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Ten years of the Spanish Virtual Observatory

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Abstract

The main objective of the Virtual Observatory (VO) is to guarantee an easy and efficient access and analysis of the information hosted in astronomical archives. The Spanish Virtual Observatory (SVO) is a project that was born in 2004 with the goal of promoting and coordinating the VO-related activities at national level. SVO is also the national contact point for the international VO initiatives, in particular the International Virtual Observatory Alliance (IVOA) and the Euro-VO project. The project, led by Centro de Astrobiología (INTA-CSIC), is structured around four major topics: a) VO compliance of astronomical archives, b) VO-science, c) VO and data mining-tools, and d) Education and outreach.
In this paper I will describe the most important results obtained by the Spanish Virtual Observatory in its first ten years of life as well as the future lines of work.

1 Introduction

Astronomy has been for a long time at the forefront for widespread sharing and re-use of data. National and international ground- and space-based observatories produce terabytes of data per year which are publicly available all around the world from data centres. Archives are efficient resources that allow to re-use a set of observations for many different purposes. Moreover, archives have an unquestionable legacy value allowing the usage of scientific data well beyond the end of the operational phase of a satellite or telescope. Finally, there are research lines that, simply, cannot be carried out without the existence of archives (multi-wavelength studies; analysis of objects that, suddenly, change brightness like supernovae or GRB; analysis of objects that change brightness in a periodic way along decades; or objects that do not change brightness but position like high proper motion stellar and substellar objects or solar system objects).

Although this e-infrastructure (the astronomical archives distributed worldwide) should potentially lead to a more complete and less biased understanding of complex astrophysical phenomena, the reality is that the progress in the scientific exploitation is not keeping pace with the exponential growth of data in astronomical archives. The lack of interoperability among the huge databases that populate the astronomical data centres is the major limiting factor that hinders the optimum scientific and technical exploitation of the information. This is the challenge the Virtual Observatory has to face.

The Virtual Observatory (VO) represents a step forward towards interoperability and data integration. VO, under way since the turn of the century, is an international project aiming to: a) create a federation of astronomical archives that, with the implementation of a common set of rules (*VO standards*), provides a seamless and efficient access to astronomical data (*data grid*), and b) develop and implement analysis tools (*service grid*) to be used by the community (*VO-science*).

The importance of the Virtual Observatory as a key research e-infrastructure has been recognized at European level by Astronet[1] which, in its Infrastructure Roadmap, recommends the VO long-term sustainability and suggests that VO should be an integral part of any future astronomical instrumentation. The Virtual Observatory has also been a strong keyword for the European Community which, through different FP6 and FP7 projects, has supported the development and operational phases of the Euro-VO, the Virtual Observatory initiative at European level. At international level it is also remarkable the role that the Virtual Observatory plays in the Research Data Alliance (RDA[2]), an alliance among the European Union, Australia and the United States to build the bridges that enable open data sharing across disciplinary borders. The VO history of success in terms of coordination and development of standards is given by RDA as the model to follow in other scientific disciplines.

The development of VO standards and tools is overseen by the International Virtual Observatory Alliance (IVOA[3]),an alliance of all Virtual Observatory initiatives. IVOA was established in June 2002 and, at present, is formed by 21 members. The Spanish Virtual Observatory (SVO[4]) became an IVOA member in 2004 and, since then, is playing an active role both at technical, scientific and managerial level. The core of the SVO project is at Centro de Astrobiologa (CAB, INTA-CSIC). CAB hosts the largest astronomical data centre managed by an Spanish institution and has a large experience in the development and exploitation of astronomical archives. The main objectives of the Spanish Virtual Observatory are the following:

- Improve the performance of the Spanish astronomical data centres by making them VO-compliant. These data centres will take advantage of becoming part of an homogeneous international framework (the Virtual Observatory) to make their datasets interoperable, facilitating their discovery and access through VO tools.

- Train Spanish data centres staff in the usage and implementation of the VO standards and tools, and make them active participants in development of the VO framework.

