The Role of the Virtual Observatory in the Next Decade

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1. Introduction

Astronomy is entering an era characterized by huge amounts of data requiring extensive computation for calibration, analysis, and understanding. There is also an explosion in the number of datasets being published and disseminated. While the role of the astronomer as a creative agent will never be replaced, researchers will not be able to fully exploit the great wealth of data which is already upon us, and which will soon be increasing by orders of magnitude, without new ways to locate, access, analyze, synthesize, and visualize information. The Virtual Observatory[1] constitutes the core of a new approach, both national and international, to the management of astronomical data and its associated computational resources.

One of the very first initiatives in realizing the Virtual Observatory concept arose in the US approximately seven years ago with the creation of the US National Virtual Observatory (NVO). This initiative, funded by the National Science Foundation, was brought into being in order to create the infrastructure necessary for a functioning VO in the US. Though the NVO worked toward creating tools and applications for the astronomy community in addition to developing infrastructure, its mandate did not include the creation of a "user ready" VO in final form for astronomers. Prior to the end of the funding period for the NVO, a proposal was submitted to both the NSF and to NASA for a unique, jointly funded extension of the US VO effort that would bring VO to a fully operational phase and integrate the VO into the US astronomy research infrastructure. After some delay, the funding for this initiative has been secured, and the new entity, called the Virtual Astronomical Observatory (VAO), will begin its start-up phase in the coming months. The current funding cycle for the VAO is five years at a proposed funding level of about $6M per year. The major objective of the VAO is to create an operational entity that is highly distributed but functions much like any other national observatory, with an operating philosophy that is strongly focused upon user services and which is very responsive to changing user needs and demands and to the implementation of new technologies. The emphasis will be to create an operating VO that facilitates the research of all astronomers, not just the specialists who are experts in the latest complexities of IT technology. The following pages present highlights of the scientific motivation for the US VO and also provide a summary of some of the structural and functional features of the VO in its operational phase. At the end of the current VAO funding cycle it is presumed that the capabilities provided by the facility will have proven to be useful to US research astronomers on a routine basis. As a result, there will be a continuing demand for VAO-like capabilities beyond the current five-year VAO funding, and hence the US astronomy community will require resources to support a US VO facility during (and beyond) the second half of the decade covered by Astro2010.

Thus the purpose of this white paper is twofold. First, it is intended to provide for the panels a brief overview of the motivation behind a US VO and to summarize how such a facility might function in its operational phase. Second, it is to bring to the attention of the panels a need for continuing support of a US VAO, which, after the next five years, will probably be seen as an essential asset to the efficient and effective execution of astronomy research in the US.

2. Scientific Motivation

The scientific motivation for the VO is broad and compelling. All areas of astronomy, from

[1] Throughout this document we use Virtual Observatory (VO) to refer to the generic and worldwide approach to the federation of astronomical data and its associated computational resources. The US VO initiatives will be referred to as either the current National Virtual Observatory (NVO) or the forthcoming Virtual Astronomical Observatory (VAO).

planet formation to cosmology and from education to telescope and instrument design will benefit from the services and capabilities offered by the VO. Basic astrophysical questions of today are being addressed by data gathering on scales that are orders of magnitude larger than we are used to, and from many facilities, current and planned, both on the ground and in space. Moreover, a great potential for discovery lies in the combinations of such data sets. We are building a grand, panchromatic, synoptic, multi-scale picture of the physical universe and its contents. While individual astronomical observations and surveys provide snapshots of a subset of the Universe at a given observational epoch and in a restricted range of wavelength, a more complete understanding of the Universe and of its evolution requires the study of the full electromagnetic spectrum or the analysis of the temporal behavior of celestial objects. Questions such as the formation and evolution of galaxies, the nature of dark matter and dark energy, the origins and evolution of active galactic nuclei, the processes of star formation, and the evolution of stellar systems are being investigated with increasing sophistication in both observation and theory. For example, following the constituents of galaxies at all epochs requires the detection of their signatures across the entire electromagnetic spectrum. The synthesis of information gained from different facilities, together with detailed theoretical modeling, is vital to understanding galaxy formation and evolution. Multi-wavelength imaging and spectroscopic surveys of tens of thousands of galaxies will permit definitive statistical studies of the mechanisms responsible for the onset of rapid star formation, its location and mass function, and its decline, including the role of "feedback" from AGN and supernovae. Similarly, imaging and spectroscopic surveys are required to follow the formation, kinematics and chemical evolution of stellar groups and systems, locally and in more distant regions. Panchromatic surveys of regions of star formation, both local and distant, are needed to unravel the complex physical processes present in the formation of protostellar disks and stars, the evolution of molecular clouds and the ISM, and the roles of chemical processes, magnetic fields, and radiation in stellar and planetary birth and astrobiology.

