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Access, Discovery and Interoperability of Multi-wavelength/multi-messenger Data

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Collaboration between European teams to build the astronomical Virtual Observatory has been funded by the European Commission though a series of projects which, between 2001 and 2014, were centred on collaborative work between European teams to develop the Virtual Observatory (VO) interoperability framework. The ASTERICS cluster was a new stage for the European Virtual Observatory: the VO was identified as one possible synergy within the cluster aim "to address cross-cutting synergies and common challenges shared by the Astronomy and Astroparticle ESFRI facilities". That synergy was addressed by ASTERICS WP4, focused on *Data Access, Discovery and Interoperability*. The Work Package fully met its aims to build a collaboration between VO teams and the teams from the large ESFRI and ESFRI-like facilities, to support the community in the scientific usage of the VO, and to enable technological development of VO standards and tools customized to the facility needs. The facilities use the VO standards and tools for their own needs, and some of their staff have become actors in the development of the Virtual Observatory.

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1. Introduction

Astronomy has been at the forefront of Open Science, by developing a common format, FITS, and a global disciplinary data sharing framework, the astronomical Virtual Observatory (VO), which allow all astronomers to find, access, interoperate and reuse data, as summarized by the so-called FAIR principles (Wilkinson et al., 2016). A series of projects funded by the European Commission supported the coordination of Virtual Observatory activities in Europe (Genova at al., 2015). At the start of ASTERICS in 2015, the Virtual Observatory had been operational for years, with more than 100 "authorities" providing resources and widely used tools such as Aladin/AladinLite, TOPCAT and VOSA taking advantage of it.

Space and ground-based observatories had been involved from the beginning in the Virtual Observatory endeavour as developers participating in the definition of the VO standards and/or users providing their requirements and/or giving access to their data in the VO. ASTERICS was the occasion to build a closer relationship with large ESFRI and ESFRI-like facilities, and moreover to include the astroparticle physics community, which is evolving from the development of experiments such as HESS or MAGIC to the implementation of observatories such as CTA. ASTERICS Work Package 4, *Data Access, Discovery and Interoperability* (DADI), included VO teams from France, Germany, Italy, Spain and UK, and teams working on CTA, EGO-VIRGO, KM3Net, SKA and their pathfinders. ESO (ELT) was associated to ASTERICS, and ESA continues to be an active participant in the VO development in close collaboration with the other European VO teams. EST joined the project in 2018. A large palette of wavelengths and messengers was thus represented. The aim was to optimize the scientific usage of data from the future large projects, and to make them active participants in the VO development.

2. DADI activities

DADI activities covered the three pillars identified for a successful VO development:

- Support to science usage, which includes gathering end-user requirements, in particular through Schools aimed at early career researchers;
- Support to data providers, which also includes gathering their requirements – the target was mainly ESFRI and ESFRI-like projects but two events were aimed at the general European astronomical data provider community;
- Technological work to update the Virtual Observatory standards and tools, this work being coordinated at the international level by the International Virtual Observatory Alliance (IVOA).

3. DADI highlights and legacy

DADI has indeed enabled the initial Euro-VO partners to continue their collaborations, but it has also built collaborations between these VO-knowledgeable teams and teams from the large facilities and their pathfinders, both in astronomy and in astroparticle physics. The VO and facility teams worked together on brainstorming on requirements, and feedback on the VO standards and tools. Several facilities have been using VO standards and tools for their own needs, and they also became actors of the development of the VO. One can cite as examples of the impact of the VO for the facilities the inclusion of 5921 events from ANTARES, one of KM3Net pathfinders, in the GAVO data centre, a test case for KM3Net; the active participation of CTA in the definition of the IVOA model for Provenance, and the inclusion of the model in CTA data management system

to define Provenance Configuration; the development of the GWSky (http://www.virgo-gw.eu/skymap.html) tool, based on VO standards and tools, to define the follow-up strategy of gravitational wave events; and the implementation of VO standards in the new ESO programmatic interface (Romaniello et al, 2018), and the possible reuse of VO building blocks when relevant in the implementation strategy of the ESO Archive Services.

Building collaboration between astronomy and astroparticle in ASTERICS was particularly timely, with the first observations of gravitational waves, including one with electromagnetic counterparts, triggering a new era for multi-messenger astronomy during the project. VO tools were used to display the location of GW170814 in the press release.

Highlights also include the successful Schools and their tutorials, and the development of IVOA standards and tools used for multi-wavelength and multi-messenger astronomy. One can cite a standards suite to deal with multi-dimensional data; significant advances of the VO time domain standards; the completion of the HiPS sky tessellation standard, and its widespread implementation; the development of a standard for Provenance in collaboration between CTA and VO teams.

4. Conclusion

The ASTERICS *Data Access, Discovery and Interoperability* Work Package has met a full success in demonstrating that the Virtual Observatory is a powerful synergy field for the ESFRIs and other large facilities and in bridging the astronomical Virtual Observatory with the astroparticle physics community, and then the solar physics one. The next step is to interface the Virtual Observatory framework with the European Science Cloud, which will be the aim of the *Connecting ESFRI projects to EOSC through VO framework* Work Package of the ESCAPE Cluster.

References

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