobate in shape. This fluidized morphology is thought to result from deposition by ground-hugging flows. On Mercury, seven ejecta flow deposits were reported by Xiao and Komatsu (2013), described as single layer deposits, extending into adjacent, older craters. These flows could have occurred during the impact process, or afterwards by mass-wasting. Hokusai crater also has an apparent ejecta flow (Barnouin et al., 2015), but by contrast it occurs on relatively flat ground and does not flow into an adjacent crater.

Here we present a global survey of Mercury identifying 36 craters with ejecta flows and a further 27 probable examples. The majority occur around craters ∼30-80 km in diameter and are widespread across the planet. All but two of the ejecta flows appear to extend into adjacent craters or other topographic lows. In addition to Hokusai, an unnamed crater, also on the northern plains, has an ejecta flow on relatively flat ground ($<2^\circ$ slope) and not extending into an adjacent crater. These two flows look distinct from other examples on Mercury, resembling single-layer ejecta craters on Mars, with distal ramparts and a ropey texture. The prevalence of Mercurian ejecta flows shown by this survey is also of note, representing at least a fourfold increase in the number of known flows.

For ejecta flows on Mars, Earth, and some icy moons, volatiles are proposed to drive the fluidization of the flow. As Mercury has volatile-bearing materials at the surface, these could be a factor in ejecta fluidization. However, we find no evidence for volatile involvement, and features indicative of local volatile concentration (e.g. hollows) don't occur preferentially near to ejecta flows. Slope of local terrain is clearly a major factor in influencing ejecta flow development on Mercury, since most flows extend downslope into adjacent craters. Perhaps some flows are post-impact mass movements, rather than forming during the impact process. However, other work shows that for at least one example, the time of emplacement was contemporaneous with impact (Lennox et al., this meeting).

Of the flows on low slopes, Hokusai crater exhibits evidence of excess impact melt: a possible fluidizing agent (Barnouin et al., 2015). However, the other crater with a flow on relatively flat ground has no identifiable impact melt present outside the crater rim. The crater is also considerably smaller than Hokusai (∼37 km vs 95 km diameter), and smaller craters tend to have proportionally less impact melt. Understanding how this crater's ejecta flow formed would give insight into the factors influencing ejecta fluidization on Mercury, as for this crater the slope of local terrain, volatile presence, and impact melt excess do not appear to be obvious factors.

Simulating micrometeoroid bombardment of Mercury analog samples

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Space weathering (SW) refers to continuous processes like solar wind irradiation and micrometeoroid (MM) bombardment that cause the alteration of airless surfaces across the solar system (Pieters and Noble 2016). The effects of SW vary depending on the initial planetary surface composition (Lantz et al. 2017). The microstructural, chemical and spectral effects of SW are fairly well-understood for the Moon and S-type asteroids but are far less-constrained for Mercury and other highly reduced parent bodies like E-type asteroids. Mercury has a unique surface composition (low Fe/high volatile content wrt. the Moon). Its proximity to the Sun results in a more intense solar wind flux, and the high-flux and velocity nature of its MM impactors population (Cintala et al. 1992) create an extreme SW environment, which require further investigation through laboratory experiments.

In this work, we considered several forsteritic olivine pressed-powder pellets samples with different FeO contents but similar grain size (45-125 μm): SC-001 (San Carlos olivine, Fo_{90-91}), F-T-004 (0.53 wt.% Fe) and F-S-002 (0.05 wt.% Fe). All samples were mixed with powdered graphite (5 wt.%) to reproduce the high amount of carbon on Mercury, as seen in the LRM. Here we focus on pulsed-laser irradiation of the samples to simulate the short duration high-temperature events associated with MM impacts on the surface of Mercury. Each sample has been irradiated by a Nd-YAG laser (1064 nm, ~6 ns pulse duration, energy of 48 mJ/pulse) with 1 and 5 pulses under ultra-high vacuum. See (Thompson et al. 2021) for more details.

The SC-001 sample has a higher near-infrared (0.65-2.5 μm) reflectance and a deeper 1 μm band after 1 laser pulse than originally, but these parameters decrease to their lowest value after 5 pulses. F-T-004 initially has a blue spectral slope but becomes redder and brighter with the continued laser irradiation dose. The same trend is observed for F-S-002, with more significant reddening and brightening after irradiation.
Analyses with scanning electron microscopy revealed two main textures in the irradiated samples: one is carbon-rich and fluffy, the other is a melt containing vesicles. Further analyses with energy dispersive X-ray spectroscopy in the transmission electron microscope showed the carbon-rich texture is composed of several C-globule-like deposits distinct from the original graphite, and the melt contains a uniform, amorphous material, rich in Si and poor in Mg and O.

Our results confirm the effects of SW on optical, morphological, microstructural and chemical properties of airless surfaces are intimately dependent on their composition. By considering low-Fe samples, we reproduced results from previous graphite-free SW studies (e.g., reddening of NIR spectra, presence of nanoparticles in the melt layer (Sasaki and Kurahashi 2004; Trang et al. 2018)) and we also observed new features like carbon-rich fluffy textures due to the presence of graphite.

Evolution of Mercury's crust: A common process for the formation of smooth plains associated with impact basins

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Impact basins have a significant role in modifying Mercury's surface, notably through the redistribution of material. They provide access to vertical heterogeneities in the crust and allow the sampling of deep units such as the ancient graphite crust of Low Reflectance Material (LRM) buried under the volcanic resurfacing (Klima et al., 2018). However, impact basins and large craters can also be modified after their formation by the emplacement of younger layers. It appears that several impact basins are filled with a smooth, volcanic in origin, High-reflectance Red Plains (HRP). Moreover, some basins are surrounded by a smooth Low-reflectance Blue Plain (LBP) for which the origin is still uncertain between impact melt or volcanism (Whitten et al., 2015; Rothery et al., 2017). This work presents a study of 4 impact basins currently showing HRP, LBP and LRM. We aim to understand whether their actual similarities are due to the initial composition of their location area or whether there is a common process to their formation independent of the location at the surface.

We mapped HRP, LBP and LRM units using multispectral images obtained by the Mercury Dual Imaging System (MDIS) and spectral observations acquired by the Mercury Atmospheric and Surface composition Spectrometer (MASCS) onboard MESSENGER. MASCS/VIRS data used in this present work are contained in the Mercury Surface Spectroscopy (MeSS) database (this conference Munoz et al 2022 and Cornet et al., 2022). The sampling and spectral characterization of HRP and LBP have been performed within the Caloris basin (this conference Doressoundiram et al., 2022). The LRM was in turn sampled around the Rachmaninoff Basin which is considered to be the most visible, carbon rich and least altered LRM deposit (Klima et al., 2018). A statistical study of the sampled areas allows to obtain a spectral characterization for each of the HRP, LBP and LRM units. This characterization was then used to map the different units interacting in our basins' study.

This study reveals a similarity in the distribution of spectral units associated with impact basins showing a trend according to their size and age. We propose that the formation of spectral units in and around impact basins on Mercury is a common process resulting in different final appearance depending on the basins. The current appearance of basins would be more related to their age and size rather than to the location on the surface.

Topography, Illumination, and Thermal Models of Mercury's Polar Deposits

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The first evidence for water ice near Mercury's poles was obtained three decades ago using Earth-based radar. Roughly two decades later, NASA's MESSENGER spacecraft became the first to orbit the innermost planet, transforming our knowledge of Mercury. MESSENGER's observations provided compelling support for the presence of water ice and other volatile compounds in Permanently Shadowed Regions (PSRs) near both of Mercury's poles. Following the end of MESSENGER's mission, we were funded by NASA for a three-year study to utilize the available MESSENGER data to investigate volatile polar deposits of high science interest in greater detail. Here we provide our results to date from this multi-year effort:

Polar deposits with low-reflectance surfaces: High-resolution local Digital Elevation Models (DEM) were produced for eight craters that host volatile deposits with low-reflectance surfaces, as observed by both MESSENGER's Mercury Laser Altimeter (MLA) and Mercury Dual Imaging System (MDIS). Illumination and thermal models derived from these new DEMs indicate that the low-reflectance surfaces can extend slightly beyond the PSRs and are consistent with being due to the presence of volatile organic compounds.

Surface water ice in Prokofiev: Prokofiev (diameter: 112 km) hosts a deposit with a high-reflectance surface in MLA and MDIS observations, interpreted to be surface water ice. Using a high-resolution local DEM produced for this crater, Prokofiev is found to be the first location identified on Mercury to host a large radar-bright region that extends for several kilometers beyond its PSR. Modeling also shows its surface ice is not pure.

Northernmost craters: High-resolution DEMs were created for four large craters near Mercury's north pole that host extensive radar-bright deposits. The thermal models indicate surface ice and low-reflectance volatile compounds are stable at the surface in these craters, but MESSENGER observations this close to the pole are sparse.

Lowest-latitude deposits: Radar-bright regions have been identified in small PSRs located at latitudes below 70°N. Such low latitudes may present challenging thermal environments for the presence of water ice and earlier thermal studies all but neglected these low-altitude deposits. Local, high-resolution DEMs have been constructed for these low-latitude craters, and thermal models are currently being examined.

Mercury's south pole: The global Mercury DEM lacked the resolution needed for investigations of south polar deposits. A higher resolution DEM that covers Mercury's south polar region from the pole to 75°S was constructed from MDIS images and used to determine the thermal environments for Mercury's south polar deposits for the first time.

These results give new insight into the nature and origin of Mercury's polar volatile deposits as well as provide key products that can inform BepiColombo's future exploration of Mercury.

EUV reflectance of Mercury measured by BepiColombo/PHEBUS

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BepiColombo will be inserted around Mercury in December 2025, but during the cruise phase, several opportunities to perform disk-integrated observations of Mercury are possible. The first observations of the illuminated surface of Mercury by PHEBUS (Probing of Hermean Environment by Ultraviolet Spectroscopy) with the EUV channel (~55-160 nm) were done on 9 and 10 Oct 2021, few days after the first flyby, from a distance of ~.03 AU at a phase angle of 72°. The solar reflected spectrum is detected from 80 nm to 160 nm. We present the EUV reflectance of Mercury derived from these observations and compare its spectral variations to the measurements by Mariner 10 done at few wavelengths in this spectral range and to the MESSENGER observations done at longer wavelengths.

Landforms caused by downslope mass wasting on Mercury

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Results from NASA MESSEGNER spacecraft have revealed that Mercury's surface is more active than previously thought. New surface features such as faculae and hollows have been described that reveal the influence of volatiles in shaping the hermean landscape. In this study we focus our attention on sloping surfaces and use images to investigate small-scale mass wasting processes. On other bodies, such as Mars and Vesta, downslope mass wasting can be driven by volatiles, hence the objective of this study is to investigate the possible relation between mass wasting and slope-processes on Mercury.
We performed a survey of MESSENGER NAC images at better than 100 m/pix between 20°N and 60°N latitudes. These images cover 53% of the surface of Mercury at these latitudes. We did not extend the survey further north to avoid deep shadows, nor further south where images at better than 100 m/pix are rare. Steep slopes are found within impact craters and vents. We systematically catalogued the presence of spur-and-gully morphology and downslope-oriented high albedo streaks. We found both landforms were randomly distributed over the surface, with a few tens of examples of each landform. Spur-and-gully morphology is only clearly visible in images with medium to low incidence angles, and only on steep slopes. Whereas streaks are visible independent of the lighting incidence and can be found on any type of sloping terrain.
Spur-and-gully morphology is formed by the natural degradation of bedrock exposures. On the Moon this morphology is rare because of the thick regolith (and only visible in 50 cm/pix images). On Mercury the regolith is thought to be thicker than on the Moon, so the finding of widely distributed spur-and-gully morphology is surprising. The streaks could be related to differential erosion of materials with different albedos. Yet some are found on shallower hillslopes, where factors other than gravity would be required to initiate motion.

Exploring the MASCS data set through the MeSS database

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The MESSENGER/Mercury Atmospheric and Surface Composition Spectrometer (MASCS) instrument operated between 2011 and 2015 in orbit around Mercury. During its lifetime, the MASCS instrument produced more than ∼4.7 millions of spectra of Mercury's surface with the Visible Infrared Spectrograph (VIRS), scattered all over the planet, allowing the extensive characterisation of its spectral properties from 300 to 1450 nm, with a spectral resolution of 5 nm.

