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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)

Contents

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 6 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 the status of the service C5 led by IAPS-INAF, Rome, Italy, made operational at the end of the second year of the project.

2. Exospheric models. Brief description and rationale

Service C5 is devoted to modelling of the exospheres of Mercury and of some Galilean moons.

2.1 Mercury

The first year of project was focused on the prototype of a service for the simulation of the exosphere of Mercury. The generation mechanisms, the compositions and the configuration of the Hermean exosphere will provide crucial insight in the planet status and evolution. The first detection of the exospheric environment have been provided by the Mariner 10 measurements of H, He and O during its fly-bys in 1974-75; later, thanks to ground-based observations, the presence of Na, K and Ca have been discovered. Even if MESSENGER visited Mercury in 2011 and added a consistent amount of data, still the actual knowledge about the morphology of this extremely tenuous atmosphere is anyway very poor and only some speculations can be done before the next BepiColombo measurements; a global description of Mercury's exosphere is still not available. For this reason, it's important to have a modelling tool ready for testing different hypothesis on release mechanism, as well as interpreting observational data. Several processes, such as photon, chemical and ion sputtering, thermal desorption and micro-meteoroids vaporization, has been proposed to be responsible of the formation of such an exosphere, and their relative importance is still discussed. In this frame we propose a MonteCarlo, three-dimensional model of the Hermean exosphere complete with all possible release sources and loss mechanisms, which also include the exo-ionospehere and the SW plasma circulation. Details of the model can be found in the references section.

2.2 Europa

The second step of the program focused on the implementation of an analytical model of the Europa O2 exosphere. The origin of the exosphere of Europa is its water ice surface. The existing exosphere models predict that the major constituent of the exosphere is molecular oxygen. Specifically, O_2, together with H_2 and H_2O, is generated at the surface through radiolysis, ion sputtering and chemical interactions of the water dissociation products. The non-escaping O_2 molecules circulate around the moon impacting the surface several times, due to their long lifetime and due to their non- sticking, suffering thermalization to the surface temperature after each impact. The O_2 molecules are expected to be the major constituents of the exosphere for two main reasons: i) O_2 lacks the sufficient energy to overcome Europa's gravity, contrary to H_2, ii) it does not stick to the surface as H_2O. The Hubble Space Telescope (HST) observations of the O emission lines (proxy of O2) proved the presence of an asymmetric atomic Oxygen distribution. The existing MonteCarlo EGEON model (Plainaki et al. 2013), supported by the HST observations, suggest that there is a clear modulation of the exospheric distribution along the Europa orbit around Jupiter. To avoid running the EGEON model at each Moon-Jupiter configuration, and considering that the two identified main components of molecular oxygen exosphere cannot be described by a simple exponential function, we developed an analytical model derived by EGEON (Milillo et al. 2016) able to describe the 3D O_2 exosphere at any phase angle (angle between Sun - Europa – Jupiter).

3. Exospheric models. Implementation and details

3.1 Mercury

The spatial distribution of a neutral exospheric component is obtained by using a Monte-Carlo single-particle model (see references). The particles are accumulated over a 7-dimensional grid (radius r; latitude f; longitude λ,, energy E, mass, charge, pitch angle). For a given source process, the surface S where the process occurs is defined. Some (N_{tp}) test-particles are launched from a random starting point P_0 within S; the starting velocity $\mathbf{v}_0$ is also chosen randomly, according to the velocity distribution function of the source. A weight w is associated to the test-particle, which takes into account the number of real particles that it represents. Then, the trajectory of the test particle is computed using classical equation of motion, including gravity force in Mercury reference frame, and radiation pressure, if appropriate (the acceleration due to the non-inertial frame can also be added even if it is negligible in the case of Mercury). The test-particle trajectory ends at the surface of the planet or when it is too far from the planet (in our model, this is a user setting, usually many Mercury radii). Other loss processes do not remove test-particles, but they are taken into account by decreasing w according to λ_i , the lifetime of process i. presently we have included photo-ionisation and charge-exchange. Each time a test-particle crosses a grid cell, a quantity q is added to that cell:

$$q = w(t)\Delta t \, , \tag{1}$$

where delta-t is the time elapsed inside the cell. After all trajectories have been simulated, the density in each grid cell *ijkl* is calculated by dividing Q_{ijkl} by the volume of the cell.

