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Science with the help of the Virtual Observatory

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Abstract

Ground-based observatories and space-based surveys generate terabytes of data that are publicly available for the astronomical community. Considering the large volume of heterogeneous data that is distributed, which has exponentially increased over the past years, the Virtual Observatory (VO) initiative was created to ensure an optimum scientific data exploitation under FAIR principles, where all data are easily Findable, Accessible, Interoperable, and Reusable. VO services and tools are frequently used for a wide range of scientific cases, where the analysis of multi-wavelength, multi-epoch data is needed, accounting for thousands of peer-reviewed papers making use of these facilites. In this talk, the role of the Spanish Virtual Observatory (SVO) group on supporting the scientific community will be detailed, from the exploitation of archival data to training activities aimed to expose astronomers to the available VO tools and services and ensure an efficient use in their own research.

1 Introduction

More and more frequently, new scientific discoveries rely on the methods and focus of data exploration within scientific records, rather than on acquiring new data. Historically, astronomical archives were built independently, without consideration for accessible, interoperable access. Searching for concurrent data was typically a slow and inefficient process. Most of the times, the simultaneous query to multiple databases was done slowly, in a difficult and inefficient way.

Nowadays, particularly with support from the Virtual Observatory, this scenario has changed significantly, allowing everyone to access multi-wavelength data from both space-based and ground-based telescopes. So, what exactly is the Virtual Observatory? In addition to being a goldmine of data, it is an initiative aimed at assisting astronomers in locating data of all kinds.

The VO has become a science driver in astronomy, particularly for those areas of research that require large-scale data analysis. VO projects range from establishing standards to make data interoperable to creating tools and services that help advance scientific research. After its initial phase focused on technical development, for over a decade, the VO is being regularly used by the scientific community.

The International Virtual Observatory Alliance (IVOA) was established in 2002 to enable international coordination and collaboration. It is structured into working groups that define VO standards, tools, and a roadmap, which serve as the foundation for VO projects and more. One of the reasons for the success of the VO initiative is that it has developed its standards based on the principles known as FAIR, where optimal exploitation is achieved by making data easy to find and access, and allowing them to be interoperable and reusable.

In 2004, the Spanish Virtual Observatory (SVO) project was created and this year it is celebrating its 20th anniversary. The SVO emerged as part of IVOA, unifying efforts to facilitate astronomical data access, processing, and analysis of multiple sources. Throughout the years, the SVO has developed multiple tools and services that follow international VO standards, for instance, the VO Sed Analyzer[1] (VOSA; [1]) and the Filter's Profile Service "Carlos Rodrigo"[2] (FPS; [5]), among other services.

In the following, the role of VO in the development of science will be described, along with the various strategies employed to engage the Astronomical community. A special highlight will be given to the contributions the SVO team has made in recent years.

2 Engaging the scientific community

The primary objective of the VO is to produce better science more efficiently. This objective was clearly defined by the IVOA, which established the Scientific Priorities Committee in 2009, recognizing that sustaining the role and impact that the VO has on science requires continuous commitment and dedication to the international astronomical community.

To accomplish this, and to ensure maximum exploitation of the resources that the VO has to offer, we must demonstrate to the community the benefits of working in a VO environment. Some of them are: The increased scientific return from data, the ability to discover, access, and combine different datasets, and the implementation of VO strategies when planning observations and new surveys.

The lack of familiarity with the VO poses a potential challenge that could limit the scientific impact. For instance, if the services developed by the VO are not scientifically oriented, they will not be used by the community. This is where the Scientific Priorities Committee plays a role: to create a connection between those who develop the services and tools and the scientific community.

There are several mechanisms adopted to encourage community usage of VO services. The four main approaches adopted by the IVOA members to promote community engagement are

[1] `http://svo2.cab.inta-csic.es/theory/vosa/`
[2] `http://svo2.cab.inta-csic.es/theory/fps/`

presented as follows:

- **Conferences**

  The first mechanism is participating in conferences and meetings. The presence of VO-related contributions in conferences like this gives visibility to the initiative and helps to connect the VO groups with the community. In particular, the SVO team's participation focuses on the disseminations of recent VO-science papers, highlighting the role of VO tools and services. In parallel to this, conferences are an excellent forum to promote discussions on the needs of the scientific community and how to improve the existing VO infrastructure.

