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Virtual Planetary Space Weather Services offered by the Europlanet H2020 Research Infrastructure

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ABSTRACT

Under Horizon 2020, the Europlanet 2020 Research Infrastructure (EPN2020-RI) will include an entirely new Virtual Access Service, "Planetary Space Weather Services" (PSWS) that will extend the concepts of space weather and space situational awareness to other planets in our Solar System and in particular to spacecraft that voyage through it. PSWS will make twelve new services accessible to the research community, space agencies, and industrial partners planning for space missions. These services will in particular be dedicated to the following key planetary environments: Mars (in support of the NASA MAVEN and European Space Agency (ESA) Mars Express and ExoMars missions), comets (building on the outstanding success of the ESA Rosetta mission), and outer planets (in preparation for the ESA JUpiter ICy moon Explorer mission), and one of these services will aim at predicting and detecting planetary events like meteor showers and impacts in the Solar System. This will give the European planetary science community new methods, interfaces, functionalities and/or plugins dedicated to planetary space weather as well as to space situational awareness in the tools and models available within the partner institutes. A variety of tools (in the form of web applications, standalone software, or numerical models in various degrees of implementation) are available for tracing propagation of planetary and/or solar events through the Solar System and modelling the response of the planetary environment (surfaces, atmospheres, ionospheres, and magnetospheres) to those events. But these tools were not originally designed for planetary event prediction and space weather applications. PSWS will provide the additional research and tailoring required to apply them for these purposes. PSWS will be to review, test, improve and adapt methods and tools available within the partner institutes in order to make prototype planetary event and space weather services operational in Europe at the end of 2017. To achieve its objectives PSWS will use a few tools and standards developed for the Astronomy Virtual Observatory (VO). This paper gives an overview of the project together with a few illustrations of prototype services based on VO standards and protocols.

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1. Introduction

Planetary Space Weather Services (PSWS) aims at extending the concept of space weather to other planets in our Solar System and in particular to spacecraft that voyage through it. PSWS will give the European planetary scientists for the first time new methods, interfaces, functionalities and/or plug-ins dedicated to planetary space weather in the form of tools and models available in the partner institutes.

Space Weather – the monitoring and prediction of disturbances in our near-space environment and how they are controlled by the Sun - is now recognised as an important aspect of understanding our Earth and protecting vital assets such as orbiting satellites and power grids. The Europlanet 2020 Research Infrastructure (http://www.europlanet-2020-ri.eu/) aims to transform the science of space weather, by extending its scope throughout the Solar System. An entirely new Virtual Access Service, "Planetary Space Weather Services" (PSWS, http://planetaryspaceweather-europlanet.irap.omp.eu/) has therefore been included in the Europlanet H2020 Research Infrastructure funded by the European Union Framework Programme for Research and Innovation.

Planetary Space Weather can be seen as the physical and phenomenological state of natural space environments; the associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and now-casting the possible impacts on biological and technological systems' (Lilensten and Belehaki, 2011). Planetary Space Weather therefore refers to the study of the variability of planetary (or satellite) environments (e.g. atmospheres, exospheres, intrinsic magnetospheres) determined by the variability of the solar activity or/and the interplanetary space dynamics (Plainaki et al., 2016). A detailed discussion on why we need to take account for planetary space weather as well as a few illustrations on some planetary space weather impacts on space environments, spacecraft and technology can be found in Lilensten et al. (2014).

A variety of tools (in the form of web applications, standalone software, or numerical models in various degrees of implementation) are available for tracing propagation of 1) planetary or 2) Solar events through the Solar System and modelling the response of the planetary environment (surfaces, atmospheres, ionospheres, and magnetospheres) to those events. As these tools were usually not designed for 1) planetary event prediction and 2) space weather applications, additional research and tailoring is required to apply them for these purposes. The overall objectives of PSWS will be to review, test, improve and adapt methods and tools available within the partner institutes in order to make prototype 1) planetary event and 2) space weather services operational in Europe at the end of the programme. In particular the aims are:

- To define a service for 1) planetary event and 2) planetary space weather predictions. Such a service is motivated by various needs including (a) the need to protect planetary probes from dust events (e.g., when a C/2013 A1 (Siding Spring) passed nearby Mars in 2014, see Tricarco, 2015) or solar/solar wind disturbances during cruise or at destination; (b) the need to gain new insights on other planetary environments in relation to the evolution of the Solar System in general (e.g., The Mars Atmosphere and Volatile Evolution (MAVEN) Mission that is dedicated to the study of the importance of loss to space in changing the Mars climate and atmosphere through time, see Jakovsky et al., 2015); (c) the need for providing multi-scale context to the analysis of data or to the preparation of special observational campaigns for a given planetary mission (e.g., scheduling Hubble Space Telescope observations of Uranus' aurorae through solar wind tracking, see Lamy et al., 2012);
- To develop new methods, interfaces, functionalities and/or plug-ins dedicated to planetary space weather in the tools and models already available within the partner institutes;
- To define planetary proxies and reliability factors for planetary space weather applications;
- To validate, compare and enhance the capability of the existing models and tools in order to predict the impact of solar events in the vicinity of Solar System objects;
- To identify user requirements, develop the way to implement event alerts, and chain those to the 1) planetary event and 2) planetary space weather predictions;
- To facilitate discovery or prediction announcements within the PSWS user community in order to watch or warn against specific 1) planetary and 2) planetary space weather events;
- To set up dedicated amateur and/or professional observation campaigns, diffuse contextual information for science data analysis, and enable safety operations of planet-orbiting spacecraft against the risks of impacts from 1) meteors and 2) solar wind disturbances.

The Planetary Space Weather Services will provide 12 services distributed over 4 different service domains – Prediction, Detection, Modelling, Alerts - having each its specific groups of end users. The PSWS portal (http://planetaryspaceweather-europlanet.irap.omp.eu/) gives access to an initial presentation of PSWS activities. Section 2 gives an overview of the foreseen services. Each service will be implemented through a combination of data products, software tools, technical reports, and tutorials. Section 3 describes how the services will comply with Virtual Observatory (VO) methods and standards. Section 4 illustrates some of the VO-compliant functionalities already implemented in some services that are already operational. Section 5 summarizes the status of the project and lists a few perspectives for PSWS services in the VO context and beyond.

2. Overview of Planetary Space Weather Services

The Planetary Space Weather Services will provide 12 services distributed over 4 different service domains – Prediction, Detection, Modelling, Alerts. These services are summarized in the Table below and detailed in this section.(Table 1).