This list of major issues is by no means complete, but it exemplifies a recurring theme in contemporary astronomical research: the acquisition of very large datasets over a very large range in wavelength. This need for deep and extensive panchromatic information can be satisfied through extensive use of the suite of present and planned observing facilities. Ground and space based facilities spanning wavelengths from X-ray to radio are needed for studying atomic and molecular processes, magnetic fields, energetic particles, stellar populations, hydrodynamic and MHD phenomena, and gravitational interactions on all scales. Foremost among these facilities are major observatories, both extant and planned. Each of these will provide very large datasets in a particular wavelength region that make essential contributions to the panchromatic studies mentioned previously. These and similar datasets are required to produce statistical analyses and cross correlations, multi-wavelength images, spectral libraries, time domain studies, and extensive comparisons with theoretical calculations, all of which are needed to enable the large-scale studies across all wavelengths that will help provide answers to the outstanding astrophysical questions of our era.

However, if each major facility in a given wavelength regime were to undertake separate, incompatible approaches to the archiving, retrieval, and analysis of the terabytes and petabytes of data they are collecting and will collect then the required multi-wavelength images, cross-matches, and statistical analyses containing millions of objects could be very difficult. Each individual investigation would have to create its own set of tools for access and analysis of data in differing formats. Few research teams could accomplish this in a reasonable time, and small groups and individual investigators would face serious difficulties. Thus, what is required is a structure that rapidly and transparently acquires data from diverse facilities for transmission, reduction, and analysis. Only in this way will investigators not be overwhelmed by the data avalanche, but instead, will be able to take advantage of it. It is this horizontal integration that will be made possible by the VAO. It will enable the integration of diverse data sources into a single system, and it will provide a stable foundation of standards and services which future instruments, facilities, and space missions can incorporate.

2.1 What is the Virtual Astronomical Observatory?

The VAO is an environment in which scientists can bring together diverse data products—images, spectra, catalogs, light curves, and records of transient events—in intelligent and useful ways. They can not only browse through data easily to quickly zero in on the most relevant products, but also visualize these products together in scientifically meaningful ways, such as overlaying images from multiple wavelengths along with graphics showing observational footprints (sky coverage) and the locations of cataloged sources. Once data are discovered, chosen, and brought together, analysis can begin immediately. Astronomers will have access to services and tools that can cross-correlate catalogs, resample images, accurately determine an image's world coordinates, calculate fluxes, and identify spectral lines. Many of these tools will exist as services that can operate on the remote data; however, the VAO environment does not stop at the network. Many tools that can work on the desktop (particularly those that researchers are already familiar with) will be VAO-aware, allowing scientists to seamlessly download the data directly into local applications for specialized analysis. In the VAO astronomers can move quickly and easily through this process from discovery to analysis in a single session and they can iterate over this process over multiple sessions, building up a diverse but refined collection of data along with a rich understanding of its contents.

Inherent in the VAO is a distributed model for data and services. Existing data archives remain the active repositories where researchers interact with the data. The local experts at the archives continue to curate the data in a manner best suited for their target user community, and they provide the user services best suited for interacting with the data. The key to providing the VAO environment described above is *interoperability*—an infrastructure that can federate these archives through common and standard ways of describing and accessing data, much as the HTML standard enabled the web itself in the 1990s. In this distributed model based on interoperability, the archives are critical partners in enabling VAO capabilities.