The PDS archived MASCS DDR data have been ingested in the Mercury Surface Spectroscopy (MeSS) PostGreSQL database (Munoz et al., 2022, this conference), hosted at the European Space Astronomy Centre (ESA/ESAC). In addition, derived data (combined spectra from Besse et al. (2015), and spectral parameters) were also incorporated to this framework. This database framework facilitates a rapid access and extraction of information from many MASCS orbits at once, in order to characterise the spectral properties of surface features (Besse et al., 2020 ; Barraud et al. 2021). It also makes possible to explore the data set in an integrated way through detailed coverage analyses. A set of tools is being developed to ease the access and usage of the data. In this work, we will present the outcome of the coverage analysis performed on the MeSS database.

Investigating 1064-nm Albedo along Mercury's Hot and Cold Poles

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Because of its eccentric orbit and 3:2 spin-orbit resonance, Mercury has a surface thermal environment that varies not only with latitude, but also with longitude. "Hot-pole" longitudes, centered at 0°E and 180°E, reach maximum temperatures as much as 130 K warmer than "cold-pole" longitudes (90°E and 270°E) due to enhanced solar insolation [1]. Here we investigate whether these longitudinal variations in surface temperature may result in differential space weathering, leading to variations in the 1064-nm normal albedo of the surface.

Space weathering can influence the regolith"s optical surface in many ways, including lowering albedo [e.g., 4]. We analyze how the 1064-nm albedo varies along hot- and cold-pole longitudes using zero-phase angle MESSENGER Mercury Laser Altimeter (MLA) data. We present a new empirical correction for the MLA data, accounting for (1) drift and the natural degradation of the laser, (2) obliquity to mitigate bias associated with longitude, since a more oblique geometry was required to obtain ranges at the equatorial hot-pole longitudes, and (3) the receiver response in the case of high emission angle and extended range, both of which enlarge the laser footprint and cause the return pulse amplitude to decrease. The third of these corrections was applied more strongly to oblique data as the mission was extended and the laser strength and beam quality declined. The result is a photometrically near-uniform dataset independent of solar illumination geometry.

Previous analyses revealed possible longitude-dependent space-weathering effects on Mercury, including a decrease in optical maturity at the cold poles [2]. Visible and Infrared Spectrograph (VIRS) data are consistent with an enhancement of microphase Fe at equatorial latitudes ($<60°$) relative to poleward latitudes, and an enhancement of microphase Fe at hot-pole longitudes relative to cold-pole longitudes [3]. These trends may be consistent with Ostwald ripening, a process where nanophase opaque particles grow to produce larger (microphase) particles at high temperatures, which has been predicted to occur at Mercury's equatorial latitudes and hot-pole longitudes [4]. Nanophase opaque particles are a product of space weathering and result in lower albedo [e.g., 4].

Our initial results indicate the 1064-nm albedo of hot poles is lower than that of cold poles at low-mid latitudes. Ongoing work includes analyzing albedo variations with respect to geologic unit and surface age, and comparing results with Mercury Dual Imaging

System (MDIS) reflectance parameters. Preliminary results present an interesting test for the BepiColombo Laser Altimeter (BELA), which will measure albedo at the same wavelength as MLA and will provide more complete observations of equatorial regions.

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A spectral study of the Caloris basin and its smooth plains' relationship

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The study of geological processes such as cratering and volcanism provides information on the evolution of Mercury's surface and its interior since its formation. The Caloris basin is one of the most important geological features on Mercury giving an overview of morphological, chemical and spectral units (Fassett et al. 2009; Nittler et al. 2020) as well as deep material (Klima et al. 2018). It is commonly accepted that the basin is associated with two smooth plains, one in its interior and one surrounding the basin (Rothery et al. 2017). These spectrally different smooth plains appear to be both volcanic in origin and emplaced after the formation of the basin, certainly partially related with the long-term outcome of the basin formation (Roberts et al. 2012). The exterior plain is used to define the Low reflectance Blue Plains (LBP) while the interior plain together with the northern plains form the High reflectance Red Plains (HRP). The formation of large impact craters brings to the surface deep material such as the ancient graphite crust of Low Reflectance Material (LRM) buried under the secondary magmatic crust.

We present in this work a new spectral study of the Caloris Basin in order to improve our understanding of the basin emplacement and the avent of volcanic smooth plains in interaction with the underlying layers including LRM. Our method was to make use of the home-built Mercury Surface Spectroscopy (MeSS) database (this conference, Munoz et al. 2022 and Cornet et al. 2022). MeSS provide useful spectral parameters extracted from the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) instrument, onboard MESSENGER. Thanks to a rigorous statistical approach, we were able to characterize uniquely the interior HRP and exterior LBP within the Caloris basin, as well the LRM material.

Our approach allows to distinguish and map the interior plain from the exterior plain of the Caloris basin. Furthermore, we also show evidence of LRM excavated from craters inside the basin, supporting the idea that a layer of LRM was excavated by the emplacement of the main basin and then overlaid by at least one HRP volcanic layer. However, we also observe the presence of LRM concentrated in the western part of the exterior plain. These deposits are located in a geochemically different area from the overall outer plains. This result suggests that it is possible that the formation process of the exterior plain is not homogeneous all around the basin and could depend on different processes. The question of the age and timing of these interior and exterior smooth plains remain uncertain but our study is promising in order to better understand their interaction.

Spectral detection of ices in Mercury's PSRs by SIMBIOSYS-VIHI on BepiColombo mission

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The illumination geometry occurring at Mercury's poles are largely varying during the hermean year [1]. In particular, Permanent Shadowed Regions (PSRs), occurring on deep craters and rough terrains, experience multiple scattered light coming from nearby illuminated areas. Despite the orbital vicinity to the Sun, Mercury's PSRs can maintain cryogenic temperatures across geological timescales thus favoring the condensation and accumulation of volatile species [2]. The total surface area of PSRs between latitudes 80-90° south is estimated at about 25.000 km^2 [3], about two times larger than the same geographic area on the North Pole [4]. The exploration of surface ices in polar regions' PSRs [5] is one of the primary targets of the VIHI imaging spectrometer [6], one of the three optical channels of the SIMBIO-SYS experiment [7] on ESA's BepiColombo mission. The illumination conditions occurring on the PSR located in craters' floor could allow the detection of water ice from orbit within the shadowed areas thanks to the light scattered by the illuminated portion of the crater's rim [1]. Moreover, the extended dimension of the Sun (between 1.15° and 1.75° at perihelion and aphelion, respectively) causes the presence of blurred shadows (penumbras) favoring a further faded illumination towards otherwise shadowed areas. In this work, we extend similar spectral simulations to other volatile species apart from water ice, like SO_2, H_2S, and volatile organics, intending to verify their detectability from orbit and to optimize VIHI observations. The spectral simulations, performed following the method described in [8], and including the ice-regolith mixing (areal or intimate) as modeled in [9], allow for exploring different volatile species abundances and grain size distribution. The resulting ices detection threshold is evaluated through the computation of VIHI's instrumental signal-to-noise ratio as given by the instrumental radiometric model [10].

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Principal Component Analysis and Spectral Angle Mapper on MASCS/MESSENGER data for the spectral characterization of Mercury surface

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The Principal Component Analysis (PCA) applied on MDIS [1] photometrically-corrected images acquired during the first two MESSENGER flybys revealed several spectral units on Mercury [2-5], mainly distinct for differences in reflectance and spectral slope. All units have a positive spectral slope, but they are described as "red" or "blue" depending on a steeper or less steep slope than the average Mercury terrain in MDIS spectral range (395-1040 nm). The three major terrain classes are the Low-Reflectance Material (LRM), the Intermediate Terrain (IT), and Smooth Plains, which are subdivided into High-reflectance Red Plains (HRP), Intermediate Plains (IP), and Low-reflectance Blue Plains (LBP). HRP are the brightest and reddest smooth plains; IP and IT are spectrally similar to the global mean; the LBP is intermediate between IP and LRM, the latter is the darkest unit on Mercury [4]. Minor classes include fresh crater ejecta, hollows, and "red units"[2,5]. Fresh crater ejecta are interpreted to be among the least space-weathered materials on Mercury, having higher reflectance and bluer spectral slopes than their mature counterparts [2]. Hollows are shallow, irregularly shaped, and rimless flat-floored depressions with bright interiors and halos and flat spectral slopes [5]. The red units are distinguished in red material (RM) emplaced during the impact process [6] and pyroclastic deposits, formed after explosive eruptions [2,3,7]. The spectral units on Mercury were also classified with MASCS data [8]: a PCA and a cluster analysis was applied on MASCS spectra acquired during the first two MESSENGER flybys and not corrected for viewing geometries[9].
In this work, we applied both the PCA and the Spectral Angle Mapper (SAM [10]) on photometrically-corrected and quality-filtered MASCS spectra acquired during the MESSENGER orbital phases. PC1, PC2, and PC3 are responsible for 98.72%, 0.95%, and 0.17% of the spectral variability in the dataset, and appear correlated with the reflectance at 550 nm, the VIS Slope, and the UV Slope, respectively. By combining the PC1, PC2, and PC3 maps in an RGB image, hollows, fresh ejecta, and red units are readily distinguishable, as well as the IT, LRM, HRP, and LBP. Mean spectra of representative regions for each major and minor terrain are used as end-members driving the SAM classification. As a result, 87.5% of the data is classified as smooth plains, 2.8% as IT, 6% as LRM, and the minor classes involve 3.8% of the dataset. Results from PCA and SAM classification are compared to derive physical/chemical properties of Hermean terrain classes.

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Investigation of Hollow Locations in Craters of Different Degradation Classes

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Hollows are steep-walled, ~1 km-wide rimless depressions commonly associated with bright deposits on the surface of Mercury, related to volatile loss (Blewett et al., 2011, Thomas et al., 2014). These features are usually found in clusters and commonly occur within craters and their ejecta, as well as in areas of low reflectance material (LRM) (Thomas et al., 2014). Within individual craters, hollow location has been found to depend on crater type (simple, complex) and degradation state (Thomas et al., 2014). At complex craters, hollows are found on proximal ejecta blankets and on the crater walls, floors and central structures. At simple craters, hollows generally occur as bands at the tops of crater walls. At some degraded craters, hollows have been observed to occur on cross-cutting faults or superposed simple craters. Here we further investigate relationships among the locations of hollows on crater walls, floors and within central structures as a function of degradation class (Kinczyk et al., 2020). We select craters from the named crater database at the PDS Geosciences Node Mercury Orbital Data Explorer (ODE), and use the degradation classification index from Kinczyk et al. (2020). Hollows were identified using MDIS-Narrow Angle Camera and MDIS-Wide Angle Camera Regional Targeted Mosaics (RTMs) of 208 of the 415 named craters . We report findings for 57 of the 73 named craters with hollows that have a degradation index of 1 to 5, where Class 1 represents highly degraded craters, and Class 5 represents fresh, rayed craters. Hollows are preferentially found in relatively fresh craters. Of the 3253 craters indexed by Kinczyk et al. (2020), named craters with hollows comprise 34% of craters in degradation class 4 or 5, 3.5% of craters in Class 3 and ~1% of craters in Class 1 or 2. Of the 57 named craters with hollows, 21 are in Class 4 or 5, 18 in Class 3, and 18 in Class 1 or 2. We classify hollows according to their location inside the crater: wall, floor, wall-floor intersection, central structure and superposed craters. In named craters with degradation class 1 or 2, hollows occur mostly in superposed craters. Although RTM coverage of degraded craters is less extensive than that of fresher craters, degraded craters of Class 1 or 2 sometimes have hollows on their central structures or floors and only occasionally on the walls, unassociated with superposed craters. In named craters of classes 4 and 5, hollows are more likely to be found on the central structures, but are also found on the walls and floors.

Investigating the Distribution of Surface Ice in Mercury's Northernmost Craters

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Earth-based radar observations by Goldstone and Arecibo Observatory revealed radar-bright features in Mercury's polar regions that have been interpreted as evidence for water-ice deposits. Following these observations, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft collected a myriad of evidence in its time orbiting Mercury that confirmed the hypothesis that the radar-bright deposits consist primarily of water-ice. MESSENGER data were then used to identify Permanently Shadowed Regions (PSRs) in Mercury's north polar region and model their thermal environments. Such models indicated that the radar-bright regions correspond to extensive PSRs in the northernmost craters on Mercury, which have thermal environments conducive to the presence of exposed water-ice at the surface. However, detailed illumination and thermal studies of these northernmost craters have been impeded by the limited topographic data acquired by MESSENGER's Mercury Laser Altimeter (MLA) within 5° of the north pole.

