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# Science with Virtual Observatory Tools

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**Abstract.** The Virtual Observatory is now mature enough to produce cutting-edge science results. The exploitation of astronomical data beyond classical identification limits with interoperable tools for statistical identification of sources has become a reality. I present the discovery of 68 optically faint, obscured (i.e., type 2) active galactic nuclei (AGN) candidates in the two GOODS fields using the Astrophysical Virtual Observatory (AVO) prototype. Thirty-one of these sources have high estimated X-ray powers ($> 10^{44}$ erg/s) and therefore qualify as optically obscured quasars, the so-called QSO 2. The number of these objects in the GOODS fields is now 40, an improvement of a factor $> 4$ when compared to the only 9 such sources previously known. By going $\sim 3$ magnitudes fainter than previously known type 2 AGN in the GOODS fields the AVO is sampling a region of redshift – power space much harder to reach with classical methods. I also discuss the AVO move to our next phase, the EURO-VO, and our short-term plans to continue doing science with the Virtual Observatory.

## 1. Astronomy in the XXI century

Astronomy is facing the need for radical changes. When dealing with surveys of up to $\sim 1,000$ sources, one could apply for telescope time and obtain an optical spectrum for each one of them to identify the whole sample. Nowadays, we have to deal with huge surveys (e.g., the Sloan Digital Sky Survey [SDSS[2]], the Two Micron All Sky Survey [2MASS[3]], the Massive Compact Halo Object [MACHO[4]] survey), reaching (and surpassing) the 100 million objects. Even at, say, 3,000 spectra at night, which is only feasible with the most efficient multi-object spectrographs and for relatively bright sources, such surveys would require more than 100 years to be completely identified, a time which is clearly much longer than the life span of the average astronomer! But even taking a spectrum might not be enough to classify an object. We are in fact reaching

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[2] `http://www.sdss.org/`

[3] `http://www.ipac.caltech.edu/2mass/`

[4] `http://wwwmacho.anu.edu.au/`

fainter and fainter sources, routinely beyond the typical identification limits of the largest telescopes available (approximately 25 magnitude for 2 - 4 hour exposures), which makes "classical" identification problematic. These very large surveys are also producing a huge amount of data: it would take more than two months to download at 1 Mbytes/s (a very good rate for most astronomical institutions) the Data Release 3 (DR3[5]) SDSS images, about a month for the catalogues. The images would fill up $\sim$ 1,300 DVDs ($\sim$ 650 if using dual-layer technology). And the final SDSS will be about twice as large as the DR3. These data, once downloaded, need also to be analysed, which requires tools which may not be available locally and, given the complexity of astronomical data, are different for different energy ranges. Moreover, the breathtaking capabilities and ultra-high efficiency of new ground- and space-based observatories have led to a "data explosion", with astronomers world-wide accumulating more than one Terabyte of data per night (judging from some of the talks at this conference, this is very likely to be an underestimate). For example, the European Southern Observatory (ESO)/Space Telescope European Coordinating Facility (ST-ECF) archive is predicted to increase its size by two orders of magnitude in the next eight years or so, reaching $\approx 1,000$ Terabytes. Finally, one would like to be able to use all of these data, including multi-million-object catalogues, by putting this huge amount of information together in a coherent and relatively simple way, something which is impossible at present.

All these hard, unescapable facts call for innovative solutions. For example, the observing efficiency can be increased by a clever pre-selection of the targets, which will require some "data-mining" to characterise the sources' properties before hand, so that less time is "wasted" on sources which are not of the type under investigation. One can expand this concept even further and provide a "statistical" identification of astronomical sources by using all the available, multi-wavelength information without the need for a spectrum. The data-download problem can be solved by doing the analysis where the data reside. And finally, easy and clever access to all astronomical data worldwide would certainly help in dealing with the data explosion and would allow astronomers to take advantage of it in the best of ways.

## 2. The Virtual Observatory

The name of the solution is the Virtual Observatory (VO). The VO is an innovative, evolving system, which will allow users to interrogate multiple data centres in a seamless and transparent way, to make the best use of astronomical data. Within the VO, data analysis tools and models, appropriate to deal also with large data volumes, will be made more accessible. New science will be enabled, by moving Astronomy beyond "classical" identification with the characterisation of the properties of very faint sources by using all the available information. All this will require good communication, that is the adoption of common standards and protocols between data providers, tool users and developers. This is being defined now using new international standards for data access and mining

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[5] `http://www.sdss.org/dr3/`

protocols under the auspices of the recently formed International Virtual Observatory Alliance (IVOA[6]), a global collaboration of the world's astronomical communities.

