HELIO, a powerful tool for Space Weather Science

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ABSTRACT

HELIO is a project funded under Framework Program 7 of the European Commission. Thirteen partners were involved in it during forty two months, from June 2009 to November 2012.

HELIO is a service-oriented tool that aims at providing a new way to query and access data, and provide added values to the data. It can be mainly accessed through a global web interface (http://hfe.helio-vo.eu/Helio/), which provides a unique and simplified access to most of the services, or individually to each of them (http://www.helio-vo.eu/services/service_interfaces.php). Advanced use is possible using IDL software to connect to the services, or using a workflow method. The communication between services is based as often as possible on

IVOA (International Virtual Observatory Alliance) standards, when they fit heliophysics descriptions.

HELIO gives access to observations from more than 200 instruments from more than 60 observatories in the world, and to 60 catalogues of heliophysics events, scattered all around the world and in space. A Heliophysics Feature Catalogue (HFC) provides a description of 10 features over at least a solar cycle for most of them. A ballistic propagation model allows to connect phenomena through the whole solar system, onwards and backwards.

HELIO makes it possible to select instruments by capabilities or by location and target, and a data query can be related to heliospheric phenomena. This powerful tool is then very appropriate for the study of the Solar-Terrestrial relationship.

Note that this paper gives a description of HELIO at the date of October the 13th, 2013.

Key words. Sun – heliopshere – data access - virtual observatory – Sun-Earth connection

1. Introduction

Several tools are available to enhance the efficiency of data query in the domain of heliophysics. Some of them provide a wide access to scattered data, others help to visualize the context of the Sun at a given date, some help in data mining. Among the many available, here are some which are used or connected in some way to HELIO:

- Virtual Solar Observatory, VSO (http://vso.nascom.nasa.gov/) is a tool to query and access data which is used in HELIO to access a number of Solar datasets.
- Heliophysics Events Knowledgebase, HEK (http://www.lmsal.com/hek/), developed in support to Solar Dynamics Observatory (SDO) gives an overview of the features and events that have been observed on the Sun (see Hurlburt et al., 2012). Some of the codes used for automatic detection have been written in common between HELIO and HEK.
- Automated Multi Dataset Analysis, AMDA (http://cdpp-amda.cesr.fr/) is used to perform data mining on plasma space physics data (see Jacquey et al., 2010 and Génot et al, 2010).

Besides, the International Virtual Observatory Alliance, IVOA (http://www.ivoa.net/) has defined recommendations and standards to describe data. It is oriented towards astronomy, and, in several cases, cannot be applied directly to heliophysics, but some standards are wide enough to be of use. It is very important to be as close as possible to these standards, as it's the most efficient way to ensure interoperability between applications, as well as data exchanges.
For instance, HEK use the VOEvent format (http://www.ivoa.net/documents/VOEvent/20110711/) to describe features and events. The format used to exchange information between HELIO services follows the IVOA VOTable standard (http://www.ivoa.net/documents/VOTable/20091130/) and a registry describes HELIO content in the same way as an IVOA registry.

In Section 2, we explain what is HELIO and describe the way it is organized. Section 3 shows the various possible ways to query data and to exchange information between services. Some examples of the science that can be done with HELIO are detailed in Section 4, and we conclude in Section 5 on the efficiency of HELIO for performing space weather studies.

2. HELIO description

HELIO is built by a consortium of science laboratories (see Table 1) involved in solar, plasma physics as well as computer science. This mix ensures that developments use the most recent software developments in direct connexion with physics needs. This is fundamental to obtain a tool that is both efficient and user-friendly. Some global overview of HELIO can be found in Bentley, Csillaghy and Aboudarham (2009 and 2010a), in Bentley et al. (2010b) and in Aboudarham, Bentley and Csillaghy (2012).

The most obvious way to use HELIO is to use its main interface, which is described in detail in Section 3. In a very easy-to-learn manner, HELIO performs the following:

– Search for existing data from numerous data sets, using the usual (date-based) as well as unusual (event-based, solar system location, ...) query systems. That way, users can discover data unknown to them

– Search for events in various parts of the solar system

– Connect events in the solar system forwards and backwards to the Sun

– Perform data mining in heliospheric plasma data

– Have an overview of the solar or heliospheric context at a given time

– Automate complex queries to apply to huge datasets using workflows

Table 1. HELIO partners. SP = Solar Physics; PP = Plasma Physics; CS = Computer Science

Short name	**Long name**	**Country**	**SP**	**PP**	**CS**
UCL	University College London, Mullard Space Science Laboratory	UK	X	X	
FHNW	Fachhochschule Nordwestschweiz	Switzerland	X		X
OBSPARIS	Observatoire de Paris	France	X	X	
UPST	Université Paul Sabatier Toulouse III	France		X	
STFC	Science and Technology Facilities Council	UK		X	
UPS	Université Paris-Sud XI	France	X		
INAF	Istituto Nazionale di Astrofisica, Astronomical Observatory of Trieste	Italy	X		
UNIMAN	University of Manchester	UK			X
TCD	The Provost Fellows and Scholars of the College of the Unidivided Trinity of Queen Elizabeth near Dublin	Ireland	X		X
NASA-HSD	National Aeronautics and Space Administration, Heliophysics Science Division	USA	X	X	
RPI	Rensselaer Polytechnic Institute	USA	X	X	X
LMATC	Lockheed Martin Space Systems Company	USA	X	X	
ESA	European Space Agency	Europe	X		

2.1. Services

A very short description of each service is given in Table 2. Details can be found in the following subsections. Several other services exist in HELIO, but cannot be accessed directly, such as Coordinate Transformation Service.