In this study, we constructed local high-resolution (125 m/pixel) digital elevation models (DEMs) for four of the largest northernmost craters, Kandinsky (60 km), Chesterton (37 km), Tolkien (50 km), and Tryggvadottir (31 km), using MLA data in conjunction with the shape-from-shading techniques based on Mercury Dual Imaging System (MDIS) images collected by MESSENGER. These DEMs were then leveraged to create high-resolution illumination and thermal models. The illumination models mapped out accurate PSRs for each crater and informed how scattered light reflecting off the topography could be responsible for brightness variations observed in MDIS images (rather than variations in volatile composition). Our high-resolution thermal models then indicated the maximum and average surface temperatures over a Mercury solar day, from which we inferred the depth at which various volatiles would be stable.

Using these new high-resolution models, we investigated where the models predict that ice or volatile organic compounds are stable at the surface in these craters. Previous work concluded that coronene is one appropriate volatile to model the low-reflectance surfaces observed within many of Mercury's PSRs that have thermal conditions too warm for the presence of water-ice at the surface. The predictions of our thermal models were then compared against the MLA and MDIS data to search for evidence of ice or low-reflectance volatiles at the surface. Preliminary MLA results agree with previous findings that these craters have a surface reflectance that is much brighter than the average reflectance of Mercury, suggesting the presence of water-ice at the surface. Preliminary comparisons to the limited MDIS images that successfully reveal the surface features within the PSRs are so far inconclusive to verify the presence of high-reflectance surfaces due to water-ice or low-reflectance surfaces due to complex organic compounds.

Comparison of magma eruption fluxes in the Rembrandt and Caloris interior plains: implications for the north-south smooth plains asymmetry

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The surface observations performed during the MESSENGER mission revealed that smooth plains occupy ∼27% of the surface of Mercury and are potentially formed by volcanic resurfacing. Comparing the two hemispheres, the plains area within the northern hemisphere is approximately 7 times larger than that within the southern hemisphere. This asymmetric distribution may reflect the differences in the thermal condition in the mantle and/or the ease of magma eruption.
In this study, we estimated the magma eruption fluxes within the two smooth plains interior to impact basins, the Rembrandt basin in the southern hemisphere and the Caloris basin in the northern hemisphere. By comparing the volcanic activities, we discuss the factor that may cause the asymmetric distribution of smooth plains.
The estimation of the resurfacing ages and the basin formation ages were conducted based on the crater measurements using the surface images acquired by MDIS/MESSENGER. We adopted the crater chronology model of Le Feuvre and Wieczorek (2011) (Mercury, porous-target). The observed crater size-frequency distributions hold kinks, suggesting the preferential removal of smaller craters by multiple eruptions. The thicknesses of the surface lava layers were estimated from the crater diameter corresponding to the kinks. Also, the total thicknesses of the volcanic materials were investigated using the enhanced color map. By classifying all the craters into two groups by the color properties, blue craters and yellow craters.
The basin formation ages were estimated as 3.93 ± 0.06 and 3.94 ± 0.04 Gy, while the volcanic resurfacing ages were from 3.87 ± 0.04 to 3.76 ± 0.01 Gy and 3.88 ± 0.03 to 3.74 ± 0.01 Gy, and the magma eruption fluxes were estimated as 5.2-12.3 km/Gy and 9.3-15.1 km/Gy, respectively. The magma eruption flux is at most 3 times larger in the Caloris basin than in the Rembrandt basin.
Based on the gravitational data, the crustal thickness model has been proposed. Considering the difference in basin diameter, the Caloris-forming impact excavated ∼2 times deeper than the Rembrandt-forming impact. The crust beneath the Caloris basin is likely to be ∼1.8 times thinner, which might make the ascent of magma to the surface easier, comparing with the Rembrandt basin. Thus, the magma production quantities in the mantle beneath these two basins should not differ by a factor of <3.
We finally discuss the spatial variations in the abundance of heat-producing elements in the mantle, which can be an energy source for volcanic activities.

Magnetic Anomalies Aligned Radial to the Caloris Impact Basin: Further Evidence for Ejecta Deposit Sources

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We have previously reported mapping of MESSENGER magnetometer data at northern midlatitudes showing that crustal anomalies are strongest within and near the Caloris impact basin and also occur within and near a number of other Hermean impact craters and basins (Hood, GRL, 2015; JGR, 2016; Hood et al., JGR, 2018; Oliveira et al., JGR, 2019; Galluzzi et al., GRL, 2021). One hypothesis that is consistent with the observed anomaly distribution is that Hermean crustal magnetic sources consist mainly of impact melt and ejecta that was enriched in iron from impactors that created large basins and craters on Mercury. During cooling, these deposits would have acquired thermoremanent magnetization from the early Hermean core dynamo magnetic field. This hypothesis is based on previous work at the Moon dating from the post-Apollo period and continuing to recent improved mapping and interpretation of the lunar crustal field (Hood et al., JGR, 2021). Most of Mercury's original crust has been volcanically resurfaced over a period continuing until about 3.5 Gyr ago (e.g., Thomas and Rothery, Elements, 2019). Therefore, at least some iron-enriched impact melt and ejecta from basins such as Caloris may lie beneath these flows rather than at the surface. However, in the case of relatively young impact craters such as Rustaveli and Stieglitz, correlations of magnetic anomalies with the distribution of visible impact melt deposits have been found (Galluzzi et al., GRL, 2021).

Here, preliminary improved mapping of magnetic anomalies at 35 to 75 degrees north latitude on the Caloris side of Mercury is reported. Specifically, a denser equivalent source dipole array with a spacing of 0.5 degrees of latitude and 1 degree of longitude was applied to the cubic detrended MESSENGER magnetometer field measurements along the orbit tracks with a maximum passed wavelength of 20 degrees of latitude. The resulting higher-resolution map in polar stereographic projection shows that many anomalies, including that over the volcanic plain, Suisei Planitia, lie along lines oriented approximately radial to Caloris. Such radial alignments have also been recently found to exist south of the lunar Imbrium basin (Hood et al., JGR, 2021) and are consistent with similar alignments obtained in numerical simulations of the impact of iron-rich projectiles producing a large-scale lunar basin (Wieczorek et al., Science, 2012).

Late accretion onto Mercury

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Impacts are a fundamental process by which planets grow and are modified. Stochastic giant impacts on the terrestrial bodies mechanically and thermally affect a large portion of the planet's surface (Benz et al., 1988; Nakajima and Stevenson, 2015; Chau et al. 2018). Contrarily, small impacts, namely the cratering impacts, affect only a small area of the planet's surface and are much more frequent (Melosh 2011).

Here, using analytical and Monte Carlo approaches combined with the updated scaling laws (Hyodo and Genda 2020, 2021) for the escape mass of the target material and the accretion mass of the impactor material during the cratering impacts, we studied (1) whether late accretion significantly erodes Mercury, and (2) the fate of the impactors to Mercury during late accretion.

Existing dynamical models of late accretion indicate that Mercury experienced an intense impact bombardment after 4.5 Ga (a total mass of $\sim 8 \times 10^{18} - 8 \times 10^{20}$ kg with a typical impact velocity of $30 - 40$ km s^{-1}, depending on dynamical models). For this parameter range, we found that late accretion could remove 50 m to 10 km of the early (post-formation) crust of Mercury, but the change to its core-to-mantle ratio is negligible. Although the cratering is notable for erasing the older geological surface records on Mercury, we showed that $\sim 40 - 50$wt.% of the impactor's exogenic materials, including the volatile-bearing materials, can be heterogeneously implanted on Mercury's surface as a late veneer (at least $\sim 3 \times 10^{18} - 1.6 \times 10^{19}$ kg in total). About half of the accreted impactor's materials are vaporized, and the rest is completely melted upon the impact.

In short, late accretion seems an inevitable dynamical process at the very last stage of the planet formation, and it affects Mercury's surface in both mechanical, chemical, and thermal aspects (Hyodo et al. 2021; see also Mojzsis et al. 2018).

Understanding the Age and Distribution of Explosive Volcanism on Mercury: Insights from Pyroclastic Deposits

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The geologic history of Mercury has been interpreted to fall into two distinct periods: an early history that was dominated by the successive emplacement of generations of effusive volcanic plains, followed by a protracted period of cooling and contraction dominated by the formation of lobate scarps and other compressional tectonic features. The MESSENGER mission also revealed previously unanticipated evidence for explosive volcanism on Mercury in the form of vents surrounded by pyroclastic deposits. The timing of this explosive volcanic activity, and the distribution of vent ages across the surface of the planet provides critical information on the thermal evolution of Mercury's interior.

Several lines of evidence have been used to suggest that the largest, and brightest vent and deposit, Nathair Facula, is less than 1Ga; while additional crater superposition evidence supports explosive volcanic activity during the Mansurian and Kuiperian periods. Here, we present new geomorphological evidence supporting the conclusion for young explosive volcanism on Mercury. Through use of a relative degradation classification system, we can investigate vent age independently of host crater age. All of our analyses continue to support the conclusion that not only was explosive volcanism occurring in Mercury's recent geologic past, but the majority of explosive volcanic vents on Mercury may have formed well after the cessation of effusive volcanism. This has significant implications for thermal models of Mercury's evolution, which must now provide mechanisms for melt production and magma ascent well past what was thought possible. These results pose the additional question of whether or not explosive volcanism occurred during the interval between the cessation of effusive plains emplacement and the formation of the recognized explosive vents. We discuss how Bepi-Colombo imaging strategies can be leveraged to understand this fascinating aspect of Mercury's geologic history.

Ponded Melt Deposits Antipodal to Large Young Impact Craters on Mercury

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On the Moon, there are geologically young ponded melt deposits in a ∼100 km area approximately antipodal to young crater Tycho (diameter ∼ 86 km) of Copernican age. The deposits have distinctive morphology apparent in high-resolution images obtained by LROC NAC camera (LRO mission to the Moon). This morphology is very similar to morphology of impact melt ponds observed on walls and proximal ejecta of Tycho itself and other large Copernican-age lunar craters. The ponded deposits are also characterized by relatively high night-time temperature consistent with a large number of rocks observed in the images; they also have a distinctive microwave radar signature. These ponded melt deposits have been interpreted as a result of ejecta focusing in the Tycho antipode. The majority of large lunar Copernican-age craters do not have associated antipodal melt deposits; this is explained by the fact that to reach the antipode, ejecta should be launched at a grazing ejection angle, which only occurs, if the primary impact is sufficiently oblique.

I developed an analytical theory of impact ejecta focusing in the vicinity of the primary impact antipode. The theoretical results confirm that melt formation in the antipodal region likely occurs due to in-situ conversion of ejecta kinetic energy into heat (aka "frictional melting") and does not require delivery of primary melt. The analytical theory enables effective quantitative comparison of antipode ejecta focusing between different planetary bodies. On Mercury, reaching the antipode requires a higher launch velocity, therefore, less ejecta get there, however, the kinetic energy per unit mass is higher than on the Moon, which in combination results in more effective melt production. A few (2 - 5) antipodal impact melt deposits are anticipated on Mercury.

Some ponded deposits in small depressions on Mercury are seen in high-resolution images obtained by MDIS NAC camera (MESSENGER mission) near antipode of large (∼85 km) young crater Debussy of Kuiperian age. I suggest that they are analogous to the lunar Tycho antipodal deposits and formed by melting due to focusing of Debussy ejecta. BepiColombo data will enable testing this hypothesis through analysis of their fine-scale morphology and thermal signature. Limited resolution of MDIS NAC images in the equatorial zone and Southern hemisphere preclude systematic search for such deposits on Mercury. BepiColombo mission data will enable exhaustive search for antipodal melt deposits.