The NSF-funded Information Technology Research project now known as the National Virtual Observatory (NVO) has over the last seven years not only been laying the foundation for the VAO in the US, but also deploying tools for discovering and integrating data that are useful for real research. This effort has involved the participation of all of the major US data providers—not only the core partners but also curators of smaller but valuable data collections based at various observatories and universities. The NVO effort has been part of a worldwide movement with similar projects being funded throughout Europe, Asia, and Australia. These projects have agreed to coordinate their activities in supportive ways, leading to the formation of the *International Virtual Observatory Alliance* (IVOA), an association that was founded in order to facilitate this coordination. The critical theme of interoperability spells out the IVOA's primary role as providing a process for developing standards and promoting their use through the constituent member projects.

It is important to be clear about what the VAO is *not*. It is not a central repository for all astronomical data. Rather, it provides a means for providers to publish data so that users may find it where it is managed and curated. The VAO is not a system of closed, proprietary software. Not only can anyone publish data to the VAO, anyone can build new VAO-compliant tools based on open standards. Tools have been written in a variety of software languages and targeted to a whole range of users, from novice to expert. Finally, the VAO is not a "data police force." Instead we rely on the domain experts associated with the archives that provide the data, as well as the scientific peer-review process associated with the published literature that describe the data. However, the VAO will make sure that the *description* of data is accurate and complete, so that the data itself can be effectively discovered, accessed, understood, and utilized. The VAO will also periodically check that registered services are still working, and correspond with providers to resolve problems.

3. Technical Program Plan

3.1. Operations

The operations plan for the VAO includes three basic areas: *User Services*, *Quality Assurance*, and *Facility Support*. User Services assures that all services seen by the community are robustly accessible, while the Quality Assurance activities ensure that they meet all applicable standards, including formatting standards and data quality standards defined in the VAO. Facility Support ensures that capabilities used within the VAO itself function properly.

A user of the VAO will interact with a variety of different services (directory, inventory, cross-matching, etc.) and will use data from many different archives. Given this reliance on multiple sites, it is essential to minimize the downtime for all key VO services.

The VAO reviews the quality of the data that users have provided to the virtual observatory, especially the directory metadata. All directory entries will be scrutinized to ensure that they provide adequate information for data discovery, access, and use. We will utilize the directory's data quality and validation flags to denote the VAO's assessment and allow users to filter data discovery requests based on these quality metrics.

One of the elements of the VAO is helping to support long-term data preservation. While the strategy heretofore has been to rely almost exclusively on the data storage facilities provided by our constituent organizations, the VAO will enable scientists to store data in the VAO provided data storage facilities. During the first two years of the facility we anticipate that we will continue to share significant hardware facilities with the host institutions. However given the long term decline in the costs of hardware relative to other costs in the facility, we anticipate that an increasing fraction of our services will be hosted on machines dedicated to VO operations

3.2. User Support

The VAO User Support group will be the primary interface between the VAO and the user community. In addition to web site, help desk, and other standard features, the VAO is promoted through community engagement and advocacy. This will include training at various levels, ranging from new users to power users and programmers. The NVO has run Summer Schools that have served mostly a more technically oriented audience. We will broaden this approach to include science workshops and other training events that focus on the use of the VAO (and broader VO) through its web-based applications and integration into familiar software systems. The regular AAS meetings provide an excellent venue for such activities, and we will organize an active (as opposed to passive) presence at the AAS to take advantage of this opportunity to reach new users.

Other key components to the advocacy and training activities include communication to the community through regular electronic newsletters and, more generally, through tutorials and related documentation.

In order to evolve into the most useful facility that it can be, the VAO must actively pursue community feedback to collect ideas for improvements, ranging from basic improvements to existing user interfaces to broader suggestions for new features and totally new tools and services. This active pursuit of feedback from the VAO user community, as well as those who may not currently be VAO users, is woven into community engagement activities so that advocacy becomes a two-way flow of information. The vehicles for this will be diverse, including a formal Users Committee, workshops and training sessions, presence at AAS meetings, and surveys of the community that document their usage patterns and future needs.

3.3. Product Development

The VAO will provide applications, products, and software templates and libraries that are tested and robust on the computer platforms that are widely used in the community. End-user applications will be primarily in the form of web applications that run through a web browser and do not require user installations. Many VAO software products will build upon NVO prototypes. These will be recast into operational services and tools following a *Software Development Plan* that incorporates industry standard processes for testing, quality assurance, and revision control, adapted to the distributed nature of the effort. Regular development cycles will assure that new capabilities are made available to the community frequently and that bug fixes are deployed promptly. While part of the VAO product development will be for key projects listed below, there will also be significant resources devoted to the tools best known to the astronomy community, such as IRAF, IDL, and DS9, making these favorites well-integrated with the VAO.