The services can be grouped according to their use:

1. First, the HELIO Registry Service provides a complete description of HELIO services, compatible with IVOA standards.
2. A set of services provides help on data query:
   Instrument Capabilities Service, Instrument Location Service and Context Service.
3. A set of services that access data:
   Unified Observing Catalogue (helps also on data query) and Data Provider Access Service
4. A set of added value services:
   Heliophysics Event Catalogue, Data Evaluation Service, Heliophysics Feature Catalogue

We made a distinction between ’event’ and ’feature’, assuming that an event is a transient phenomenon and a feature, a long duration one. For instance, a filament is a feature, but its disappearance is an event. i.e. an event occurs at a given time while a feature can last for several days, or even Sun’s rotations.

Table 2. List and rough description of HELIO services

Acronym	**Name**	**Short description**
HRS	HELIO Registry Service	Complete description of HELIO services, based on IVOA standards
ICS	Instrument Capabilities Service	Describes the type of observations made by instruments and characteristics of observatories
ILS	Instrument Location Service	Contains the location of planets and spacecraft in the solar system
CXS	Context Service	Generates different types of plots to assist the user
UOC	Unified Observing Catalogue	Provides information on targets of observations and information about availability of data
DPAS	Data Provider Access Service	Gives direct access to data
HEC	Heliophysics Event Catalogue	Contains a variety of event lists accessible through a unique portal
DES	Data Evaluation Service	Tool for the data mining of in-situ data
HFC	Heliophysics Feature Catalogue	Contains detailed information about various solar and heliospheric features

2.1.1. HELIO Registry Service

HELIO Registry Service (HRS) complies with IVOA recommendations. The goal of a registry is to be able to locate resources, get details on them and so be able to use them, based on the information provided by the registry. It allows appropriate tools to retrieve useful information automatically. IVOA Registry Interfaces are defined in a document by Benson et al. (2009). Our service is built according to IVOA recommendations and then can be understood by any astronomical VO tool able to read a registry. HRS is available at: http://registry.helio-vo.eu/helio_registry/

2.1.2. Instrument Capabilities Service

Instrument Capabilities Service, ICS (http://www.helio-vo.eu/services/interfaces/helio-ics_uix.php) describes the types of observations that can be made by the instruments accessed by HELIO. This is a way for the user to look for existing instruments by searching them by observing domain, entity, or keywords.

2.1.3. Instrument Location Service

Instrument Location Service, ILS (http://www.helio-vo.eu/services/interfaces/helio-ils_uix.php) provides a way to look for instruments available at a given place of the Solar System in a given time interval.

2.1.4. Context Service

The Context Service, CXS (http://www.helio-vo.eu/services/interfaces/helio-cxs_uix.php) is used to generate different types of plots to assist the user, providing a background of the Sun and Heliosphere at the date the user is looking at. The plots available are the GEOS lightcurves, flare locations, and the Parker spiral. It is also possible to look at various movies from the NASA-GSFC CDAW Movie Generator (http://cdaw.gsfc.nasa.gov).

2.1.5. Unified Observing Catalogue

Unified Observing Catalogue, UOC (http://www.helio-vo.eu/services/interfaces/helio-uoc_uix.php) is a dual-purpose interface which allows users, on one hand, to find information about observations of the Sun made by instruments with restricted fields-of-view, and, on the other hand, to give access to complex archive interfaces.

2.1.6. Data Provider Access Service

Data Provider Access Service, DPAS (http://www.helio-vo.eu/services/interfaces/helio-dpas_uix.php) provides integrated access to observations from 210 different instruments. This service is used to access data.

2.1.7. Heliophysics Event Catalogue

Heliophysics Event Catalogue, HEC (http://hec.helio-vo.eu/hec/) brings together a varity of lists produced by a number of different organizations. At the date of this paper, HEC gives access to nearly 70 catalogues of heliospheric events, concerning CMEs, flares, solar wind or particles. More information about each list and the parameters it provides can be found using an ”Info” button.

2.1.8. Data Evaluation Service

Data Evaluation Service, DES (http://manunja.cesr.fr/Amda-Helio/) allows specific data mining in plasma in-situ observations to be carried out. This tool is derived from the AMDA (Automated Multi Dataset Analysis) tool (see http://cdpp-amda.cesr.fr/ for detailed information).

