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Co-ordinator:	Prof Nigel Mason

1. **Nature:** R = Report, P = Prototype, D = Demonstrator, O = Other
2. **Dissemination level:**

PU	PP	RE	CO
Public	Restricted to other programme participants (including the Commission Service)	Restricted to a group specified by the consortium (including the Commission Services)	Confidential, only for members of the consortium (excluding the Commission Services)

Executive Summary / Abstract: We report the developments and services made operational during the fourth year of the Sun Planetary Interactions Digital Environment on Request (SPIDER) Virtual Activity of the Europlanet 2024 Research Infrastructure. During the fourth year of the project, all the six foreseen services are now operational and used.

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Deliverable

1. Explanation of work & Overview of progress

1.1 Objectives

The H2020 Europlanet –2020 Research Infrastructure (RI) programme, which ended on Aug 31st, 2019, included an activity called Planetary Space Weather Services (PSWS), which provided 12 services distributed over four different domains (A. Prediction, B. Detection, C. Modelling, D. Alerts) and accessed through the PSWS portal (http://spider-europlanet.irap.omp.eu/#europlanet):

A1. 1D MHD Solar Wind Prediction Tool – HELIOPROPA,

A2. Propagation Tool,

A3. Meteor showers,

A4. Cometary tail crossings – TAILCATCHER,

B1. Lunar impacts – ALFIE,

B2. Giant planet fireballs – DeTeCt3.1,

B3. Cometary tails – WINDSOCKS,

C1. Earth, Mars, Venus, Jupiter coupling- TRANSPLANET,

C2. Mars radiation environment – RADMAREE,

C3. Giant planet magnetodiscs – MAGNETODISC,

C4. Jupiter's thermosphere,

D. Alerts.

In the framework of the Europlanet 2024 Research Infrastructure (EPN 2024 RI) programme, the Virtual Activity (VA) SPIDER (Sun-Planet Interactions Digital Environment on Request) has extended PSWS domain (A. Prediction, C. Modelling, E. Databases) services and gives European planetary scientists, space agencies and industries access to six unique, publicly available and sophisticated services, in order to model planetary environments and solar wind interactions through the deployment of a dedicated run on request infrastructure and associated databases.

C5. A service for runs on request of models of Jupiter's moon exospheres as well as the exosphere of Mercury.

C6. A service to connect the open-source Spacecraft-Plasma Interaction Software (SPIS) software with models of space environments in order to compute the effect of spacecraft potential on the scientific performances of charged particle instruments onboard space missions. Pre-configured simulations will be made for Bepi-Colombo and JUICE (JUpiter ICy moon Explorer) missions.

C7. A service for runs on request of particle tracing models in planetary magnetospheres.

E1. A database of the high-energy particle flux proxy at Mars, Venus and comet 67P using background counts observed in the data obtained by the plasma instruments onboard Mars Express (operational from 2003), Venus Express (2006–2014), and Rosetta (2014–2015).

E2. A simulation database for Mercury and Jupiter's moons magnetospheres and link them with prediction of the solar wind parameters from PSWS.

A1. An extension of the PSWS Heliopropa service in order to ingest new observations from Solar missions like the ESA Solar Orbiter or NASA Solar Parker Probe missions and use them as input parameters for solar wind prediction.

The annual report of SPIDER at the end of the fourth year of the project is described below.

1.2 Explanation of the work carried per WP

SPIDER consists of 4 tasks and the work performed during the fourth year of the project for each of them is detailed below:

Task 1. Coordination **(Lead: CNRS, Deputy: WIGNER).**

Task 1 coordinates and manages the overall WP. CNRS reports the status of SPIDER developments and services during monthly telecons with the EPN 2024 RI Project Management Committee (PMC). Since each of the foreseen SPIDER services to be developed are independent, CNRS is directly interacting with each of the responsible institutes by email or telecons. This was still the case during the fourth year of the project.

Task 2. Implementation of new space weather services **(Lead: CNRS, Deputy: INAF, Participants: IRF, ONERA, UCL).**

All six SPIDER services are operational at http://spider-europlanet.irap.omp.eu/. Work is ongoing in the fourth year to improve and extend three of these services E1, E2, and A1.

The E1 service is operational and available in the Automated Multi-Dataset Analysis (AMDA) tool developed by CNRS http://amda.cdpp.eu. The Mars Express database is extended when the new data from the mission that is still in operation are analysed. Extension to Rosetta ICA is being considered.

