



HAL
open science

Inner southern magnetosphere observation of Mercury via SERENA ion sensors in BepiColombo mission

Stefano Orsini, A. Milillo, H. Lichtenegger, A. Varsani, S. Barabash, S. Livi,
E. de Angelis, T. Alberti, G. Laky, H. Nilsson, et al.

► **To cite this version:**

Stefano Orsini, A. Milillo, H. Lichtenegger, A. Varsani, S. Barabash, et al.. Inner southern magnetosphere observation of Mercury via SERENA ion sensors in BepiColombo mission. *Nature Communications*, 2022, 13, pp.7390. 10.1038/s41467-022-34988-x . hal-03851795v1

HAL Id: hal-03851795

<https://hal.science/hal-03851795v1>

Submitted on 14 Nov 2022 (v1), last revised 20 Dec 2022 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Inner southern magnetosphere observation of Mercury via SERENA ion sensors in BepiColombo mission

S. Orsini^{1*}, A. Milillo¹, H. Lichtenegger², A. Varsani², S. Barabash³, S. Livi^{4,5}, E. De Angelis¹, T. Alberti¹, G. Laky², H. Nilsson³, M. Phillips⁴, A. Aronica¹, E. Kallio⁶, P. Wurz⁷, A. Olivieri⁸, C. Plainaki⁸, J. A. Slavin⁵, I. Dandouras⁹, J. M. Raines⁵, J. Benkhoff¹⁰, J. Zender¹⁰, J.-J. Berthelier¹¹, M. Dosa¹², G. C. Ho¹³, R. M. Killen¹⁴, S. McKenna-Lawlor¹⁵, K. Torkar², O. Vaisberg¹⁶, F. Allegrini^{4,17}, I. A. Daglis^{18,19}, C. Dong²⁰, C. P. Escoubet¹⁰, S. Fatemi²¹, M. Fränz²², S. Ivanovski²³, N. Krupp²², H. Lammer², François Leblanc¹¹, V. Mangano¹, A. Mura¹, R. Rispoli¹, M. Sarantos¹⁴, H. T. Smith¹³, M. Wieser³, F. Camozzi²⁴, A. M. Di Lellis²⁵, G. Fremuth², F. Giner², R. Gurnee²⁶, J. Hayes¹³, H. Jeszenszky², B. Trantham², J. Balaz²⁷, W. Baumjohann², M. Cantatore²⁴, D. Delcourt²⁸, M. Delva², M. Desai⁴, H. Fischer²², A. Galli⁷, M. Grande²⁹, M. Holmström³, I. Horvath¹², K.C. Hsieh³⁰, R. Jarvinen^{6,31}, R. E. Johnson³², A. Kazakov¹, K. Kecskemety¹², H. Krüger²², C. Kürbisch², Frederic Leblanc³³, M. Leichtfried², E. Mangraviti²³, S. Masetti¹, D. Moissenko¹⁶, M. Moroni¹, R. Noschese¹, F. Nuccilli¹, N. Paschalidis¹⁴, J. Ryno³¹, K. Seki³⁴, A. Shestakov¹⁶, S. Shuvalov¹⁶, R. Sordini¹, F. Stenbeck³, J. Svensson³, S. Szalai¹², K. Szego^{12**}, D. Toublanc⁹, N. Vertolli¹, R. Wallner², A. Vorburget⁷.

Affiliations

¹Institute of Space Astrophysics and Planetology, INAF, Roma, Italy.

²Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

³Swedish Institute of Space Physics, Kiruna, Sweden.

⁴Southwest Research Institute, San Antonio, TX, USA.

⁵University of Michigan, Department of Climate and Space Sciences and Engineering, Ann Arbor, MI, USA.

⁶Aalto University, Department of Electronics and Nanoengineering, School of Electrical Engineering Helsinki, Finland.

⁷University of Bern, Institute of Physics, Bern, Switzerland.

⁸Italian Space Agency, ASI, Roma, Italy.

⁹Institut de Recherche en Astrophysique et Planétologie, CNRS, CNES, Université de Toulouse, Toulouse, France.

¹⁰ESA-ESTEC, Noordwijk, The Netherlands.

¹¹LATMOS/IPSL, CNRS, Sorbonne Université, Paris, France.

¹²Wigner Research Centre for Physics, Budapest, Hungary.