2.1.9. Heliophysics Feature Catalogue

Heliophysics Feature Catalogue, HFC (http://hfc.helio-vo.eu/hfc-gui/) holds information derived by using automatic feature recognition codes on observations at various wavelengths. The features currently available are filaments, coronal holes, active regions, sunspots, type III radio bursts and metric radio sources.
Description of some of the codes used to populate HFC can be found in Fuller et al. (2005) and Bonnin et al. (2013) for filaments; Krista and Gallagher (2009) and Barra et al. (2009) for coronal holes; Higgins et al. (2009) and Barra et al. (2009) for Active regions; and Zharkov et al. (2005) for sunspots.
As HFC is often used by itself, and not in conjunction with data query, it is not included in the HELIO Front End. But communication is possible between the two interfaces by saving or downloading VOTable files.

2.2. Workflows

Workflows give an automated way to make repetitive complex queries. It is an easy way to perform them once each elementary brick is defined. A complete description of the way to use workflows in heliophysics is given in Leblanc et al. (2013). In HELIO, workflows are based on the Taverna workbench (http://www.taverna.org.uk/introduction/related-projects/helio/) and several more or less complex workflows can be obtained and used there.

2.3. IDL use of HELIO

A branch of IDL SolarSoft (http://www.helio-vo.eu/documents/help/ssw/helio_installing_software.html) allows direct access to some HELIO services through IDL codes. A wide set of pre-defined routines and examples helps users to build their own code.

3. HELIO Front End

HELIO Front End (HFE), available at http://hfe.helio-vo.eu/Helio/, is a centralized Graphical User Interface (GUI) that allows the user to access most of the HELIO services through a single interface. It provides a non-hierarchical way to search for data, even if it's not known *a priori* by the user.
HFE is a non linear GUI where users can build queries in their most convenient way. Parts of queries can be exchanged between the various components of HFE as well as parts of results, allowing queries to be chained together and direct them toward*s the most precise way to look for data.

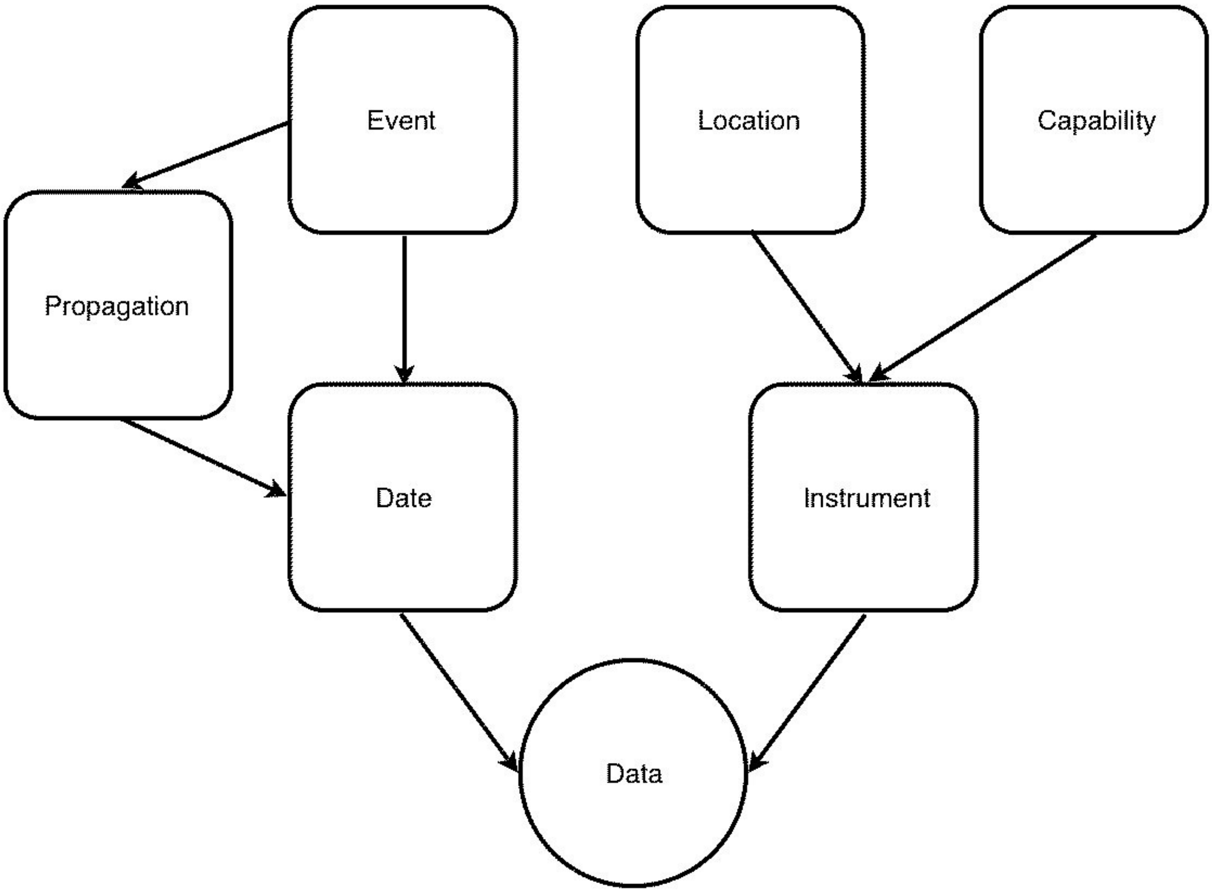

Fig. 1. Simplified diagram showing the various ways to access data

A 'data cart' can be used to keep basic elements from each query, as well as time information from some results, in order to be able to re-use them in different searches.
Fig. 1 shows various way to build a query and access data. Users can begin their query at various levels, depending on the knowledge they have of available data. In the following subsections, we shall detail some of the most common ways to access observations.

