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# The LatHyS database for planetary plasma environment investigations: Overview and a case study of data/model comparisons

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A B S T R A C T

We present the Latmos Hybrid Simulation (LatHyS) database, which is dedicated to the investigations of planetary plasma environment. Simulation results of several planetary objects (Mars, Mercury, Ganymede) are available in an online catalogue. The full description of the simulations and their results is compliant with a data model developped in the framework of the FP7 IMPEx project. The catalogue is interfaced with VO-visualization tools such AMDA, 3DView, TOPCAT, CLweb or the IMPEx portal. Web services ensure the possibilities of accessing and extracting simulated quantities/data. We illustrate the interoperability between the simulation database and VO-tools using a detailed science case that focuses on a three-dimensional representation of the solar wind interaction with the Martian upper atmosphere, combining MAVEN and Mars Express observations and simulation results.

## 1. Introduction

During 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 sets from different space missions represents 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 give 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), was developped 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 developped 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

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experimental data, filling gaps in the measurement by appropriate modeling 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 visualization tools. The paper is organized as follow: 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 detail 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 for understanding 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 characterizes the atmospheric erosion while distinguishing processes responsible for this escape. The model, initially developed to describe the Martian plasma environment (Modolo et al., 2005, 2006, 2012, 2016), has been adapted to describe Titan (Modolo et al., 2007; Modolo and 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 stands out for several strengths:

- A multi-species description of the plasma. Such a model allows describing the dynamics of several ion species for both incident and planetary plasmas. These populations differ not only in chemical identity but also from their properties (density, speed, temperature, …).
- The possibility of taking into account the energetic population of Saturn and Jupiter magnetopsheric plasma (i.e. introducing an energetic population which make an important contribution to the magnetospheric total pressure).
- Taking into account self-consistently the charge exchange interaction between neutral and ions.
- The possibility of describing non-Maxwellian velocity distribution functions, for instance related to acceleration processes
- Many physical processes, such as ionosphere conductivities, ion-nteural collisions, local production calculation, two electronic fluids,…are taken into account.
- It is a generic multi-object parallelized model.

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

A project including simulation archiving and dissemination of simulation results has been undertaken in the frame of the FP7 IMPEx IMPEx (#262863, 2011–2015, (Khodachenko et al., 2011) http://impex-fp7.oeaw.ac.at/). Simulation results are publically available on our web-interface (http://impex.latmos.ipsl.fr/LatHyS.htm) and are interoperable with powerfull visualization tools through webservices. Simulation results can be displayed with VO-tools like TOPCAT (http://www.star.bris.ac.uk/~mbt/topcat/), AMDA (http://amda.cdpp.eu/), 3DView (http://3dview.cdpp.eu/), CLweb (http://clweb.irap.omp.eu/) or the IMPEx portal (http://impex-portal.oeaw.ac.at/#/portal).

In this context, the development of a Data Model (i.e. a set of XML dictionary and grammar) has been developped by the IMPEx team (Hess et al., 2013). The Data Model is used to produce metadata which are parsable 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 the IMPEx extensions are now fully integrated in the last version of the SPASE data model.

To ensure access to the simulation catalogue 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, and quantities available as well as the different IMPEx data products.

The LatHyS web interface allows the interactive exploration of the simulation catalogue. It allows parsing the simulation resources to display several information types 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 simulations, pre-computed products are available. It includes 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" is displayed when one simulation product is selected.

Several functionalities are implemented in the LatHyS web interface:

- The ability to download the simulation file
- The ability 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 sends the data file as a VOTable into TOPCAT.

The LatHyS webpage provides different information: 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 developed web services to access quantities/data which are not pre-computed but can be generated with the available simulation runs. The web service 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 describes the services that are implemented by the SMDB and gives information about how to request a data set and return a 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. The 3D, 2D or 1D data products which are not stored in the LatHyS database, e.g. a 2D cut different from the pre-computed archived 2D cuts, IMPEx tools (AMDA and/or 3DView, CLWeb, IMPEx Portal) can request the information through a

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