The LatHyS database for planetary plasma environment investigations. Comparison between MAVEN and Mars Express observations and simulation results - a case study.

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Abstract

The Latmos Hybrid Simulation (LatHyS) database dedicated to the investigations of planetary plasma environment is presented. Simulations results of several planetary objects (Mars, Mercury, Ganymede) are proposed in an online catalogue. The full description of the simulations and their results is compliant with a data model developed in the frame of the FP7 IMPEX project. The catalogue is interfaced with VO-visualization tools such AMDA, 3DView, TOPCAT, CLweb or the IMPEX portal. Webservices ensure the possibilities to access and extract simulated quantities/data. To illustrate the interoperability between the simulation database and VO-tools, a science case is detailed. We focused on a three-dimensional representation of the solar wind interaction with the Martian upper atmosphere, combining MAVEN and Mars Express observa-
tions and simulation results.

Keywords: Mars. Numerical modeling. Solar wind interactions with unmagnetized bodies. Data management.

1. Introduction

Since fifty years of space exploration, several planetary magnetospheres have been explored, leading to a large amount of scientific data. More recently, several space missions, or multi-spacecraft missions, are (or will be) operating simultaneously in the vicinity of various celestial bodies, providing multi-point information. The development of an infrastructure which allows the combination of several data set from different space missions represent a major step forward for the understanding of the solar wind interaction with planetary environments. The Virtual Observatory (VO) interoperable standards developed for Astronomy by the International Virtual Observatory Alliance (IVOA) can be adapted to Planetary Sciences and gives such powerful capabilities.

In addition, modeling efforts have been conducted to support the analysis of space plasma data and to give a three-dimensional context of the observations. A global hybrid simulation model, called LatHyS (Modolo et al., 2016), has been developed to describe the interaction between an incoming plasma (the solar wind or a magnetospheric plasma) and planets and moons. Some of the simulation results are described and archived in our simulation database. The simulation database on planetary plasma environments has been developed during the FP7 Integrated Medium for Planetary Exploration - IMPEX project (Khodachenko et al., 2011). The aim of the project is to create an interactive framework where data from planetary missions are interconnected with numerical models providing a variety of possibilities for an external user such as simulating planetary phenomena and interpreting space missions measurements, testing models versus experimental data, filling gaps in the measurement by appropriate modelling runs or performing preparation of specific mission operations.
The present paper reports on the description of the simulation database and presents the different steps to perform a model-observation comparison with VO visualisation tools. The paper is organized as follows: a brief introduction of the LatHyS model and its simulation database is discussed in section 2. A science case focusing on the solar wind interaction with the Martian environment is presented in details in section 3.

2. The LatHyS model and database

During the last fifteen years, we have conducted a modeling effort to develop, parallelize and implement various physical processes in the global simulation model called LatHyS (Latmos Hybrid Simulation, Modolo et al., 2016) to describe the plasma interaction with planetary environments. The model is based on the so-called 'hybrid' formalism where ions are described by a set of numerical particles (called macro-particles) with adjustable weight while electrons are represented by an inertialess fluid conserving the charge neutrality of the plasma. Ions and electrons are coupled via the electromagnetic field. The temporal evolution of electromagnetic fields and the motion of charged particles are computed self-consistently retaining kinetic effects for ions, which is of prime importance to understand the interaction of an incident plasma and the upper atmosphere/surface of certain bodies in the solar system (e.g. Modolo et al., 2005). This simulation model describes the dynamic and the structure of the ionized environment in the neighborhood of these bodies and contribute characterizing the atmospheric erosion while distinguishing processes responsible for this escape. The model, initially develop to describe the Martian plasma environment (Modolo et al., 2005, 2006, 2012, 2016), has been adapted to describe Titan (Modolo et al., 2007, Modolo & Chanteur, 2008), Mercury (Richer et al., 2012) and Ganymede’s environment (Leclercq et al., 2016) and to model a magnetic cloud interaction with a terrestrial bow shock (Turc et al., 2015).

Besides the kinetic description advantages, this hybrid model stand out for several strengths:
• A multi-species description of the plasma. Such model allows describing the dynamic of several ion species for both incident and planetary plasmas. These populations differ not only from the chemical identity but also from their properties (density, speed, temperature,...).