3.1. Date and data query

This is probably the most familiar way to build a query: Users select a time interval then, from the instrument list they select from a series of interesting datasets, and submit the query. A list of results is proposed, ordered by instrument, as showed in Fig. 2. From this list, it is possible either to use the *URL* to download observations, or group them to make a global download, or else to select some of the results to keep the time information for a further query. It is also possible to export the result of the query in a VOTable format (xml-based) in order to process it using external applications.

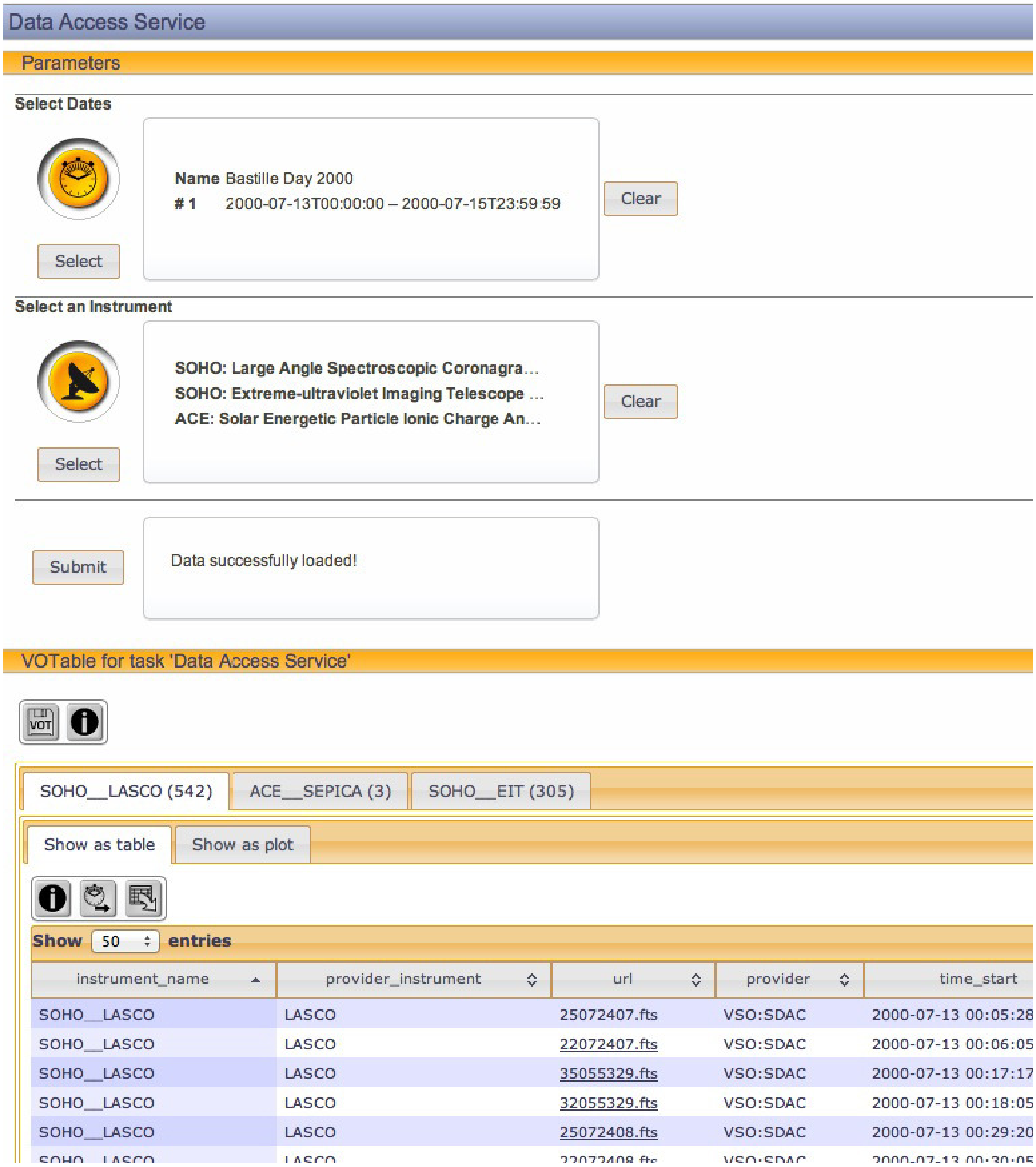

Fig. 2. Example of a basic query by date and instrument.

