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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)

1. Introduction

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

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 starting Europlanet-2024 programme, the Virtual Activity (VA) SPIDER (Sun-Planet Interactions Digital Environment on Request) will extend PSWS domains (A. Prediction, C. Modelling, E. Databases) services and give the 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 scientific 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 Europlanet-RI H2020 PSWS services.

A1. An extension of the Europlanet-RI H2020 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;

This report describes the status of a charged particle tracing tool, for use with planetary magnetic field models from the PSWS service C3 (Giant planet magnetodiscs – MAGNETODISC). The possibility will thus be provided to users to be able to obtain a magnetic field model from C3, and use that model in the final version of this particle-tracing service (which we shall refer to from here on as PTracer).

2. Particle tracing model outputs, brief description and rationale

Service C3 (MAGNETODISC), as described above, can be used to provide a magnetic field model appropriate for a rapidly rotating planetary magnetosphere, such as that of Jupiter or Saturn. The main 'free parameters' prescribed by the MAGNETODISC user are: (1) K_h, a 'hot plasma index' which sets the global level of hot plasma pressure in the magnetosphere (Caudal, 1986; Achilleos et al., 2010); (2) R_{MP} the 'magnetodisc radius' or 'magnetopause standoff distance' which is used to represent the global size of the system in response to, for example, variation in upstream solar wind dynamic pressure (Achilleos et al., 2008).

PTracer is a natural extension of the functionality provided by MAGNETODISC. In its final form, it will make use of a MAGNETODISC field model prescribed by the user, and calculate charged particle trajectories and associated, derived quantities such as the bounce and drift periods of the particle. The particle's initial properties are prescribed by the user, and these are: (1) Initial equatorial distance from the centre of the parent planet; (2) Particle type (mass and charge); (3) Kinetic energy; (4) Initial equatorial pitch angle (angle between velocity and local magnetic field). Total run time is also prescribed by the user in logical units of bounce and / or drift period for an equivalent dipole field.

In terms of scientific applications, the service would be particularly useful for exploring the non-adiabatic effects which cause particle motion to deviate from purely periodic behaviour which can arise, for example, when the equatorial curvature radius of the magnetic field becomes comparable to the gyroradius of the particle. This has been demonstrated to lead to a particular form of 'pitch angle scattering' when particles above a critical energy bounce across the equator (Achilleos et al., 2021).

3. Implementation and details

The particle trajectory is integrated in time using the algorithm of Boris (Ozturk, 2012; Qin et al., 2013) which is specifically designed for accuracy and stability, which in turn promotes a high degree of energy conservation, while at the same time requiring comparatively few time steps per gyroperiod. The magnetic field is assumed to be axially symmetric, as a first approximation to describing actual 'middle magnetospheres' of Jupiter and Saturn.

In terms of output, the trajectory information is output as a time series of: (1) Vectors which describe the Cartesian and cylindrical coordinates of the particle, as well as its latitude and longitude; (2) Vectors which describe the Cartesian velocity of the particle ($m.s^{-1}$ units); (3) Reporting of derived quantities - consisting of particle bounce and drift periods (arising from least-squares fitting of the latitude and longitude variability), the first adiabatic invariant of the particle (essentially the ratio of kinetic energy of field-perpendicular motion to the local field strength), and varying the pitch angle of the particle.

The code itself is written in Matlab, and has been compiled into a binary executable using the internal Matlab compiler, as was done previously for the MAGNETODISC service.

The following figures show examples of particle trajectory outputs [Figure 1] and a schematic of the model input page to be presented to the user [Figure 2].