One could think that the VO will only be useful to astronomers who deal with colossal surveys, huge teams and Terabytes of data! That is not the case, for the following reason. The World Wide Web is equivalent to having all the documents of the world inside one's computer, as they are all reachable with a click of a mouse. Similarly, the VO will be like having all the astronomical data of the world inside one's desktop. That will clearly benefit not only professional astronomers but also anybody interested in having a closer look at astronomical data. Consider the following example: imagine one wants to find *all* the observations of a given source available in *all* astronomical archives in a given wavelength range. One also needs to know which ones are in raw or processed format, one wants to retrieve them and, if raw, one wants also to have access to the tools to reduce them on-the-fly. At present, this is extremely time consuming, if at all possible, and would require, even to simply find out what is available, the use a variety of search interfaces, all different from one another and located at different sites. The VO will make all this possible very easily.

## 3. The VO in Europe and the Astrophysical Virtual Observatory

The status of the VO in Europe is very good. In addition to seven current national VO projects, the European funded collaborative Astrophysical Virtual Observatory initiative (AVO[7]) is creating the foundations of a regional scale infrastructure by conducting a research and demonstration programme on the VO scientific requirements and necessary technologies. The AVO has been jointly funded by the European Commission (under the Fifth Framework Programme [FP5]) with six European organisations participating in a three year Phase-A work programme. The partner organisations are ESO in Munich, the European Space Agency, AstroGrid (funded by PPARC as part of the United Kingdom's E-Science programme), the CNRS-supported Centre de Donnees Astronomiques de Strasbourg (CDS) and TERAPIX astronomical data centre at the Institut d'Astrophysique in Paris, the University Louis Pasteur in Strasbourg, and the Jodrell Bank Observatory of the Victoria University of Manchester. The AVO is the definition and study phase leading towards the Euro-VO - the development and deployment of a fully fledged operational VO for the European astronomical research community. A Science Working Group was also established to provide scientific advice to the project.

The AVO project is driven by its strategy of regular scientific demonstrations of VO technology, held on an annual basis in coordination with the IVOA. For this purpose progressively more complex AVO demonstrators are being constructed. The current one, a downloadable Java application, is an evolution of Aladin ([O5-2] this volume), developed at CDS, and has become a set of various software components, provided by AVO and international partners, which allows

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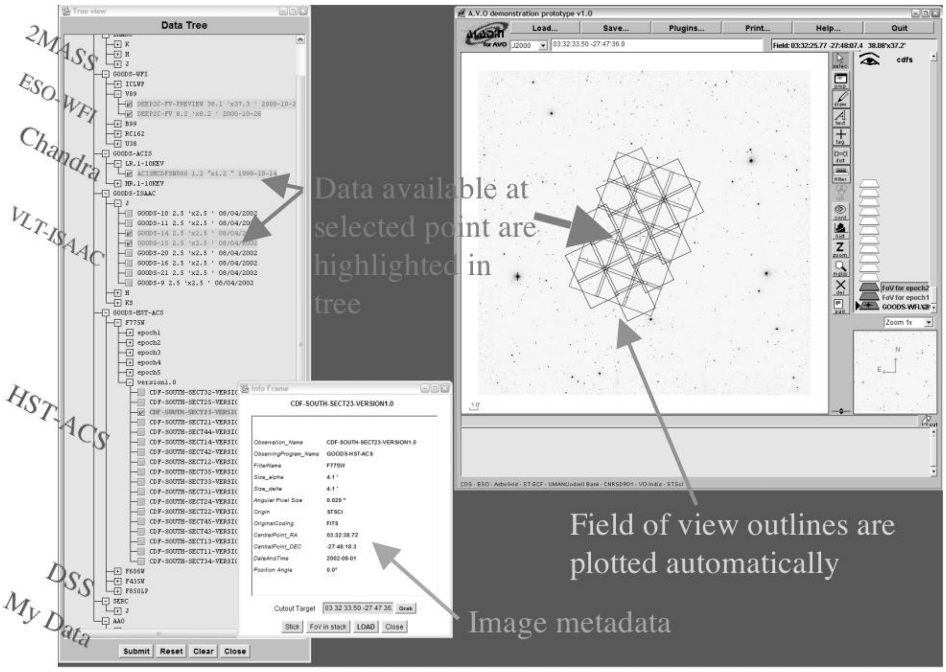
[6] `http://ivoa.net`