- Promote and support VO science projects among the Spanish astronomical community

[1] `http://www.astronet-eu.org/`
[2] `https://rd-alliance.org/`
[3] `http://www.ivoa.net`
[4] `http://svo.cab.inta-csic.es`

and gather their requirements and feedback. A key element in the support to the community will be the organisation of the VO schools.

- Improve and develop VO standards, data analysis and data mining tools.

- Open the Virtual Observatory capabilities to the educational and astronomical amateur communities and the general public.

In what follows, I will describe the main activities carried out towards the above-identified communities.

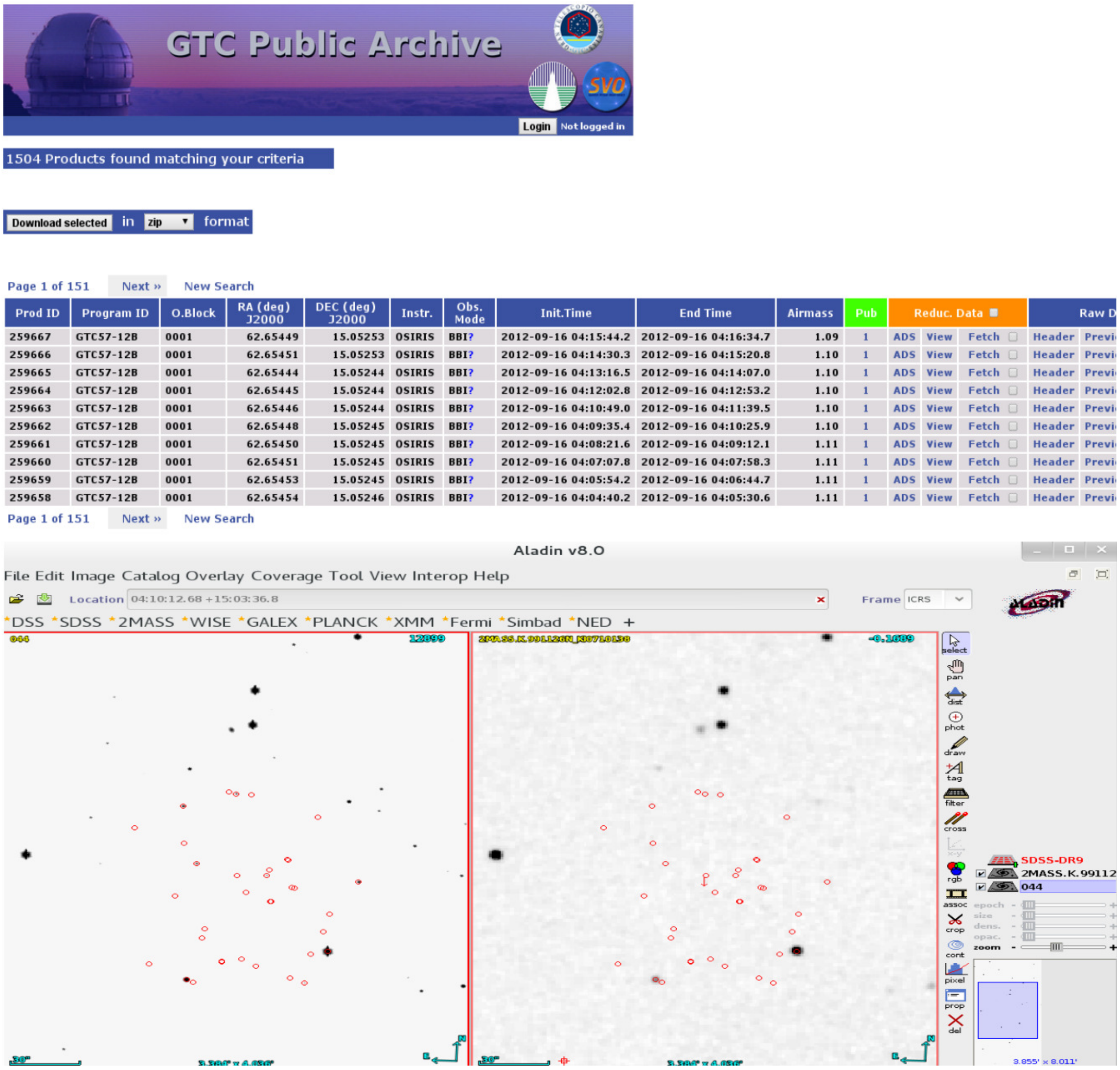
2 The Spanish astronomical data providers

Data providers are an integral part of Virtual Observatories: Without data there is no VO. I prefer to use here the term *data providers* instead of *data centres* as it is a broader concept that fits better with the definition of what a VO data centre is: any group of people willing to provide a service to the community (data or tools), with some kind of sustainability and concern for quality.