¹³The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.

¹⁴NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

¹⁵Space Technology Ireland, Ltd., Maynooth, Co. Kildare, Ireland.

¹⁶IKI Space Research Institute, Moscow, Russia.

¹⁷[University of Texas at San Antonio, Department of Physics and Astronomy, San Antonio, Texas, USA](#)

¹⁸National and Kapodistrian University of Athens, Department of Physics, Athens, Greece.

¹⁹Hellenic Space Center, Athens, Greece.

²⁰Princeton Plasma Physics Laboratory and Department of Astrophysical Sciences, Princeton University, Princeton NJ, USA.

²¹Department of Physics, Umeå University, Umeå, Sweden.

²²Max-Planck-Institut für Sonnensystemforschung, MPS, 37077 Göttingen, Germany.

²³Astronomical Observatory, INAF, Trieste, Italy.

²⁴OHB-Italia SpA, Milano, Italy.

²⁵AMDL srl, Roma, Italy.

²⁶Laboratory for Atmospheric and Space Physics, Boulder, CO, USA.

²⁷Institute of Experimental Physics SAS, Slovak Academy of Sciences, 040 01 Košice, Slovakia.

²⁸Université d'Orleans, Orleans, France.

²⁹Aberystwyth University, Aberystwyth, Ceredigion, UK.

³⁰University of Arizona, Tucson, AZ, USA.

³¹Finnish Meteorological Institute FMI, Helsinki, Finland.

³²University of Virginia, Charlottesville, Virginia 22904, USA.

³³LPP, École polytechnique, 91128 Palaiseau Cedex, Paris, France.

³⁴University of Tokyo, Department of Earth and Planetary Science, Graduate School of Science, Tokyo, Japan.

*Corresponding author: stefano.orsini@inaf.it

**Prof K. Szego has deceased on Jan 22, 2022

Abstract

In this study we present the observation of Mercury's inner southern magnetosphere and surrounding regions, never previously explored, as detected by the two ion sensors of the instrument package: 'Search for Exospheric Refilling and Emitted Natural Abundances' (SERENA), named 'Planetary Ion CAMera' (PICAM) and 'Miniaturized Ion Precipitation Analyzer' (MIPA), on board BepiColombo mission during the first Mercury flyby, on 1st October 2021. Here we show the analysis of the data acquired during this flyby, a glimpse of what we will get from the nominal mission: in particular we observe and describe specific ion features nearby and inside the Hermean environment, like: intermittent high energy signal due to an interplanetary magnetic flux rope; magnetospheric ions with different energy drifting at low altitudes above the planet and determining specific plasma regimes; ion signals detected outside the magnetosphere at low energy.

Introduction

The ESA-JAXA BepiColombo (BC) mission was launched from the ESA space base in Kourou (French Guiana) in October 2018 on an Ariane 5 rocket, with the goal of studying the planet Mercury (1). In the past, this planet was already visited by other two satellites: first with three flybys by Mariner-10 in 1974 and 1975 (2), and then by the 'Mercury Surface, Space ENvironment, GEochemistry, and Ranging' (MESSENGER) satellite, which orbited Mercury with a polar trajectory for four years from 2011 to 2015 (3). Mariner 10 and MESSENGER made many new and surprising observations. Mariner-10 discovered an unexpected existence of an internal dipolar magnetic field and a magnetospheric cavity, much weaker than the Earth's magnetosphere (4). The observations of MESSENGER during flybys and during the whole mission confirmed the presence of internal magnetic dipole moment of $190 \text{ nT } R_M^3$ and found that the dipole is offset northward by about $0.2 R_M$. (5). Furthermore, MESSENGER observations depicted a really dynamic magnetosphere, with a strong coupling with the external solar wind conditions and a high reconnection rate that produces a frequent and efficient solar wind entry and circulation inside the magnetosphere (6). BC is a much more complex mission, carrying many instruments on board two different elements: MPO (Mercury Planetary Orbiter, ESA), and Mio (Mercury Magnetospheric Orbiter, JAXA). After having travelled in the interplanetary space for the first three years, BC passed by its target planet Mercury for the first time on 1st October 2021. The final orbital insertion of the two elements MPO and Mio will take place at the end of 2025: MPO will be inserted in a polar orbital path, at beginning between 480 and 1500 km; Mio will have a polar orbital path as well, at beginning between 590 and 11640 km. Before the beginning of the nominal phase, it will perform six Mercury Flybys in total (7). In the actual cruise configuration of the composite spacecraft, not all BC instruments can operate. In particular, the SERENA suite of four units, devoted to the study of the ion and neutral particle populations around the planet (8), has the possibility to perform scientific measurements during cruise via two units, PICAM and MIPA, both devoted to the observation of positive ions coming from the solar wind as well as from the planet's environment. PICAM and MIPA have a 3D Field-of-View (FoV) $< 2\pi$, with the boresight pointing perpendicular to the Sun direction (see Supplementary Materials for details). Both sensors are nominally able to detect the solar wind in their extreme lateral views: in this case, due to the sensitivity trend versus angle from the boresight, only PICAM is able to clearly detect the solar wind signal. Moreover, the two sensors together observe plasma regimes over a wide energy range, covering both solar wind and planetary ion populations, outside and inside Mercury's magnetosphere. A short description of PICAM and MIPA technical features is given in the supplementary material. In the following, the timing of the observations along the BC trajectory near-by Mercury is described, and the PICAM and MIPA data are shown. The trajectory of the first Mercury flyby (MFB1) covers regions in the southern hemisphere at low altitudes not explored by previous missions, so that the collected data allow showing ion energy distributions at the bow shock and closer to Mercury in the southern hemisphere.