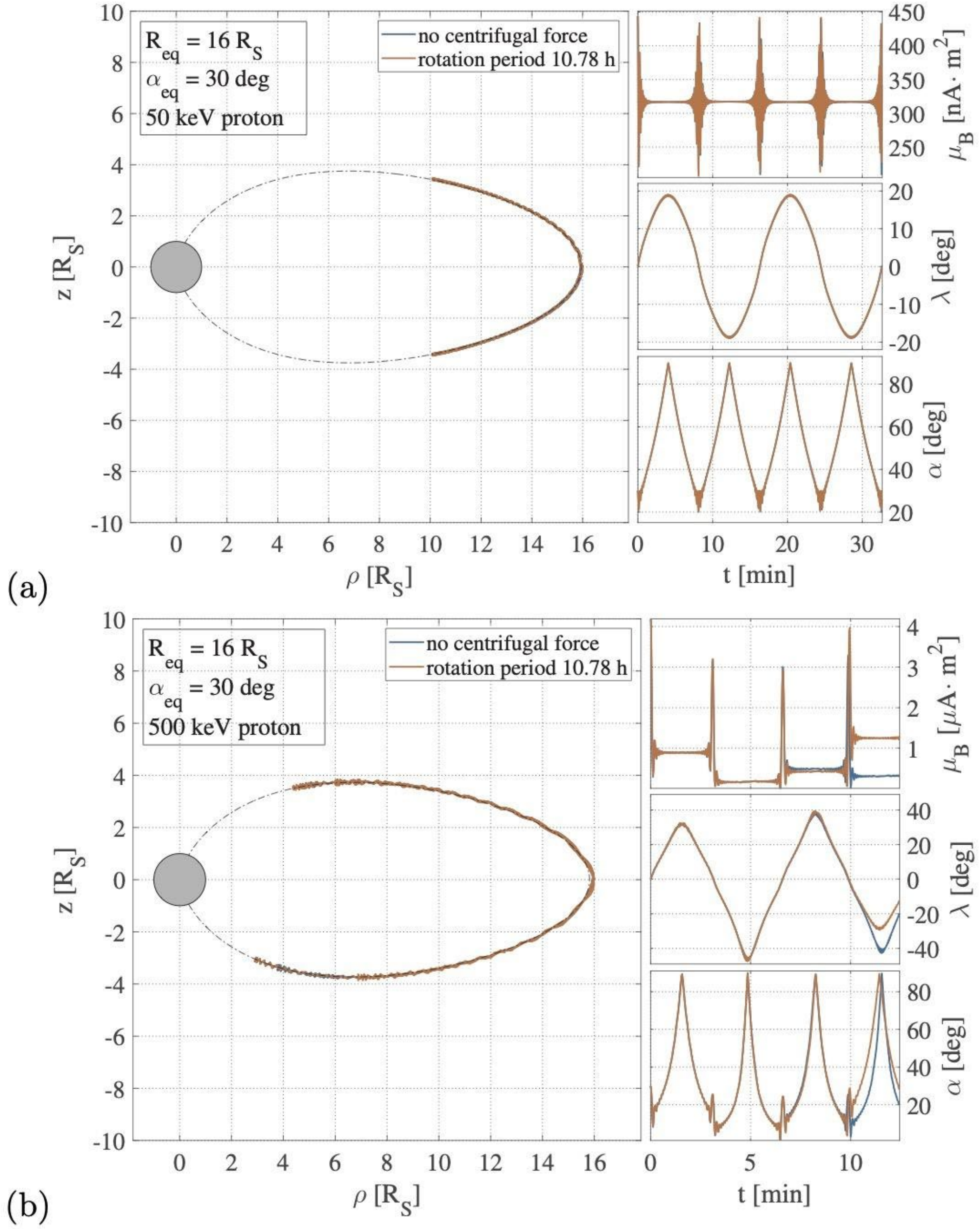

Figure 1: Particle tracing results, for a proton of energy (a) 50 keV and (b) 500 keV in the Kronian magnetosphere. The main panel shows the calculated trajectory projected onto the meridian plane of a magnetic field line. The smaller panels show, as a function of time, the particle's magnetic moment μ_B, its latitude λ and its pitch angle α. Note that these trajectories show considerable 'jitter' or scattering in pitch angle when $\lambda \sim 0$ and the particle crosses the equator, where its gyroradius becomes comparable to the curvature scale of the magnetodisc field. Taken from *Achilleos et al. (2021).*

