The New Paradigm: Novel, Virtual Observatory Enabled Science

R.J. Brunner

Department of Astronomy, California Institute of Technology,
Pasadena, CA, 91125

Abstract. A virtual observatory will not only enhance many current scientific investigations, but it will also enable entirely new scientific explorations due to both the federation of vast amounts of multiwavelength data and the new archival services which will, as a necessity, be developed. The detailing of specific science use cases is important in order to properly facilitate the development of the necessary infrastructure of a virtual observatory. The understanding of high velocity clouds is presented as an example science use case, demonstrating the future synergy between the data (either catalog or images), and the desired analysis in the new paradigm of a virtual observatory.

1. Introduction

A diverse and exciting array of scientific possibilities, whose exploration are enhanced by the existence of a Virtual Observatory, are detailed elsewhere in this volume. Certain lines of scientific inquiry, however, are not just enhanced by a virtual observatory, but are actually enabled by it. For example, a panchromatic study of active galactic nuclei (see, e.g., Boroson, these proceedings), studies of the low surface brightness universe (see, e.g., Schombert, these proceedings), a study of Galactic structure (see, e.g., Kent, these proceedings), or a panchromatic study of galaxy clusters, are all extremely interesting projects that are facilitated by a virtual observatory.

In this article, I will discuss some specific technical challenges which must be overcome in order to fully enable this new type of scientific inquiry. This is not as difficult as it may first appear, as many of these challenges are already being tackled, as is evidenced by the prototype services which are currently available at many of the leading data centers. In order to truly make revolutionary, and not merely evolutionary, leaps forward in our ability to answer the important scientific questions of our time, we need to “think outside the box”, not just in the design and implementation of a virtual observatory, but in the actual scientific methodology we wish to employ (see, e.g., Figure 1, which demonstrates this concept by combining large image viewing with the ability to selectively mark objects in the image based on their statistical properties).
2. Technological Challenges

While many of the technical challenges are rather self-evident upon a cursory examination, such as the federation of existing archival centers, other challenges are considerably more difficult to elucidate. This effect is primarily a result of the difficulty in designing scientific programs for the, as yet unavailable, virtual observatory. This is exactly the time where “thinking outside the box” applies, as one needs to ask not “what can I do right now?”, but “what would I like to be able to do?”.

The first step in this process is to consider, in its entirety, all of the data which might be available for ingestion into a virtual observatory. This includes the obligatory data catalogs, which are the most often used derivative of survey programs, and perhaps more importantly, the original imaging data and any associated metadata (that is, data which describes the data). Similar extensions likewise apply to other types of astronomical data, including spectral and temporal.

After taking this revolutionary leap, we can now consider querying not just catalogs, but also the data from which the catalogs were extracted. This would allow for new techniques to be applied, which might, for example, perform source extraction using multiple wavelength images simultaneously (e.g., $\chi^2$ detection, Szalay et al. 1999), or perhaps to extract flux limits for objects detected in other
wavelengths, or, finally, to extract matched parameters (e.g., matched aperture photometry).

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\begin{array}{cccc}
J & F & N & J & H & K \\
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Figure 2. The multiwavelength nature of nearby galaxies, constructed from the optical data of the DPOSS survey (J, F, and N) and the near-infrared data of the 2MASS survey (J, H, and K). Figure courtesy of Steve Odewahn, Arizona State University.

This is demonstrated in Figure 2, where the multiwavelength nature of nearby galaxies is explored, from the optical, extracted from the DPOSS survey (Djorgovski et al. 1998), to the near-infrared, extracted from the 2MASS survey (Skrutskie et al. 1997). As this example demonstrates, multiwavelength image processing is a pressing need, since objects bright in one wavelength are often much fainter, if even detected at all, at other wavelengths.