Results

(a) BepiColombo trajectory and region traversals.

The BC MFB1 occurred between the 1st and the 2nd of October 2021. The Mercury Solar Magnetospheric coordinated system (MSM) is centered on the planetary magnetic dipole with the X-axis positive in the solar direction and an offset northward along the MSM Z-axis by 480 km (about $0.2 R_M$), parallel to the planetary rotation axis (5). The Y-axis is positive opposite to the direction of Mercury's orbital velocity which completes the right-handed MSM system. The spacecraft approached the planet from the dusk flank, the magnetosheath and near

magnetotail, and exited the magnetosphere in the dawn dayside, again crossing the magnetosheath (Fig. 1). The closest approach occurred on October 1st, at 23:34 UT at an altitude of 199 km and Z_{MSM} about $-0.7 R_{\text{M}}$ in the nightside. As shown in Fig. 2, PICAM operated during 4 distinct time periods and observed the solar wind ion flux (Panel a, inserts 1 and 4), the inbound magnetosheath, and the inner magnetosphere (Panel a, insert 2), and the region upstream of the bow shock (Panel a, insert 3), while MIPA operated continuously from 22:35 UT to 23:56 UT, and observed the magnetosheath adjacent to the tail, the inner magnetosphere and the outbound magnetopause and bow shock (Panel b).

(b) Solar wind observations.

The solar wind was not always visible to PICAM and MIPA during the cruise, depending on the FoV direction (the FoV edge being about 30° off the Sun direction). Nevertheless, while approaching Mercury, PICAM was able to see part of the solar wind distribution that appeared to be quite warm, dense, and at low energy (peaking at about 600 eV). Between 19:00 UT and 21:00 UT, at a distance of about $25 R_{\text{M}}$ from Mercury center, in the dusk side, the spacecraft rotated and the PICAM boresight moved from the $-Z_{\text{MSM}}$ direction, i.e., the southern hemisphere to $+Z_{\text{MSM}}$ in the northern hemisphere (see Fig. 3). In doing so, PICAM FoV passed through the $-Y_{\text{MSM}}$ direction (i.e., moving to the same direction as the planet moves pointing along the ecliptic plane toward the bow shock).