Lobate Ejecta Deposits at Mercury's South Pole (H15)

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During geological mapping of H15, we have discovered unrecorded lobate ejecta deposits. One example, at Nairne crater (c4; 70.36° S, 1.65° E), exhibits two distinct lobes that propagate into the floor of a pre-existing, more degraded (c1) crater. The lobes exhibit steep fronts and are thicker and rougher than typical ballistically emplaced ejecta. Nairne exhibits asymmetrical terracing and ejecta deposition, an off-centre bright blue central peak, and bright red impact ejecta. We identify what we interpret as perched impact melt occupying topographic lows on top of the larger of the two lobes. Lobate ejecta deposits are relatively rare on Mercury; Xiao & Komatsu compiled a database of only 7 craters with ejecta flows globally [1], and Blance et al. [2] found more. However, timing of emplacement has remained ambiguous.
We mapped using a MESSENGER MDIS monochrome basemap (166 mpp) and individual monochrome NAC images at higher resolutions. We used 665mpp enhanced color mosaic and DEM to distinguish units by colour and to assist in the mapping of topographic features We mapped the following units: crater wall material, central peak material, crater floor material (smooth/hummocky), and three types of ejecta material. Continuous proximal ejecta exhibits higher relief and rougher texture than the flat, low-lying discontinuous distal ejecta; both are spectrally red. Lastly, ponded impact melt is characterised by very smooth localised deposits and is spectrally blue.
We used shadow-height measurements to calculate a lobe height of 56.7±0.6 km and an ejecta mobility of 2.3±0.06. These were calculated to integrate Nairne with the database published by Xiao and Komatsu [1], wherein the morphological and geometrical parameters of their 7 candidates are listed.
Key factors affecting the formation of ejecta flows on Mercury include the slope of the underlying terrain, high surface temperature and volatiles. Two emplacement scenarios are being considered: a mass-wasting event producing an ejecta flow similar to that at Tsiolkovskiy crater on the Moon, or a fluidised ejecta flow. We are also considering the influence of an oblique impact in formatting lobate ejecta deposits.
Previously there has been no evidence to demonstrate whether ejecta flows on Mercury formed during or after the impact event that formed the crater. Our interpretation of ponded ejecta melt on the larger of the two lobes provides the first evidence that the ejecta flows occurred early in the impact process. The impact melt on the lobe and that of the crater floor share a similar blue colour, indicative of a similar composition and may reflect synchronous formation.

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Newly discovered widespread extensional grabens on Mercury's compressional structures

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Mercury is a shrinking planet with a surface dominated by compressional tectonic landforms as first identified by Mariner 10 and then confirmed by MESSENGER. Extensional structures are present but are much rarer, with almost all reported examples found exclusively in smooth plains material within craters [1]. The only two reported examples of extensional structures outside of the aforementioned setting are extensional grabens associated with lobate scarps; pristine back-scarp grabens associated with small lobate scarps (10s of kms in length and 10s of metres in relief) [2], and crestal grabens found on Calypso Rupes (381km in length and $\sim$ 1km in relief) [3,4]. These grabens form when thrusting produces a hanging wall anticline resulting in local tensional stresses along the anticlinal axis parallel or sub-parallel to the hinge zone. Here, tensional stresses cause antithetic faults to form, which results in a narrow down-dropped fault block.

We find that extensional grabens on compressional structures are much more common than previously recognised. These small-scale landforms (often less than 1km in width, 10s of km in length and likely 10s to 100s metres in depth) are not expected to survive 100s of millions of years due to continual regolith formation and impact gardening masking their signature [1,2]. Our discovery and documentation of potentially young extensional grabens may indicate that many of Mercury's compressional structures have continued to move until geologically recent times. This work therefore may call into question the old absolute age estimates of tectonic features' last movements calculated using crater counting [5-9].

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Investigating the Incidence Angle Effect on X-ray Fluorescence with the MIXS Ground Reference Facility

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The Mercury Imaging X-ray Spectrometer (MIXS) on board BepiColombo will determine the surface composition of Mercury to a high imaging resolution with improved energy resolution. MIXS uses an analytical technique called x-ray fluorescence (XRF) to observe the "fingerprint" of characteristic x-rays emitted by Mercury's surface to determine its elemental abundances. Laboratory measurements of XRF typically use a constant x-ray source and detector angle to yield consistent results. However, this is not the case at Mercury, with the viewing geometry of MIXS ever changing and the angle of the Sun above Mercury also changing throughout the Mercurian year. The angles between the detector and x-ray source have profound implications on the x-ray spectra. As the incidence angle of the x-ray source increases the intensity of the spectrum tends to also increase. However, higher energy elements are less affected by the change in incidence angle, and as such results in a hardening of the spectrum.

If unaccounted for, this bias towards higher energy elements may lead to an underestimate of the actual abundances of lower energy elements on Mercury's surface. Although the effect of changing incidence angle is known and has been studied by several authors (e.g. Weider et al. 2011), the magnitude of the incidence angle effect at different energies is yet to be established. The MIXS Ground Reference Facility has the ability to change the viewing geometry between the x-ray source, detector and sample, and so will be able to provide empirical evidence to determine the magnitude of the incidence angle effect.

We showcase the most recent developments on how spectra are affected by the incidence angle using the MIXS Ground Reference Facility. Using a combination of MIXS data and our empirical results of the incidence angle effect we hope to achieve a more accurate global elemental abundance map of Mercury's surface upon BepiColombo's arrival.

Quantifying Mineral and Position Specific Surface Binding Energies for Multiscale Modelling of Solar Wind Sputtering on Mercury

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Surface sputtering by solar wind (SW) ion irradiation is an important process for understanding Mercury's exosphere. As SW ions impact the surface, they deposit energy, leading to sputtered atoms which can be detected in Mercury's exosphere. The most common sputtering models use the binary collision approximation (BCA) and thus consider sputtering to be a result of binary collision cascades. These models can be used to predict the energy distribution and yield of sputtered atoms as a function of incoming ion type, energy, and angle, with only modest computational requirements. A fundamental physical parameter for BCA models is the surface binding energy (SBE) of the atoms being ejected. The SBE affects the overall sputtering yield, composition of the yield, and energy of the ejecta. However, despite the clear importance of the SBE, its actual value is not well understood for many species and substrates important for Mercury's surface. For example, while Na is easily observed in the Hermean exosphere, there is still disagreement on the primary source of this exospheric Na. This is complicated by a large range of SBE values (0.27-2.6 eV) that have been used for SW sputtering simulations of Na. Similarly, while O is expected to be one of the most abundant elemental species found on the silicate-rich Hermean surface, it is less abundant in the exosphere. Again, there is a lack of consensus on what SBE value to use with previously suggested values ranging from 1 to 6.5 eV. Given that BCA methods rely on a user defined SBE, this can be a significant source of error for predicting the importance of SW induced sputtering from minerals.

We use molecular dynamics (MD) to provide the first accurate SBE data we are aware of for Na and O sputtered from albite (NaAlSi3O8)., which is expected to be an important plagioclase feldspar endmember. An iterative method was used to determine the minimum energy needed to remove one Na or O atom completely from the surface of the substrate. For both Na and O, the SBE from MD was significantly higher (7.9 and 7.4 eV respectively) compared to the commonly used monatomic cohesive energy approximation and other fitting values. SBE values for O were shown to also be dependent on the surface lattice position. Therefore, SBEs are both mineral and surface-position specific. After calculating the SBEs, we then used BCA models to determine the effect of SBE on the predicted yield and energy distributions of sputtered Na and O due to SW ions. As the SBE was increased, there was a significant decrease in the sputtering yield and an increase in the peak and broadness of the sputtered atom energy distribution.

This shifted energy distribution also affected the proportion of atoms sputtered with an energy above the Mercury escape velocity. We then discuss the future of SBE-focused simulations for direct comparison to samples relevant to planetary science.

Mid-Infrared Reflectance Studies of Mercury Surface Regolith Analogs

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Introduction: The IRIS (Infrared and Raman for Interplanetary Spectroscopy) laboratory generates mid-infrared spectra for a database for the ESA/JAXA BepiColombo mission to Mercury. Onboard is a mid-infrared spectrometer (MERTIS-Mercury Radiometer and Thermal Infrared Spectrometer), which will allow to map the mineralogy in the 7-14 μm range [1, 2]. In order to interpret the future data, a database of laboratory spectra is assembled at the Institut für Planetologie in Münster (IRIS) and the DLR in Berlin. Synthetic analogue materials have become one of the foci of our work, since they allow to produce 'tailor-made' materials based on remote sensing data and/or modelling and experiments. These are closer than natural terrestrial materials, which formed usually under different conditions as expected on Mercury [e.g. 3].
Here, we present the new infrared data of mineral and glass mixtures based on the compositions according to recent laboratory experiments [4], that studied melting of hermean mantle at high pressures, high temperatures and appropriate oxygen fugacities. These experiments suggested that the hermean surface mineralogy should be dominated by variable abundances of plagioclase, olivine, clino- and orthopyroxene, with unconstrained proportions of silicate glass.
Based on the model mineralogy of representative results, we produced mineral/glass mixtures based on the Low-Mg Northern Volcanic Plains (NVP)(Y121, Y131, Y172), High-Mg NVP (Y143, Y144), Smooth Plains (Y140, Y143, Y144), Inter crater Plain and Heavily Cratered Terrains (IcP-HCT) (Y126, Y131, Y132, Y146), and High-Mg Province (Y126, Y131, Y146) [4].

Samples and Techniques:
We conducted diffuse reflectance studies of sieved size fractions (0-25 μm, 25-63 μm, 63-125 μm and 125-250 μm) under vacuum conditions, ambient heat, and variable geometries. We used a Bruker Vertex 70v with A513 variable geometry stage. The results will be made available in the IRIS Database [1].
Results:
First results show the Christiansen Feature (CF), a characteristic, easy to identify reflectance low (or emission high) ranging from 7.9 μm to 8.2 μm (always average of all size fractions). The Transparency Feature (TF), typical for the finest size fraction (0-25 μm) is in many mineral mixtures less pronounced than for pure mineral phases. Here the individual TF of the components result in a broad feature.

Outlook:

In a next step, we will study these mixtures under more realistic conditions, i.e., high vacuum and high temperature, in order to better simulate the hermean surface. Also, these mixtures will be used to test spectral unmixing routines, which allow to identify abundances of single minerals in a complex mixture of phases.

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Photometric modelling of Mercury surface features from multiangular MESSENGER/MDIS observations

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The physical properties of a particulate surface, like roughness, grain size, shape and transparency affect how it reflects incoming light. This concept is used in planetary photometry to infer the surface properties of a celestial object from multiple observations taken from different directions and solar illumination (Hapke et al. 2021). Models linking the observed surface brightness with parameters related physical properties of the surface have been established. The estimation of such parameters is referred as photometric modelling (Domingue et al., 2012). On Mercury, this technique has been employed to construct monochrome and color global mosaics, but it was never applied to investigate local surface features (Domingue et al., 2012). Therefore, the photometric modelling of Mercury's surface features represents a novel and useful tool to investigate their nature.

We first analyze the Tyagaraja and Canova craters hollows (i.e., tens meters to several km-sized shallow, irregular, flat-floored depressions characterized by bright interiors and haloes, Blewett et al., 2011), which are covered by multiple overlapping 8 filter MDIS/WAC (Hawkins et al.,2007) images with resolution higher than 665 m/px and phase angles from 30° to $>$ 100°. Over this region, we construct a latitude-longitude sampling grid with 665 m spacing. For each point we retrieve the surface reflectance and the solar illumination and observation angles using the 3D information of the global USGS DTM and the spacecraft and Sun position information within the observation SPICE kernels. This dataset is fitted with the Hapke and Kaasalainen-Shkuratov photometric models and estimates of their parameter are obtained for each point of the grid.

Our results suggest that hollows are more backscattering than the floor of the crater in which they form. This is consistent with hollows being made of a material rich in holes and/or vescicles, in agreement with a formation by devolatilization. In addition, we find that they are smoother than the crater floor, consistently with the emplacement of a fine particles halo during hollow growth.

This analysis is also being performed at an unnamed crater at (-29°N, 60°E) characterized by exposures of bright and dark materials, and we will extend it even to other surface features (bright rays, pyroclastic deposits, etc...). Updated results will be presented at the conference.

Finally, our results shows that this approach improves the modelling accuracy with respect to global photometric models of Mercury, making it an interesting methodology to be employed for the cross-calibration of the three channels of the SIMBIO-SYS instrument on BepiColombo (Cremonese et al.,2020).

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BepiColombo surface science objectives

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Thanks to MESSENGER, it is now clear that Mercury is more interesting and more perplexing than most would have expected when BepiColombo planning began, over two decades ago. Many new questions need to be answered to meet the mission's objectives. We now know that Mercury's surface, and probably its crust as a whole, is rich in volatiles. Evidence includes high abundances of Na, S, K and Cl measured by X- and gamma-ray spectroscopy. There are also clear visual signs of volatile-driven activity such as explosive volcanic eruptions that have excavated compound vents and showered the adjacent area with diffuse explosive deposits, and the growth of 'hollows' where patches of surface are somehow dispersed to space, presumably in atomic form. S and C have been suggested in the gas phase to power explosive eruptions, whereas sulfides and chlorides have been suggested as the active constituent of hollow-forming material. Elemental and mineralogic determinations by BepiColombo with improved spatial resolution and greater sensitivity should enable more robust comparisons between explosive volcanic deposits and their surroundings, and between hollows and hollow-forming material. This should tell us more about which volatiles are lost in explosive eruptions and hollow formation, and what minerals host them. Higher resolution imaging of vents and hollows will help us to better understand the physical processes, their history, and their ages.