The census of Spanish astronomical data providers is quite diverse in size and objectives ranging from small and specific to large and general. It is possible to find large observatories and telescopes like GTC, Calar Alto or Javalambre, medium-size observatories like Izaña, Sierra Nevada, and Joan Oró, groups that provide access to data generated by the community like PVOL in Bilbao which distributes images of the giant planets or the service available at the Universidad Complutense de Madrid to access libraries of stellar spectra. We can even find data collections generated by small groups or individual researchers who want to share them with the community.

The Spanish Virtual Observatory provides support to the Spanish data providers in two different scenarios. The first scenario is that in which the group that generates the data does not have either the expertise of the willingness to create and maintain the archive. In this case, we offer them the possibility of distributing their datasets through the CAB Astronomical Data Centre[5] (formerly known as LAEFF Data Centre). Among others data collections, the CAB Data Centre includes the Gran Telescopio Canarias and the Calar Alto Observatory VO-compliant archives. At this point it is important to stress that the CAB Data Centre is the ONLY entry point for the national and international community to access GTC and Calar Alto data. As neither of the two projects provide reduced data (a major drawback in the scientific exploitation of the archive by the community), the SVO has developed a procedure (currently implemented in the GTC archive) for the community to return reduced data to the archive. The reduced datasets are available through the web interface, linked to the associated raw data and with functionalities for visualization and massive download (Fig. 1). At the time of writing, more than one hundred authors have been contacted and one third of them have accepted to upload their datasets in the archive.

[5]http://svo.cab.inta-csic.es



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259667	GTC57-12B	0001	62.65449	15.05253	OSIRIS	BBI?	2012-09-16 04:15:44.2	2012-09-16 04:16:34.7	1.09	1	ADS	View	Fetch	Header	Previ
259666	GTC57-12B	0001	62.65451	15.05253	OSIRIS	BBI?	2012-09-16 04:14:30.3	2012-09-16 04:15:20.8	1.10	1	ADS	View	Fetch	Header	Previ
259665	GTC57-12B	0001	62.65444	15.05244	OSIRIS	BBI?	2012-09-16 04:13:16.5	2012-09-16 04:14:07.0	1.10	1	ADS	View	Fetch	Header	Previ
259664	GTC57-12B	0001	62.65445	15.05244	OSIRIS	BBI?	2012-09-16 04:12:02.8	2012-09-16 04:12:53.2	1.10	1	ADS	View	Fetch	Header	Previ
259663	GTC57-12B	0001	62.65446	15.05244	OSIRIS	BBI?	2012-09-16 04:10:49.0	2012-09-16 04:11:39.5	1.10	1	ADS	View	Fetch	Header	Previ
259662	GTC57-12B	0001	62.65448	15.05245	OSIRIS	BBI?	2012-09-16 04:09:35.4	2012-09-16 04:10:25.9	1.10	1	ADS	View	Fetch	Header	Previ
259661	GTC57-12B	0001	62.65450	15.05245	OSIRIS	BBI?	2012-09-16 04:08:21.6	2012-09-16 04:09:12.1	1.11	1	ADS	View	Fetch	Header	Previ
259660	GTC57-12B	0001	62.65451	15.05245	OSIRIS	BBI?	2012-09-16 04:07:07.8	2012-09-16 04:07:58.3	1.11	1	ADS	View	Fetch	Header	Previ
259659	GTC57-12B	0001	62.65453	15.05245	OSIRIS	BBI?	2012-09-16 04:05:54.2	2012-09-16 04:06:44.7	1.11	1	ADS	View	Fetch	Header	Previ
259658	GTC57-12B	0001	62.65454	15.05246	OSIRIS	BBI?	2012-09-16 04:04:40.2	2012-09-16 04:05:30.6	1.11	1	ADS	View	Fetch	Header	Previ

Figure 1: *Top:* result of a query in the GTC archive including reduced data (yellow box). *Bottom:* by clicking *View* Aladin is launched allowing the visualization of the GTC reduce image (*left*) and its comparison with any other catalogue or image available in the VO. As an example, a 2MASS image (*right*) and the SDSS catalogue (overplotted in both images) have been used.