Simulations of Mercury's magnetosphere for the E2 service are available in the Automated Multi-Dataset Analysis (AMDA) tool developed by CNRS https://amda.cdpp.eu and work is ongoing to extend the database when the submitted publications are accepted.

The A1 service for predictions of the solar wind parameters propagated to BepiColombo, Solar Orbiter and Parker Solar Probe is operational and available through the Heliopropa service http://heliopropa.cdpp.eu and the Automated Multi-Dataset Analysis (AMDA) tool developed by CNRS http://amda.cdpp.eu. It is currently being extended to use Solar Orbiter data as inputs for predictions to planets, spacecraft, and comets.

Task 3. Deployment of consolidated runs on request architecture **(OBSPARIS, CNRS).**

This has so far been driven by VESPA needs but will be adapted and applied in the last months of SPIDER. The implementation of an OPUS server at CNRS/IRAP, for managing the jobs of the hosted modelling codes, started in October 2023. It relies on the development done at OBSPARIS (https://github.com/ParisAstronomicalDataCentre/OPUS) and will be applied to PSWS services too (Transplanet, Magnetodisc). The use of the eduTEAMS-hosted Europlanet VESPA AAI (Authorization and Authentication Infrastructure), provided by GÉANT, to manage the user access authorizations as well as the implementation of OPUS on EOSC facilities remains to be studied in a later stage in coordination with the ESCAPE H2020 project.

Task 4. Dissemination and Liaisons **(WIGNER RCP, CNRS)**

CNRS has developed and maintained a website to promote SPIDER activities, available at http://spider-europlanet.irap.omp.eu/about. CNRS regularly presents SPIDER developments to the BepiColombo, Juno, JUICE, and Solar Orbiter communities. CNRS and WIGNER RCP contributed to the Europlanet Research Infrastructure Meeting (ERIM) in June 2023, as well as proposed and organized a Topical Discussion Meeting devoted to Planetary Space Weather (TDM11) during the ESWW European Space Weather Week conference on 23 November 2023 (https://esww2023.org/topical-discussion-meetings-during-esww-2023#1693996507302-68c1523a-6345).

TDM Conveners: Nicolas André, Sae Aizawa

TDM Secretary: Andrea Opitz

Date and time: Thursday 23nd November 2023 at 11:45-12:45

Description: Planetary space weather is the extension of the solar-terrestrial relations to other planets, celestial bodies or interplanetary spacecraft in the Solar System. The emphasis of the session is on all aspects of the conditions in the Sun, solar wind and magnetospheric plasmas that extend the concepts of space weather and space situational awareness to other planets. New services accessible to the research community, space agencies, and industrial partners planning for space missions, for instance addressing the effects of the environment on components and systems, will be discussed. This session will in particular summarize the planetary space weather services developed during Europlanet 2024 RI with the Sun Planetary Interactions Digital Environment Run on request (SPIDER) funded as part of the Europlanet H2024 Research Infrastucture by the European Union's Horizon 2020 research and innovation programme under grant agreement No 871149.

It was attended by approximately 40 people.

1.3 Impact

In practice, several actions have been conducted during the fourth year:

- Continuous involvement, promotion and use of services for current (Juno) or future planetary missions (BepiColombo, JUICE) as well as heliophysics missions (Solar Orbiter)

  - Juno Data Analysis Workshop for Community Building, Rome, 17-20 July 2023 https://junoworkshop.space.swri.edu/romejuly2023workshop/
  - BepiColombo Science Working Team, 18-21 September 2023, Muenster, Germany
  - Juno Galilean satellites and radiation environment workshop, San Antonio, USA, 07-08 October 2023 https://junoworkshop.space.swri.edu/saoct2023workshop/
  - Juno Science Team Meeting, San Antonio, USA, 09-12 October 2023
  - JUICE SWT, ESAC, Madrid, Spain, 20-22 November 2023, https://www.cosmos.esa.int/web/juice-swt-meeting

One press release was done by Europlanet in issue 5 of the Europlanet Magazine:

Europlanet 2024 RI

SPIDER Space Weather Service Supports BepiColombo Studies at Venus and Mercury

Europlanet's SPIDER space weather modelling tools have been used in two recent studies, published in Nature Communications, involving flybys by the joint European Space Agency (ESA) and Japanese (JAXA) BepiColombo mission, which is on its way to Mercury.