Ion-sputtering: Ion-sputtering results from the impinging of an ion of mass m_1 onto a surface; if the impact energy (E_i) is high enough, a new particle (m_2) may be extracted. For light ions, ion sputtering is a double-step process: backscattering of the ion over a surface target, and ejection of a second surface atom by the backscattered ion; in most cases, the ejected particle is neutral. The distribution function (f_S) of the ejection energy usually peaks at few eV and can be empirically reproduced by the function in Siegmund, (1969). This is implemented in different ways into the tool: one can simulate the ions precipitating and then simulate the released neutrals, or can just impose an arbitrary plasma flux onto the surface and then simulate just the neutrals.

Photon stimulated desorption: The dayside surface of Mercury is exposed to an intense flux of photons; those of sufficiently high energy (UV or shorten wavelengths) may extract neutral atoms from the planetary surface. Above approximately 250 nm (hv = 5 eV), photons can extract Na from a SiO_2 surface at 250 K with a cross-section between 1 to 3 10^{-20} cm^{-2}; the cross-section rises with the photon energy. The physical mechanism of the process varies for different adsorbate/substrate systems, and is either a direct or an indirect photon-induced electronic excitation of a surface atom. The process yield at Mercury, in general, should be lower than that founded experimentally, because surface regolith is supposed to be depleted in sodium content by exposure to bombardment, and because of the regolith trapping effect. Moreover, the PSD yield is proportional to soil temperature but a soil temperature increase will produce an higher thermal desorption, which acts in concurrency with PSD. The energy distribution of the emitted particles atoms has been extrapolated by laboratory measurements of electron (200 eV) stimulated desorption (ESD) of adsorbed Na from SiO_2 film and from amorphous ice assuming that the electron energy has little impact on the emitted neutral energy, and that PSD and ESD cause desorption of atoms via similar electronic processes. Different velocity distribution models are available in the tool.

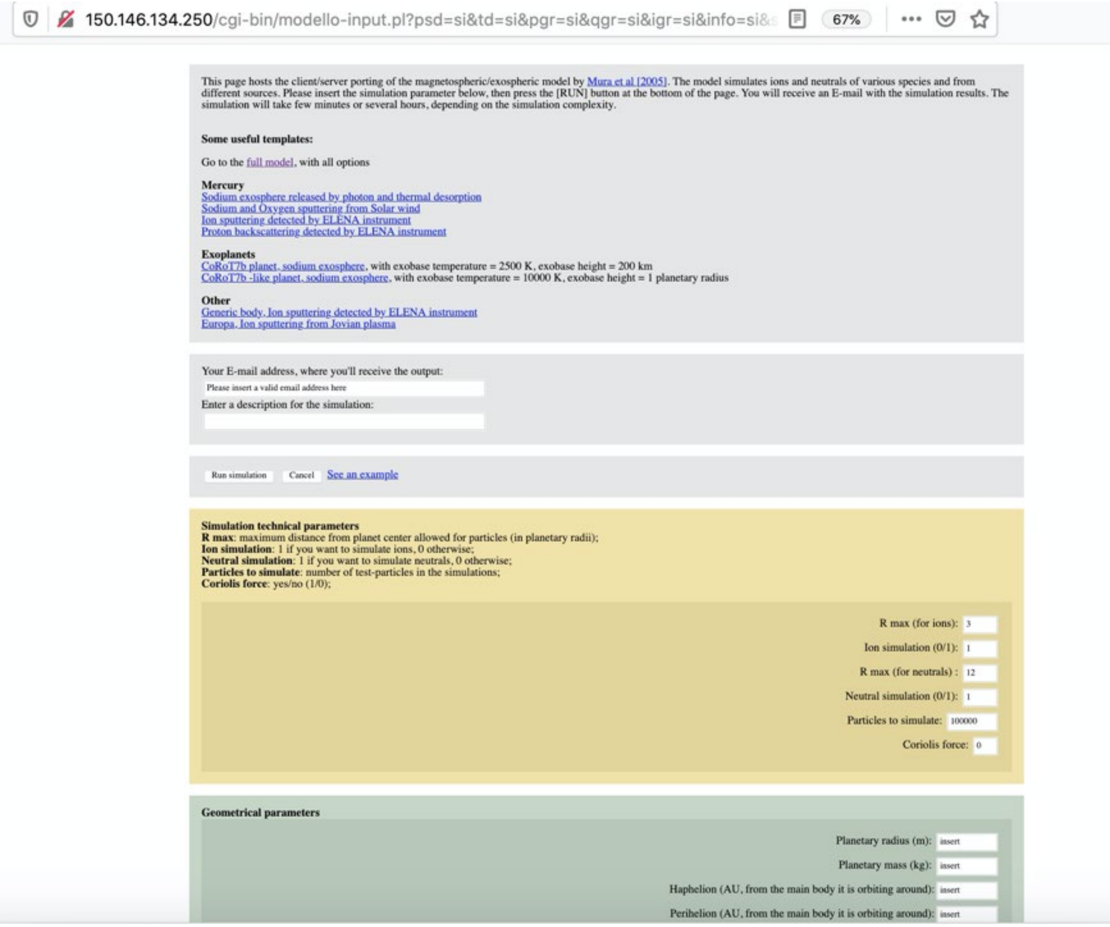
Thermal desorption: Thermal desorption of sodium atoms from Mercury's surface becomes very efficient as the temperature of the soil becomes greater than 400 K. It has been noted that the sodium production rate should be limited to approximately 10^7 cm^{-2} s^{-1} by the diffusion rate within the soil; in this model however consider an unrestricted sodium flux from the surface. The evaporated particles are in thermal equilibrium with the surface, so that a Maxwellian –Boltzmann flux distribution can be applied. Usually the dayside surface temperature T is reproduced by a cosine function between the sub-solar point temperature T_d and the night-side temperature T_n; T_d varies from 725 K at perihelion to 590 K at aphelion; for other orbital distances, T_d is obtained with a linear interpolation; the night-side temperature T_n is uniform and always equal to 110 K. Alternatively, the tool can use an external surface temperature model.