VAO Portal

There are now many applications that use VO protocols, and the VAO will maintain the software assets built by the NVO project and will build enhanced applications. These are linked so that users can move from one to another seamlessly, working with the same data and program context across a range of applications; this collection of cross-linked applications is known as the VAO Portal.

Elements of the portal include DataScope, for retrieving multi-wavelength datasets about a sky position; VIM (Virtual observatory Integration and Mining), for retrieving and federating data at multiple sky positions; OpenSkyQuery, for large or complex crossmatch queries across distributed databases; footprint services, for representing and computing spatial regions on the sky; inventory tools for matching sky positions against large numbers of catalogs; VOClient, for desktop-based scripting access to standard services and science analysis tools; spectrum services, for retrieving and analyzing spectra; mosaic and cutout services for images, applications to run source extraction and cross-matching, tools to manipulate and transform space-time coordinates, tools to work with the literature and other text-based data, and tools for working with transient events.

Federated Database

At the heart of the VAO enhanced science capabilities will be a merged and integrated database of stars, clusters, nebulae, and galaxies, to be built up initially from the fusion of data sets in wide use in astronomy such as SDSS, 2MASS, NED, WGACAT, and the HST WFPC2 associations. Development will involve close collaboration between all the data centers and observatories. This VAO federated database will progressively grow to contain the names, cross-identifications, positions, and basic data, including spectral energy distributions, on all 1-2 billion objects and datasets in publicly accessible archives.

Astronomers will interrogate the VAO merged database with increasingly detailed and complex queries. With an extensively augmented database of descriptors and attributes, new astrophysical query services will allow the science-driven interrogation of archive holdings. The IVOA Astronomical Data Query Language (ADQL) will be the standard XML representation for database queries. For example, *"Find the X-ray fluxes of all galaxies in the southern hemisphere known to have radio jets, also having ACS or WFPC2 images, and at redshifts less than 0.1,"* will become a valid and answerable question within this program.

Data Mining Tools

VAO users will require effective methods for analysis, data mining, visualization, and knowledge extraction from massive, complex data sets, and will need facilities to compare observational results and derived parameters with equally complex numerical simulations. The tools in the hands of astronomers today simply do not scale to the regime where the daily data production in astronomy will be measured in tens of terabytes, and archival holdings will grow to many petabytes. In consultation with the astronomical community and VO collaborators world-wide, we will adopt, adapt, and develop the capabilities needed to embrace this new age of data- and computation-intensive astronomy.

Registry/Directory

VAO applications will offer fast data discovery and exploration tools through the use of the VAO Resource Registry. The VAO registry is part of a distributed global Directory which VAO tools will use to discover datasets, archive collections, tools and applications, and other astronomical resources of interest (such as Public Outreach data). The VO registry architecture is similar to the Internet domain-name server system. A "registry of registries" will allow an overall view of all registry nodes. The Registry is an interface not just to astronomers seeking data, but also to those who would provide it. We will encourage sharing of data by making it simple to log in and publish data and other resources; a set of human and machine steps will be created to ingest and check such resources.

Astronomical Transients

Exploration of transient sources represents one of the newest frontiers in modern astronomy. The development of a comprehensive understanding of a new event requires real-time observation with multiple instruments. To date there has been no concerted effort to ensure real-time communications of astronomical events, and a federated response must be enabled to push this subfield ahead in the 21st century. Already a number of astronomical surveys and experiments are addressing some of these goals, and much more ambitious enterprises are being planned (e.g., Pan-STARRS, LSST. To effectively probe the nature of these sudden events, there is an upsurge of interest in intelligent autonomous robotic observatories. The goal of the VAO Transient Facility is to construct a cutting-edge, fully operational system for astronomy, providing services that allow publication of multi-sourced event streams and receipt by subscribers within seconds.

3.4. Standards and Protocols

Fundamental to the success of the Virtual Observatory is the establishment of international standards for data discovery, access, analysis, and integration. In the NVO development phase initial standards have been developed for all core functions. These standards will continue to evolve and gain increased functionality, and approaches will change with time as more sophisticated base technologies become available. To ensure quality standards and correct implementation by the community, standards development in the VAO facility will include reference implementations and verification and test suites developed in concert with the specifications.