The lead authors of the studies, Moa Persson and Sae Aizawa, both received funding to carry out the research at the Institut de Recherche en Astrophysique et Planétologie (IRAP) in France through the Europlanet 2024 Research Infrastructure (RI) project.

The first study, published in December 2022, combined observations of the solar wind by BepiColombo and the ESA/NASA Solar Orbiter, which both serendipitously flew by Venus within a day of each other in August 2021. The flybys resulted in data from eight sensors and two vantage points in space. The results of the study reveal how, without the protection of a global magnetic field, Venus's thick atmosphere avoids erosion by the solar wind.

BepiColombo's flyby of Venus was a rare opportunity to investigate the 'stagnation region', an area at the nose of the magnetosphere where some of the largest effects of the interaction between Venus and the solar wind are observed. The data gathered gave the first experimental evidence that charged particles in this region are slowed significantly by the interactions between the solar wind and Venus.

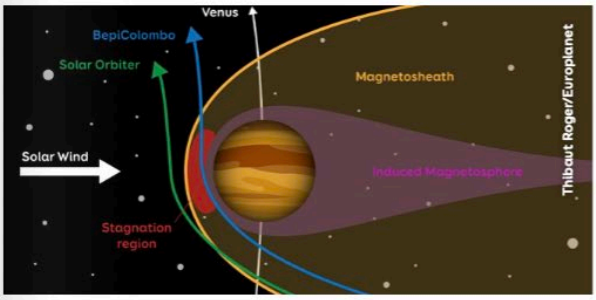
The observations also showed that the induced magnetosphere provides a stable barrier that protects the atmosphere of Venus from 'stripping' by the solar wind.

Artist's representation of BepiColombo encountering X-ray auroras at Mercury

The second study, published in July 2023, relates to BepiColombo's first flyby of Mercury on 1 October 2021. Analysis of data from three of BepiColombo's instruments during the encounter has revealed how electrons raining down onto the surface of Mercury can trigger high-energy auroras.

The study revealed how high energy electrons are transported from the tail region of the magnetosphere towards the planet, where they eventually rain down on the Mercury's surface. Unimpeded by an atmosphere, they interact with material on the surface and cause X-rays to be emitted, resulting in an auroral glow. The study also confirms that the mechanism that generates auroras is the same throughout the Solar System.

Together, the studies demonstrate how turning sensors on during planetary flybys and cruise phases can lead to unique science.



Infographic showing the Venus flybys of BepiColombo and Solar Orbiter. The Venus flyby occurred during remarkably stable and quiet solar wind conditions, in contrast to high-pressure solar wind conditions observed during the Mercury flyby.

Persson et al. DOI: 10.1038/ s41467-022-35061-3

Aizawa et al. DOI: 10.1038/ s41467-023-39565-4

- A SPIDER Topical Discussion Meeting on Planetary Space Weather and a SPIDER booth were held at the ESWW (European Space Weather Week) conference in Toulouse, 20-24 November 2023.

- Several publications resulted from the use of SPIDER services in 2023:

1. Persson, A., S. Aizawa, N. André, S. Barabash, S. Saito, Y. Harada, S. Heyner, S. Orsini, A. Fedorov, C. Mazelle, Y. Futaana, L. Z. Hadid, M. Volwerk, G. Collinson, B. Sanchez-Cano, A. Barthe, E. Penou, S. Yokota, V. Genot, J. A. Sauvaud, D. Delcourt, M. Fraenz, R. Modolo, A. Milillo, H.-U. Auster, I. Richter, J. Z. D. Mieth, P. Louarn, C. J. Owen. T. S. Horbury, K. Asamura, S. Matsuda, H. Nilsson, M. Wieser, T. Alberti, A. Varsani, V. Mangano, A. Mura, L. Gunter, G. Laky, H. Jeszenszky, K. Masunaga, C. Signoles, M. Rojo, and G. Murakami, Persson, M., Aizawa, S., André, N. et al. BepiColombo mission confirms stagnation region of Venus and reveals its large extent. Nature Communications 13, 7743 (2022). https://doi.org/10.1038/s41467-022-35061-3