Another example of the need for image reprocessing is shown in Figure 3, where the detection of a nearby, low surface brightness dwarf spheroidal galaxy is demonstrated. The vast majority of survey pipelines are designed to detect the dominant source population, namely high surface brightness point-type sources. As a result, an implicit surface-brightness selection effect exists in nearly all catalogs (see, e.g., Schombert, these proceedings for a more detailed account). In the future, one would ideally like to be able to reprocess survey data in an effort to find objects at varying spatial scales and surface brightnesses.
3. Science Use Case: Understanding High Velocity Clouds

As a demonstration of how a virtual observatory can enable new science, consider the specific science use case of understanding high velocity clouds (HVCs). HVCs are defined as systems consisting of neutral Hydrogen which have velocities that are incompatible with simple models of Galactic rotation (Wakker and van Woerden 1997). Their origin, however, remains uncertain, with various arguments being made in support of a wide range of hypothesis, including that they are Galactic constituents, that they are the remnants of galaxy interactions, or that they are fragments from the hierarchical formation of our local group of galaxies.

In an effort to truly understand these systems, we also would like to understand their composition. Although these systems are, by definition, found in neutral Hydrogen surveys, we can perform either follow-up observations at other wavelengths, or else correlate the HI data with existing surveys at other wavelengths in order to learn more about them (see, e.g., Figure 4 for a demonstration of multiwavelength image correlation for a known HVC). This process can often require the construction of large image mosaics involving multiple POSS-II photographic plates in order to map structures that span several tens of square degrees. This service should clearly be one of the principal design requirements for a virtual observatory.

The most powerful method for understanding the composition of HVCs, however, is to study their absorption effects on the spectra of background sources, most notably quasars. In order to find suitable targets, we need to be able to...
dynamically correlate the HVC images with published quasar catalogs in order to determine the optimal line-of-sights for quantifying the composition of the intervening HVCs with follow-up spectral observations.

![Figure 4](image.png)

Figure 4. A demonstration of the image correlation process for a known high velocity cloud complex. The figure on the left is a DPOSS F (approximately R) plate image, selected since it would contain any $H\alpha$ emission. The HVC is detected by the low surface brightness emission near the center of the image. The figure on the right is the correlated IRAS 100$\mu$m image, which demonstrates a remarkable correlation with the diffuse emission seen in the figure on the right (see Brunner et al. 2001).

Finally, we also would like to understand the evolution of these systems, which has obvious implications for understanding their origin. This can optimally be done by comparing the predictions of theoretical models to our correlated multiwavelength observations. This implies a need for a virtual observatory to allow seamless access to not only astronomical data but also the results of dynamical analysis, either through persisted calculations or a real-time process.

4. The New Paradigm

To accomplish these ambitious scientific goals, we need powerful tools, which should be implemented as part of a virtual observatory. First, we need the ability to process and visualize large amounts of imaging data. This should be done in both a manner which is suitable for public consumption (i.e., the virtualsky.org project) and also a manner which preserves scientific calibrations. These services will also need to provide coordinate transformations, overlays and arbitrary re-pixelizations. Ideally, these operations occur as part of a service which can also accept user-defined functions to further process the data, minimizing the size of the data stream which must be established with the end-user.

Next, we need the ability to federate an arbitrary collection of catalogs, selected from geographically diverse archives, a prime computational grid ap-
To completely enable the discovery process, we also need intelligent display mechanisms to explore the high-dimensionality spaces which will result from this federation process. We also will need to allow the user to post-process these federations using user-defined tools or functions (e.g., statistical analysis) as well as combine these processes with image operations and visualizations.

Finally, a complete census and subsequent description of science use cases (e.g., the previous section, see also, Boroson, these proceedings), inevitably leads one to the formulation of a new paradigm for doing astronomy with a virtual observatory. In the future, anyone, anywhere, will be able to do cutting edge science, as researchers will only be limited by their creativity and energy, not their access to restricted observations or telescopes. Not only will this revolutionize the scientific output of our community, but it will also have an important effect on the sociology of our field as well, since students will need to be trained in these new tools and techniques.

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