The second scenario is that in which the groups generating the data do have the willingness and the expertise to develop and maintain the data archive. This scenario nicely fits with the Virtual Observatory concept of creating a grid of data centres distributed worldwide in contrast with the idea of a monolithic, centralised database. Support to data centres willing to publish their contents in the Virtual Observatory is provided through four different mechanisms:

- Training. Technical visits of experienced SVO staff provide on-site support and local training. These expert visits are designed to enable projects to take responsibility for their VO implementation and are customised to their specific needs, schedule and resources. Previous SVO projects have demonstrated how useful personal contact to SVO staff has been for the data centres.

- Networking. The goal here is to organise workshops (the first one already took place in April 2014[6]), to bring together SVO staff and data providers to foster an interchange of ideas and requirements. Data providers are invited to give talks on their work and needs, while SVO staff introduces technologies and software to make data publishing in the Virtual Observatory easier, more effective and more sustainable. Much of the program of these workshops is devoted to practical cases on how to implement VO standards in existing archives and how to develop a VO archive from scratch. The meeting includes a Forum session to share lessons learn, discuss requirements and gather feedback.

- Development of publishing tools. A major need identified by data centers is a clear guidance of what to do and how to proceed to publish VO-compliant data. The Spanish Virtual Observatory has developed tools to ease the publication of catalogues, images and spectra in the Virtual Observatory. These tools are widely used in the workshops mentioned in the previous item.

3 Development of VO-standards

The foundations of the Virtual Observatory rest on standards that allow the creation of an interoperable data grid. These standards solve the problem of how to discover (registry), query (access protocols) and describe (data models and formats) astronomical information. With standards in place, VO-tools have been built and are used in VO-science projects. Although standardization was one of the first activities tackled by the VO projects and a lot of work has been done in this field, there are still many issues that must be dealt with. The development of access protocols for datacubes (SIAP v2.0) or standards to associate different products in a single VOTable (Datalink) are good examples of the efforts that are being presently carried out in the IVOA context.

In these last years the Spanish Virtual Observatory has actively participated in the development of standards for theoretical data (at present, roughly half of the VO services providing access to models belong to the Spanish Virtual Observatory which manages more

[6] `http://svo.cab.inta-csic.es/meetings/datapublication/`

than 30 collections of theoretical spectra, 45 collections of isochrones and tracks and one billion measurements of synthetic photometry), photometry (we are responsible for the Filter Profile Service[7], an homogeneous database which provides VO access and VO description of the photometric filters available in most of the main ground- and space-based observatories. This is the only service of this kind in the VO framework), time series (one of the IVOA science priorities) and asteroseismic data.

4 Development of VO tools

The interaction of the VO infrastructure with end-users (the scientists) is provided by a number of applications (the VO tools). Virtual Observatory tools take advantage of VO standardization and open new lines of research by facilitating the discovery, access and inter-comparison of astronomical datasets. In this section I will focus on VOSA, TOUCAN and TESELA as examples of the tools developed by the Spanish Virtual Observatory.

4.1 VOSA

VOSA[8] (VO Sed Analyzer) is a web-based tool designed to combine user photometric measurements with data available in VO services to build the observational spectral energy distributions (SEDs) of hundreds of objects. VOSA also accesses various collections of models to simulate the equivalent theoretical SEDs, allows the user to decide the range of physical parameters to explore, performs the SED comparison, provides the best fitting models to the user following two different approaches (chi square and Bayesian fitting), and, for stellar sources, compares these parameters with isochrones and evolutionary tracks to estimate masses and ages. VOSA was firstly released in 2008 and its functionalities are described in [3]. At the time of writing there are more than 300 users in VOSA who have published more than 60 refereed papers.