• The possibility to take into account the energetic population of Saturn and Jupiter magnetospheric plasma (i.e. introducing an energetic population which can play an important contribution to the magnetospheric total pressure).

• It takes into account self-consistently charge exchange reaction between neutral and ions.

• The possibility to describe non-Maxwellian velocity distribution functions, for instance related to acceleration processes

• Many physical processes such ionospheric conductivities, ion-neutral collisions, local production calculation, two electronic fluids, ... are taken into account.

• It is a generic multi-objects parallelized model.

The hybrid formalism, its hypothesis and limitation, are described in details in [Kallio et al.] (2011) and [Ledvina et al.] (2008).

In this context, the development of a Data Model (i.e. a set of XML dictionary and grammar) has been developed by the IMPEx team (Hess et al., 2013). The Data Model is used to produce metadata which are parseable by automated tools. This Data Model extends the SPASE-Data Model (http://www.spase-group.org/), which is widely used to describe observations and measurements in the solar and space plasma domains and it is now fully integrated in the last version of the SPASE data model.

To ensure access to the simulation catalog and simulation products, we used the IMPEx data model to completely describe the simulations and their results. Two files are required to communicate with visualization tools.

The "Tree.xml" consists of a complete description of each simulation and data files stored in the simulation database (SMDB). It provides all the information required to fully describe simulation runs, inputs, quantities available as well as the different IMPEx data products.

The LatHyS web-interface proposes to interactively explore the simulation catalogue. It allows parsing the simulation resources and display several information such as the data products available (3D cubes, 2D cut and 1D time series) for the selected simulation run as well as basic input description concerning the selected run. For all archived simulation, pre-computed products are available. It takes into account the following simulation results:

- IonComposition (information for density, velocity and temperature of ion species tracked in the simulation)
- MagneticField (3 components of the magnetic field)
- ElectricField (3 components of the electric field)
- ThermalPlasma (electron density, plasma bulk velocity, electron temperature)

"Run Information" are displayed when one simulation product is selected. Several functionalities are implemented in the LatHyS web-interface:
The possibility to download the simulation file

The possibility to activate the SAMP (Simple Application Message Protocol) functionality. This functionality allows transferring a selected 2D or 1D product into visualization tools like AMDA or TOPCAT.

A "Send" Application which send the data file (VOTable) into TOPCAT.

The LatHyS webpage provides different information: a documentation of the hybrid simulation model, the schema documentation as well as the user’s guide for the data model implementation.

In addition to static data products, we developped webservices to access quantities/data which are not pre-computed but can be generated with the available simulation runs. The webservice technology is a standardized method of machine-to-machine communication over the internet.

The list of web-services available and implemented in SMDB is described in the "Methods.xml" file. This file informs about services which are implemented by the SMDB and give information about how to request a data set and return data product. The "Methods.xml" is described in a machine-processable format (WSDL, Web Services Description Language which is an XML language). The interface defines all services (methods) that the server provides along with all necessary input and output format descriptions. 3D, 2D or 1D data products which are not stored in the LatHyS database, e.g. a 2D cut different than the pre-computed archived 2D cuts, IMPEx tools (AMDA and/or 3DView, CLWeb, IMPEx Portal) can request the information through a webservice. The eight available webservices are:

1. getFileURL ⇒ This method returns the URL/granule of a data product.
2. getDataPointValue ⇒ This a generic method which can be used to determine and to return a simulated quantity for 0D (a given point), 1D (along a curve/trajectory), 2D (in a plane) or 3D (inside a volume) specified input.
3. getDataPointValueSpacecraft ⇒ This method extracts and returns the physical simulation parameters along a specified spacecraft trajectory.
4. getSurface ⇒ This method a- generates a 2D regular mesh defined by a specified point and a normal vector, and b- computes and returns a specified simulated quantity on this mesh.

5. getFiledLine ⇒ This method computes and returns field or flow lines for requested positions or passing through the spacecraft track.

6. getDataPointSpectra ⇒ This method computes and returns ion spectra for a requested positions in 0D (a given point), 1D (along a curve/trajectory).