Large scale effusive eruptions ended about 3.5 Ga ago, but there is evidence for a long tail of waning activity on smaller scales. Improved spatial and spectroscopic resolution by BepiColombo should enable late stage lava effusions to be better identified, and to be more confidently distinguished from impact melt. Mineralogic and elemental data should enable the compositions of lavas of all ages to be determined well enough to understand source region composition, the depth, extent and causes of partial melting, and whether these changed over time.

The degree to which Mercury remains tectonically active, through secular global cooling or another process, remains in doubt. Understanding will be improved by high-resolution imaging of fault breaks, including small keystone grabens on the crests of lobate scarps.

Volatiles are known to be concentrated in polar cold traps. BepiColombo will study these well at both poles, whereas MESSENGER could do little in the far south. We want to know what volatiles occur other than water-ice, to measure the temperatures where each volatile appears to be stable, and to assess the ages and mobility of volatile deposits.

The ability of BepiColombo's Xray spectrometer (MIXS) to detect, measure and spatially resolve the surface abundance of more elements than MESSENGER's XRS, such as Ti, Cr, P and Ni whose partitioning between silicates, sulfides, metals and melts depends on oxygen fugacity may teach us much about Mercury's differentiation history and the depths and mechanisms of magmagenesis.

Expected characterization of Mercury's surface from global to local scales by the BepiColombo Laser Altimeter (BELA)

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The BepiColombo Laser Altimeter (BELA) is on route to Mercury as payload of the Mercury Planetary Orbiter (MPO). After orbit insertion at Mercury the instrument will characterize the surface of Mercury by obtaining topographic profiles consisting of highly accurate height measurements (range errors are mostly below 1 m). With the natural evolution of MPO's orbit (drift of pericenter latitude) and the ranging capabilities of BELA, reaching up to 1400 km above the surface, the complete surface of Mercury can be observed with gaps in coverage not larger than a few km. However, as a consequence of the polar orbit of MPO the density of BELA measurements is strongly varying with latitude, with highest density at the polar regions where the profiles converge. Local features at the polar regions, e.g. craters in permanent shadow, can be characterized with lateral resolutions below 100 m. Moreover, in contrast to previous laser altimeter measurements at Mercury, BELA will extend the analysis of the surface down to the meter scale by performing a detailed analysis of the return pulse shape. Besides the measurement of the exact arrival time of the return pulse, the pulse shape analysis also provides estimates on the surface albedo and roughness within the BELA footprint (diameter from 20 to 80 m depending on altitude). We present the expected coverage of Mercury's surface by BELA by taking the latest ranging performance assessments based on ground and cruise tests. Furthermore, we will generate realistic return pulse shapes from different surface landforms. The generated data will be analyzed and the results will be checked against the data used for simulation. This will allow us to demonstrate the expected capabilities of BELA and their potential use for detailed geomorphological and geologic analysis of Mercury's surface.

Accurate 3D Reconstruction of Mercury with Shape from Shading

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Accurate 3D models are essential for geomorphologic analysis, reflectance modeling, and spectral analysis. Our group developed a Shape-from-Shading (SfS) algorithm to create digital terrain models (DTMs) of the Lunar [1] and the Martian surface [2]. Recently, we refined our Shape from Shading (SfS) algorithm to generate high-resolution DTMs of Mercury from MESSENGER imagery [3]. To adapt the reconstruction procedure to the specific conditions of Mercury and the available imagery, we introduced two methodic innovations. First, we extended the SfS algorithm to enable the 3D-reconstruction from image mosaics. Because most mosaic tiles were acquired at different times and under various illumination conditions, the brightness of adjacent tiles may vary. We found that the relaxation of the constraint for a continuous albedo map improves the topographic results of an extensive region yields seamless transitions at tile borders. The second innovation enables the generation of accurate DTMs from images with substantial albedo variations, such as hollows. We employed an iterative procedure that initializes the SfS algorithm with the albedo map obtained by the previous iteration step. This approach converges and yields a reasonable albedo map and topography. We generated DTMs of several science targets such as the Rachmaninoff basin, Praxiteles crater, fault lines, and several hollows with these approaches. We compared our DTMs with stereo DTMs and laser altimeter data to evaluate the results. In contrast to coarse laser altimetry tracks and stereo algorithms, which tend to be affected by interpolation artifacts, SfS can generate DTMs almost at image resolution. The root mean squared errors (RMSE) at our target sites are below the size of the horizontal image resolution. For some targets, we could achieve an effective resolution of less than ten m/pixel, which is the best resolution of Mercury to date.

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Targets definition for BepiColombo in eastern H9 Eminescu quadrangle

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Data from NASA MESSENGER spacecraft highlighted that Mercury's surface and composition are more variegated than previously thought. Despite being the closest planet to the Sun, indeed, Mercury is rich in volatiles and its surface shows evidence of volatile-driven processes such as the formation of hollows and explosive volcanism. Even MESSENGER's color-derived basemaps, moreover, highlight relevant color variations of the hermean surface possibly indicating age and compositional differences between adjacent materials.
The ongoing mapping for the eastern H9 Eminescu quadrangle (22.5°N-22.5°S, 108°E-144°E) led to a thorough knowledge of the area that allowed the definition of scientific targets of interest to be investigated by the SIMBIO-SYS cameras onboard the ESA-JAXA BepiColombo mission coupled with other instruments such as MERTIS, BELA, MGNS and MIXS. Proposed targets range from hollows to volcanic features, from craters and deformational structures and specific terrains and aim at shedding light on scientific questions concerning Mercury's origin and evolution. In particular, proposed targets aim to i) determine the abundance and distribution of key elements, minerals and rocks on the hermean crust, ii) characterize and correlate geomorphological features with compositional variations, iii) investigate the nature, evolution, composition and mechanisms of effusive and explosive events, iv) determine the nature of processes related with volatile loss, the mineralogical and elemental composition of volatiles and, in particular, the formation and growth rates of hollows, v) determine the displacement and kinematics of tectonic deformations and the mechanisms responsible for their formation and vi) verify the occurrence of any detectable change in and around hollows and pyroclastic deposits since MESSENGER observations.

A Mystery solved: Wavelength-dependent Seeing changes the normalized spectral slope of Mercury

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Mercury is notoriously difficult to observe with a telescope due to the planet's small angular separation from the sun and the low elevation above the horizon. However, around twenty measurements in the last three decades have provided optical and infrared data of Mercury. Several studies [1,2,3,4] consistently report systematic variations of the normalized spectral slope of visible-to-near-infrared reflectance spectra correlated with the emission angle. This effect was previously assumed a photometric property of the regolith [2,3], but it is not yet fully understood. After the MESSENGER mission, global multispectral maps of Mercury are available that constrain Mercury's photometry. So far, wavelength-dependent seeing has not been considered in the context of telescopic observations of Mercury. In our recent paper [5], we investigate the effect of wavelength-dependent seeing on systematic variations of Mercury's normalized spectral reflectance slope. Therefore, we simulate the disk of Mercury for an idealized scenario, as seen by four different telescopic campaigns using the Hapke and the Kaasalainen-Shkuratov (KS) photometric model, the MDIS global mosaic, and a simple wavelength-dependent seeing model. The simulation results are compared with the observations of previous telescopic studies. We find that wavelength-dependent seeing affects the normalized spectral slope in several ways. The normalized slopes are enhanced near the limb, decrease toward the rim of the seeing disk, and even become negative. The decrease of the normalized spectral slope is consistent with previous observations. However, previous studies have associated the spectral slope variations with photometric effects that correlate with the emission angle. Our study suggests that wavelength-dependent seeing may cause these systematic variations. The combined reflectance and seeing model can also account for slope variations between different measurement campaigns. We report no qualitative differences between results based on the Hapke model or the KS model.

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Mercury is hot: A fractal thermal roughness Model for MERTIS spectral calibration

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The BepiColombo mission is a joint project of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). The Mercury Planetary Orbiter (MPO) carries the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) that is planned to acquire infrared spectra of Mercury in the range of $7 - 14\mu$m. The instrument is designed to characterize Mercury's surface composition, identify rock-forming minerals, map the surface mineralogy, and study the surface temperature variations and the thermal inertia [1]. For mineralogical analysis, the emissivity has to be extracted from radiance measurements. In a laboratory setting, for a smooth surface or observations of planetary bodies under small emission and incidence angles, simple division of the measured spectral radiance by the Planck function for a single temperature value is sufficient. However, airless planetary bodies are rough and have comparatively low thermal inertias such that strong thermal gradients establish on scales of a few millimeters. Consequently, the thermal radiation detected by an infrared sensor significantly deviates from a simple black body spectrum, mainly when observed under oblique illumination geometry. The radiation due to thermal emission is no longer a simple Planck function but a non-linear superposition of many Planck functions with a unique mathematical structure. Consequently, surface roughness, self-heating, shadowing, and the spatial scales on which these effects occur must be considered. Various approaches to model surface roughness have been discussed before, e.g., [4,5,6].

We implemented a comprehensive thermal roughness model for airless bodies that enables accurate emissivity calibration and roughness analysis of the Moon and Mercury. Several methodic improvements such as fractal surfaces, fast self-heating computation, and angular dependent bolometic albedo make the model accurate and versatile. We present the most recent update of our model applied to two interesting datasets: Lunar infrared images taken by the Chinese weather satellite Gaofen 4 [5] and MERTIS lunar measurements acquired during a gravity assist maneuver in April 2020 [6]. These datasets serve to test the model and prepare it for the prospective analysis of Mercury.

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Combining spectral and morphostratigraphic units on Mercury: A case study of the Rachmaninoff basin area

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MESSENGER-era quadrangle geological maps are primarily made by observing Mercury's geomorphology in monochrome MDIS mosaics [1], and so might more accurately be called morphostratigraphic maps. Geological maps of Earth incorporate more information, such as rock lithology, composition, and origin [2]. Until landed Mercury science begins [3], most bedrock properties will probably remain elusive, hence the convention for planetary geological maps to be descriptive and conservative. MESSENGER did collect spectroscopic data, indicative of composition, but this information has not systematically been incorporated into the planet's geological maps thus far.

Recently, [4] produced spectral unit maps of Mercury using MDIS data, including the Hokusai quadrangle. In this work, we combine the morphostratigraphic units of [5] with these spectral units. We focus on Rachmaninoff basin and its surroundings, including Nathair Facula. Our aim was to augment the descriptions and correlation of map units of [5].

We summarized the spectral unit map, originally produced as a ∼450 m/pixel raster, by digitizing new spectral contacts between regions dominated by different spectral units. We observed that these spectral contacts either closely align with morphostratigraphic contacts, indicating spectrally and geomorphically distinct units in contact with each other, or spectral contacts diverge from morphostratigraphic contacts, indicating spectral diversity within a morphostratigraphic unit. We added these diverging spectral contacts to the morphostratigraphic contacts to create a new geostratigraphic map.

By combining spectral and morphostratigraphic datasets, we have been able to distinguish impact melt and volcanic plains deposits within Rachmaninoff, which formerly had to be grouped together [5]. Our method can be applied retroactively to preexisting morphostratigraphic maps of Mercury [6] and other planetary bodies [7], and it produces similar results to maps created from the outset using color data [8]. Our approach brings planetary geologic maps closer to their Earth equivalents.

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Georeferenced M-CAM images from BepiColombo's first Mercury swingby

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On 1st October 2021, the ESA/JAXA BepiColombo spacecraft completed its first Mercury swingby. Closest approach was at 23:34 UTC at 199 km altitude. Two of the three engineering Monitoring Cameras (M-CAMs) on BepiColombo's Mercury Transfer Module captured images of Mercury. Since BepiColombo approached on Mercury's nightside, only images captured later than five minutes after closest approach, when the spacecraft s altitude had risen to ~1180 km, observed the planet's illuminated surface. Illumination varies from local dawn to noon across these images, which include tracts of the Kuiper and Discovery quadrangles. In this work, we georeferenced four M-CAM images and compared them with MESSENGER data.

We used ArcGIS Pro to georeference M-CAM images. To minimise projection distortions, we used individual "Vertical Near Side Perspective" projections for each image. These simulate a planet's surface as seen from a spacecraft's altitude along camera boresights. We used manually placed control point networks to georeference the M-CAM images to MESSENGER MDIS basemaps. With this approach, we created accurately georeferenced products and we were able to check for surface changes since the MESSENGER images were taken.