2.1. Prediction

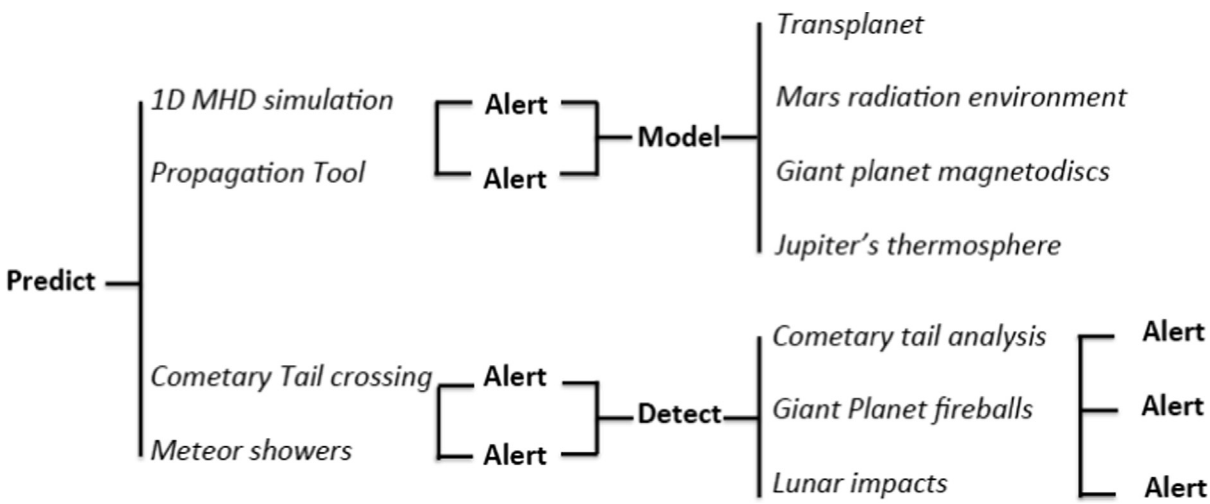
2.1.1. 1D MHD solar wind Prediction Tool

The *Centre de Données de Physique des Plasmas* (CDPP) within the *Institut de Recherche en Astrophysique et Planétologie* (IRAP/CNRS) will provide real time and archive access to solar activity proxies (e.g. the solar decimetric radio flux, F10.7), galactic cosmic ray fluxes, propagated solar wind parameters (density, velocity, temperature, dynamic pressure, angle of the Parker spiral, tangential magnetic field component) at various planetary bodies (Mercury, Venus, Mars, Jupiter, Saturn,…) and spacecraft (Rosetta, Juno, Maven,…) using a 1D magnetohydrodynamic (MHD) code available through the CDPP/AMDA tool (http://amda.cdpp.eu) initially developed by Chihiro Tao (Tao et al., 2005).

2.1.2. Extensions of the CDPP Propagation Tool

The *GFI Informatique* (GFI) will extend the Propagation Tool (Rouillard et al., this issue) available at CDPP (http://propagationtool.cdpp.eu) to the case of comets, giant planet auroral emissions, and catalogues of solar wind disturbances. The Propagation Tool includes as targets all eight planets of the Solar System as well as various spacecraft (Rosetta, Cassini, Mars Express, Venus Express, STEREO A and B, WIND, ACE, MESSENGER, SOHO, Juno, plus Voyager 1 and 2, and New Horizons to be added in the near future). The service will provide new plug-ins including selection of comets as targets, visualization of their trajectories, projection onto solar maps, projection onto J-maps (maps of solar wind outflows obtained from the Helio-

Table 1
Overview plot of PSWS services and domains (in bold). Two services will be developed in order to make predictions of the solar wind parameters and of the arrival time of solar wind disturbances at a planetary body or spacecraft. Two services will be developed in order to build calendar of meteor showers and cometary tail crossing by a planetary body or a spacecraft, respectively. Alerts will be issued from these four services in order to warn users against the occurrence of remarkable events. The two services related to solar wind predictions will provide input parameters for four planetary environment models, whereas the two services related to the building of calendar of events will be linked to observational campaigns of comets, giant planets, or the Moon. Three dedicated analysis software for planetary images will be provided to PSWS users in order to detect potential impact of the predicted events on the relevant planetary bodies. Alerts will be issued in case of positive detection in order to stimulate follow-up observational campaigns.



spheric Imagers onboard STEREO spacecraft, in which multiple elongation profiles along a constant position angle are stacked in time, building an image in which radially propagating transients form curved tracks in the J-map. The way J-maps are produced is described in e.g. Davies et al., 2009), and estimates of solar wind disturbance arrival times; tit will enable the user to use catalogue of solar wind disturbances in order to identify those that have impacted the planetary environments.

2.1.3. Meteor showers

The *Observatoire de Paris* (OBSPARIS) will link ephemerides of Solar System objects to predictable meteor showers that impact terrestrial planet surfaces or giant planet atmospheres.

2.1.4. Cometary tail crossings

The *Mullard Space Science Laboratory* (MSSL) within the *University College London* (UCL) will develop and post online a software in order to enable users to predict cometary ion tail crossings by any interplanetary spacecraft including future missions like Solar Orbiter, BepiColombo, and JUICE.

2.2. Detection

2.2.1. Lunar impacts

Aberystwyth University (ABER) will upgrade and convert its lunar impact software (https://www.britastro.org/lunar/tlp.htm) and post it online in order to enable users to detect visible flashes in lunar amateur or professional images.

2.2.2. Giant planet fireballs

The *Universidad del Pais Vasco* (UPV/EHU) will upgrade and convert its giant planet fireball detection software (http://pvol2.ehu.eus/psws/jovian_impacts/) and post it online in order to enable users to detect visible fireballs in giant planet amateur or professional images. This will be done in collaboration with a network of amateur astronomers already participating in the search of impacts in the planet and accumulating several dozens of hours each year. The detection software will also provide statistics of its use towards a better understanding on how significant are the objects already detected (4 events from 2010 to 2016). In case of finding an impact we would issue alerts to the amateur community through several services including the PVOL2 portal. This would potentially provide multiple light curves of the same impacts.

2.2.3. Cometary ion tails

Mullard Space Science Laboratory (MSSL) within *University College London* (UCL) will upgrade and convert its cometary ion tail analysis software and post it online, with the aim of also providing it as an interactive suite. The software will be readily accessible to any users (professional or amateur) who work with comet images and wish to obtain an estimate for the solar wind speed at the comet from their observations.

2.3. Modelling

2.3.1. Transplanet – Earth, Mars (Venus), Jupiter (Saturn)

The *Centre de Données de Physique des Plasmas* (CDPP) within the *Institut de Recherche en Astrophysique et Planétologie* (IRAP/CNRS) will develop an online version of the hybrid-fluid TRANSPLANET ionospheric model (Marchaudon and Blelly, 2015) that will enable users to make runs on request for Venus, Earth, Mars, Jupiter, and Saturn. Particle precipitation corresponding to particular solar wind conditions can be set by the user. The service is operational and can be accessed at http://transplanet.irap.omp.eu.