During this time-period, PICAM observed clear intermittent features (with a time scale of a few minutes) at high energies (above 1 keV, Fig. 4a). Actually, their appearance is clearly associated with PICAM's FoV pointing towards the bow shock, as opposed to the solar wind direction, but the possibility that these intermittent structures could be related to a source from the bow-shock (11) is hardly applicable by considering that the vantage point is too far away from the bow shock itself. A combined analysis with magnetic field data from BC/MAG (MPO magnetometer) would be needed, to verify that these keV particles could be associated with the passage of an interplanetary magnetic flux rope with its axis oriented along the Y-axis. In this case, MAG should observe the typical signature of this structure, i.e., an increase of the average magnetic field magnitude (with respect to the main background field), a decrease of the variance of magnetic field fluctuations, and a smooth rotation of one of the field components. Such findings have a chance to be also validated by means of Solar Orbiter (SolO) magnetic field observations. In fact, SolO (12) was located at a distance of 0.64 AU from the Sun (0.26 AU ahead BC) and the two spacecraft were reasonably radially aligned, longitudinally separated by less than 10° , and lying on the same side of the heliospheric current sheet. Details of the results of this analysis will be reported in a forthcoming paper, as soon as the MAG data will be confirmed and officially validated. The actual effect over the Mercury environment would have been the subject of an interesting study, but unfortunately the solar wind structure vanished well before the flyby, and any possible internal effect was not observed. It likely produces enhanced flux transfer events and magnetic reconnection sites, together with small substorm-like activity in the nightside of the Hermean magnetosphere. However, as we will show in the next section the Mercury's magnetosphere was in quiet conditions, thus suggesting that it reconfigured after the passage of the flux rope. Such kind of events will be further investigated during the nominal mission (after satellite orbital insertions, in late 2025), when Mio will observe the solar wind conditions and simultaneously MPO will record any internal reaction. The solar wind observed upstream, on the dawn side of Mercury (Fig. 4c), shows a similar average energy, but appears to be more variable with a sharp drop in intensity after 5 UT, indicating an unstable condition. Just behind Mercury's bow shock, PICAM performed ion observations within an extended energy range, including lower energies. The solar wind energy was somewhat low, corresponding to about 550 eV (Fig. 4b). Two signals at even lower energies (the bands at 38 eV and 60 eV) were clearly observed, with a variable density on time scales of 30 minutes, with sunward and anti-sunward directions, respectively. Further investigation is needed by cumulating more events statistically significant with different environmental conditions and satellite orientations, in order to clarify whether this signal is originating from Mercury's interaction with the solar wind, or alternatively it is induced by spacecraft outgassing (13). The Mass Spectrum Analyzer (MSA), a unit of the MPPE (Mercury Plasma Particle Experiment) consortium onboard BC-Mio, confirms the existence of a distinct double-band feature at low energies and that O^+ is the dominant ion species (Anna Milillo, ESA BepiColombo Interdisciplinary Scientist, personal communication). The simultaneous observation by two separate BC instruments of such a low energy signal excludes the possibility that it could come from instrumental effects. The persistent presence of outgassing material around spacecraft was discovered several years ago in the surrounding of Rosetta spacecraft (14). In that case, a neutral gas cloud was actually discovered and the reason why such outgassing material was staying around the

spacecraft is still not clearly understood. The possibility that the low energy ion observations by BC could actually be determined by ionization and acceleration processes occurring on such a neutral gas cloud needs more investigations, so that several cruise campaigns have been planned to see when and in which conditions such a phenomenon is actually observed. Outbound from Mercury, the about 550 eV slow solar wind is again observed when BC returned to cross the bow shock.

(c) Magnetosheath and inner magnetosphere observations.

The inbound bow shock crossing occurred before MIPA and PICAM were turned ON (after the wheel off-loading -WOL- operations). As shown in Fig. 5 (panel b), immediately after switch-on at 22:35 UT MIPA observed a weak signal at 800 eV - 1 keV, corresponding to relatively hot magnetosheath population just barely observable within the MIPA FoV perpendicular to the Sun direction. As the spacecraft was moving upstream and closer to the planet, the ion temperature increased and a larger fraction of the distribution function was observed by both PICAM and MIPA (panels a and b). In fact, between about 23:10 UT and about 23:25 UT a signature of ion population was clearly observed by both PICAM and MIPA sensors as a wide distribution centered at about 1 keV. This population can be identified as low latitude boundary layer (LLBL) (15) similarly of what has been observed in the Earth magnetosphere (16), marking the transition between magnetosheath and magnetosphere. Just after this high density and hot signal at around 23:25 UT, the ion density decreased abruptly, possibly indicating that BC was inside the magnetosphere. At about 23:35 UT, the PICAM and MIPA ion intensity increased again (likely corresponding to the crossing of the plasma sheet), and simultaneously the PICAM background noise decreased significantly. This PICAM background noise decrease was observed also during the second Venus fly-by and it was interpreted as the shielding of galactic cosmic rays induced by the planet. Approaching the planet, where BC moved northward through the dawn flank plasma sheet, both PICAM and MIPA observed ions at energies between 300 eV and 2000 eV, just before the outbound magnetopause crossing occurred around 23:40 UT. Inside the magnetosphere, the only ion species clearly identified by PICAM is ionized hydrogen: further investigations are needed to identify possible presence of planetary ions in the data. This ion population could be the solar wind entered into the dayside magnetosphere and drifting clockwise around the planet viewed from the north rotational pole, i.e., ion grad B or curvature drift directions as with Earth's ring current (e.g.: 17) and seen at higher altitudes by MESSENGER (18,19). Approaching the dayside magnetopause at dawn, MIPA observed an increase in plasma ion densities and a decrease in the energy. This clear signature of dayside magnetosheath was registered only by MIPA between 23:40 UT and 23:45 UT (Fig. 5, panel b), while PICAM was switching its operation mode between 23:38 and 23:46 UT. In this observation, the magnetopause and bow shock crossings were registered at distances of $1.5 R_M$ and $4 R_M$, respectively, which is closer to the planet with respect to the average MESSENGER positions for these boundaries (Fig. 2). The predicted crossing times for the bow shock and for the outbound magnetopause are about one to two minutes (note that the MIPA time resolution is 22 s) after the MFB1 observations by SERENA ion sensors.