Other sources: Mercury is exposed to the constant precipitation of particles of small sizes (<100 µm), impacting the surface at a mean velocity of 20 km/s, churning the regolith and vaporizing the surface. Larger objects impact the surface as well, causing local enhancement of the sodium exospheric density, but the contribution by these meteorites to the global Hermean exosphere is considered to be negligible. One can assume different thermal velocity distribution for the ejecta (usually, this is about 2500 K), and whether the precipitating particles are uniformly distributed over the surface or not. Then the tools obtain the simulated densities.

4. C5 Service Exospheric model - prototype

The model is written in Fortran 90 (~50'000 lines of code, ~300 routines) and run on a dedicated server. The server has a HTPPD interface (Apache 2) that can be reached at http://150.146.134.250 (go to "model" and then to "full model").

The HTTPD server run a Perl script that build a HTML form (see figure). The form "action" is another Perl script that gets the inputs and write a properly formatted input file (input.txt) for the Fortran model. This input.txt is put on a queue. A third Perl script routinely checks for the queue, and select the first input.txt file to be run. If such a simulation already exists in the internal database, with all identical input parameters, then the Fortran model is not run and the results are taken from the database. Otherwise, the simulation starts. At the end, a fourth Perl script collects all the outputs, and send an email to the address that has been indicated by the user.



150.146.134.250/cgi-bin/modello-input.pl?psd=si&td=si&pgr=si&qgr=si&igr=si&info=si&

This page hosts the client/server porting of the magnetospheric/exospheric model by Mura et al [2005]. The model simulates ions and neutrals of various species and from different sources. Please insert the simulation parameter below, then press the [RUN] button at the bottom of the page. You will receive an E-mail with the simulation results. The simulation will take few minutes or several hours, depending on the simulation complexity.

Some useful templates:

Go to the full model, with all options

Mercury
Sodium exosphere released by photon and thermal desorption
Sodium and Oxygen sputtering from Solar wind
Ion sputtering detected by ELENA instrument
Proton backscattering detected by ELENA instrument

Exoplanets
CoRoT7b planet, sodium exosphere, with exobase temperature = 2500 K, exobase height = 200 km
CoRoT7b -like planet, sodium exosphere, with exobase temperature = 10000 K, exobase height = 1 planetary radius

Other
Generic body, Ion sputtering detected by ELENA instrument
Europa, Ion sputtering from Jovian plasma

Your E-mail address, where you'll receive the output: Please insert a valid email address here
Enter a description for the simulation:

See an example

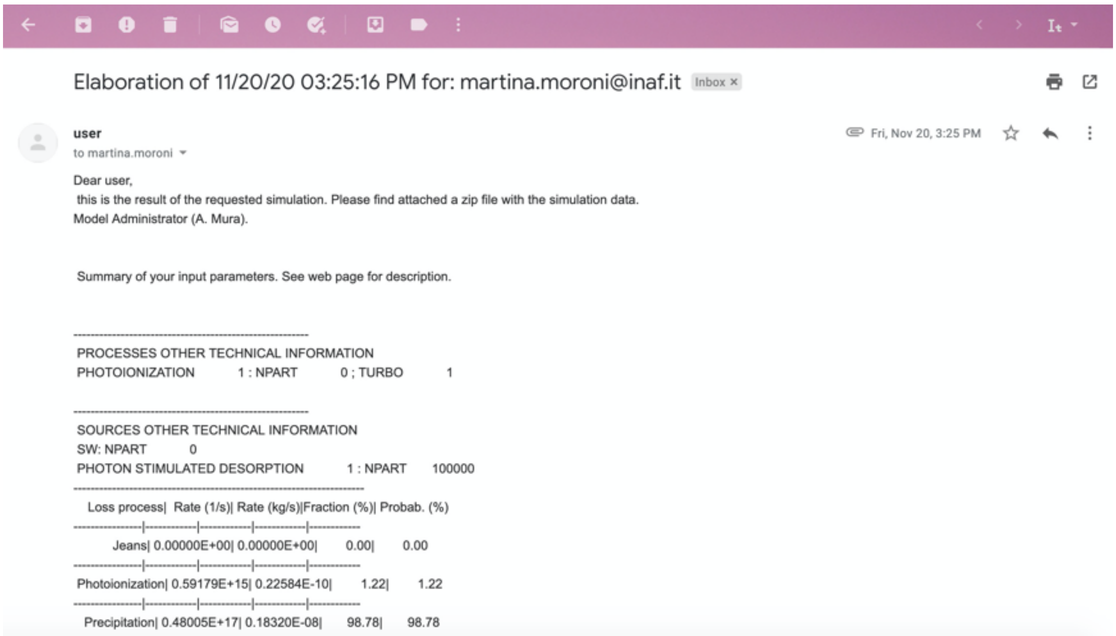
Simulation technical parameters
R max: maximum distance from planet center allowed for particles (in planetary radii);
Ion simulation: 1 if you want to simulate ions, 0 otherwise;
Neutral simulation: 1 if you want to simulate neutrals, 0 otherwise;
Particles to simulate: number of test-particles in the simulations;
Coriolis force: yes/no (1/0);

R max (for ions): 3
Ion simulation (0/1): 1
R max (for neutrals) : 12
Neutral simulation (0/1): 1
Particles to simulate: 100000
Coriolis force: 0

Geometrical parameters

Planetary radius (m): insert
Planetary mass (kg): insert
Haphelion (AU, from the main body it is orbiting around): insert
Perihelion (AU, from the main body it is orbiting around): insert

Figure 1: Model input page (part).



Elaboration of 11/20/20 03:25:16 PM for: martina.moroni@inaf.it

user
to martina.moroni

Fri, Nov 20, 3:25 PM

Dear user,
this is the result of the requested simulation. Please find attached a zip file with the simulation data.
Model Administrator (A. Mura).

Summary of your input parameters. See web page for description.

```
-------------------------------------------------------
 PROCESSES OTHER TECHNICAL INFORMATION
 PHOTOIONIZATION         1 : NPART         0 ; TURBO         1

-------------------------------------------------------
 SOURCES OTHER TECHNICAL INFORMATION
 SW: NPART         0
 PHOTON STIMULATED DESORPTION         1 : NPART      100000
---------------------------------------------------------------------
   Loss process|  Rate (1/s)| Rate (kg/s)|Fraction (%)| Probab. (%)
----------------|------------|------------|------------|------------
        Jeans| 0.00000E+00| 0.00000E+00|       0.00|       0.00
----------------|------------|------------|------------|------------
 Photoionization| 0.59179E+15| 0.22584E-10|       1.22|       1.22
----------------|------------|------------|------------|------------
  Precipitation| 0.48005E+17| 0.18320E-08|      98.78|      98.78
```

Figure 2: example of email from the tool, with results (attached).