  The SVO team is participating actively in conferences at national and international level. For instance, we organized the Special Session "Science with the Virtual Observatory: status, success cases, the future" that occurred during the annual meeting of the European Astronomical Society in 2022, in Poland. Also, among several national meetings, the group is frequently present at SEA meetings that happen every two years, having for instance 9 contributions in 2018 and 12 in 2020. This year's meeting, we organised a special session "20 years of science with the Virtual Observatory: a story of success (VL)", to foster collaboration and discussions.

- **Liaison with the community**

  The second mechanism is acting as a liaison with the community, since it is highly important to understand the scientific priorities and requirements that will lead to the development of new services, protocols, and tools by the IVOA and its members. These priorities are derived, for instance, from scientific cases developed in cooperation with the community. In addition, providing the necessary support for the creation of tutorials, workshops, and training materials is crucial.

  Since its creation, the SVO project has contributed significantly in bringing the VO to the local astronomical community, actively seeking collaboration with research groups that can benefit from VO methodologies. In addition to informing and supporting the community, it has also developed new tools and services. One notable example is VOSA ([1]), a widely used tool that was created within the context of these collaborations in 2008, counting with over 4600 users and over 14.6 million objects analysed. VOSA continues to be extensively utilized by the community, as evidenced by the fact that it has been cited in 478 papers to date. The SVO FPS ([5]), which is a repository of astronomical, Solar System and Earth observation photometric systems, has around 200 citations.

  Finally, it is also important to highlight the leading role that, for several years now, SVO is playing at an international level in the field of VO-science. This is demonstrated by the large number of VO-related papers that involve Spanish authors, with 131 publications from the total of 666 entries[3] that mention the Virtual Observatory in their abstracts, according to the SAO Astrophysics Data System[4] (ADS).

[3]These data were verified in January 2025.

[4]`https://ui.adsabs.harvard.edu`

- **VO schools**

  Training is considered a key element to ensure the adoption of the VO framework by the community. The VO schools organised in previous European and national VO initiatives have demonstrated to be the most effective instrument to engage the astronomical community towards the VO, showcasing its capabilities in terms of data discovery, access and analysis.

  The programme of the schools is structured around four main topics: Introduction to the VO, guided tutorials, use cases proposed by the participants, and feedback sessions. Different tutorials adapted to the participants' profile (beginners, intermediate, advanced) are usually offered.

  Since 2008, the SVO have organised 11 VO European schools, 22 national schools, and one Latin American school, with hundreds of participants. All the details concerning the SVO schools and its impact are presented in [4].

- **Participation in large projects**

  It is also important to ensure the VO participation in large scientific projects. From collaborations at European level, such as ASTERICS[5] and ESCAPE[6], the VO standards are applied widely.

  The recent ESCAPE project, for instance, addressed specific challenges of data-driven research and supported interoperable, and FAIR-compliant data management. It also fostered cross-disciplinary collaboration for the advance of multi-wavelength and multi-messenger science. The project generated several outputs of great interest, such as a software repository for scientific tools, a science analysis platform, infrastructure for large-scale data, and a citizen science activities.

  The SVO team was particularly involved in some of the educational programs of the project, focusing on the training of young astronomers and promoting the correct use of VO tools and services.

3 The VOpubs service: a way to measure the VO impact

One way to measure the impact of the VO actions is to search for metrics showing the use of all offered VO services and tools. Currently, the three VO tools most widely used by the Astronomical community are: the Tool for OPerations on Catalogues And Tables[7] (TOPCAT; [6]); the Aladin[8] interactive sky atlas ([2]), and VOSA ([1]), with hundreds of citations per year (Fig. 1).