7. getDataPointSpectraSpacecraft ⇒ This method computes and returns ion spectra along a specified spacecraft track.

8. isAlive ⇒ This method returns the status of the database (alive or not).

An additional webservice, getMostRelevantRun, will be developed and will help selecting the most relevant simulation according to specified inputs.

Figure 1 shows a schematic description of one of the webservices. A full documentation of LATMOS webservice are provided online as an XML documentation (http://impex.latmos.ipsl.fr/Methods_LATMOS.html) and through the IMPEX technical documentation (http://impex-fp7.oeaw.ac.at/fileadmin/user_upload/pdf/ListofWebservices_for_LATMOS_v1.0.pdf).
3. Science case: Comparison of space plasma observations from MAVEN/Mars Express and global hybrid simulation results with VO-tools AMDA, 3DView, TOPCAT

The goal of this science case is to use simultaneous plasma observations from MAVEN and Mars Express in the Martian environment and compare them to modelling results with VO tools.

3.1. Multi-spacecraft space plasma observations at Mars

Mars Express (MEX) is exploring the Martian environment since December 2003, providing unprecedented results on the Martian plasma environment and its ionized escaping flux (e.g., Barabash et al., 2007; Nilsson et al., 2011). Recently, with the Mars orbit insertion of Mars Atmosphere Volatile and EvolutioN (MAVEN) in September 2014 (Jakosky et al., 2015), two spacecrafts equipped with plasma instruments are probing the different regions and plasma boundaries of the planet. It is therefore a unique opportunity to understand the global structure of the solar wind plasma interaction with the upper atmosphere. As an example we examine here bow shock positions observed by both spacecrafts and we compare them with the average BS location determined from an empirical fit (Edberg et al., 2008). To identify bow shock crossings observed by MAVEN and MEX, we use the Automated Multi-Dataset Analysis tool (AMDA, http://amda.cdpp.eu) (Jacquey et al., 2010; Génot et al., 2010). Among the various functionalities, AMDA allows time series visualization of plasma data sets which are available on national space mission archive like NASA PDS (Planetary Data Set), ESA PSA (Planetary Science Archive), and other (observation or modeling) data centers. Figure 2 presents some of the MAVEN and MEX observations on December 10, 2014. From top to bottom, figure 2 shows the total magnetic field measured by MAVEN (Connerney et al., 2015), MAVEN ion spectrograms measured by the Supra-Thermal Analyzer and Thermal Ion Composition-STATIC (McFadden et al., 2015), the distance between Mars and MAVEN/MEX, the electron and the proton spectrograms from MEX (Barabash et al., 2015).
et al., 2004). During this day, MAVEN has achieved five almost identical orbits, exploring different regions such as the solar wind, the magnetosheath, the induced magnetosphere and the ionosphere and crossing plasma boundaries (eg. the bow shock and the induced magnetosphere boundary). Similarly, MEX has performed about three equal orbits, exploring the same regions and boundaries. The quasi-periodic signatures are associated to the repeated orbits. Small scales differences are attributed to responses of the Martian environment to external driver variations.

From the MAG measurements, we can easily determine the signature of the bow shock through its sharp jump on the total magnetic field, suggesting a quasi-perpendicular shock. Coincidentally, the bow shock signature on electron and ion spectrograms corresponds to the thermalisation of the charged particles, where electrons/ions temperature goes from a few eVs to hundreds of eV (or reciprocally). A list (a time table) of BS crossings from both spacecrafts has been reported in table 1. It is possible to store this time table in AMDA and to use it on other VO-tools.

In order to determine if the locations of these BS crossings coincide with their average positions we use the 3DView visualization tool (Génot et al., 2016). This tool provides a 3D orbit visualisation in maneuverable scenes but it is also possible to enrich the scene with observations, models and simulation results. Figure 3 displays such functionality where both spacecraft trajectories are plotted with a 3D representation of the average BS location (Edberg et al., 2008). The intersections between spacecraft orbits and the empirical BS position can be automatically detected and are identified by red dots in figure 3. The time evolution of the scene enables the determination of the expected times of BS crossings from both spacecrafts. These times are reported in Table 1. Observed and expected times are relatively close each other, suggesting that solar wind parameters were close to average values.