Dataset example

We show some examples of Na exosphere as simulated by the numerical model for specific surface processes. Every independent sources is created by a set of parameters: the first value of the code indicates the loss process (PSD, TD, Sputtering ecc.), other values change according to the source.
Figure 3 indicates a PSD exosphere simulated using different description of the energy spectrum (Panel B and C) and a TD exosphere (panel C), assuming a uniform distribution of the ejected species. These depend on the parameters as temperature T= 1000 K, cross section= 2 x 10^{-24} cm^2 ,sodium relative composition c = 0.53%; regolith density N = 7.5 x 10^{14} cm^{-2}; binding energy U= 1.85 eV; vibrational frequency v =10^{13} s^{-1}.

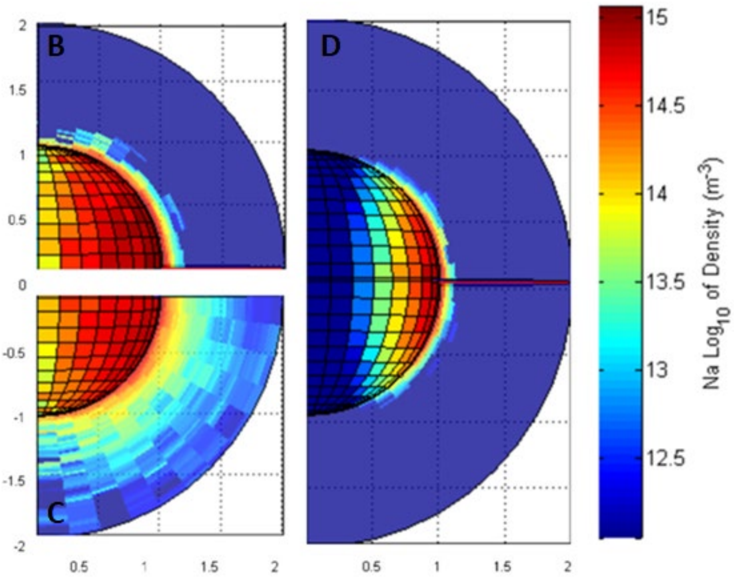


Figure 3: Sodium density is simulated by the numerical model for different processes: photo-stimulated desorption (Panel B and C); thermal desorption (Panel D).

4.1 Europa

The O_2 analytical model (Milillo et al 2016) is obtained by a non-linear fit procedure of the EGEON MonteCarlo model to a Chamberlain density radial profile simplified by Rairden et al. (1986):

$$\boldsymbol{log_{10}\rho = d\, e^{-c(R-1)} - \frac{R-1}{a} + b,}$$

where ρ is the density, R is the Europa centric distance (in Europa's radii) ranging between 1.05 and 5 R_E, and, a, b, c, d are parameters.

The radial profile fitted for latitudes and longitudes of the Jupiter's moon results in a description of the 3D exospheric distribution with 7 parameters for each Sun-Europa-Jupiter configuration.

$$log_{10}\rho\ (R, \alpha_N, \alpha_{lat}) = (p5 + p6\cos(\alpha_N - p7)\cos\,(\alpha_{lat}))\ e^{-(p4)(R-1)} - \frac{(R-1)}{p1} + p2 + p3\cos\,(\alpha_N - p7)\cos\,(\alpha_{lat})$$

Where a_N is the angle from the noon meridian and a_{lat} is the latitude.
When adding also the illumination phase angle a_S, the 7 parameters are described as in Table 1. This simple function is able to describe the O_2 exosphere in every condition.

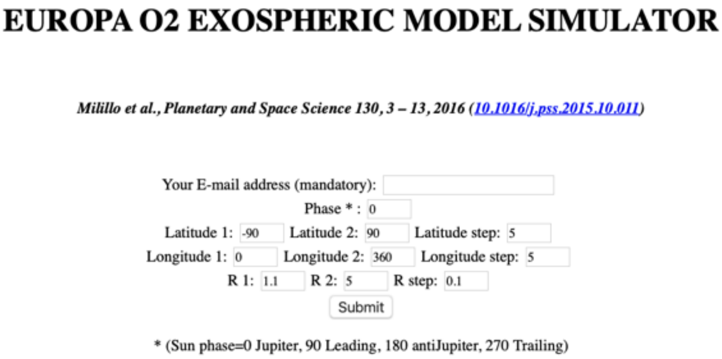
Table 1: Parameters of Europa O_2 exosphere as a function of phase angle