2.3.2. Mars radiation environment

Aberystwyth University (ABER) together with the Institute of Aerospace Medicine (DLR Cologne) will develop a Mars radiation surface environment model (Matthiä et al., 2016), using modelled average conditions available from Planetocosmics (https://www.spenvis.oma.be/help/models/planetocosmics.html) and synthesised into look-up tables parameterized to variable external conditions (e.g., galactic cosmic radiation) at Mars for appropriate seasons, and locations. The service will enable in particular estimates of radiation doses in the atmosphere (e.g., for orbiters) and at the surface of the planet (e.g., for rovers like the one of the Exomars mission or astronauts).

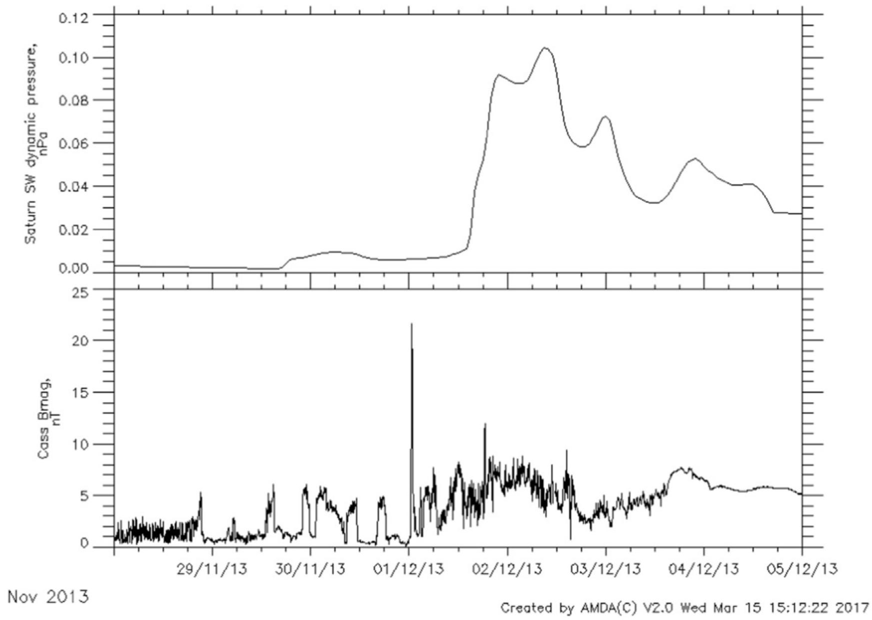


Fig. 1. Predicted solar wind dynamic pressure at Saturn (top) from a 1D MHD propagation model (Tao et al., 2005) and magnetic field magnitude observed from Cassini (bottom), as a function of time. The Titan T96 flyby on December 01, 2013 occurred in the solar wind (Bertucci et al., 2015), when the model predicted the arrival of a large-scale compression 12 h later. Plot done with the CDPP/AMDA tool.

Table 2
PSWS services, type of developments, and VO protocols to be implemented within the corresponding services.

PSWS services	Type of developments	Use of EPN-TAP	Use of SAMP	Use of VOEvent
1D MHD Solar Wind Prediction Tool	Website + Database + Alerts	yes	yes	yes
Propagation Tool	Software + Database + Alerts	yes	yes	yes
Meteor showers	Website + Alerts	no	no	yes
Cometary tail crossings	Software + Alerts	no	no	yes
Lunar impacts	Software + Database + Alerts	yes	yes	yes
Giant planet fireballs	Software + Database + Alerts	yes	yes	yes
Cometary tails	Software + Database	yes	yes	no
Transplanet	Runs on request + Database	yes	yes	no
Mars Radiation Environment	Runs on request + Database	yes	yes	no
Giant planet magnetodiscs	Runs on request + Database	yes	yes	no
Jupiter's thermosphere/ionosphere	Runs on request + Database	yes	yes	no
Alerts	Database + Alerts	yes	no	yes

2.3.3. Giant planet magnetodiscs

University College London (UCL) will adapt the parametric magnetodisc model for Jupiter and Saturn as well as the resulting magnetic field mapping in their ionospheres in order to take into account realistic, rapid solar wind compressions (Achilleos et al., 2010), based on time-dependent predictions of dynamic pressure from the CDPP Propagation Tool and/or observations of solar wind at Jupiter orbit.

2.3.4. Jupiter's thermosphere

University College London (UCL) will adapt the 2D thermospheric models available for Jupiter and its space environment in order to take into account realistic, rapid solar wind compressions (Yates et al., 2014), based on time-dependent predictions of dynamic pressure from the CDPP Propagation Tool and/or observations of solar wind at Jupiter orbit.

2.4. Alerts

The *Observatoire de Paris* (OBSPARIS) together with *University College London* (UCL), the *Institut de Recherche en Astrophysique et Planétologie* (IRAP/CNRS), and the *Space Research Centre* (PAS/SRC) will create an Alert service linked to prediction of planetary events of various kinds: solar energetic particles (SEP), solar wind disturbances triggering to magnetospheric or auroral events, planetary meteor showers, cometary tail disconnection events, lunar flashes, giant planet fireballs, radio type III. We propose to broadcast these events with VOEvent, an alert service infrastructure developed in the frame of IVOA (White et al., 2006). This alert service has been forged for the Gamma Ray Bursts events, and is now used by many projects (including linking with amateurs) such as: SDO (Solar Dynamic Observatory), LSST (Large Synoptic Survey Telescope), LOFAR (Low Frequency Array), or GCN (Gamma Ray Coordinate Network).

There are 4 types (roles) of VOEvents:

- Observation (default)
- Prediction
- Utility (for instance: mode change of the observatory)
- Test

The *Observation* and *Prediction* roles will be used by PSWS. The VOEvent documentation concentrates on the *Observation* role, but the *Prediction* role can be used in a very similar manner.