3.2. Query by event

The possibility of driving a query based on an event selection is probably the most original query option proposed by HELIO. Especially in Space Weather applications, it is common to look for specific events occurring in some places of the solar system. HELIO currently gives access to nearly seventy catalogues scattered all around the world. That way, users can look for a specific event, in a given place of the solar system, using appropriate catalogues. But the most powerful way to use event query is in conjunction with the propagation model (section 3.4). Users can select an event

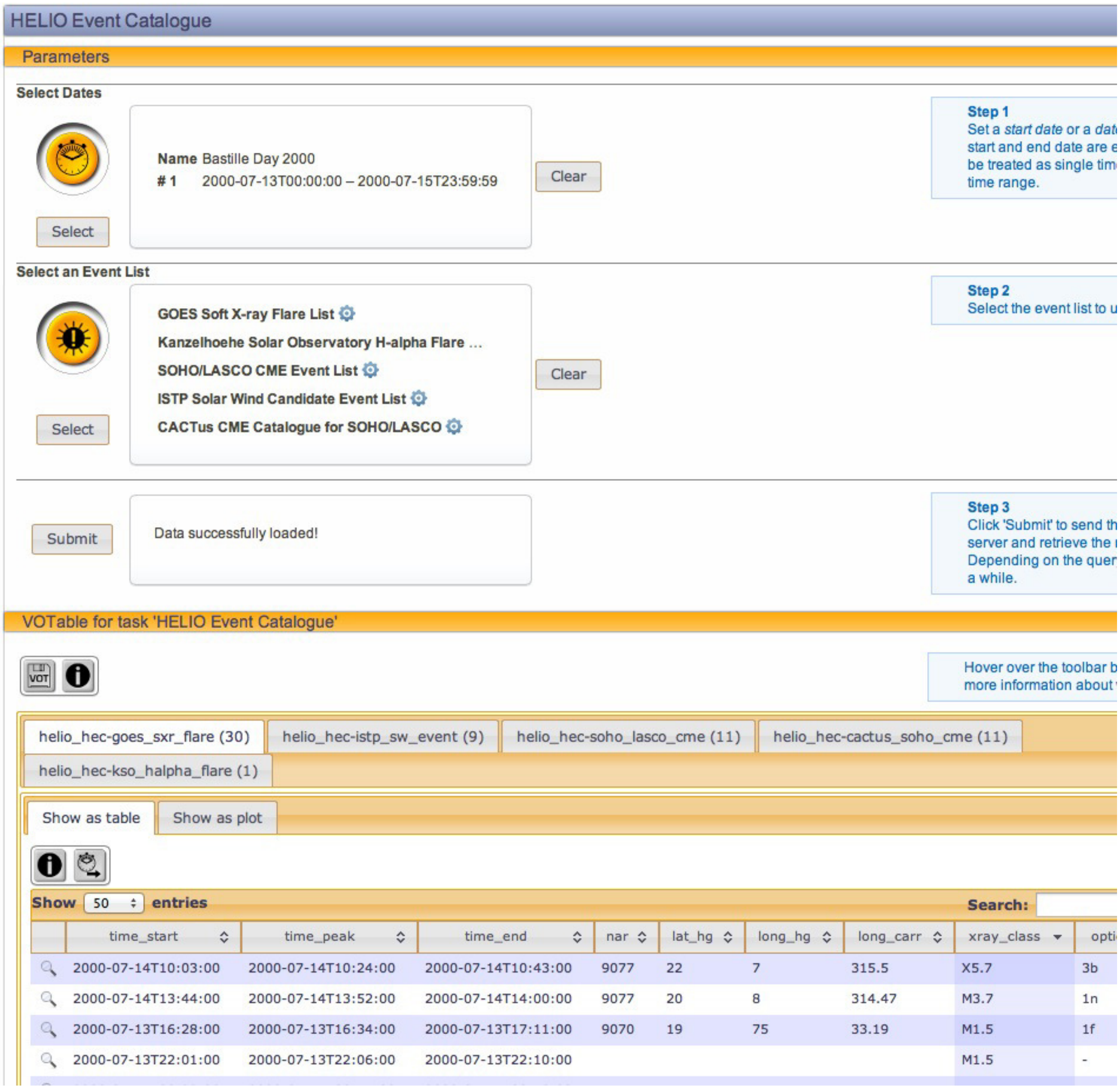

Fig. 3. Example of a basic query by date and event

at some place in the solar system, estimate the arrival time of the propagating event at another place, and look for events at this new place. It is possible, in this way, to follow a space weather phenomenon during the whole of its propagation from the Sun to planets or probes, as well as to find the solar origin of a planetary event.