Parameter	Functions
p1	2.51(±0.4)
p2	9.0-0.3*sin(a_S)
p3	0.71-0.09* sin(a_S)

p4	5.2
p5	5.825-0.045* sin(a_S)
p6	-0.92+0.155* sin(a_S)
p7	-28*cos(a_S)

C5 Service Europa exospheric model - prototype

The model is written in Python 3 and run on a dedicated server at the link http://bepi.iaps.inaf.it/europa_O2model.html



EUROPA O2 EXOSPHERIC MODEL SIMULATOR

Milillo et al., Planetary and Space Science 130, 3 – 13, 2016 (10.1016/j.pss.2015.10.011)

Your E-mail address (mandatory):
Phase * : 0
Latitude 1: -90 Latitude 2: 90 Latitude step: 5
Longitude 1: 0 Longitude 2: 360 Longitude step: 5
R 1: 1.1 R 2: 5 R step: 0.1

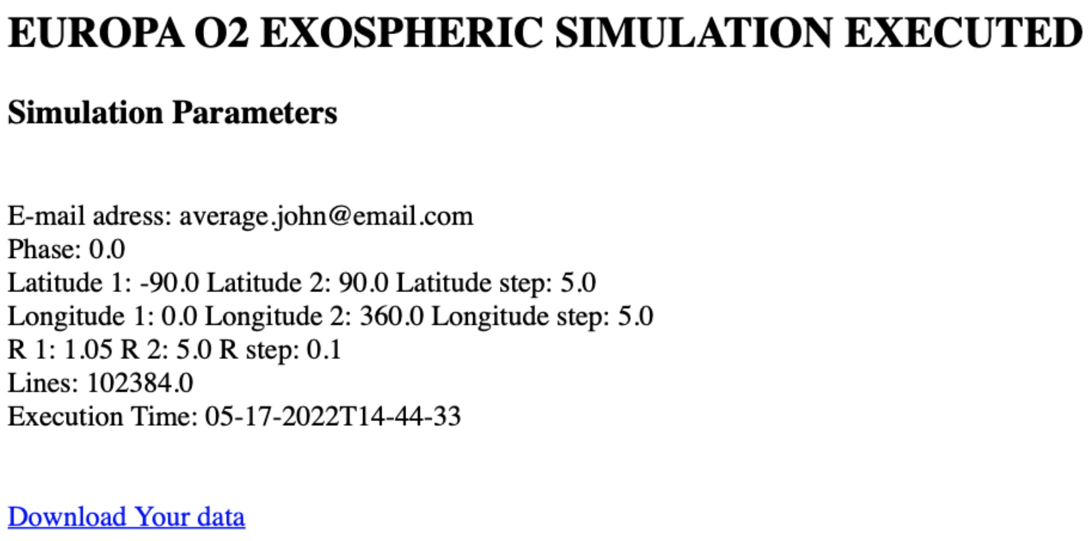
* (Sun phase=0 Jupiter, 90 Leading, 180 antiJupiter, 270 Trailing)

Figure 4: Input page

The required input parameters are:

- Email address (mandatory)
- Phase angle (angle between Sun-Europa-Jupiter), range 0° : 360°. Note that (phase=0 the Sun is below Jupiter, 90 Sun is in the Leading side, 180 antiJupiter, 270 Sun is in the Trailing side)
- Europa latitude (minimum, maximum and interval in degrees), range -90° : 90°
- Europa longitude (minimum, maximum and interval in degrees), range 0° : 360°
- Europa body-centred distance (minimum, maximum and interval in Europa Radius), range 1.05 : 5 or above.

After pushing the “Submit” button the user sees a new html page in which are reposted all the set parameters and a link where to download the output data. The output file name is “model-” the provided email address plus date and time of execution “.txt”, in the example “model-average.john-at-email.com_05-17-2022T14-44-33.txt”.



EUROPA O2 EXOSPHERIC SIMULATION EXECUTED

Simulation Parameters

E-mail adress: average.john@email.com
Phase: 0.0
Latitude 1: -90.0 Latitude 2: 90.0 Latitude step: 5.0
Longitude 1: 0.0 Longitude 2: 360.0 Longitude step: 5.0
R 1: 1.05 R 2: 5.0 R step: 0.1
Lines: 102384.0
Execution Time: 05-17-2022T14-44-33

Download Your data

5. References

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