The VOEvent structure includes:

- < Who > Identification of scientifically responsible Author
- < What > Event Characterization modelled by the Author
- < WhereWhen > Space-Time Coordinates of the event
- < How > Instrument Configuration

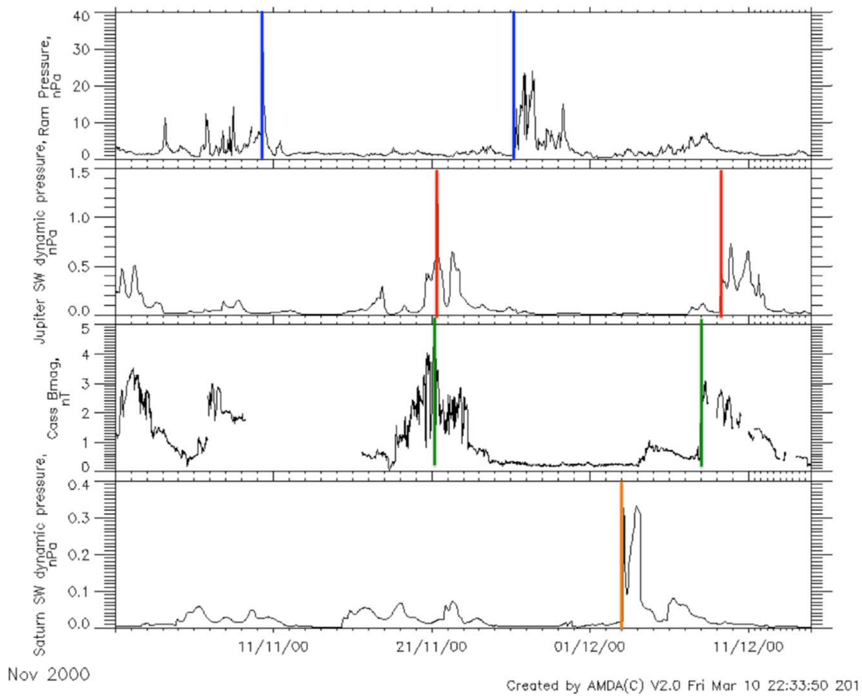


Fig. 2. Dynamic Pressure (in nPa) versus time: OMNI observations at Earth (first panel), 1D MHD simulations at Jupiter (second panel) and at Saturn (fourth panel), and Cassini magnetic field observations (third panel). Plot done with the CDPP/AMDA tool.

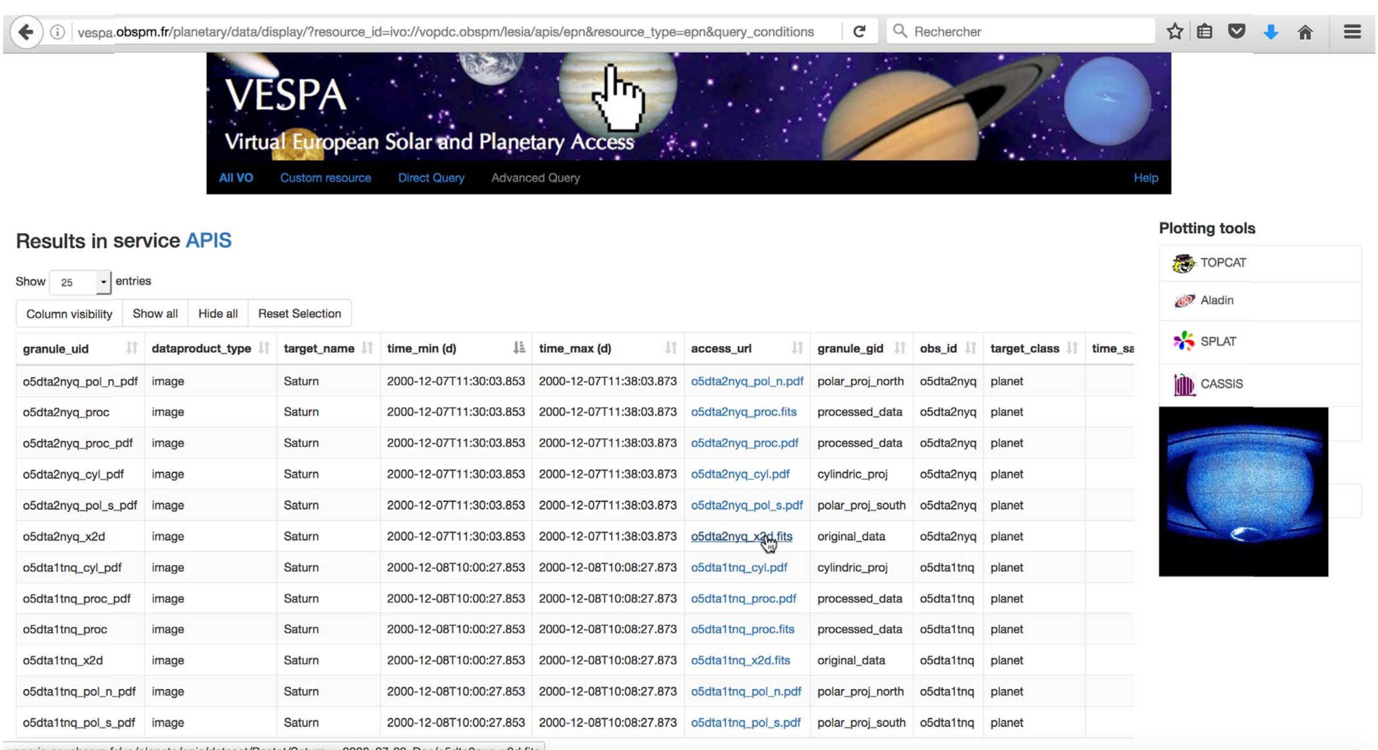


Fig. 3. Results of an EPN-TAP query from the VESPA interface searching for Saturn observations during the time period 01/11/2000-15/12/2000 in the APIS service.

- < Why > Initial Scientific Assessment
- < Citations > Follow-up Observations
- < Description > Human Oriented Content
- < Reference > External Content

This service will be developed in order to facilitate discovery or make predictions within the PSWS user community, in order to watch or warn against specific events across several timescales, ranging from minutes following cometary disconnection events or giant planet fireballs to days for solar wind propagation or meteor showers in the Solar System. The ultimate objective is to set up dedicated observation campaigns, distribute contextual information for science data analysis, and enable safety operations of planet-orbiting spacecraft against the risks of impacts from meteors or solar wind disturbances. When possible, a solar wind disturbance will be automatically followed after eruption and tested whether it reaches a given planet or spacecraft