3.3. Look for instruments

It is common not to be aware of all instruments available at a given time, and not knowing what data can be used is an important factor in making a space weather study difficult.. HELIO gives access to an instrument query where users can choose the characteristics of the instruments they need. In practice, this means that users can select a time interval first, and then search for instruments having given characteristics. These characteristics are the Observing Domain (region of the solar system or of the solar/planetary environment), Instrument Type (remote or in-situ), Observable Entity (kind

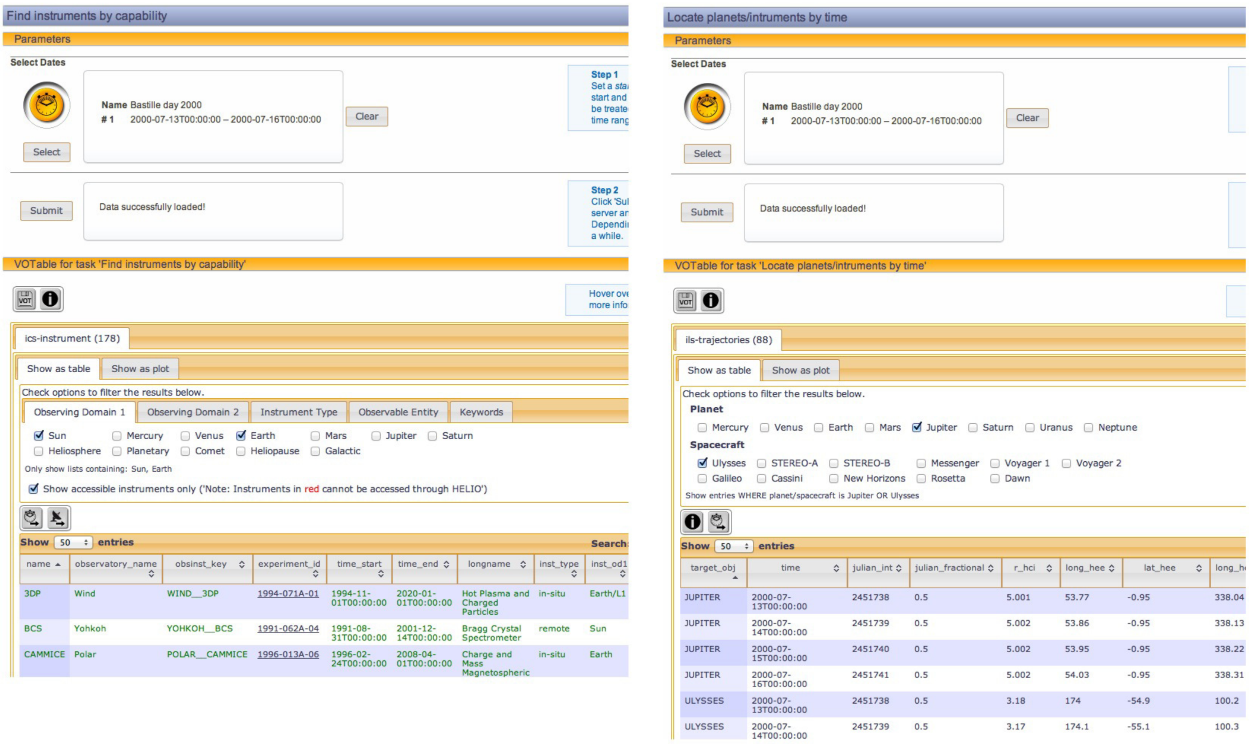

Fig. 4. Example of a instrument query. Left panel shows a query for available instrument corresponding to users' needs. Right panel show planets and spacecraft locations at a given date.

of photons, of particles, or of fields), as well as some keywords describing the generic kind of instrument.

The other way to select instruments or spatial probes consists of using the location search option of HELIO, which gives the position of planets and spacecraft at a given time. It is then possible, for instance, to know which probe may provide observations at a given place in the solar system.

Using these HELIO capabilities (obtained under 'Search' menu) allows the users to focus on the specific instruments corresponding exactly to their needs.

3.4. Propagation model

The propagation model used in HELIO can be used as a standalone service at http://cagnode58.cs.tcd.ie:8080/PropagationModelGUI/. But it is also available through the HFE in order to be able to link phenomena at various places of the solar system. The propagation model is a ballistic one. Its goal is not to provide the best possible estimation of the propagation of a phenomenon, but to give a very fast idea of the approximate time of arrival of an event (or of its origin). The HELIO propagation model (see Fig. 5) calculates the propagation of: coronal mass ejections, solar wind (co-rotating interaction regions) and solar energetic particles. It works either starting from the Sun or backwards towards the Sun starting from any planet or major space probes..