However, for several years, there has been a need for a curated list of refereed papers that used the available VO services for their science. In response to this need, the SVO team

[5] `https://www.asterics2020.eu`
[6] `https://projectescape.eu/`
[7] `https://www.star.bristol.ac.uk/mbt/topcat/`
[8] `http://aladin.cds.unistra.fr`

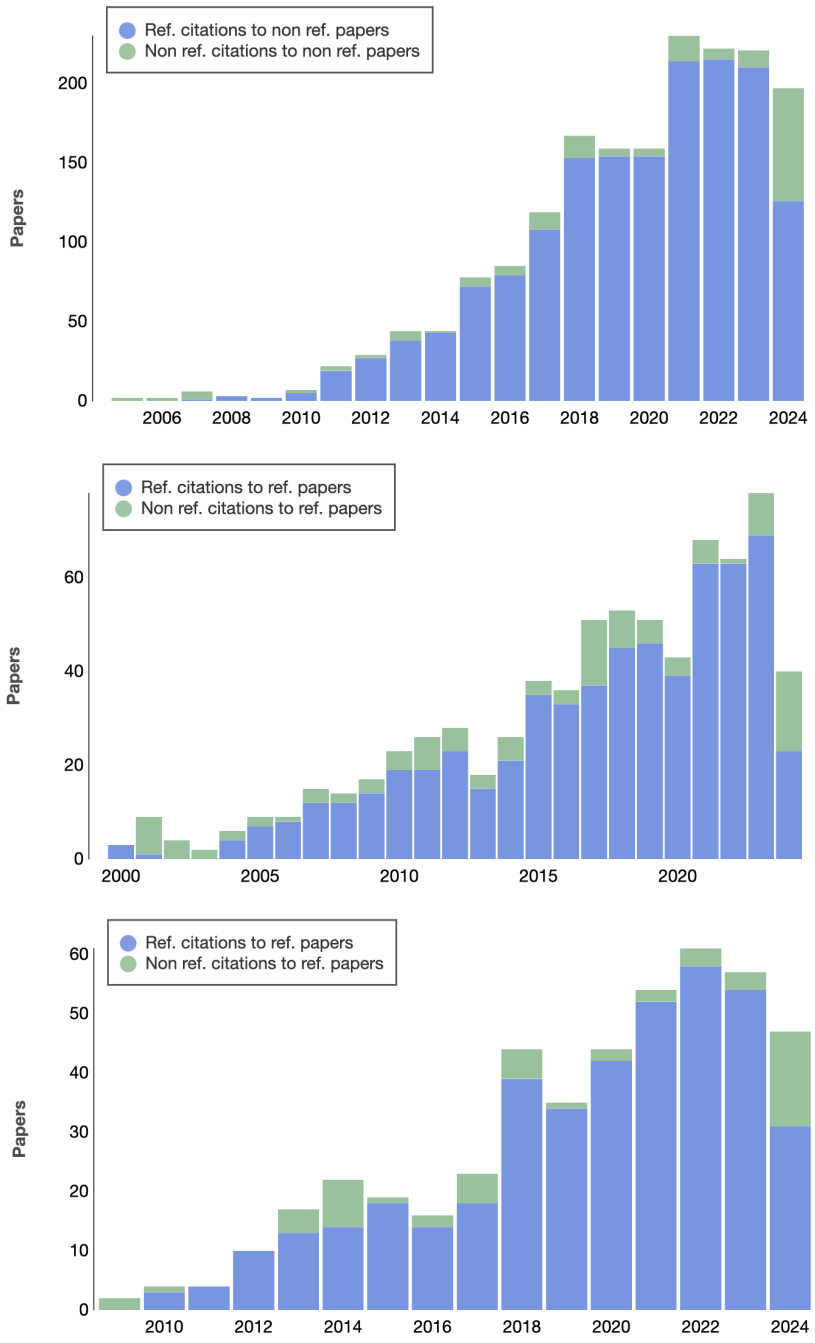

Figure 1: Number of citations according to ADS for the three most used VO tools: TOPCAT (top panel); Aladin (middle panel); and VOSA (bottom panel). The total of citations per year is shown, where the blue portion of the histogram represents the citations in refereed articles and the green part is for non-refereed articles. *Credit:* Figures generated by ADS.