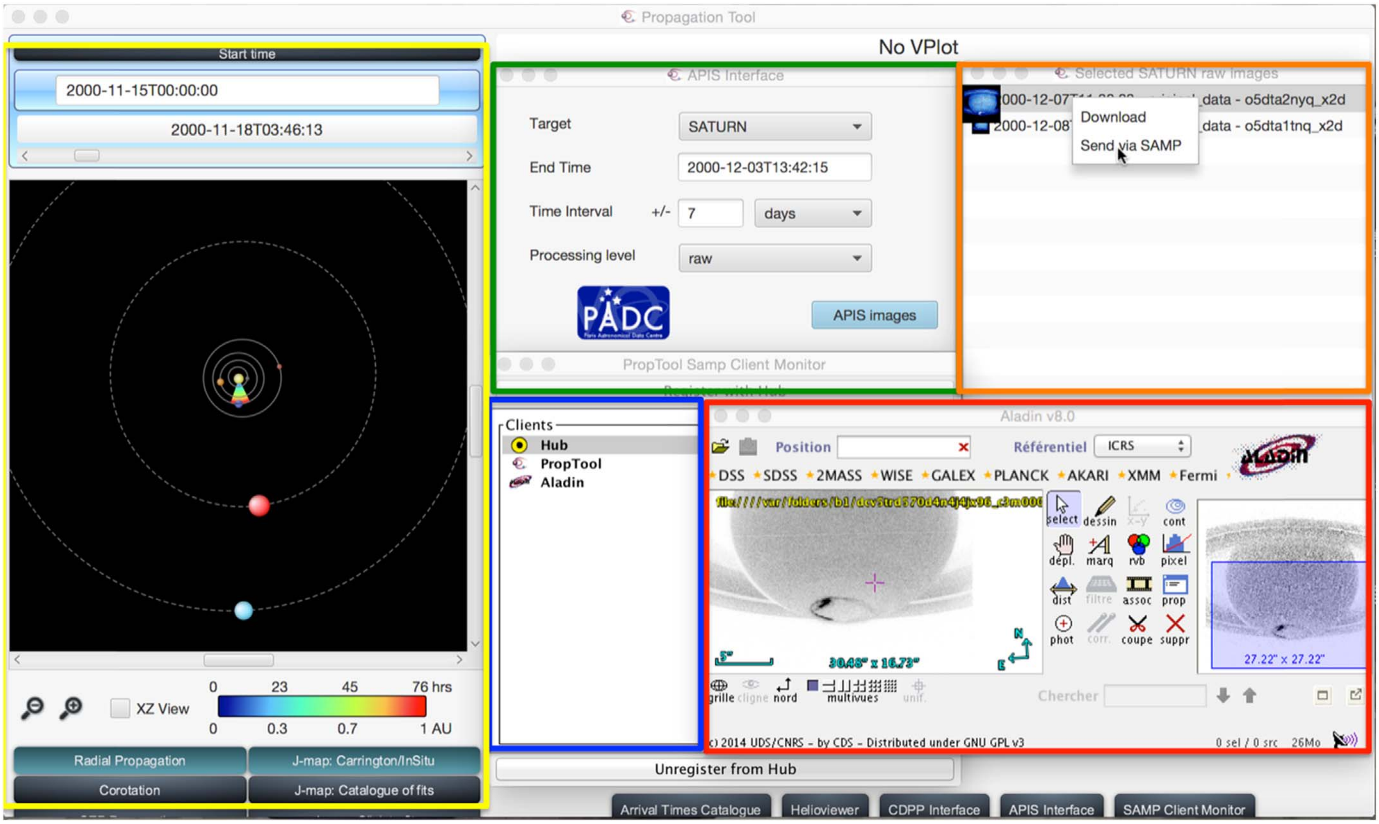


Fig. 4. Illustration of some VO functionalities available in the CDPP Propagation Tool. Yellow box: Location of the planets in the heliosphere (Earth in dark blue, Jupiter in red, Saturn in light blue) for the time period 15/11/2000-18/11/2000. Green box: APIS interface to query Hubble Space Telescope giant planet auroral observations using the EPN-TAP protocol. Orange box: results of the query. Blue box: SAMP client monitor activated. Red box: visualization in the Aladin tool of a giant planet auroral observation from the APIS database enabled by SAMP. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

using for example the CDPP Propagation Tool; in case of positive detection, the < Citations > element of the VOEvent structure will be updated in order to refine the prediction. In addition, when linked to models of magnetospheric boundaries (e.g., bow shock, magnetopause) and taking into account real spacecraft trajectories, the service could be used to predict the crossing of magnetospheric boundaries at Mercury (for BepiColombo) and Jupiter (for JUICE) following solar wind compressions. If available at the time of Cassini, such a service could have been used in order to predict Titan flybys when Titan is in the Saturnian magnetosheath or in the solar wind (Fig. 1), with potential impact on the operation modes of instruments onboard Cassini.

3. Planetary space weather services and the virtual observatory

3.1. VO protocols of interest for PSWS

We have identified the three VO protocols below for implementation within PSWS services:

- ***SAMP*** (Taylor et al., 2015), the Simple Application Messaging Protocol is developed now for many years in the frame of the International Virtual Observatory Alliance (IVOA). It enabled easy communication and interoperability between astronomy software, stand-alone and web-based, before being rapidly and largely adopted by the planetary sciences and space physics community. Its attractiveness is based, on one hand, on the use of standardized file formats (e.g., FITS images, VO Tables, jpegs, …) for exchange and, on the other hand, on established messaging models.
- ***EPN-TAP*** (Erard et al., 2014a, b; Erard et al., this issue) is a specific Data Access Protocol developed by the Virtual European Solar and Planetary Access (VESPA) facility within the Europlanet H2020 Research Infrastructure in order to search and retrieve Planetary Science data in general. This protocol allows the user to select a subset of data from an archive in a standardized way and relies on an underlying Data Model and reference dictionaries. Using EPN-TAP, data are accessed in two steps. The first one consists in searching for available EPN-TAP services registered in the IVOA registries, while the second step consists in sending a query searching for data according to specific values of the parameters contained in a table in order to filter the database contents.
- ***VOEvent*** (Cecconi et al., this issue) is a standardized language used to report observations of astronomical events; it was officially adopted in 2006 by the IVOA. Although most VOEvent messages currently issued are related to supernovae, gravitational microlensing, and gamma-ray bursts, they are intended to be general enough to describe all types of observations of astronomical events.

3.2. Implementation of VO protocols within PSWS

The three VO protocols identified previously will be implemented in the PSWS services as described in the Table below. This will make in particular the PSWS services VO-compliant with the developments of VESPA, notably in term of interoperability.(Table 2).