4.2 TOUCAN

Space missions (SoHO, MOST, CoRoT, Kepler, SDO, etc.) have caused a dramatic increase of the asteroseismic data. Other current and future projects like Gaia and PLATO will increase by a factor of hundreds the available datasets. Ground-based networks (e.g. GONG, Bison) and dedicated photometric and spectroscopic follow-up observations for the above-mentioned space missions also continuously increase the amount of related data.

A proper understanding and full exploitation of this huge amount of information requires a similar leap forward on the theoretical side. TOUCAN[9] ([22]) is a tool developed by the Spanish VO designed to easily handle stellar and seismic models. Following VO requirements, the tool presently provides access to 500 000 theoretical models representative

[7]http://svo2.cab.inta-csic.es/theory/fps3/
[8]http://svo2.cab.inta-csic.es/theory/vosa/
[9]http://svo.cab.inta-csic.es/theory/sisms3/

of intermediate mass stars. Our next step is to build a distributed architecture for TOUCAN consisting in a central service that will manage the user queries to TOUCAN and will communicate with peripheral services and with users. Some of these peripheral services may have implemented a Grid/Cloud infrastructure to accept on-demand modelling queries and launch local scripts to run the computations. This way we aim at merging two technological paradigms in astrophysics: the Virtual Observatory as the standard framework for discovery, access, and representation of data, and the Grid/Cloud environment for massive computing.

4.3 TESELA

The observation of blank fields, regions of the sky devoid of stars down to a given threshold magnitude, constitutes one of the typical important calibration procedures required for the proper reduction of astronomical data obtained in imaging mode. The Spanish Virtual Observatory has developed a tool name TESELA[10] ([6]) to easily identify, visualize and retrieve the blank fields available near a given position in the sky.

5 Big data

Data-to-Knowledge is an important field for the present and future of astronomical research, which will be dominated by extensive surveys covering the entire wavelength and time domains. Data mining techniques applied to astronomy include advanced statistical methods, methods for pattern recognition and supervised/unsupervised classification techniques in multi-dimensional data spaces that offer insight on hidden astrophysical parameters. The data mining group of the Spanish Virtual Observatory has been involved in Gaia-related activities since late 2005 mainly focused on two topics: stellar variability and determination of astrophysical parameters ([19]). SVO has also participated in the supervised classification of the light curves observed in the CoRoT mission ([7]). The results of this work have been included in the CoRoT archive[11] allowing to perform high level queries of the type "Give me all objects of a given variability class with a membership probability higher than a given value". Without this information, the user would be forced to download the whole contents of the CoroT archive (more than 150 000 light curves) for a local, off-line analysis to identify his/her objects of interest. This classification has been further improved using spectroscopic data ([18]).

Other SVO data mining activity has been the study of cluster membership. Thousands of multi-wavelength observations of objects in star forming regions and clusters at several epochs are available in astronomical archives. This allows for the estimation of accurate proper motion and physical parameters and the application of sound probabilistic inference techniques for the determination of membership probabilities, which are the stepping stone for the study of these stellar aggregates. This methodology has been successfully tested in the Pleiades star cluster [20] and will be applied to a set of star forming regions and clusters of increasing complexity.

[10] `http://sdc.cab.inta-csic.es/tesela/`
[11] `http://sdc.cab.inta-csic.es/corotfa/jsp/frontpage.jsp`

6 VO-science

The Virtual Observatory project is driven by science and it is becoming a science driver. After an initial phase mainly focused on technical developments, VO is now mature enough to be used as a research tool for the astronomical community.

One of the potential problems that may affect the adoption of the Virtual Observatory by the astronomical community is its novelty. The absence of strong links between the VO project and the research groups may strongly limit the VO scientific impact. So, for instance, if the services developed by the VO are not scientifically oriented, they will not be used by the community. Since its creation, the SVO efforts have been oriented to avoid this situation. Two have been the main concurrent tasks designed to bring the Spanish astronomical community to the VO.

6.1 Organisation of VO schools

Training is considered a key element to ensure the adoption of the VO framework by the Spanish astronomers. The schools organized both at European and national level have proven to be the most efficient instrument to attract the astronomical community towards the Virtual Observatory.