Discussion and Conclusions

In the present paper we report on the observation of the ion distributions in the environment of planet Mercury, at energies up to 15 keV, as detected by the sensors SERENA-PICAM and -MIPA, during the BC MFB1, on 1st October 2021. The data presented are ion observations in the southern hemisphere of the planet, down to an altitude of about 200 km, the closest approach during MFB1. The solar wind observed by SERENA before and after the magnetospheric crossing reveals the presence of a quite low-energy solar wind of about 500–600 eV. Moreover, we report the observation of intermittent events of high-energy solar wind pulses at about 1500 eV, which were observed during the inbound phase, far outside the bow shock, possibly due to the passage of an interplanetary flux rope. In addition, the outbound observation of the solar wind after the bow shock crossing revealed the presence of two beam-like signals at about 60 eV. This low energy ion signal (which could be associated with satellite outgassing) is present in PICAM observations only outside the Mercury's Magnetosphere, and well separated from the higher energy solar wind signal. Hence, there is no indication that the observation of planetary plasma by PICAM could be affected by this phenomenon. Both the energetic spikes and the low-energy signals will be investigated in dedicated studies. Inside of Mercury's nightside magnetosphere, protons with energies of one to several keV are observed at low altitudes in the region where a weak ring current composed of drifting ions and electrons has been hypothesized (17, 18). These initial BC PICAM and

MIPA data provide evidence for ring current-like distribution plasma around Mercury, as tentatively reported by MESSENGER data (19, and reviews 20, 21). Further, the MIPA observations revealed a strong increase in plasma ion densities near the dawn magnetopause, slightly upstream of the terminator plane. Such increases in plasma beta (ratio of plasma thermal energy to magnetic energy) on the dawn side of Mercury's magnetosphere were also observed by MESSENGER during their flybys (22, 23). These new PICAM and MIPA observations appear to confirm the presence of this unexpected dayside magnetospheric asymmetry, tentatively reported by MESSENGER. Further analysis of the PICAM and MIPA measurements may lead the identification of its formation mechanism that is still eluded in the analyses of magnetosphere observations, e.g. double magnetopause (24), sunward transport of plasma sheet plasma (25) or a solar wind-driven low latitude boundary layer (15). To summarize, SERENA ion sensors PICAM and MIPA detected various plasma regimes inside Mercury's magnetosphere, possibly allowing the identification of specific ion species and plasma populations, typical of plasma sheet, magnetosheath and magnetopause, up to the bow-shock crossing during the outbound phase. The relevance of these measurements emphasize the importance of the SERENA positive ion sensors. Once their data will be analyzed together with the MAG instrument magnetic field data and other instruments on board Mio and MPO, they will reveal important insight into many unknown aspects of a magnetosphere deep inside the inner heliosphere, like the case of Mercury. The observed plasma regions and features will be investigated in more detail by using new observations from the forthcoming five new Mercury flyby's and the nominal phases in Mercury's orbit starting in 2026 (26).