4. Planetary space weather VO services illustrated

4.1. 1D MHD solar wind Prediction Tool

The lack of solar wind monitoring just upstream of Solar System bodies can be overcome by using simulations that propagate the solar wind from in situ observations obtained elsewhere in the Solar System (e.g., Zieger and Hansen, 2008). We have implemented in the CDPP

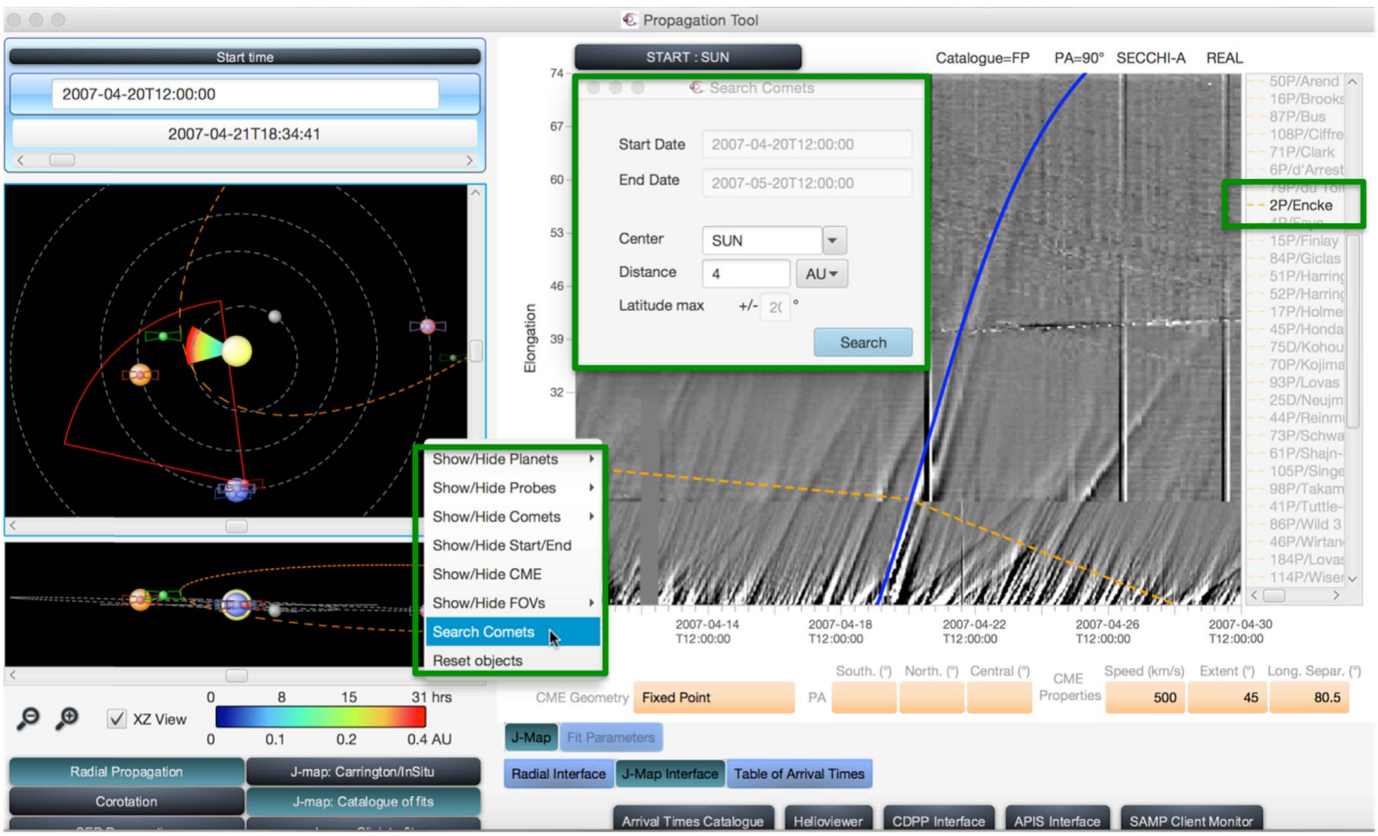


Fig. 5. Illustration of the new PSWS functionality implemented within the CDPP Propagation Tool and dedicated to comets. Green box: search window to identify comets flying by a central body at a particular distance during the selected time period. Once a comet is identified and selected (here 2 P/Encke), its orbit is displayed on the left in red-dashed line. Its location in a J-map obtained from STEREO-A observations is displayed on the right in orange-dashed line. The blue line corresponds to a particular CME identified from a catalogue of fits. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

tools AMDA (Automated Multi-Dataset Analysis, Génot et al., 2010), 3DView (Génot et al., this issue), and Propagation Tool (Rouillard et al., this issue), a one-dimensional (1D) magnetohydrodynamic (MHD) simulation of the solar wind propagation developed by Tao et al. (2005). The simulation uses time-varying boundary conditions at one Astronomical Unit (AU) obtained either from hourly solar wind data observed near the Earth made available by OMNI (http://omniweb.gsfc.nasa.gov/), or real-time ACE observations. Simulated propagated solar wind parameters such as density, temperature, velocity, dynamic pressure, and tangential magnetic field in Radial Tangential Normal coordinates (RTN, a spacecraft-centered coordinate system with X axis pointing from Sun to Spacecraft, Y axis cross-product of solar rotational axis and X axis, lying in the solar equatorial plane towards the West limb, and Z axis completing the right-handed trial) are available for various planetary bodies (Mercury, Venus, Earth, Mars, Jupiter, Saturn, and comet Churyumov-Gerasimenko) and spacecraft (e.g., Rosetta, Juno). The use of real-time ACE observations will enable us in the near future to make predictions for the potential interactions of solar wind disturbances with planetary bodies.

Fig. 2 displays in the AMDA tool observed and simulated dynamic pressure at Earth, Jupiter, and Saturn for a time period when the three planets are aligned in November/December 2000 (Prangé et al., 2004) together with Cassini magnetic field observations in the solar wind during its Jupiter flyby. We can see at the beginning of the time interval a series of CMEs observed in situ at Earth (blue lines delineating the maximum of the dynamic pressure for the first event and the shock front for the second event) that propagate in the Solar System, evolve, and eventually merge before to reach Jupiter (red lines) as well as Saturn (orange lines) at the end of the time interval as predicted by the 1D MHD simulation. The Cassini magnetic field observations (green lines) in the vicinity of Jupiter enable us to test the reliability of the prediction at Jupiter, about less than ± 10 h for the first event and ± 30 h for the second event.

Fig. 3 illustrates how the EPN-TAP protocol can be used from the Virtual European Solar and Planetary Access (VESPA) interface (Erard et al., this issue) in order to search for remote Hubble Space Telescope observations of giant planets ultraviolet aurorae available in APIS (Lamy et al., 2015a, b) during the same time period.

In order to facilitate similar queries an APIS interface has been directly implemented within the AMDA and Propagation Tool (Fig. 4). These two tools are connected through the SAMP Protocol (Génot et al., 2014) with more sophisticated astrophysical VO tools such as Aladin in order to enable further visualization and analysis of the combined remote and in situ observations.