The main goal of the schools is to expose participants to the variety of VO tools and services available today so that they can use them efficiently for their own research. To achieve this goal, VO experts lecture and tutor the participants on the usage of such tools. Real life examples of scientific applications are given, some of them selected from the science cases proposed by the participants. A large fraction of the time is dedicated to hands-on exercises, which allows participants to become fully familiar with the VO capabilities on their own laptops. VO schools also serve to gather requirements and feedback to ensure that the interoperability framework and tools really fulfill the scientist needs. Training materials developed for VO schools are curated as an enduring resource in the form of on-line tutorials available at the SVO portal.

The Spanish Virtual Observatory has a long and successful experience in organizing this type of events. In addition to the schools organized at European level, eight schools have taken place in different Spanish astronomical institutes since 2009. More information about the scope and the structure of the SVO schools can be found in the SVO portal[12]

6.2 VO-science collaborations

Science collaborations are an excellent mechanism to both assisting the community in their scientific effort and to validate VO standards and tools. The SVO role in these collaborations focuses on three main aspects: I) assessment of the science case from the VO point of view, II) provision of information about the existing VO tools to tackle the proposed case, and III) if needed, development of new tools. The aforementioned TOUCAN and VOSA are

[12] `http://svo.cab.inta-csic.es/docs/index.php?pagename=Meetings`

excellent examples of general-purpose VO tools that were developed in the context of these collaborations.

VO-science is a line of work in which SVO is playing a leading role at international level as demonstrated by the fact that 55% of the refereed VO-papers published in the last three years include a member of the Spanish astronomical community. Among the SVO papers, we could highlight the following ones:

- [2] on the discovery of bright nearby M dwarfs. These type of objects are, among other fields, very important for extrasolar planet studies. Our work was able to find new low proper motion M dwarfs that escaped from previous searches.
- [14], [13] on the kinematical characterization of the Chamaeleon star-forming region concluding that Chamaeleon I and II regions could be larger and spread over a larger area of the sky than suggested by previous studies.
- [16] on the search for transiting planets around very low-mass stars observed by Kepler. We demonstrate that super-Earth planets with sizes around 2 Earth radii are detectable with Kepler, independently of their level of chromospheric activity.
- [11] [10] on the identification of ultracool subdwarfs in large sky surveys.
- [9] [8] on the discovery of nearby bright M giants and blue high proper motion objects after crossmatching the Tycho-2 and 2MASS catalogues.
- [1] on the discovery of some of the first brown dwarfs detected using WISE data. One of the objects (WISE J0838+1511) is the only triple T-dwarf system known so far. Another of the objects we found (WISE J0920+4538) is also very interesting as it lies in the L/T transition region.
- [15] on the definition of a search methodology to identify new hot subdwarfs with a success ratio of 90% (estimated from spectroscopic follow-up observations) .
- [12] on the kinematical characterisation of the Lupus dark cloud population.
- [23] on the discovery of new accreting, very low-mass objects.
- [5] on the discovery of very low-mass stars and brown dwarfs in Orion.
- [4] on the discovery of white dwarfs.

7 Education & Outreach

SVO education and outreach activities are built on the curiosity about astronomy from high educational and university students, amateurs astronomers and the general public. We use VO capabilities to enable them to investigate the universe using professional, but simplified VO tools. In particular, four types of activities have been conducted:

- Participation in master courses in Astronomy.

  The involvement of the new generations of astronomers is a must to ensure the long-term sustainability of the Virtual Observatory. This is why, since 2002, we are conducting master courses on Virtual Observatories at different Spanish universities (Complutense of Madrid, Granada, Valencian International University). These courses are complemented with the supervision of PhD thesis (the first SVO thesis was defended in 2009 [17] and there are two other thesis to be defended in 2015) as well as Bachelor and Master thesis.

- Pro-Am technical collaborations: Implementation of an operational VO archive for the amateur astronomical community.