3.5. Data Preservation and Curation

Although the bulk of primary data in astronomy resides in well-established archive centers and national facilities, the images, spectra, and time series that researchers publish in graphical form in the peer-reviewed literature are not stored in digital form in any systematic way. These data have often been processed with custom software and thus are not the same as the data in the principle archives. These data, however, are the basis for the analyses and interpretations that appear in the literature. By not preserving this data the scholarly research record is incomplete; analysis cannot be verified, and results cannot be readily compared with new information. We have been working with the American Astronomical Society and their publishing partners and with university research libraries, to provide a system in which the digital data associated with publications can be captured and made available to the research community for comparison with other data and for further analysis. The VAO will provide data preservation and curation services as part of this collaboration.

When astronomers make use of the VAO, they must be able to trace the provenance of their data and understand its scientific strengths and limitations. They must also be able to locate data using standard keywords and nomenclature (e.g., for photometric passbands and spectral lines) that are shared in common between distributed repositories. Therefore, the VAO has a responsibility to facilitate standard methods for data repositories to curate and annotate their data holdings and ensure archive quality and registry integrity. The Data Preservation and Curation activity will coordinate these standards and monitor their implementation, while providing a link between astronomy and the digital library community.

In addition, the VAO will coordinate and support the preservation of valuable datasets published by individuals and organizations unable to maintain their own persistent repositories. A key challenge is to engage authors of journal articles in the preservation of data and metadata, with automation via web-based forms or Wiki technology, during the refereeing and publication process.

Data preservation includes an obligation to migrate data from one storage medium to another, apace with advances in capacities and I/O performance. For the most part this obligation is met by the data centers, observatory archives, and supercomputer centers who are the primary data providers to the VAO. Our approach to data preservation is based on an infrastructure that is media-independent and which provides a level of abstraction that enables easy transitions among the underlying hardware and operating systems.

3.6. Technology Evaluation

The Virtual Observatory is built on advanced information technologies that facilitate network-based data discovery, access, and sharing, and these technologies are advancing rapidly in sophistication and capabilities. Developers inside and outside of the VAO will generate innovative approaches that may be powerful enough to be injected into the VAO software development. The technology evaluation team is responsible for recognizing and prototyping new technologies from within the core team that may become useful to the VAO, giving enough attention for proper evaluation but without allowing hero-programmers to split away from their core tasks. The VAO will be active in injection of new technology and new ideas from within the VAO team into the development cycle; requesting prototyping and evaluation of new technologies that can benefit all of the VAO.

4. Education and Public Outreach

EPO professionals involved in formal education, especially at the high school level and above, have the best chance of making substantial use of VAO data sets. High school courses tend to be topical in nature, with students typically participating in courses such as biology, chemistry, and physics. While earth and space science is not emphasized in most statewide curricula, real-world data has become a need for educators and developers. Standards relevant to analyzing and synthesizing data through scientific investigations are cited within the National Research Council's National Science Education Standards and AAAS's Project 2061 benchmarks. A challenge for educators and developers, however, is addressing these standards through investigations that are meaningful, relevant, and appropriate to students' skills. Appropriate science and technology related problems and data can serve as resources for developing meaningful investigations while also addressing national education standards. Providing this community with easier access to the VAO will produce a merging of interests: teachers can use real science data to teach the scientific process, and the VAO will be broadening its impact beyond the professional astronomer.

The technological and scientific barriers can be very high for EPO professionals to interface and make use of the VAO. EPO professionals need to understand the data sets before they can conceive of ways to integrate them into their education programs. Based on our needs assessment of the education community we will establish an archive of EPO-qualified data sets. These data sets will come with extensive documentation and suggested uses.