Methods

Data Downlink and processing data pipeline

Payload telemetry (P/L TM) data collected by BC is downlinked to Earth through the Deep Space Network (DSN) antennas of ESA/NASA Ground Segment. From there data are transferred and stored at the Ground Operation System's Data Dissemination System (EDDS) server located at ESA-ESOC (Germany) where they are ready to be retrieved directly by the instrument teams or by the ESA Science Ground Segment (SGS) servers located at ESA-ESAC (Spain). P/L TM is binary data produced according to the SCOS-2000 standard. They basically consist of science (SC) measurements and instrument housekeeping (HK) data. Once received on-ground, TM data are sorted by generation time (Spacecraft (S/C) Elapsed Time -SCET-), packed and stored into the EDDS server, and finally provided to the instrument teams and SGS team as DDS binary data. SERENA team has developed a scientific data processing and archiving architecture in cooperation with BC SGS team. The SERENA data processing pipeline is designed to run at both INAF-IAPS and SGS, and provides validated data sets and a quick-look analysis tool. Data processed by the pipeline are formatted according to the Planetary Data System, Version 4 (PDS4) standards, maintained by NASA, and archived into the public Planetary Science Archive (PSA), maintained by ESA. The pipeline has two different processing branches: telemetry-to-raw (TM2RAW) data and raw-to-calibrated (RAW2CAL) data. The former generates RAW data from the TM files, the latter uses RAW data to produce CALibrated data. Usually, the two modules work in sequence, but they can also work separately, e.g. for instrument health checks (TM2RAW) or re-calibration purposes (RAW2CAL). The inputs of TM2RAW are the DDS files retrieved by the S/C and the SPICE kernels provided by the NASA's Navigation and Ancillary Information Facility (NAIF) team. The TM2RAW routine extracts all relevant binary data packets (SC and HK) from DDS files, generates proper UTC time stamps, and converts the data into ASCII RAW data files. The SPICE kernels contain the information to calculate the spacecraft position, the FoV of the sensors and the parameters for the time conversions for each SC and HK packet. Additionally, PDS4 label files in XML format are generated to provide ancillary information. The RAW data includes unprocessed (ADC counts) original SC and HK data from the instrument which is mainly used for diagnostic purposes. If compression, reformatting, packetization, or other translation has been applied to facilitate data transmission or storage, all data generated by the pipeline are available as ASCII files and grouped in RAW, CALIBRATED & DERIVED data. Below this level, data are grouped by mission phases, e.g.: Near Earth Commissioning or Cruise. The next logical level distinguishes data sensor by sensor, and then separates the housekeeping HK from science SC data. Additionally, browse plots for a quick data overview and useful information for the data end-user can be found in the archived datasets. In the present paper only RAW data are shown, as in Fig.4 and Fig. 5.

Data availability

The data referring to Fig. 1, Fig. 2, and Fig.3 generated in this study are provided in the Supplementary Source Data file. The raw data shown in Fig. 4 and Fig. 5 are protected and cannot be distributed, due to BepiColombo data privacy regulations. Presently, all data, codes, and materials shown in Fig. 4 and Fig. 5 may be only accessed via permission in the SERENA team archive, through request to the SERENA team (PI, Stefano Orsini, stefano.orsini@inaf.it; or PI Deputy, Anna Milillo, anna.milillo@inaf.it).