The first M-CAM2-M-CAM3 image pair (images 1 and 2), taken ~5 minutes after closest approach, shows the Kuiper and Discovery quadrangles with high incidence angle solar illumination, highlighting lobate scarps such as Astrolabe Rupes. The second image pair (images 6 and 8) shows more of the Kuiper and Discovery quadrangles, with mutual overlap resulting in a continuous view of Mercury's terminator. We searched for MESSENGER images of these locations taken under similar illumination conditions. We found that there are not many equivalent images, which means BepiColombo has imaged parts of the Kuiper and Discovery quadrangles uniquely. For example, MESSENGER WAC image EW07617663G has similar illumination conditions to, but lower spatial resolution (2593 m/pix) than, MCAM image 1 (1370 m/pix) where they overlap.

There will be five more swingbys of Mercury before orbital insertion on 5th December 2025. M-CAM will capture new images of Mercury covering a range of latitudes and longitudes, under various illumination conditions. We will use these to identify and interpret features not, or imperfectly, revealed in MESSENGER images and to revise recent geological mapping. This will be particularly important for fault scarps and catenae, whose detection is highly dependent on illumination conditions [1]. M-CAM images will also be useful for defining BepiColombo observations, particularly those of the SIMBIO-SYS instrument [2].

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Spectral analysis of features of interest on Mercury northern hemisphere

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During its orbit around Mercury, MESSENGER mission acquired a huge amount of data, allowing for a spectral and compositional analysis never achieved before.
MESSENGER/Mercury Dual Imaging System (MDIS) [1] mapped for the first time, the entire surface of the planet at different spatial resolutions, with both a narrow and a multi filter wide angle camera, covering a range of wavelengths between ~0.4 and 1 μm. MDIS together with the Mercury Atmospheric and Surface Composition Spectrometer - Visible and Infrared Spectrometer (MASCS-VIRS) [2], permitted a detailed geological and spectral analysis at different spatial scales.
In recent years, morphostratigraphic studies of several Mercury quadrangles have been performed by many authors (e.g. [3, 4, 5]), emphasizing a plenty of different terrains and geological features, in some cases associated with spectral variations [6, 7].
Here, we focus on localized features showing peculiar spectral characteristics, such as fresh material, low reflectance material and faculae, by using proper spectral parameters. In particular, our analysis is concentrated on the Mercury northern hemisphere, where the best MDIS-WAC and MASCS-VIRS spatial resolution data are available.
This work is preparatory for the BepiColombo/SIMBIO-SYS instrument [8], both for the selection of possible targets of interest, and for the integration of the data acquired by VIHI spectrometer and the STC and HRIC cameras.

Acknowledgments
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Theme 3: Deep interior geophysics and planetary evolution

Mercury gravity field and rotational state with the BepiColombo MORE experiment

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The Mercury Orbiter Radioscience Experiment (MORE) onboard the BepiColombo mission was designed to provide an accurate estimation of the gravity field and the rotational state of Mercury and to perform fundamental physics tests during the cruise phase and the orbital phase of the mission. The Mercury Planetary Orbiter (MPO) is equipped with a state-of-the-art radio tracking system composed of the MORE's Ka-band Transponder (KaT), which enables Ka-band Doppler and Pseudo-Noise (PN) range data at 24 Mcps, and the Deep Space Transponder (DST) which enables the X/X and X/Ka Doppler and range data at 3 Mcps. The 5-way link configuration allows us to obtain range-rate and range coherent two-way measurements respectively accurate to 0.003 mm/s (at 1000 s integration time) and a 5 cm (after a few seconds of integration time), nearly at all solar elongation angles. The radiometric data will permit obtaining a precise reconstruction of the spacecraft orbit and estimating the spherical harmonic coefficients of the Hermean gravity field at least up to degree 45 (Imperi et al. 2019), the tide, and the rotational parameters (right ascension and declination of the pole and physical librations in longitude). The BepiColombo low eccentric orbit will provide global and uniform coverage of the planet, improving the MESSENGER gravity measurements, especially in the southern hemisphere. A full numerical simulation of the radio science orbit determination process has been carried out including the onboard Italian Spring Accelerometer (ISA) noise model. In this work, we report on the results of numerical simulations aiming at a realistic assessment of the attainable accuracy in the determination of the gravity field and the rotation of Mercury and focusing on the geophysical implications. The benefits of an extended mission will be highlighted.

A consistent model for the chemical, mineralogical, and physical characteristics of Mercury's crust

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Unique physical and chemical characteristics of Mercury have been revealed by measurements from NASA's MESSENGER spacecraft. The crust of Mercury was built over the first billion years of the planet by intense volcanic activity. Mantle melting and emplacement of lava to the surface produced a secondary magmatic crust varying spatially and over time in composition. These surface compositions for major elements can be converted to expected mineralogy based on phase equilibria under highly reducing conditions. The crustal mineralogy is supposed to be dominated by silicates (olivine, clinopyroxene, orthopyroxene, plagioclase, trydimite) and CaMg sulfides (Namur and Charlier 2017). Crustal mineralogy and porosity (produced by impacts and regolith formation) have implications for the density of the crust. The silicate mineralogy at the surface translates to pore-free crustal densities of 2,800-3,150 kg.m^{-3}. Maximum crustal density (3,100-3,150 kg.m^{-3}) is found in High-Mg regions that are modelled to be forsterite-dominated and plagioclase-poor. The lightest crust (2,750-2,800 kg.m^{-3}) is found in Al-rich regions such as the North Volcanic Plain that are plagioclase-dominated. Calculations of the thickness of the crust can be made using the MESSENGER gravity and topography data and lateral variations of crustal density should be considered. Using the assumptions that the surface density is representative for the density at depth, we find that the calculated local thickness of the crust is correlated with the degree of mantle melting (Beuthe et al. 2020). Low-degree melting of the mantle below the Northern Volcanic Plains produced a thin crust while the highest melting degree in the ancient High-Mg region produced the thickest crust, excluding mantle excavation by an impact in that region. However, uncertainties remain about the abundance of oxygen in surface rocks, with implications for the mineralogy that could be dominated by silicates and abundant Si metals, potentially produced by smelting reaction of lavas with graphite (McCubbin et al. 2017). The unconstrained abundance of metal phases and graphite in crustal rocks would require crustal densities to be reevaluated. Independent approaches to evaluate crustal density and porosity from gravity data are also necessary. These interpretations and their caveats will be discussed in light of the MESSENGER data and the BepiColombo measurements that are expected from 2025.

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The Evolution of Mercury's Crust

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Understanding the origin and evolution of Mercury's crust was a key goal of the MESSENGER mission. Prior to MESSENGER's exploration of Mercury, a leading hypothesis for the formation of the planet's crust was through crystal-liquid fractionation of a magma ocean, leading to a plagioclase flotation crust analogous to that of the Moon. However, reflectance observations and elemental abundance data make it clear that Mercury's crust is very different from the Moon's, and interpretations based on the planet's geomorphology and crater size-frequency distributions imply widespread resurfacing occurred, likely through a combination of volcanism and impact cratering. This geologic activity complicates an examination of Mercury's early crust. Here we present an investigation of Mercury's stratigraphy in order to evaluate the mode(s) of formation of key crustal units. We explore whether the global occurrences and regional variations are consistent with a graphite flotation crust, and investigate the role of early volcanism in the formation of Mercury's crust.

Mercury Magmatic, Tectonic and Geodynamic History: A Comparative Planetology Analysis

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Planetary exploration has provided insight into variation of volcanic-tectonic records, global lithospheric stress states/magnitudes, and mantle convection patterns with increasing planetary radius:

(1) The Moon's tectonic-magmatic history is dominated by a thick primary crust whose magma oceanography and aftermath dictated a volumetrically insignificant secondary crust generated from deeper mantle sources through a low-density crust/thickening lithosphere that precluded formation of magmatic-volcanic-tectonic (MVT) rises; relatively rapid conductive cooling changed global lithospheric stress state to modest contraction at ∼3.5 Ga; the role of subsequent mantle convection is still debated.

(2) Mercury's magma oceanography suggests a distinctly different primary crust (sulfur and carbon-rich). There is little evidence of mantle convection patterns (MVT rises/mantle plumes). Regional flood basalt volcanism from now-buried fissures dominated early volcanic history. The syn-post volcanism global lithospheric stress state implies significant radial contraction over the last several BY (widely distributed wrinkle ridges, huge tectonic arches). Evolution of the lithosphere was also affected by the presence of sulfides (possibly >10 vol%), which could reduce viscosity and concentrate radiogenic heat production.

(3) Mars magma oceanography suggests basaltic primary and secondary crusts; secondary crustal volcanism was near-global early on but rapidly focused to mantle-plume-like upwellings (MVT rises Tharsis/Elysium). The global lithospheric stress state implies decreasing modest contraction for the last several BY (widely distributed post-regional plains wrinkle ridges).

(4 and 5) Geological records of the first 80% of Venus and Earth histories are poorly known. Venus is currently (and for the last 0.5-1.0 BY) a one-plate planet losing heat conductively, and displaying a wide range of features implying both global-scale flood volcanism (regional plains) and vigorous mantle convection at several scales (rises, rift zones, coronae, large volcanoes). Earth currently displays bimodal MVT patterns: plate recycling and vigorous mantle convection at a range of scales (mantle plumes, hot spot,

rises, LIPs).

Differences in planetary core-mantle radius ratios (Moon ∼0.29, to Mercury ∼5.2?) are clearly an important evolutionary factor. As an endmember on this spectrum, Mercury offers insights into planetary geodynamic evolution. We currently focus on 3 questions: 1) Magma oceanography aftermath and predictions for mantle composition, fO2, sulfide distribution, volatile content parameter space; 2) How magnitude and timing of global contraction can help constrain the nature of heat sources/timing for mantle melting (relative roles of mantle internal heating and core heat flux mantle bottom-heating); & 3) How the observed volcanic record of magma generation, ascent & eruption is related to Mercury's thin mantle, sulfur-rich lithology and convection patterns & scale.

Mercury: Thermal evolution of a layered system

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The discoveries of the MESSENGER mission to Mercury have revealed puzzling evidence regarding Mercury's thermal evolution. The highly reduced mantle chemistry (suggested by the surface composition) combined with geodetic data point to a thin mantle, a large core, and a core composition only ∼5-15% less dense than pure liquid iron, indicating a light-element-poor core alloy. These characteristics should have led to rapid cooling, an early transition to sluggish or absent mantle convection, and substantial core solidification. Instead, estimates of global contraction suggest low to moderate secular cooling; relatively young pyroclastic deposits suggest long-lived mantle convection and (locally) supersolidus mantle temperatures; the low-order shape of Mercury's magnetic field suggests a small inner core. High mantle radiogenic heating can explain these features to some extent but must be reconciled with evidence that the planet and core began cooling early (e.g., the onset of global contraction in the Calorian Era, and crustal remanent magnetization indicating a long-lived early dynamo).

We evaluate the possibility that Mercury's highly reducing chemistry led to a stratified and unevenly heated mantle, which influenced its thermal evolution. Mercury's surface composition suggests a sulfide-bearing, reduced mantle. These sulfides should be (1) abundant, up to 20 wt.% of the mantle, (2) low-density, ∼15-20% lighter than the silicates, and (3) strongly heated, if radiogenic elements are chalcophile at Mercury magma ocean conditions. The combination of these features implies that the distribution of radiogenic heating would differ from what is predicted for a pure silicate mantle. Furthermore, initial heterogeneity could be stabilized against convective mixing by compositional stratification. Therefore, predictions from models that assume a homogenous mantle may not be capturing important thermal consequences of mantle heterogeneity. We model the thermal evolution of Mercury with a mantle that is layered in density and/or radiogenic heating, exploring a range of plausible initial mantle configurations. We evaluate the implications of that layering for Mercury's history of volcanism, magnetic field generation, and secular cooling.

Carbon partitioning under reducing conditions: implications for Mercury

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Mercury is the smallest planet of our Solar system and also the closest to the Sun. It is characterized by a very large core (70 vol.% of the planet) and its surface is highly depleted in FeO. These features have been interpreted as an evidence for primary differentiation of Mercury under very reducing conditions (IW−5 ± 2; with IW being the iron-wustite equilibrium). The primordial crust of Mercury may have been made up of graphite and would have formed by graphite flotation during solidification of a magma ocean. Recent neutron spectroscopy measurements in deep craters by the MESSENGER spacecraft show abundant C concentration (1-3 wt%) interpreted as relict from a primordial graphite crust. In order to model the formation of such a crust and to understand how carbon is distributed amongst the various geochemical reservoirs of Mercury, new data of carbon partitioning between silicate and metal is needed.