2. Hadid, L. Z., D. Delcourt, Y. Saito, M. Franz, S. Yokota, B. Fiethe, C, Verdeil, B Katra, F. Leblanc, H. Fischer, M. Persson, S. Aizawa, N. André, A. Fedorov, D. Fontaine, N. Krupp, H. Michalik, J-M. Illiano, J-J. Berthelier, H. Kruger, Y. Harada, G. Murakami, and S. Matsuda, BepiColombo observations of escaping carbon and oxygen ions in Venus magnetosheath, Nature Astronomy, accepted, 2023

3. Aizawa, S., Y. Harada, N. André, Y. Saito, et al., Direct evidence of substorm-related impulsive injections of electrons at Mercury, Nature Communications, Nature Communications, Volume 14, article id. 4019, 2023

4. Aizawa, S., M. Rojo, N. André et al., Inverted-V accelerated electrons reveal a particular current connection between the magnetosphere and the surface of Mercury, Nature, submitted, 2023

5. The yearly variability of the sodium exosphere of Mercury: A toy model. Mura, A.; Plainaki, C.; Milillo, A.; Mangano, V.; Alberti, T.; Massetti, S.; Orsini, S.; Moroni, M.; De Angelis, E.; Rispoli, R.; and Sordini, R. *Icarus*, 394: 115441. April 2023.

6. Hess, S., L. Leclercq, N. André, B. Cecconi, Monitoring the spacecraft charging effects on science instruments using SPIS connection to SPASE virtual observatory databases, Astronomy and Computing, submitted, 2023

7. Pelcener, S., N. André et al., Temporal and spatial variability of the electron environment at the orbit of Ganymede as observed by Juno, Journal of Geophysical Research : Space Physics, submitted, 2023

8. Rojo, M., N. André, et al., Structure and Dynamics of the Hermean Magnetosphere revealed by Electron Observations From the Mercury Electron Analyzer After the First Three Mercury Flybys of BepiColombo Astronomy and Astrophysics, submitted, 2023

9. Jackson, B. et al., Forecasting Heliospheric CME Solar-Wind Parameters Using the UCSD Time-Dependent Tomography and ISEE Interplanetary Scintillation Data: The 10 March 2022 CME, Solar Physics, Volume 298, Issue 5, article id.74, 2023

Two press releases were done by Europlanet for Persson et al., Nature Communications, 2022 on 26 January 2023 and Aizawa et al., Nature Communications, 2023 on 18 July 2023:

- https://www.europlanet-society.org/bepicolombo-and-solar-orbiter-compare-notes-at-venus/
- https://www.europlanet-society.org/first-bepicolombo-flyby-of-mercury-finds-electron-rain-triggers-x-ray-auroras/

1.4 Access provisions to Research Infrastructures

Statistics for the SPIDER portal (website) that has been developed since the first year of the project can be found on http://spider-europlanet.irap.omp.eu/about (**9982 since 01/01/2021**)

Statistics for the SPIDER services E1 and A1 can be found at the following webpages:

– AMDA tool (total number of connections of different users, http://amda.cdpp.eu/):

http://amda.cdpp.eu/awstats/awstats.pl more than **18167 connections since 01/02/2020**

– Details on geographical distribution etc. can be found at CDPP/AMDA awstats: http://amda.cdpp.eu/awstats/awstats.pl

http://heliopropa.cdpp.eu has received **16801 visits** since 2017.

2. Update of exploitation & dissemination plan

No change since the start of the project.

3. Update of data management plan

Europlanet 2024 Research Infrastructure's full most recent data management plan can be found in Deliverable D1.11.

4. Follow-up of recommendations & comments from previous review(s)

The following actions need to be performed to follow the recommendations from previous VA boards:

- Maintenance of the PSWS portal
- Update of the SPIDER portal

5. Deviations from Annex 1 (DoA)

5.1 Tasks

N/A

5.2 Use of resources

Patrick Guio (now at University of Tromso with a more permanent position) left UCL during the course of the project but has been employed part-time by UCL (0.2 FTE) to undertake previously agreed-upon EPN-2024-RI work.

Sarah Pelcener (F) was hired for one month at CNRS in July 2023 to work on SPIDER.

Mathias Rojo (M) was hired at CNRS from December 2023 until the end of the project to work on SPIDER.

- **5.2.1 Unforeseen subcontracting**
  N/A
- **5.2.2 Unforeseen use of in-kind contributions from a 3rd party against payment or free of charge**
- N/A