2784 Results

Comment	Number
Use of VO tools: TOPCAT	1157
Use of VO tools: SIMBAD	661
Use of VO tools: Vizier	658
Use of VO tools: Aladin	402
Use of VO tools: VOSA	238
Use of VO services: SVO Filter Profile Service.	232
VO project (SVO) acknowledged in the paper.	151
Use of VO tools: STILTS	62
Australian All-Sky Virtual Observatory (ASVO)	61
Use of VO tools: CASSIS	58
Use of VO tools: SkyBot	29
VO project (China-VO) acknowledged in the paper	29
VO project (GAVO) acknowledged in the paper. Use of Millenium database.	23
Use of VO services. Theoretical model service provided by SVO.	19
Use of VO tools: CDS Cross-match	18
VO project (GAVO) acknowledged in the paper	18
Use of VO tools: ESASky	17
Use of VO tools: Sky View	17
VO project (JVO) acknowledged in the paper.	14
Use of VO services: JVO	13
Use of VO tools: Splat-VO	12
Use of VO tool: MIriade	12
VO publication of data collections. Using and accessing SVOCat	9
Use of VO tool: SsODNet	5
Use of VO services. TMAD provided by GAVO	3
Use of VO services. TOSS	2
Use of VO tools: VOSpec	2
Use of VO spectrum services	1
Use of VO tool: TheoSSA (GAVO)	1
Use of IMCEE Virtual Observatory Solar System Portal	1
VO project (GAVO) acknowledged in the paper. Use of Multidark database.	1
Use of VO services. theoretical Astrophysical Observatory provided by ASVO	1
Use of VO services: Brazilian Science Data Center (BSDC) Virtual Observatory	1
Use of Clusterix	1
Use of VO tool: TMAW (GAVO)	1
VO project VAO (US Virtual Astronomical Observatory) acknowledged in the paper.	1
Use of VO tools: GAVO cross-matcher	1
Use of VO services: GaLactic Extragalactic All-Sky MWA (GLEAM) Virtual Observatory	1
Planetary Virtual Observatory and Laboratory (PVOL) database	1

Figure 2: List of VO tools and services acknowledged in publications from June 2019 to June 2024. They are ordered by the most cited services, with a total of 2784 citations.

developed the VOpubs[9] tool, a system that compiles all mentions of VO services and tools in ADS and which are reviewed in detail.

The VOpubs service queries ADS on a weekly basis, searching for VO-related keywords in

[9] `https://sdc.cab.inta-csic.es/vopubs/`

papers published in A&A, AJ, AN, ApJ, ApJL, ApJS, Icar, MNRAS, and PASP. In a second stage, this list of papers are reviewed by members of the SVO team. This is an unavoidable step as only a visual inspection can certify correct entries in cases of clear mismatches with other services or catalogues with similar names. For instance, the manual revision allows us to eliminate citations to the CASSIS archive (Cornell Atlas of Sources with Spitzer IRS Spectra; [3]) that can be mistaken for the CASSIS[10] software (Centre d'Analyse Scientifique de Spectres Instrumentaux et Synthétiques; [7]), an interactive tool to view and analyse synthetic spectra.

As an example, Fig. 2 presents the list of all VO tools and services acknowledged in ADS for a period of five years, from June 2019 to June 2024. The results shown are ordered by the number of citations, from highest to lowest, with a total of 2784 citations in the queried period.

VOpubs is a useful way to compare how the astronomical community uses different VO tools and services. Furthermore, it helps us gather the correct information to show the usage of all VO services within the community and in front of funding agencies. It can also help find science cases that serve as real examples of VO applied to astronomical research in different fields.

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[6] Taylor, M. 2005, ASPC, 347, 29

[7] Vastel, C., et al. 2015, *SF2A-2015: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, 313

[10] `https://cassis.irap.omp.eu/`