References

1. Benkhoff, J., et al.: 'BepiColombo - Mission Overview and Science Goals'. *Space Sci Rev* 217, 90 (2021). <https://doi.org/10.1007/s11214-021-00861-4>.
2. Strom, R. G., A.L. Sprague, Exploring Mercury: The Iron Planet (Springer, New York, 2003). ISBN 185237311
3. Solomon, E. C., R.L. McNutt Jr., R.E. Gold, D.L. Domingue, MESSENGER mission overview. *Space Sci. Rev.* 131, 3–39 (2007). <https://doi.org/10.1007/s11214-007-9247-6>
4. Ness, N. F., Behannon, K. W., Lepping, R. P., and Whang, Y. C.: *Nature* 255, 204, (1975)
5. Anderson, B. J. et al., The global magnetic field of Mercury from messenger orbital observations. *Science*, 333, pp. 1859–1862 (2011)
6. Slavin, J. A., S. M. Imber, J. M. Raines, A Dungey, Cycle in the Life of Mercury's Magnetosphere, *Space Physics and Aeronomy Collection Volume 2: Magnetospheres in the Solar System*, Chapter 34, Geophysical Monograph 259 (2021)
7. Mangano, et al.: 'BepiColombo Science Investigations During Cruise and Flybys at the Earth, Venus and Mercury'. *Space Sci Rev* 217, 23 (2021). <https://doi.org/10.1007/s11214-021-00797-9>.
8. Orsini, S., et al.: 'SERENA: Particle Instrument Suite for Determining the Sun-Mercury Interaction from BepiColombo'. *Space Sci Rev*, 217, 11 (2021). <https://doi.org/10.1007/s11214-020-00787-3>.
9. Winslow, R., et al.: 'Mercury's magnetopause and bow shock from MESSENGER Magnetometer observations'. *Journal of Geophysical Research*, 118(5), pp. 2213–2227.(2013).
10. Slavin, et al.: 'MESSENGER Observations of Magnetic Reconnection in Mercury's Magnetosphere'. *Science*, 324, p. 606 (2009).
11. Jarvinen, R., et al.: 'Ultra-low frequency waves in the ion foreshock of Mercury: A global hybrid modeling study'. *Monthly Notices of the Royal Astronomical Society*, stz3257 (2020). <https://doi.org/10.1093/mnras/stz3257>.
- 12 Müller, D., St. Cyr, O. C., Zouganelis, I., et al., 'The Solar Orbiter mission. Science overview', *A&A*, 642, A1 (2020)
13. Graf, S., et al.: 'Sources for High Pressure and Contamination at the Payload Location'. *J. Spacecraft and Rockets*, 45(1), 57 (2008). <https://doi.org/10.2514/1.30600>
14. Schläppi, B., et al.: 'Influence of spacecraft outgassing on the exploration of tenuous atmospheres with in situ mass spectrometry'. *J. Geophys. Res.*, 115, A12313 (2010). doi:10.1029/2010JA015734.
15. Anderson, B. J., et al.: 'The dayside magnetospheric boundary layer at Mercury. Planet'. *Space Sci Rev*, 59, 2037–2050 (2011).
16. Eastman, T. E., et al., The magnetospheric boundary layer: Site of plasma momentum and energy transfer from the magnetosheath into the magnetosphere, *Geophys. Res. Lett.*, 3, 685021 (1976).
17. Mura, A., et al.: 'Neutral atom imaging at Mercury'. *PSS* 54 144-152 (2006).
18. Schriver, D., et al.: 'Quasi-trapped ion and electron populations at Mercury'. *Geophys Res Lett*, 38, L23103 (2011).
19. Zhao J.T., et al.: Observational evidence of ring current in the magnetosphere of Mercury. *Nat Commun.* Feb 17;13(1):924. doi: 10.1038/s41467-022-28521-3. PMID: 35177615; PMCID: PMC8854437 (2022).

20. Raines, J. M., et al.: 'Plasma Sources in Planetary Magnetospheres: Mercury'. *Space Sci Rev*, 192, pp. 91–144 (2015).
21. Slavin, J. A., et al.: 'Mercury's Dynamic Magnetosphere'. *Mercury: The view after MESSENGER*, S. C. Solomon, L. R. Nittler, and B. J. Anderson (Eds.), Chapter 17, pp. 461–496, Cambridge Univ.Press (2018). ISBN: 978-1107154452.
22. Raines, J. M., et al.: 'Distribution and compositional variations of plasma ions in Mercury's space environment: The first three Mercury years of MESSENGER observations'. *Journal of Geophysical Research*, 118, 1604-1619 (2013). doi: 10.1029/2012JA018073.
23. Slavin, J. A., et al.: 'Mercury's Magnetosphere after MESSENGER's First Flyby'. *Science*, 321, 85 – 89 (2008). doi:10.1126/science.1159040.
24. Muller, J., et al.: 'Origin of Mercury's double magnetopause: 3D hybrid simulation with A.I.K.E.F.'. *Icarus*, 218, 666–687 (2012)., doi:10.1016/j.icarus.2011.12.028.
25. Shi, Z., et al. (2022). An eastward current encircling Mercury. *Geophysical Research Letters*, 49, e2022GL098415. <https://doi.org/10.1029/2022GL098415>
26. Milillo A., et al.: 'Investigating Mercury's environment with the two-spacecraft BepiColombo mission'. *Space Sci Rev*, 216, Issue 5, id.93 (2020). doi: 10.1007/s11214-020-00712-8.