In this project, we performed high-temperature (1200-1900°C), high-pressure (0.1-26 GPa) experiments under moderately to highly reducing conditions (IW to IW-9). We will present new, high-precision SIMS data on carbon solubility in silicate melts and new EPMA data on carbon solubility in metal melts. For the silicate, carbon solubility is mainly controlled by the conditions of oxygen fugacity, reaching percentage levels at IW-9. Pressure also has an extremely large effect on carbon solubility. For the metal phase, oxygen fugacity also controls carbon solubility through its dependence on sulfur and silicon concentrations.

Our results are combined in a new parametrization of carbon partitioning. We estimate that, in contrast to terrestrial planets having formed in more oxidized conditions, Mercury's core might be depleted in carbon and Mercury's primary mantle may have contained hundreds to thousands of ppm of carbon.

Mercury's basin inventory and analysis of topography and gravity field data

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Impact structures on Mercury are predominant surface land-forms. They represent important records regarding the magnitude and timing of the "Late Heavy Bombardment" in the early inner solar system.
Geophysical data in combination with the surface morphology of impact basins may help improve our understanding of formation processes of basins and alterations with time. In particular, gravity anomalies may hint at complex mass and density distributions in the upper crust of the planet.

In this study we are using gravity and topography data obtained by MESSENGER spacecraft to create a catalogue of impact basins on Mercury larger than 150 km in diameter. 311 basins were tentatively identified and mapped. Complementary MESSENGER data sets were used to identify the basins based on morphology (USGS shaded relief maps, stereo image DTMs) and gravity signal. The confidence of identification (certain or probable) was assessed. We determined the location, diameter and depth of each basin. Moreover, we applied a classification according to type (from simple to complex) degradation state, as well as visibility of central peaks, rims and terraces.
An in-depth analysis of gravity and topography data sets was carried out to understand the information held in spherical harmonic models of different degree and order. Previously mapped impact basins from our inventory and their surroundings were characterized with respect to their local gravity field signals. Impact basins were found to show more complex gravity- and topography signatures with increasing diameters. Correlation analysis was carried out between topography and gravity signatures of individual impact structures. While, smaller basins possess a negative gravity anomaly, this values increases to the positive range with increasing basin diameter. The positive gravity signals may display high mass and density concentrations, which may be caused by an uplift of mantle material after the crater excavation phase. The excavation was followed by an isostatic adjustment caused by cooling and contraction of the melt pool. According to this, basins associated with a positive gravity anomaly may possess a thinner crust.

We selected a subset of impact basins from our inventory representing the variety of morphologies and gravity signatures. Due to MESSENGERS's highly eccentric orbit, resulting in gravity data of limited resolution in the southern hemisphere, this study is focusing on impact structures in the northern hemisphere only. Measurements by the upcoming Bepi-Colombo will provide a significant improvement in the gravity and topography models. The Bepi-Colombo Laser Altimeter (BELA) will produce accurate topographic profiles which will allow to characterize Mercury's impact basin in great detail. We assessed the expected coverage of basins by BELA profiles after two years of operation at Mercury.

Influence of insolation on Mercury's crustal thickness evolution

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Models based on gravity and topography data suggest the existence of significant large-scale variations in the thickness of Mercury's crust. In particular, models that use the surface mineralogy to guide the choice of the crustal density predict that the so-called high-Mg region is underlain by a thick crustal root resulting from a high-degree of partial melting (Beuthe et al., GRL, 2020). Numerical simulations using a constant surface temperature, however, predict that convection in Mercury's thin mantle is characterized by a laterally-uniform pattern of small-scale up- and downwellings, with nearly unitary aspect ratio (Tosi et al., JGR, 2013). While the overall amount of crust produced in these models compares favorably with estimates of the average crustal thickness, the lateral distribution of crust reflects the convection pattern and is thus difficult to reconcile with the large-scale variations inferred from the remote-sensing data. Lateral variations in surface temperature due to uneven insolation can induce long-wavelength variations of the mantle temperature at depth and in turn affect the generation of partial melt. We use 3D simulations of the thermo-chemical evolution of Mercury to investigate the influence of insolation on the production of Mercury's crust. We test the insolation associated with the present-day 3:2 resonance, as well as with other resonances (1:1 and 2:1) and eccentricities that may have characterized the orbit of Mercury before the capture into its current state. The insolations associated with the 3:2 and 2:1 resonances have a relatively small influence on crust formation. By contrast, the surface temperature distribution resulting from synchronous resonance induces a significant heating of the deep mantle beneath the dayside that causes the formation of large-scale crustal thickness variations. This scenario could contribute to explain the high-degree of melting and large thickness of the crust inferred for the high-Mg region.

Mercury's deep interior and evolution

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Mercury's high mean density together with its small size implies a larger abundance of heavy elements compared to Earth, Venus and Mars, and therefore indicates a large core and a thin mantle. Mercury's occupation of a Cassini state plays a pivotal role in the precise characterization of the core and mantle as it allows us to obtain independent estimates of their moments of inertia. Complemented with other data, notably geochemical data, some of Mercury's general interior properties are surprisingly well known for a planet that has only been visited by one orbiting spacecraft, although many basic questions remain unsolved. Mercury's unique internal structure also affects its thermal and magnetic evolution, which may be quite different from that of the other terrestrial planets of the Solar System. For example, at present, Mercury has a global magnetic field although the liquid part of the core may not be entirely convecting and convection in the mantle may have stopped. In this contribution, an overview of Mercury's interior structure and evolution will be presented from a geodetic and geodynamic point of view.

Theme 4: Fundamental physics with Bepi-Colombo

The MORE fundamental physics test at Mercury

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The Mercury Orbiter Radioscience Experiment (MORE) includes advanced radioscience instrumentation both onboard and on ground to provide accurate range and range-rate observables. Thanks to a 5-way link configuration the noise induced from the solar plasma can be compensated allowing for plasma-free radiometric measurements at nearly all solar elongation angles. This is allowed by the presence onboard of a Deep Space Transponder (DST) used for Telemetry, Tracking and Command (TT&C) functions, and a Ka-band transponder (KaT) which is the key onboard instrument for scientific investigations. The DST supports an X-band uplink (7.167 GHz) coherently retransmitted back to the ground in X- (8.420 GHz) and Ka-band (31.997 GHz), while the KaT can receive a Ka- uplink (34.384 GHz) and retransmit it coherently to ground (at 32.101 GHz). The MORE KaT is endowed with a novel wide-band ranging system, based upon a high rate (24 Mcps) pseudo-noise (PN) ranging code. Recent in-flight tests of BepiColombo have proven an extreme accuracy of less than 1 cm (at a few seconds of integration time) for MORE's PN regenerative range at 24 Mcps at 0.3 AU and confirmed range-rate accuracy at 0.003 mm/s at 1000 s integration time (Cappuccio et al. 2020b).

Thanks to the unprecedented performance of the radiotracking system, MORE will be able to probe the validity of general relativity and competing theories of gravity in the Solar System, by estimating several parametrized post-Newtonian (PPN) parameters. These parameters will be determined through an accurate estimate of the heliocentric motion of Mercury and propagation time of radio waves, which are obtained as an output of a precise orbit determination process.

We performed a comprehensive numerical simulation of the MORE fundamental physics test which will be held during the hermean phase of the mission. We report the results of the simulation describing the improvement which can be obtained on the estimated PPN parameters, and providing also an assessment of the benefits of an extended mission.

Effects of spacecraft outgassing and potential at Mercury

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During the flybys of Mercury and Venus the ion spectrometers onboard the Bepi-Colombo spacecraft observed enhanced fluxes of ions with energies of less than 50eV. Often these fluxes showed a characteristic double-band spectral shape in energy. We interpret these ion fluxes as being caused by ionized water molecules outgassing from the spacecraft. The double-band structure may be caused by a specific feature of the spacecraft potential: for a negatively charged spacecraft electrons will be rejected from the spacecraft and may form a negative space charge at distance given by the Debye length. This space charge may contribute to a separation of the observed ion fluxes into an inner and an outer source resulting in a double-band energy distribution. We show results of a particle-in-cell simulation supporting this interpretation.

Tests or relativistic gravity with the MORE investigation on BepiColombo

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The Mercury Orbiter Radio-science Experiment (MORE) will use BepiColombo's MPO (Mercury Planetary Orbiter) as a test mass to carry out classical and novel tests of relativistic gravity. The relativity experiment will exploit the same microwave instrumentation used for a precise determination of gravity field and rotational state of Mercury. The use of a full multifrequency, coherent, radio link with the spacecraft at X and Ka band (7.2-8-4 GHz, 34-32.5 GHz) will effectively cancel charged particle noise nearly all solar elongation angles, both on Doppler and range observables. The data acquired during tests in cruise and during the first superior solar conjunction (SCE1) have shown range rate accuracies < 0.003 mm/s at 1000 s integration time. The ranging system, based on a novel 24 Mcps pseudo-noise code in the Ka/Ka link has provided measurement accuracies of about 4 cm after just 1 s integration.

However, the outstanding performances of the radio system are partly limited by stray accelerations acting on the spacecraft. In the hermean phase these accelerations will be compensated by means of a high accuracy accelerometer (ISA), whose sensitivities are about 10^{-9}–10^{-8} m/s^2 in the frequency band 10^{-4}–10^{-1} Hz. However, in the cruise phase the dynamical disturbances are too small to be detected by ISA, forcing the adoption of a stochastic dynamical model to fit the data, that include the relativistic time delay on the ranging signal.

We will report on the first results from the MORE cruise relativity tests and on the expected results in the hermean phase for the precession of Mercury's perihelion, in the estimation of PPN parameters, and for a direct, dynamical determination of the solar oblateness and mass loss.

Zombie alert! Solar system tests of GR are still alive

Will, Clifford

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We have entered an era of testing general relativity in the strong-field, dynamical regime, using gravitational wave detections, direct observations of neutron stars and black holes, and cosmological observations. Yet, like the zombies of cinema, solar system tests continue to trudge along, adding new and interesting constraints on gravitational theories, while fortunately not devouring everything in their wakes. In this talk, we review some recent results, including tests of the equivalence principle using the MICROSCOPE and Galileo satellites, a test of light bending performed by an amateur astronomer, new bounds on frame dragging from the LAGEOS/LARES satellites, and a bound on the graviton mass from solar system ephemeris data. We also describe future tests that could come from the BepiColombo Mercury orbiters, the ACES clock experiment on the Space Station, and from the GAIA astrometry satellite.

Theme 5: Miscellaneous

SPIS simulation of Bepi Colombo interaction with the plasma environment encountered during the Venusian and Hermean flybys: influence on plasma measurements

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During its long journey to Mercury, Bepi Colombo will fly several times, close to Venus and Mercury. Each of those flybys represents a unique opportunity to study the Venusian and Hermean plasma environments. The Mercury Planetary Plasma Experiment (MPPE) on board the Mio spacecraft, is embedded inside the MMO Sunshield and Interface Structure (MOSIF). The MOSIF acts as a solar protection for Mio but highly limit/obstruct the MPPE instruments field of view (FOV) during its cruise phase. In addition the surface electrostatic charge can directly affect the low energy particle measurement (distortion of the FOV and particle spectrum). An other effect of MOSIF could be to increase the residence time of the outgassing particles (like water) and their chance to be ionized and then detected as low energy ions.

In this work we simulate the interaction of Bepi Colombo spacecraft with its environment during its Venus and Mercury flybys with the Spacecraft Plasma Interaction Software (SPIS). SPIS is a 3D hybrid Particle In Cell code (PIC), able to simulate complex interactions between a plasma and immersed surfaces (taking into account their material properties). By estimating the electric potentials of spacecraft surfaces, we will understand how it affects the MPPE particles measurements at Mio and where low energy particles come from.

Overview of low-energy electron observations from the Mercury Electron Analyzers onboard Mio/BepiColombo during cruise phase and planetary flybys

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BepiColombo was launched in October 2018 and is currently en route to Mercury. We will present an overview of the observations obtained by the two Mercury Electron Analyzer onboard the Mio spacecraft during the cruise phase, the Earth flyby in April 2020, and the two Venus flybys in October 2020 and August 2021, as well as during the first Mercury flyby in October 2021. We will focus on the properties of the electron populations observed in the various environments encountered by the spacecraft. We will focus on the method implemented in order to derive electron fluid parameters despite the limited field of view of the instruments during cruise.