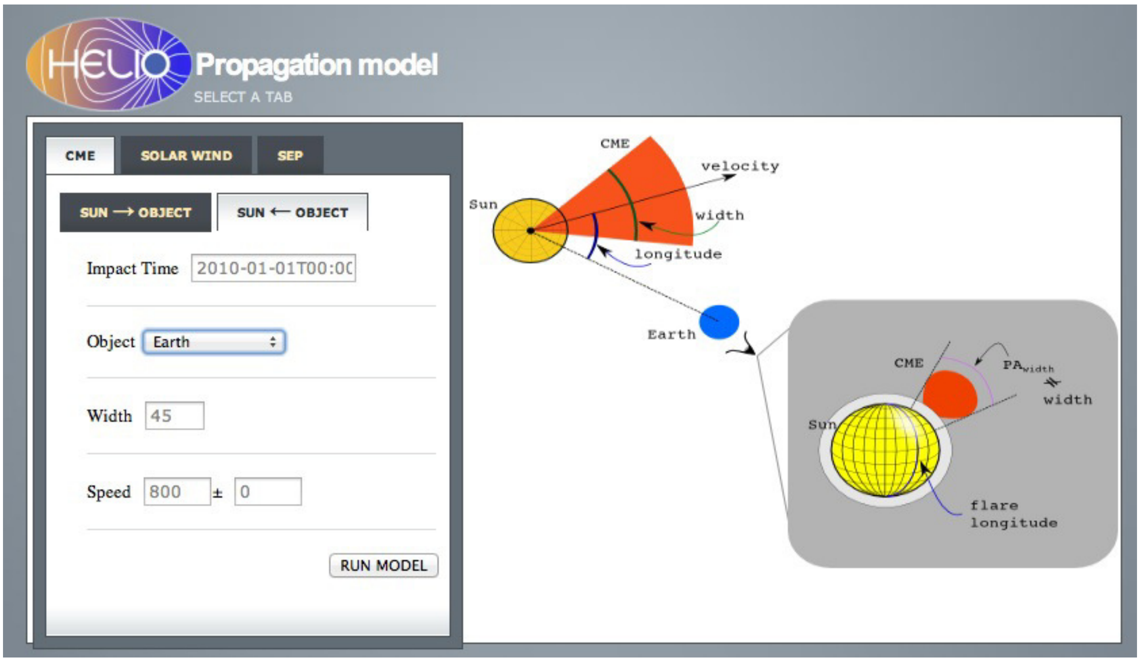

Fig. 5. HELIO propagation model positioned for finding the solar origin of a CME detected at Earth.

4. Science with HELIO

HELIO is very effective at connecting events from various places of the solar system. From any event observed somewhere in the solar system, it is possible to look for other counterparts of it elsewhere using the HELIO propagation model providing a full description of propagating phenomena. Some use cases have been presented in Perez et al. (2012). In this section, we shall summarize the most common science objectives HELIO can address.

4.1. Follow a solar event through the heliosphere

Falkenberg et al. (2011) studied the effect of a coronal mass ejection which occurred on the 17th of November, 2001. By conducting an event search in HELIO, we find that it has been detected by CACTUS (`http://sidc.oma.be/products/cactus/`) as a halo CME. From the HELIO propagation model for a CME, we find that this event should have reach Earth around the 19th of November, 20:00, and Mars around the 21st of November, 7:00. As seen in Fig. 6, a shock was detected by ACE at Earth. It appears also at Mars in the Mars-Earth Interplanetary CME list given by the authors of this paper on the 20th of November, at 3:35, which is within the error bars of the propagation model.
Such catalogues, accessed through HELIO, enrich strongly the possibility of following events through the solar system. Moreover, the context information, which is accessible through the GUI can provide additional information to aid the search process. For example, when looking at SOHO/LASCO images, the time that particles reach the LASCO detector can be deduced from the very strong noise it generates, thus giving the arrival time at the Lagrangian L1 position.