Acknowledgements

SERENA general management, System Control Unit (SCU) and Emitted Low Energy Neutral Atoms (ELENA) unit are funded by the Italian Space Agency (ASI) and by the Italian National Institute of Astrophysics (INAF), agreement n. 2018-8-HH.0. SERENA ground-based activity is also funded by the Expert support to SERENA Science Operations (EXPRO), ESA Contract Nr. C4000119196/16/ES/JD. Strofio unit is funded by NASA, through Marshall Space Flight Center under the Discovery Program Office. PICAM is funded mostly by the Austrian Space Applications Programme (ASAP) of the Austrian Research Promotion Agency (FFG), and partially by the Programme de Développement d'Expériences (PRODEX), and by the French Space Agency (CNES). MIPA is funded by the Swedish National Space Agency. Strofio and MIPA, as well as the general SERENA suite ground testing activities, have been also supported by the University of Bern, Switzerland.

Author contributions

S. Orsini (SO), A. Milillo (AM), H. Lichtenegger (HL), A. Varsani (AV), S. Barabash (SB), S. Livi (SL), E. De Angelis (EDA), G. Laky (GL), H. Nilsson (HN), M. Phillips (MP), A. Aronica (AA), E. Kallio (EK), P. Wurz (PW), T. Alberti (TA), A. Olivieri (AO), C. Plainaki (CP), J. A. Slavin (JAS), I. Dandouras (ID), J. M. Raines (JMR), all other authors (SERENA team, ST). Conceptualization: SO, AM, HL, AV, SB, SL; methodology: SO, AM, HL, AV, SB, SL, AA; investigation: SO, AM, AV, SB, EDA, GL, HN, EK, PW, TA, JAS, JMR, ID; visualization: SO, AM, AV, SB, EDA, EK, JAS, AA; funding acquisition: AO, SO, AM, HL, AV, SB, SL; project administration: AO, SO, AM, HL, AV, SB, SL; supervision: SO; writing original draft: SO, AM, HL, AV, SB, SL, EDA, GL, HN, MP, AA, EK, PW, TA, AO, CP, JAS, ID, JMR; writing review & editing: ST.

Competing interest statement

The authors declare that no competing interests (financial or non-financial) are esplicated nor implied in the content and results shown in this paper.

Figure Captions

Fig. 1. Trajectory of BC MFB1 in the X-Y (Panel a) and X-Z MSM (panel b) planes.

Fig. 2 Trajectory of BC MFB1 in the MSM reference frame: R= distance from X-axis versus X-axis. The four inserts 1-4 in panel (a) show PICAM's observations, and the insert in panel (b) shows MIPA's observations. Red lines on the trajectory mark the intervals when PICAM data was collected, while blue lines time intervals covered by MIPA. The dashed and solid gray line represent the average bow shock and magnetopause positions, respectively (9, 10). The predicted crossing times are: inbound bow shock: 22:32 UT, inbound magnetopause: 23:13 UT, outbound magnetopause: 23:42 UT, and outbound bow shock: 23:45 UT.

Fig. 3. PICAM boresight components along Y_{MSM} and Z_{MSM} .

Fig. 4. PICAM time-energy spectrograms in the solar wind before inbound bow shock crossing in the dusk sector (Panel a) and after outbound bow shock crossing, in the dawn sector. (Panels b and c).

Fig. 5. PICAM (Panel a) and MIPA (Panel b) spectrograms spanning through the magnetosheath and the inner magnetosphere regions, from 22:35 (just after the inbound bow shock crossing) and 23:55 UT, well after the outbound bow shock crossing. The dashed-dotted line refers to the expected inbound and outbound magnetopause crossings (9), the dotted line refers to the observed transition from LLBL to magnetospheric dusk lobe, LLBL and MSP and SW refer to the magnetosheath, low latitude boundary layer, the inner magnetosphere and solar wind, respectively. MIPA data in the range of 1-2 counts should not be taken into consideration. Nevertheless, we take profit from the more sensitive PICAM data for identifying some of the magnetospheric regions, as encountered during this fly-by. Actually, MIPA data are very useful in the last part of the plots, where PICAM observations stopped, whereas MIPA was still operating.