To ease the comparison between observed and expected BS crossings, orbit segments where observed BS crossing occurred are displayed in blue for MEX and green for MAVEN. The visualisation of such orbit segments, corresponding
Figure 2: MAVEN and MEX observations on December 10th, 2014. Panels a and b display MAVEN observations such as the total magnetic field (MAG) and the STATIC ion spectrogram (C0 data product). Panel c indicates the distance between MAVEN (MEX) and Mars in Martian radii (in black, respectively red, curve). Panels d and e presents observations from MEX with electron (ASPERA-ELS) and proton (ASPERA-IMA) spectrograms.
Figure 3: Pseudo-three dimensional scene of MAVEN and MEX orbits. The average BS location from Edberg et al. (2008) is identified by the yellow mesh structure. The intersection between the empirical BS and spacecrafts trajectories are indicated by red points. Observed BS locations are displayed by blue (MEX) and green (MAVEN) orbit segments.
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Table 1: Time table (UT) of expected (model) and observed (MAVEN/MEX) bow shock crossings on December 10th, 2014.

to spacecraft positions for the AMDA time tables, are proposed in the 3DView menu bar (Science/Remote data), once the user has connected AMDA with 3DView (Interoperability/AMDA login). Figure 3 shows that orbit segments almost coincide with predicted BS crossings.

3.2. Global simulation results comparisons with plasma in situ observations

To further investigate the three-dimensional aspect of the solar wind interaction with the Martian environment, simulation results from LatHyS model are used to highlight the context of the observations and to restitute them in a three-dimensional scene. Comparisons between MAVEN observations and LatHyS simulation results can be quickly obtained from AMDA, 3DView and the LatHyS database. It allows performing part the investigation done by [Ma et al., 2015], focusing on a comparison between MHD simulation results and MAVEN observations. The different steps are detailed below.
3.2.1. Finding the most relevant simulation

In order to compare simulation results with observations, we need to determine among the different simulations available in the catalogue the most relevant one (RunID). By relevant we mean the simulation having input conditions as close as possible to the observational conditions. The solar wind parameters (magnetic field direction and amplitude, the bulk velocity and proton density) are probably the most influential parameters at global scales. AMDA and TOPCAT provides useful functionalities to derived average solar wind quantities.

At this stage, both tools need to be activated or to have an open session. On AMDA, the user can select one MAVEN orbit providing the start and stop time, e.g. from 2014/12/10 15:30 to 19:30 UT (orbit 385-386), and plot the magnetic field component (MAG), the solar wind ion density, velocity components and temperature from Solar Wind Ion Analyzer - SWIA ([Halekas et al. 2015](#)) on the selected time interval.

Thanks to the AMDA implementation of the SAMP application ([Génot et al. 2014](#)), it is possible to download the data (with all the data in one file) and to send this file to TOPCAT in VOTable format. After the reception of this file in TOPCAT, the user can edit the table and re-arrange the different columns such that each 3-element array columns are replaced by 3 scalar columns. This step is required to manipulate and visualize the vector component of the magnetic field, velocity and the diagonal terms of the temperature tensor. TOPCAT enables the creation of new quantities, determined from a combination of columns/quantities. The user is therefore able to create new parameters, for instance the bulk plasma speed and temperature. The determination of average solar wind parameters requires first to figure the time period when MAVEN is in the undisturbed solar wind region. An algebraic criteria based on a combination of initial or newly created quantities/columns is used to determine a data subset. As an example we can consider that MAVEN is in the solar wind region when $|U| > 350$ km/s and $T < 50$ eV. For the time interval considered, and with this solar wind detection criteria, we found that
\begin{table}[h]
\begin{tabular}{|c|c|}
\hline
\textbf{$n_{sw}$} & $4.0 \pm 0.4 \, \text{cm}^{-3}$ \\
\textbf{$T_{sw}$} & $26.8 \pm 2.2 \, \text{eV}$ \\
\hline
$B_{IMF} = (-0.9, 2.7, 0.1) \pm (1.6, 1.2, 2.1) \, \text{nT}$ & $\mathbf{\vec{U}} = (-409.8, 24.0, -6.6) \pm (12.1, 9.1, 16.0) \, \text{km/s}$ \\
\hline
\end{tabular}
\caption{Average solar wind parameters for the MAVEN orbit 385-386 (2014/12/10 15:30 - 19:30 UT).}
\end{table}

MAVEN has spent 38\% of its time in the solar wind. Using the statistic functions of TOPCAT on the solar wind parameters, applied on the solar wind region subset, we can determine the average solar wind conditions (Table 2).