4.2. Extensions of the CDPP Propagation Tool to comets

The structure and dynamics of cometary plasma tails witness the solar wind variability. Cometary observations are particularly attractive for amateur astronomers who usually are the first witnesses of remarkable solar wind – comet interactions. We have extended the CDPP 3DView (http://3dview.cdpp.eu/, Génot et al., this issue) and Propagation Tool in order to include comets as targets so that for example the Propagation Tool can be used in order to estimate the properties of the solar wind as well as identify the arrival of a solar wind disturbance in the vicinity of a particular comet.

On 20 April 2007, a tail disconnection event on comet 2 P/Encke caused by a coronal mass ejection (CME) was observed by the STEREO-A spacecraft (Vourlidas et al., 2007). Fig. 5 illustrates how the CDPP Propagation Tool can be used in order to identify on a J-map the interaction of the comet with the CME. The corresponding J-map is generated by extracting bands of pixels in STEREO-A coronal and

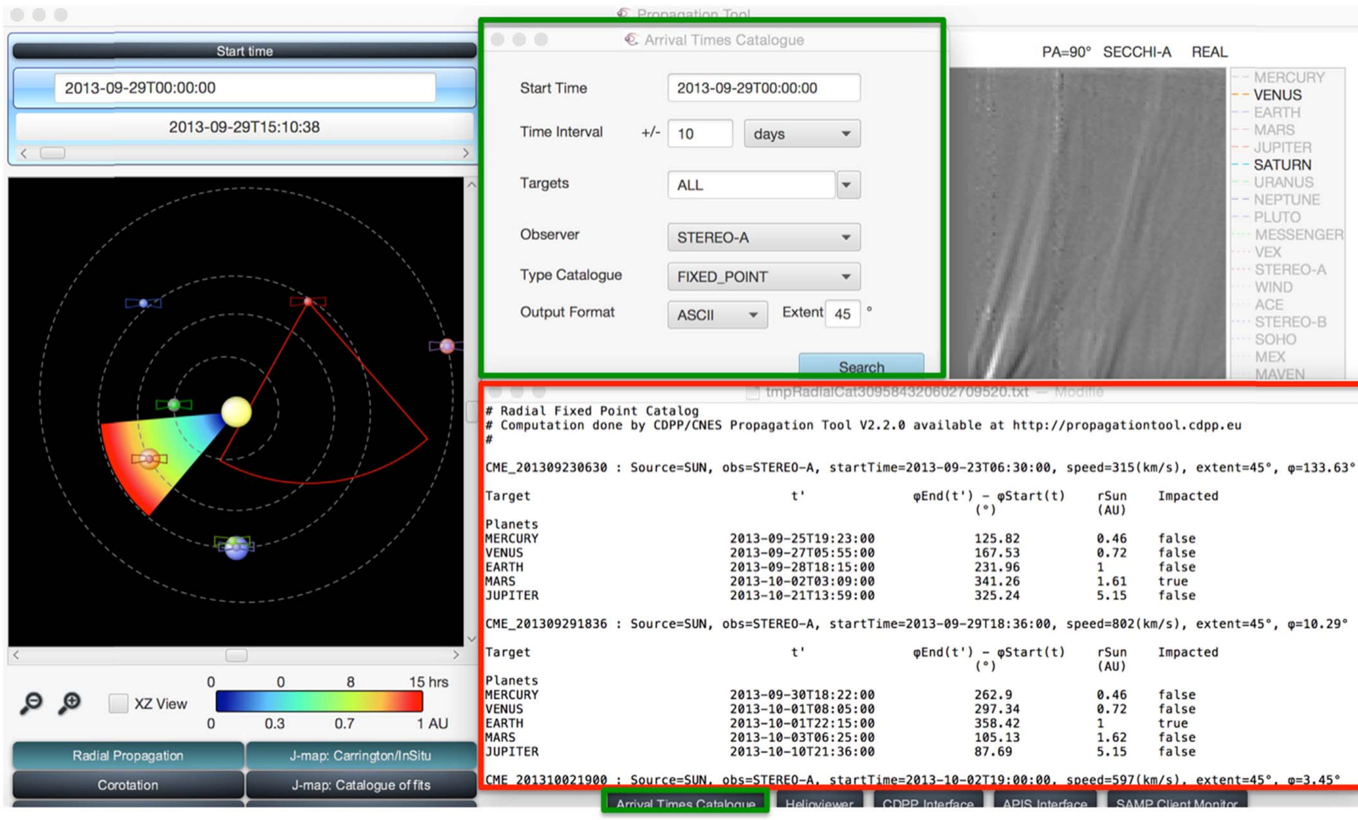


Fig. 6. Illustration of the new PSWS functionality implemented within the Propagation Tool and dedicated to the ingestion of catalogues of solar wind disturbances. These catalogues can be used to predict arrival times of each disturbance at various Solar System bodies and spacecraft. Green box: interface dedicated to the choice of catalogues based on STEREO-A, STEREO-B, and SOHO observations. Red box: output of the query showing which planet is impacted (true) by a particular Coronal Mass Ejection (CME) from the chosen catalogue during the user-defined time period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

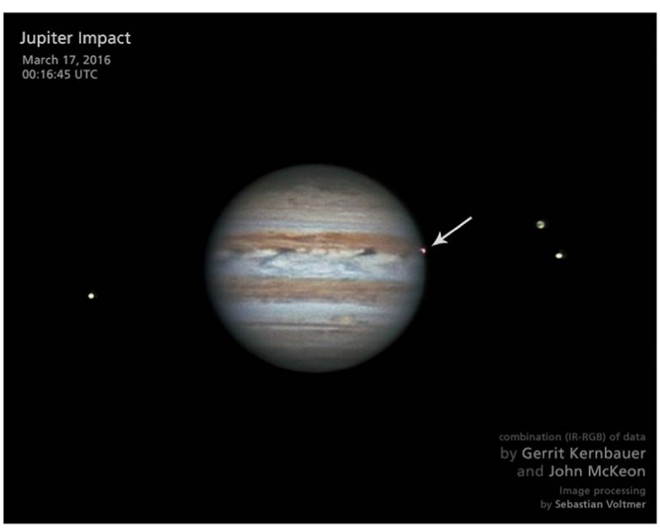


Fig. 7. 2016 March 17th fireball captured by Gerrit Kernbauer and John McKeon. Image processed by Sebastian Voltmer. Credit: G. Kernbauer, J. McKeon, S. Voltmer.

heliospheric images along the ecliptic planes and stacking them vertically (along the ordinate) with time (along the abscissae).