  The easier access of amateur astronomers to high-level instrumentation has boosted the number of Pro-Am (professional-amateur) collaborations. Typically, these are projects that require long runs of observations (study of variable phenomena, light pollution, discovery of solar system objects,...), something difficult to get in bigger, professional infrastructures. These large datasets can be of interest for many groups and for even different purposes but, in most of occasions, they are inefficiently managed and rarely are available on line. In the Spanish Virtual Observatory we have developed a VO-archive[13] specially suited for amateurs. In particular it includes light curves from the Spanish network on light pollution. Observers from the different stations of the network have just to upload their observations using a very simple form. No previous knowledge on archives and/or Virtual Observatories is required. Our aim is to improve the current capabilities of the archive and open it to amateur astronomers working in other fields.

- Pro-Am scientific collaborations: Discovery of common proper motion systems.

  Binary stars are important objects in astrophysics for several reasons like, for instance, their impact on star formation and evolution or on the determination of physical parameters (e.g. stellar masses). Although numerous lists of binaries have been compiled since many years ago (see, for instance, the Washington Double Star Catalogue,WDS), there are thousands of uncatalogued systems still hidden in astronomical archives. We are using VO capabilities to dig in these resources and efficiently extract as many new binaries as possible. In particular, we have built a VO workflow to look for common proper motion systems in POSS I & POSS II plates. The workflow is being presently used by the Garraf Astronomical Observatory (OAG), an amateur group with a long tradition in the discovery of binary stars. Using this methodology, the analysis of the Northern hemisphere led to the discovery of more than 1700 new common proper motion systems that have been already included in the WDS. This Pro-Am collaboration also generated side benefits for the "professional" community as the discovery of seven weakly bounded, very low mass systems whose analysis is going to be published in a refereed paper.

- Citizen Science: Discovery of near Earth asteroids in astronomical archives.

[13] `http://sdc.cab.inta-csic.es/pdd/jsp/busSQM.jsp`

One of the most attractive aspects to the general public of asteroid-related projects is the estimation of the risk level of a potential collision with the Earth as well as the mitigation strategies that may be adopted if necessary. Discovery alone is not enough to quantify the threat level of a NEA. Above all, it is necessary to compute reliable orbits through accurate astrometric positions covering a period of time as long as possible. Archival data can play a key role in the characterization of the asteroid orbits as almost every single image taken by the most important ground and space-based astronomical observatories eventually end up in open archives, freely available on the web and, eventually, in the Virtual Observatory.

In July 2011 the Spanish Virtual Observatory started a citizen science program[14] ([21]) to characterize the orbits of a large number of near-Earth and Mars-crosser asteroids using SDSS images. Since the public release of the system more than 3 500 users have participated in it and over 350 000 astrometric measurements corresponding to more than 1 000 NEAs and Mars-crossers (17% of the total census) have been realized. Among other results, we highlight the identification of more than 150 NEAs and Mars-crossers in images pre-dating their official discovery, by more than 1 000 days for more than 50 of them! It is important to remark that none of these asteroids were detected by the SDSS photometric pipeline which clearly stresses the success of the project. We plan to improve the capabilities of the system, in particular the mechanisms to exchange information with the users. Moreover, new surveys in different wavelength ranges (VISTA, VST, UKIDSS) are being incorporated which will open the door to new discoveries.

8 Conclusions

The Virtual Observatory is a multidisciplinar initiative whose main goal is to make the discovery, access and analysis of archive data easier, faster and more efficient. It involves IT people, data providers and astronomers and produces results for a wide variety of groups including amateurs, educators and the general public.

The Spanish Virtual Observatory is coordinating the VO initiatives at national level since 2004. In its first ten years of life SVO has achieved a position of leadership at international level in fields like VO-science and plays a relevant role in topics like VO-tools, VO-standards and data mining.

The Spanish Virtual Observatory is a project with a clear spirit of service. With this in mind, we conducted in 2013 a survey among the Spanish astronomical community to know their expectations regarding the VO and the impact of our activities in their fields of work. We got almost a hundred responses, most of them quite positive for the project. So, for instance, most of the people who answered the survey understood the importance of VO for astronomy, most of them consider we are doing our job in a professional way and they are satisfied with the type of service SVO is providing.

[14] `http://www.laeff.cab.inta-csic.es/projects/near/`

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