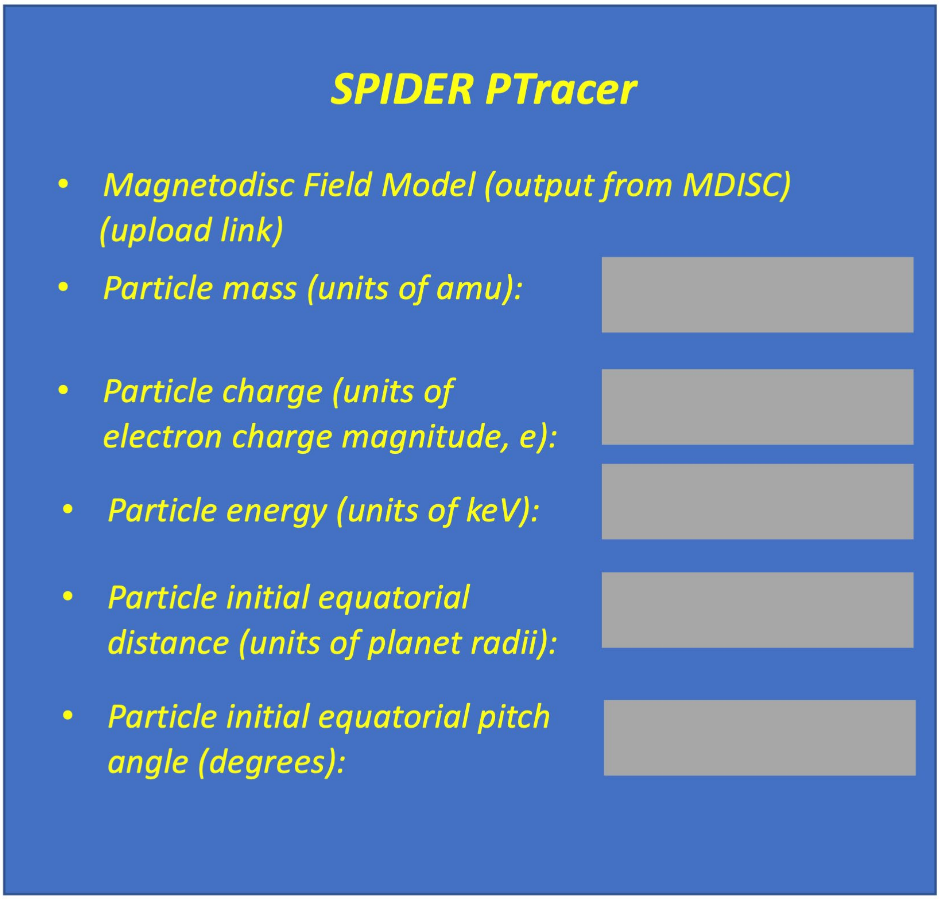

Figure 2: Model input page schematic for PTracer *(http://spider-europlanet.irap.omp.eu/modelling)*.

4. Public outreach activities

The particle tracing code, in various states of development, has been used to conduct 'tutorial style' sessions which introduce early-career researchers and secondary school students to the relevant scientific domain. Examples of these activities are:

(1) Orbyts - a highly successful public outreach programme for schools coordinated by UCL, the lead beneficiary **[https://www.ucl.ac.uk/astrophysics/outreach/orbyts]**
(2) The 2018 MHD workshop held by University of Chiang Mai, Thailand **[http://chalawan.narit.or.th/home/index.php/event/comac2018/]**
(3) The two Europlanet workshops on Planetary Data and Modelling conducted in Kalamata, Greece, in 2018 and 2019 **[e.g. https://www.ucl.ac.uk/planetary-sciences/europlanet-na1-workshop-uniting-planetary-modelling-and-data-analysis-part-2]**

Dataset example and outputs

The plots in Figure 1 show typical PTracer outputs in visual form. The code generates output in the form of a single Matlab data structure, which can be saved as a .mat file. The final form of PTracer will give the user the option to download the results in a 'friendly' format such as ASCII or .hdf5 file. A working matlab executable is available at http://spider-europlanet.irap.omp.eu/modelling .

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