4.3. Extensions of the Propagation Tool to catalogues of solar wind disturbances

The advent of wide-angle imaging of the inner heliosphere has revolutionised the study of the solar wind and, in particular, transient solar wind structures such as Coronal Mass Ejections (CMEs) and Co-rotating Interaction Regions (CIRs). With Heliospheric Imaging came the unique ability to track the evolution of these features as they propagate throughout the heliosphere. The FP7 project HELCATS (HELiospheric Cataloguing, Analysis, and Technique Service, https://www.helcats-fp7.eu/) aims to producing a definitive catalogue of CMEs imaged by the Heliospheric Imager (HI) instruments onboard the NASA STEREO spacecraft. Outputs of HELCATS Work Packages 3 (CME KINEMATICS Catalogue) and 5 (STEREO SIR/CIR Catalogue) have been included in the CDPP Propagation Tool. This functionality is illustrated in Fig. 6 and will be extended to additional catalogues publicly available when possible.

4.4. Giant planet fireballs

Meteors impacting Jupiter's upper atmosphere can create spectacular fireballs. Relatively small objects left over from the formation of the solar system 4.5 billion years ago still hit Jupiter frequently. The resulting impacts are bright enough so that amateur astronomers can serendipitously detect them. Four fireballs were first reported by amateur astronomers in in 2010 (on June 3rd and on August 20th), 2012 (on September 10th) and in 2016 (on March 17th, Fig. 7) before to be detailed by professional astronomers following on the initial amateur observations (e.g., Hueso et al., 2010, 2013). Groups of amateurs worldwide have then coordinated efforts in order to obtain improved estimates of the number of small bodies around Jupiter and how they interact with the planet. Dramatic impacts with Jupiter can indeed be captured with standard amateur equipment and analysed with easy-to-use software. Within PSWS, such software (http://pvol2.ehu.eus/psws/jovian_impacts/) will be further enhanced in order to improve their usability and reach an even wider participation by amateurs. It will be connected to the Planetary Virtual Observatory

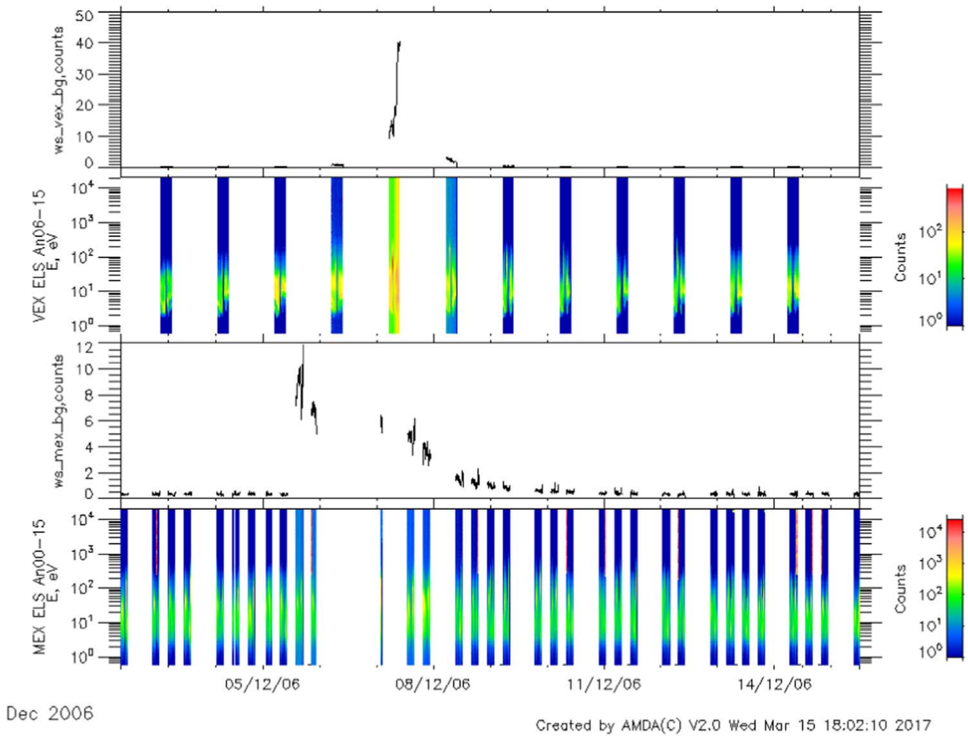


Fig. 8. Venus Express (VEX) and Mars Express (MEX) Electron Spectrometer (ELS) observations in December 2006. Time series of electron background derived from the higher energy channel of VEX ELS (first panel), VEX ELS energy-time spectrogram of electron counts (second panel), time series of electron background derived from the higher energy channel of MEX ELS (third panel), MEX ELS energy-time spectrogram of electron counts (fourth panel). A Solar Energetic Particle event has been reported to have impacted both spacecraft and saturated the plasma sensors to very high background (Futaana et al., 2008).

and Laboratory (PVOL, Hueso et al., this issue) that provides a searchable database of ground-based amateur observations of solar system planets (http://pvol2.ehu.eus/pvol2/).

5. Conclusions

Planetary Space Weather Services (PSWS) within the Europlanet H2020 Research Infrastructure are currently developed following protocols and standards available in Astrophysical, Solar Physics and Planetary Science Virtual Observatories (VO). Several VO-compliant functionalities already implemented in various tools as well as in development have been described in the present paper. We aimed at showing how planetary space weather can benefit from the VO. The proposed Planetary Space Weather Services will be accessible to the research community, amateur astronomers as well as to space agencies and industrial partners planning for space missions dedicated in particular to the following key planetary environments: Mars, in support of NASA's MAVEN and ESA's Mars Express and ExoMars missions; comets, building on the outstanding success of the ESA Rosetta mission; and outer planets, in preparation for the ESA JUpiter ICy moon Explorer (JUICE). These services will also be augmented by the future Solar Orbiter and BepiColombo observations. This new facility will be operational in late 2017. It will not only have an impact on planetary space missions but will also allow the hardness of spacecraft and their components to be evaluated under variety of known conditions, particularly radiation conditions (e.g., against Solar Energetic Particle (SEP) events whose propagation is modelled in the CDPP Propagation Tool), extending their knownflight-worthiness for terrestrial applications. Radiation effects on spacecraft instruments, represent the major technological impact of planetary space weather. Very intense solar events can lead to either a partial or a complete failure of the detection systems on board (e.g., the radiation detector of the Mars Radiation Environment Experiment (MARIE) on-board Mars Odyssey was presumed to have failed due to damage from the unusually intense SEP events of October–November 2003, see Plainaki et al. (2016) for other dramatic examples including the one displayed on Fig. 8).

In addition to their connections with the Virtual Observatory, the Planetary Space Weather Services developed within the Europlanet H2020 Research Infrastructure will be strongly linked to the space weather services developed within the ESA's Space Situational Awareness programme (http://swe.ssa.esa.int/heliospheric-weather). Connections with the CCMC (Community Coordinated Modelling Centre, http://ccmc.gsfc.nasa.gov/) in the United States will also be studied in the future.

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