The interplanetary magnetic field direction is quite varying during this orbit (Table 2) therefore a static simulation run would not be able to reproduce the responses of the Martian environment to short scale variations. In addition, due to the rotation of the planet, crustal field locations will change from orbit to orbit while for the simulation the crustal fields are fixed during the simulation. Parsing the simulation catalogue either on the LatHyS web-interface or on AMDA, we can determine the simulation run with input solar wind parameters closest to the MAVEN average solar wind values. The RunID of the identified run is LatHyS_Mars_14_03_14. The solar wind parameters for this simulation run are the following: a solar wind density of $4.2 \, \text{cm}^{-3}$ with 5\% of $He^{++}$, a bulk speed of 400 km/s along the -X_{MSO} direction ($U_y = U_z = 0 \, \text{km/s}$), and an interplanetary magnetic field $B_{IMF} = (-1.6, 2.5, 0) \, \text{nT}$. The spatial resolution of the simulation is 80 km. The upper atmosphere and exosphere is composed of the $CO_2$, $O$ and $H$ with a fixed density profile and assuming a spherical symmetry (Brain et al., 2010; Modolo et al., 2016).

### 3.2.2. Simulation results comparison with MAVEN and MEX

A time serie comparison between simulation results and observations can be obtained with AMDA. To achieve it, AMDA uses the webservice getDatapointValueSpacecraft. The data can either be visualized on AMDA or sent to TOPCAT. Figure 4 shows a comparison between MAVEN SWIA and MAG observations from 15:30 to 19:30 UT.

The LatHyS model is able to reproduce most of the regions and boundaries
explored by the spacecraft and an overall reasonable agreement is found between observations and model results. However the simulated BS is slightly closer to the planet both in the inbound and outbound pass. An inappropriate profile for hydrogen exospheric density might contribute to underestimate the mass loading in the induced magnetosphere region and therefore affect the BS but also the induced magnetosphere boundary location. The simulated BS crossings occurred at 16:45 UT and 18:49 UT. Moreover the simulated magnetic field in the induced magnetosphere region is underestimated by about 25%. Such difference, although on a different orbit, is also present in Ma et al. (2015). In the ionospheric region, the simulation predict an ionospheric peak of $O_2^+$ slightly lower than $10^5$ cm$^{-3}$. The bulk velocity observed by SWIA is relatively well reproduced by the simulation.

Such comparison can be extended to the entire day of December 10, 2014. Figure 5 shows a comparison between MAVEN SWIA and MAG observations.
Table 3: Pearson’s correlation coefficient determined between MAVEN observation and simulation results for proton density, velocity and total magnetic field.

\[
\begin{align*}
    r(n_{H^+}) &= 0.67 & r(V_x) &= 0.96 \\
    r(V_y) &= 0.36 & r(V_z) &= 0.64 \\
    r(B_{tot}) &= 0.85
\end{align*}
\]

Correlation coefficients for the different parameters are reported in table 3. Very high correlation coefficients (≥ 0.85) are found for the total magnetic field and the \( V_x \) component of the velocity, high correlation coefficient for the proton density and the \( V_z \) component of the velocity while the correlation for the \( V_y \) component velocity is relatively low. Several factors can contribute to the discrepancy. During the simulation, the input parameters are kept constant, therefore any change in the solar wind conditions will not be reproduced. Secondly, We clearly see in figure 5, that for several orbits the solar wind speed has a significant \( V_y \) component while in the simulation the solar wind plasma is supposed to be aligned with the \(-X_{MSO}\) direction. Finally, as previously said, the simulation is done for a given location of crustal field (here the sub-solar location is local at the Western longitude 180°).