[7] `http://www.euro-vo.org`



Data available at selected point are highlighted in tree

Field of view outlines are plotted automatically

Image metadata

CDF-SOUTH-SECT23-VERSION1.0

Observation_Name CDF-SOUTH-SECT23-VERSION1.0
ObservingProgram_Name GOODS-HST-ACS
FilterName F775W
Size_alpha 4.1 '
Size_delta 4.1 '
Angular Pixel Size 0.029 "
Origin STSCI
OriginalCoding FITS
CentralPoint_RA 03:32:38.72
CentralPoint_DEC -27:48:18.3
DateAndTime 2002-08-01
Position Angle 0.0°

Cutout Target 03 32 33.50 -27 47 36.

Figure 1. The AVO prototype in action. An ESO/WFI image of the GOODS southern field, overlaid with the HST/ACS data field of view outlines. The "data-tree" on the left shows the images available in the Aladin image server. Data available at selected coordinates get highlighted in the tree. Metadata information is also accessible. The user's own data can also be loaded into the prototype. This is based on the use of IVOA agreed standards, namely the Data Model, descriptive Metadata, and data interchange standards.

relatively easy access to remote data sets, manipulation of image and catalogue data, and remote calculations in a fashion similar to remote computing (see Fig. 1).

## 4. Doing Science with the AVO

The AVO held its second demonstration, 'AVO 1st Science', on January 27 - 28, 2004 at ESO. The demonstration was truly multi-wavelength, using heterogeneous and complex data covering the whole electromagnetic spectrum. These included: MERLIN, VLA (radio), ISO [spectra and images] and 2MASS (infrared), USNO, ESO 2.2m/WFI and VLT/FORS [spectra], and HST/ACS (optical), XMM and Chandra (X-ray) data and catalogues. Two cases were dealt with: an extragalactic case on obscured quasars, centred around the Great Observatories Origin Deep Survey (GOODS) public data, and a Galactic scenario on the classification of young stellar objects.

The extragalactic case was so successful that it turned into the first published science result fully enabled via end-to-end use of VO tools and systems, the discovery of $\sim$ 30 high-power, supermassive black holes in the centres of apparently normal looking galaxies.

## 5. Discovering optically faint, obscured quasars with VO tools

How did we get a scientific paper out of a science demonstration? The extragalactic science case revolved around the two GOODS fields (Giavalisco et al. 2004a, [O3-1] this volume), namely the Hubble Deep Field-North (HDF-N) and the Chandra Deep Field-South (CDF-S), the most data-rich, deep survey areas on the sky. Our idea was to use the AVO prototype to look for high-power, supermassive black holes in the centres of apparently normal looking galaxies.

Black holes lurk at the centres of active galaxies (AGN) surrounded by dust which is thought to be, on theoretical and observational grounds (see, e.g., Urry & Padovani 1995; Jaffe et al. 2004), distributed in a flattened configuration, torus-like. When we look down the axis of the dust torus and have a clear view of the black hole and its surroundings these objects are called “type 1” AGN, and display the broad lines (emitted by clouds moving very fast close to the black hole) and strong UV emission typical of quasars. “Type 2” AGN, on the other hand, lie with the dust torus edge-on as viewed from Earth so our view of the black hole is totally blocked by the dust over a range of wavelengths from the near-infrared to soft X-rays. The optical/UV spectrum of type 2 AGN is characterized by emission lines much narrower than those of quasars, as they are emitted by clouds which are further away and therefore move more slowly.

While many dust-obscured low-power black holes, the Seyfert 2s, have been identified, until recently few of their high-power counterparts were known. This was due to a simple selection effect: when the source is a low-power one and therefore, on average, closer to the observer, one can very often detect some features related to narrow emission lines on top of the emission from the host galaxy, which qualify it as a type 2 AGN. But when the source is a high-power one, a so-called QSO 2, and therefore, on average, further away from us, the source looks like a normal galaxy. Until very recently, QSO 2s were selected against by quasar surveys, most of which were tuned to find objects with very strong UV emission. The situation has changed with the advent of Chandra and XMM-Newton, which are providing a sensitive window into the hard X-ray emission of AGN.