The BepiColombo Surface and Environment Interactions Studies Group (SEIS)

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The Surface and Environment Interactions Studies (SEIS) Group, a subgroup of the BepiColombo Young Scientist Study Group (BCYSSG), was officially launched during the 20th BepiColombo Science Working Team (SWT) meeting on April 24, 2020. The aim of SEIS is to bring together the potential of an interdisciplinary approach through collaborations among motivated scientists of various research backgrounds to maximize our understanding of Hermean surface science in support of the BepiColombo mission which will arrive at Mercury in December 2025. Thus, the studies of this group examine the effects of compositional and physical properties of the Hermean surface due to a product of an interplay of solar wind interaction, larger impactors and cratering mechanisms, and interactions with internal magnetic fields. Interactions between the Hermean surface and its environment makes these actors also change individually.

SEIS encapsulates broad scientific interests, which include but are not limited to Mercury's internal magnetic field, magnetosphere-surface-exosphere interaction including space weathering, particle dynamics and precipitation, surface temperature, surface mineralogy, surface roughness, surface processes, physical properties, volatiles, polar deposits, tectonics, volcanism, impact cratering, stratigraphy, geological mapping, and 3D surface reconstruction, using ground-based, remote sensing, in situ observations, modelling, and field analogue studies. Combined together SEIS aims to answer questions about the planet's formation and evolution, and will collectively work towards the selection of targets with high-priority science objectives to aid BepiColombo mission planning. The group has currently outlined about ten different projects of major scientific interest for the study of surface-environment interactions. These projects allow the young scientists of the group to share and use their unique expertise in a common scientific goal.

This poster aims to highlight all the current SEIS projects and present the preliminary study carried out by one of these SEIS projects which aims to investigate the influences of solar extreme events on Mercury's surface and exosphere, i.e., the sputtering. The solar extreme events can lead to the direct impact of solar wind particles on Mercury's surface. The upstream conditions and the conducting core of Mercury determine the surface area that can be directly impacted by the solar wind. The precipitating solar wind particles can sputter neutrals into the exosphere and enhance the photo-desorption and thermal desorption from the grains on the surface. This extreme condition would enhance the escape of neutrals and maximize the escape of planetary ions into the interplanetary space.

BepiColombo- comprehensive exploration of Mercury: first results and mission status

Benkhoff, Johannes

ESA-ESTEC

Launched on 20 October 2018 from the European spaceport Kourou in French Guyana and after finishing more than 50% of its about seven year-long cruise-phase, BepiColombo has successfully performed several flybys (at Earth, twice at Venus and one at Mercury). On arrival in orbit around Mercury in 2025 it will perform measurements to increase our knowledge on the fundamental questions about Mercury's evolution, composition, interior, magnetosphere, and exosphere with its state of the art and very comprehensive payload. BepiColombo consists of two orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (Mio) and is a joint project between the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA).

Since the two spacecraft are in a stacked configuration during the cruise only some of the instruments will perform scientific observations. Mio and MPO are connected to each on-top of the Mercury Transfer Module (MTM). The MTM contains a solar electric propulsion engine and will bring the two spacecraft to Mercury. In late 2025, this "stack" configuration is abandoned, the MTM will be jettisoned, and the individual elements spacecraft are brought into their final Mercury orbit: 480x1500km for MPO, and 590x11640km for Mio.

Despite the reduced instrument availability, scientific and engineering operations has been scheduled during the cruise phase, especially during the flybys. A status of the mission and instruments, science operations plan during cruise, and first results of measurements taken in the first four years since launch will be given.

BepiColombo science data in the Planetary Science Archive - current status and future plans

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Working with BepiColombo science data - current status and future plans.

The BepiColombo mission to Mercury is expected to deliver a unique dataset to the scientific community. All scientific data and the ancillary products necessary to use and interpret them will be distributed through ESA's Planetary Science Archive (PSA). Data are formatted to the NASA Planetary Data System version 4 format (PDS4) which stores data and meta-data using an extensible information model designed for planetary science. PDS4 allows for compatible data formats (e.g. FITS and CDF) to be archived natively with only the addition of an XML label, giving compatibility with other archives and community data services. As well as providing long-term storage of the data, the PSA aims to provide rich data search and analysis capabilities customised to each mission.

A significant barrier to using planetary data is that, currently, users have to download data to their local computer, read the relevant documents and find the appropriate tools to build an analysis pipeline. By the time BepiColombo reaches Mercury and the first Mercury-phase data are released to the public, we hope to have several enhancements in place to improve this workflow:

- A new user interface will improve the experience of browsing and searching for data. A geographic information system (GIS) for Mercury will allow users to search for BepiColombo products in a map view.

- A new API (programmatic interface) will provide search capabilities for any custom meta-data, allowing for complex queries and data retrieval.

- Integration of the BepiColombo archive data into the ESA DataLabs project will be complete. This will allow users to execute queries and run custom code and pipelines on ESA infrastructure close to the data.

- Finally, to ease the burden of using data from a new instrument, the PI teams and BepiColombo SGS are working together to develop a series of tutorials based on open-source tools (e.g. Jupyter and python). These will be deployed on DataLabs as templates for new users to rapidly learn how to find, "slice and dice", analyse and visualise the data.

The current state and future plans for BepiColombo archive data in the PSA will be presented here. Feedback on the services provided by the PSA and feature requests and enhancements to the data or archive functionality would be particularly welcomed.

A large proto-Mercury as the aubrite parent body

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Aubrite meteorites are ancient achondrites formed under reduced conditions in the silicate portion of a differentiated planetary object whose chemical and physical properties are unknown. Here we use Ni and Co partitioning between metal and silicate to estimate the pressure and oxygen fugacity (fO2) conditions of core formation in the aubrite parent body (AuPB). Our model indicates an fO2 of IW-5.2 (-1.8 +1.4) and a pressure of 29 (-21 +32) GPa, suggesting a highly reduced and planetary-sized (0.3 - 0.8 Earth mass) AuPB, consistent with a large proto-Mercury. The chemical continuum observed between Mercury's surface and aubrites supports that proto-Mercury was the AuPB whose mantle was stripped-off by impact. Relict debris from proto-Mercury may have partly accreted to outer terrestrial planets and currently form E-type asteroids, the actual source of aubrites.

MERCURY IMPACTOR: A mission to study below the surface

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The surfaces of airless bodies like Mercury undergo processes of gardening, i.e. meteoritic bombardment, and regolith alteration, due to the direct and continuous exposition of the regolith to the solar and cosmic radiation. The long exposure to the meteoritic and to the energetic ion bombardments causes deep changes in the surface features. Eventually, to have a real knowledge of the body, it would be necessary to study the layers below the exposed surface, down to at least tens of meters.
The most conventional method to investigate the underlying surface layers and composition is to use a drill in a probe/lander to the surface. On the contrary, producing an artificial fresh impact crater with a massive projectile hitting the surface would allow to access the subsurface material. Part of it volatilizes and can be measured remotely from an orbiting spacecraft. Part of it is ejected and re-deposited around the cavity, so that it could be analyzed and studied by remote sensing instruments.
The present mission idea consists in launching a massive and high velocity projectile, able to volatilize an adequate surface volume and generate a crater of up to a hundred meters. The projectile should be built of a special alloy that would be easily distinguishable from the one of the planet surface. The science objectives of this mission will be to study i) the lower (and pristine) layers of the surface, ii) the impact by itself and its measurable consequences on the surface and iii) the variability induced in the exosphere due to the vaporization process.
Two possible mission scenarios are under investigation:

1. Using the electric propulsion or a ballistic trajectory, the cruise could last less than 6 months, but the maximum impact velocity will be about 16 km/s, thus producing

a smaller crater and allowing only shallow impacts in the polar regions. In this case, the Technological Readiness Level (TRL) is much higher and the development phase will be shorter, thus the BepiColombo MPO spacecraft could be still in orbit around Mercury; hence, its payload could observe the impact effects.

2. Using the solar sail propulsion, the cruise will last 1.5-3 years, the impact velocities could arrive up to more than 100 km/s in the case of a retrograde impact, thus producing a big and deep crater at any desired position onto the surface. The TRL is still low; hence, a relatively long development time will be required. The mother spacecraft will include a dedicated payload (mass spectrometer, UV-Vis imager, IR spectrometer, high res camera, ...).

The choice of the best suited target sites and the determination of the minimal requirements of crater size and depth is under analysis.

The MeSS (Mercury Surface Spectroscopy) Database Architecture and Contents

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The MeSS (Mercury Surface Spectroscopy) PostGreSQL database project was initially created to host MASCS MESSENGER science data in order to provide a user friendly way to query MASCS data at once, for instance to characterise the spectral properties of surface features (Besse et al., 2020 ; Barraud et al. 2021).

At this stage the MeSS database includes calibrated MESSENGER's MASCS data together with the corresponding high-level products computed by the MeSS team using those calibrated data.
We are planning the MeSS as a collection of instrument spacecraft, high level scientific products and community products related databases. In the future we plan to enrich this collection with more instrument data From MESSENGER such as MDIS and MLA instruments, but also adding new high-level products.

In this work, we will present the current structure and contents of the MeSS database, the new extension in progress and the potential future extension.

Space Weather monitoring with BepiColombo

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BepiColombo is a joint mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to the planet Mercury that was launched in October 2018 and it is due to arrive at Mercury in late 2025. It consists of two spacecraft, the Mercury Planetary Orbiter (MPO) built by ESA and the Mercury Magnetospheric Orbiter (MMO) built by JAXA. BepiColombo has a large suite of instruments dedicated to plasma and solar physics that will allow us to characterize the solar wind and solar particles interaction with the Hermean environment and, therefore, to get the most detail to date characterization of the Hermean Space Weather awareness. Most of the relevant instruments are operated during the cruise phase on a regular basis, including the Solar Intensity X-Ray and Particle Spectrometer (SIXS), the BepiColombo Environmental Radiation Monitor (BERM), the Solar Particle Monitor (SPM), the Mercury Gamma and Neutron Spectrometer (MGNS), the BepiColombo Planetary Magnetometer (MPO-MAG) and the Mercury Electron Analyzer (MEA). These instruments are being calibrated using cruise data, and they are providing good insights into the Space Weather context that BepiColombo will encounter after Mercury's orbit insertion, as well. For example, so far BepiColombo has detected tens of solar particle events during the cruise, several of them at locations in the inner Solar System that provide excellent opportunities for multispacecraft studies, such as the recent solar event occurred on 28 March 2022 where BepiColombo was well aligned with STEREO-A in the Parker spiral, and almost radially aligned with Earth. In this work, we perform an assessment of the Space Weather context that BepiColombo will encounter at Mercury based on current observations, and of the potential consequences for the Hermean environment.

Handling Cauchy Noise in Laser Altimetry of Mercury-Tests with MESSENGER Data and Prospects for BepiColombo/BELA

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It is a trivial notion that all measurements contain error or noise. To derive meaningful physical units from our measurements we need to keep error and noise as small as possible and we need to know how to handle them. How much of a problem noise is, depends on its nature. We are using laser altimetry data to derive tidal parameters 1-3. In our simulations, Gaussian noise has been shown to be have only a low impact on the resulting Love numbers. However, the Cauchy distributed noise strongly affects our results. The Cauchy distribution has long tails which translates to outliers in the data. Cauchy distribution is a “pathological” distribution: it has no defined expectant value or variance; simply cutting out outliers won’t improve results. We look into weighted nuclear norm minimization (WNNM) for regularization of our input data, an approach that has recently been used in regularization of images with Cauchy noise4.

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BepiColombo Mercury Swing-by-2 on 23 June 2022 - An Overview

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In the morning of 23 June 2022, the BepiColombo spacecraft ensemble will fly-by Mercury for the 2nd time. The spacecraft will approach the planet from the night side near to equatorial latitudes at a distance around 200 km from its surface. The spacecraft itself will undergo an eclipse period of 18 minutes at the time of the closest approach. Several of the instruments on-board ESA's Mercury Planetary Orbiter (MPO) - PHEBUS, ISA, MPO-MAG, MGNS, MORE, SIXS, SERENA, BERM, and MCAM - and on JAXA's Mercury Magnetospheric Orbiter (MMO) - MGF, MPPE, SPM, MDM, and PWI -will operate before, during, or after the closest approach (CA).

We will present the detailed geometry of this second fly-by, the overall instrument planning including the scientific and engineering goals, and the foreseen public outreach activities.

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