The simulation results can also be compared to MEX observations which is exploring other spatial regions. Since MEX was in the solar wind region for the time interval 15:30 - 19h30 UT, the model-observation comparison has been done for the time interval 19:00 - 23:00 UT (Figure 6). MEX IMA (heavy and proton) ion spectrograms are plotted on the two first panels, while the simulated bulk speed and the total speed for heavy and proton ions are compared in the last panel. As for the MAVEN observations, the LatHyS model reproduce well the MEX observations.

A new way to analyze in situ observations is to combine the multi-points
Figure 5: MAVEN observations and simulation results on December 10th, 2014. From top to bottom: Mars-MAVEN distance in Martian radii, the proton density determined from SWIA (yellow) and the simulated solar wind proton density (black), the next three panels represent the plasma velocity components measured by SWIA (in color) and simulated (in black), and the last panel displays the total magnetic field measured by MAG (in cyan) and simulated (in black).
Figure 6: MEX observations and model comparison from 19:00 to 23:00 UT. Heavy and proton ion spectra from ASPERA IMA are displayed in the top panels. The bottom panel shows a comparison between observed and simulated speed.
Figure 7: Three-dimensional scene of the MAVEN, MEX observations and simulation results. Simulated velocity is plotted in a 2D XZ plane and along MAVEN track (light green vectors) and compared to MAVEN SWIA velocity observations (light blue vectors). A simulated magnetic field line is displayed at MEX location close to the North pole (at 21:59 UT), with a color code indicating the strength of the magnetic field.

plasma information, measured by MAVEN and MEX, with the simulation results in a 3D interactive scene. 3DView visualization tool proposes such capability (Figure 7). On this scene, the user loaded a 2D simulated plane (eg the bulk speed in the XZ plane passing through the center of the planet) and the 3D MAVEN and MEX trajectories. The simulated BS is identified upstream of the plasma by an abrupt color change. We can enrich the scene by plotting observational data such the solar wind velocity measured by SWIA (light blue arrows) and predicted plasma velocity from the model (light green arrows). High-level data products are also proposed and the user can visualise the draping of the magnetic field around the planet. An example of such field lines passing through the MEX trajectory is also shown in figure 7.
These functionalities give a three-dimensional context of the in situ observations and present powerful capabilities to combine multi-points observations and global simulation results.

4. Conclusion

In this paper we have described a simulation database dedicated to planetary plasma investigations which has been developed in the frame of the FP7 IMPEx project. The LatHyS database offers to the community sophisticated simulation results of various planetary plasma environments. A variety of pre-computed data-products (1D, 2D and the entire 3D cube) for several plasma quantities (electric field, magnetic field, ion species moments, ...) are publically available. 1D and 2D archived simulation results can be visualized on VO tools like TOPCAT thanks to the implementation on the LatHyS webinterface of the SAMP functionality (Génot et al., 2014). In addition to static data, an effort of interoperability with VO tools has been conducted. Several webservices have been developed to extract high-level simulated data from the archived simulation catalogue. Some of these webservices are implemented in VO tools like AMDA, 3DView, CLweb or IMPEx Portal.

We have also presented a science case focusing on the Martian plasma environment to illustrate the powerful possibilities of the interoperability between VO tools and the LatHyS database. We have combine multi-spacecraft observations and simulation results to draw a three-dimensional pictures of the solar wind interaction with the Martian upper atmosphere.

Additional tutorial/demonstration videos on the LatHyS SMBD have been released and are available at http://impex-fp7.oeaw.ac.at/videos.html. These videos have been presented at the European Planetary Science Congress annual meeting (EPSC 2013) (September 2013) in the Virtual Observatory session and have been the result of a successful collaboration between the Europlanet infrastructure (http://www.europlanet-eu.org/) and IMPEx FP7 projects.
- Interoperability of AMDA, LatHyS and TOPCAT ([http://youtu.be/rOh4Me9xTqE](http://youtu.be/rOh4Me9xTqE))
- AMDA, 3DView and Simulation Databases (SMDBs) ([http://youtu.be/8AxJRPho334](http://youtu.be/8AxJRPho334)).

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