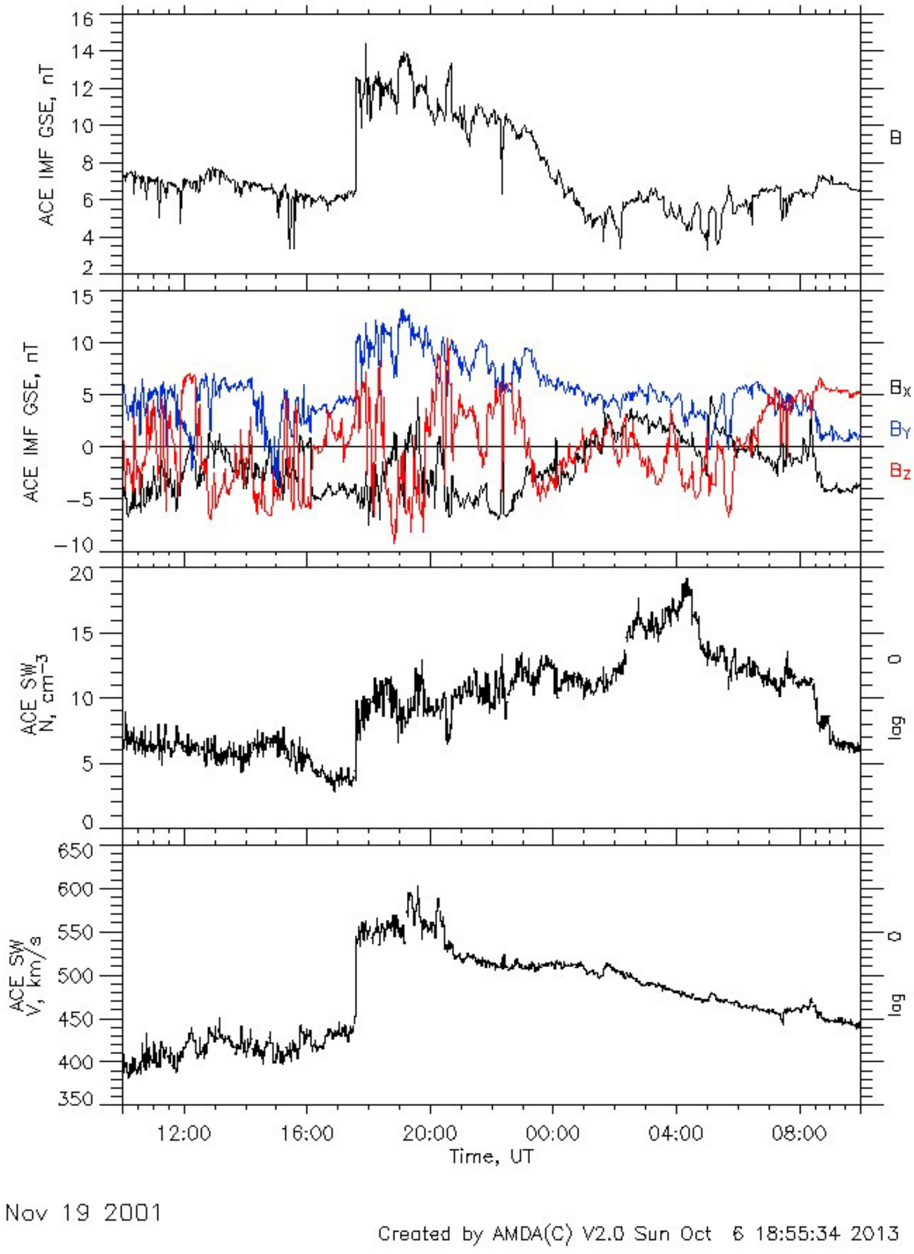

Fig. 6. ACE observations at Earth between 19th and 20th of November 2001.

4.2. From a planet, back to the Sun

In Lamy et al. (2012), the authors look for the origin of Uranus' aurorae. They focus on an aurora observed on Uranus by the Hubble Space Telescope in the far Ultraviolet during the second half of November 2011. They related those observations to Jupiter non-Io auroral emission observed on dynamic spectra obtained with STEREO A/WAVES radio observations at the end of

September/beginning of October. On the 27th of September, the NOAA Auroral power measurement at Earth shows a peak that can be associated to a CME, observed with STEREO-A, which occurred on the Sun on the 24th of September.
The long process followed by the authors to find and access data can be done without leaving the HELIO Front End. Indeed, from the Uranus aurora observation, it is possible to run the CME propagation model backwards and find dates that are compatible with those found by the authors. As the STEREO and WIND data used to identify the fly by of the CME at Earth and Jupiter are accessible through HELIO, it would have been possible to retrieve the data directly. Note that unfortunately, HST observations of Uranus are not currently available using HELIO. But one can imagine that eventually the APIS (Auroral Planetary Imaging Spectroscopy, http://lesia.obspm.fr/apis/) database could be connected to HELIO.

4.3. Statistics

Many statistical studies can be performed using HELIO, due to its provision of automated searching. The most obvious studies concern the use of the HFC, where the behaviour of features can be analyzed during one solar cycle, as well as the connection between the evolution of features. Another way to build a statistical study of the solar system phenomena consists in using the workflow to find events that could be connected in various parts of the solar system. This could be done looking for solar events, running the propagation model, and looking at various data sets (at Earth and in planetary environments) if a counterpart exists around the arrival time. Even if the ability to use the workflow needs some training, once the elementary bricks of the workflow are put together, hundreds of cases can be analyzed automatically, thus providing a list of events of interest.

5. Conclusions

HELIO provides a tool which is much more that a data access interface. It provides an easy way to:

- search for existing data corresponding to specific needs,
- connect events throughout the solar system,
- obtain timeline plots from various probes, and to use visualization to determine precisely the arrival time of a shock,
- combine event lists,
- build queries directly from IDL software,
- build workflows for long and repetitive actions,

and finally to retrieve data for processing!
Many of the studies published, which follow events propagating from the Sun to various parts of the solar system could now be done within the HELIO Front End. This does not imply that it is easy to search for propagating events, since effort and skill are required to build the searches. However users no longer need to scan tens of databases in the hope of finding appropriate data, and can even take benefit from datasets previously unknown to them. The possibility to build workflows offers

the prospect of automating complex queries thus releasing large amounts of researcher's time which can be better employed in understanding the results of the queries and in generating new research questions.
Another interesting capability, developed in HELIO, but not described in this paper, concerns the building of the basis of a heliophysics data model (see HELIO web site for more details: http://www.helio-vo.eu/) that can be more widely used and extended. The European project CASSIS, a Coordinated Action (Grant Agreement 261618), extends the work of HELIO by bringing together solar, heliospheric and planetology data.

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