Perhaps one of the more interesting stories behind the VAO is how it will be used to extend the reach of astronomical research by integrating the data from many observatories. This is not a simple idea to communicate and it is even more difficult to reach the public with traditional tools like brochures, websites, and videos because that requires them search out our message. Using media outlets that cover science topics like the Science section of the New York Times or Discover magazine is a better vehicle to reach a scientifically interested public. In order to get science journalists to cover the VAO we will host a science writers' workshop in conjunction with the science workshops that will be held to announce VAO-enabled research results and foster further VAO-enabled science. This provides science writers with a legitimate event to attend and report discoveries from and it gives us the opportunity to educate these journalists on how modern astronomy is enhanced by the VAO. The end result should be an informed journalist who can report on the most recent discovery while highlighting the benefits of science in the VAO-enhanced world.

5. Broader Impacts

The mission of the VAO, to enable data discovery and analysis from the world's astronomical data repositories, will uniquely support a broad cross-section of individuals and groups across the nation who can benefit from its contributions. Among those who will benefit are professional researchers in astronomy and no restrictions for access to the VAO, allowing students and the public to become "citizen scientists". This will broadly benefit other sectors of the economy (e.g. high-technology, manufacturing, and telecommunications), expand our nation's strategic capacity for scientific and technological innovation, and inform the public generally of the benefits of an information technology-rich society.

The VAO will encourage professional interactions within astronomy and astrophysics, as well as across the present-day boundaries of science, technology, engineering, and mathematical disciplines. Its work will accelerate the process of scientific discovery by provide unparalleled access to information resources worldwide, making it easier to communicate with collaborators through the common language of science, and making it easier to derive knowledge and insights from data. The VAO will also serve as the nexus for cooperation and collaboration between academia, observatories, other data collection missions, and industry. Since VAO data warehousing and data mining challenges are among the most complex in the world, solutions to these problems can translate to new developments that will enhance productivity and bring a competitive edge to those who are exposed to and become experienced users of the VAO.

In addition to facilitating professional contacts, the work of the VAO will substantially accelerate advancements from archive-based research in astronomy and astrophysics. Raw data originally collected to meet one set of research objectives can contain information on many other phenomena, which can be explored using VAO solutions. The tools, services and software provided by the VAO will enable sharing and annotation of data to a level that has previously been unmatched. Simultaneously, through training and outreach, the VAO will help to educate the research community in a new mode of discovery that has previously been challenged by the lack of data standards across the specializations within the field. This will have a positive (and potentially limitless) long-term impact on the research culture, both in astronomy and in encouraging cross-disciplinary collaborations between the physical sciences, mathematics, and statistics. Additionally, the work of the VAO will facilitate interactions with other archives and other disciplines that already expose services valuable to the practice of astronomy (e.g., weather archives with research-quality data that can supplement astronomical discovery when opacity and seeing information is not available with the observed astronomical data, and the archives of NASA's Planetary Data System, whose holdings complement those in the archives of pointed observations managed by the VAO partner organizations).

Straightforward access to worldwide astronomical data repositories and analysis tools, geared to a wide variety of skill levels, will help teachers infuse information technology and data-based research into their physical science and earth science courses and will inspire students to enter Science, Technology, Engineering and Mathematics (STEM) fields. Pilot educational initiatives at the George Mason University will directly engage university students, including underrepresented groups, with a more far-reaching goal of replicating a VAO/data-mining curriculum in information science. The VAO will also support bringing tools and resources created by other projects to the wider community of professional researchers, bridging the educational and research communities. By enabling students and teachers to tap into the excitement of astronomical discovery, and to get credit for their participation, the VAO will be a dynamic, exciting stimulus for attracting and developing our nation's next generation of scientists and engineers.

The VAO approach has been pioneered in the astronomy community but is applicable for the construction of distributed data systems in many disciplines. Already NASA has a number of V**x**Os (where **x** is Solar, Heliospheric, Solar-Terrestrial, Radiation Belt, etc.), and recent special sessions at the American Association for the Advancement of Science annual meeting and American Geophysical Union annual meeting featured "virtual observatories" in fields as diverse as oceanography, hydrology, seismology, medicine, and sociology.

As part of its mission, the VAO will also actively participate in dissemination of results to the scientific community as well as the general public. Continuing the efforts of the NVO project team, science results made possible by the tools and techniques of the VAO will be presented regularly at meetings of the American Astronomical Society (AAS), Astronomical Data Analysis & Software Systems conferences (ADASS), and the SPIE conferences on astronomy and instrumentation. As part of the VAO, dissemination of technical results to other communities who employ Virtual Observatories and could benefit from the findings will also be essential.