### 5.1. The Method

The two key physical properties that we use to identify type 2 AGN candidates are that they be obscured, and that they have sufficiently high power to be classed as an AGN and not a starburst. Our approach was to look for sources where nuclear emission was coming out in the hard X-ray band, with evidence of absorption in the soft band, a signature of an obscured AGN, and the optical flux was very faint, a sign of absorption. One key feature was the use of a correlation discovered by Fiore et al. (2003) between the X-ray-to-optical ratio and the X-ray power, which allowed us to select QSO 2s even when the objects were so faint that no spectrum, and therefore no redshift, was available.

We selected absorbed sources by using the Alexander et al. (2003) X-ray catalogues for the two GOODS fields, which provide counts in various X-ray bands. We define the hardness ratio $HR = (H - S)/(H + S)$, where $H$ is the hard X-ray counts ($2.0 - 8.0$ keV) and $S$ is the soft X-ray counts ($0.5 - 2.0$ keV). Szokoly et al. (2004) have shown that absorbed, type 2 AGN are characterized by $HR \geq -0.2$. We adopt this criterion and identify those sources which have $HR \geq -0.2$ as absorbed sources. We find 294 (CDF-S: 104, HDF-N: 190) such absorbed sources which represent $35^{+3}_{-2}\%$ of the X-ray sources in the Alexander catalogues. Note that increasing redshift makes the sources softer (e.g., at $z = 3$ the rest-frame $2 - 8$ keV band shifts to $0.5 - 2$ keV) so our selection criterion will mistakenly discard some high-z type 2 sources, as pointed out by Szokoly et al. (2004). The number of type 2 candidates we find has therefore to be considered a lower limit.

The optical counterparts to the X-ray sources were selected by cross-matching the absorbed X-ray sources with the GOODS ACS catalogues (29,599 sources in the CDF-S, 32,048 in the HDF-N). We used version v1.0 of the reduced, calibrated, stacked, and mosaiced images and catalogues as made available by the GOODS team[8]. The GOODS catalogues contain sources that were detected in the $z$-band, with $BVi$ photometry in matched apertures (Giavalisco et al. 2004b).

We initially searched for optical sources that lay within a relatively large threshold radius of $3.5''$ (corresponding to the maximal $3\sigma$ positional uncertainty of the X-ray positions) around each X-ray source. This was done using the cross match facility in the AVO prototype tool using the “best match” mode. Since the $3.5''$ radius is large relative to the median positional error, and given the optical source density the initial cross match inevitably includes a number of false and multiple matches. To limit our sample to good matches, we use the criterion that the cross match distance be less than the combined optical and X-ray $3\sigma$ positional uncertainty for each individual match. Applying this distance/error $< 1$ criterion we limit the number of matches to 168 (CDF-S: 65, HDF-N: 103). These matches are all within a much smaller radius than our initial $3.5''$ threshold, with most of the distance/error $< 1$ matches being within $1.25''$ (and two matches at 1.4 and $1.5''$). The estimated number of false matches we expect to have is small, between 8 and 15%.

Previously classified sources and their spectroscopic redshifts are available from Szokoly et al. (2004) for the CDF-S and Barger et al. (2003) for the HDF-N. Derivation of X-ray powers for these objects is straightforward[9]. For the unclassified sources we estimated the X-ray power as follows: we first derived the $f(2 - 10keV)/f(R)$ flux ratio (converting the ACS $i$ magnitudes to the $R$ band), and then estimated the X-ray power from the correlation found by Fiore et al. (2003), namely $\log L_{2-10} = log f(2 - 10keV)/f(R) + 43.05$ (Fiore, p.c.; see their Fig. 5). Note that this correlation has an r.m.s. of $\sim 0.5$ dex in X-ray power. We stress that our estimated X-ray powers reach $\sim 10^{45}$ erg/s and

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[8] `http://www.stsci.edu/science/goods/`

[9] Throughout this paper we adopt a cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\rm M} = 0.3$, and $\Omega_\Lambda = 0.7$

therefore fall within the range of the Fiore et al. (2003) correlation. On the other hand it should be pointed out that our sources are much fainter than the objects which have been used to calibrate the Fiore et al.'s correlation.

The work of Szokoly et al. (2004) has shown that absorbed, type 2 AGN are characterized by $HR \geq -0.2$. It is also well known that normal galaxies, irrespective of their morphology, have X-ray powers that reach, at most, $L_{\rm x} \lesssim 10^{42}$ erg/s (e.g., Forman, Jones & Tucker 1994; Cohen 2003). Therefore, any X-ray source with $HR \geq -0.2$ and $L_{\rm x} > 10^{42}$ erg/s should be an obscured AGN. Furthermore, following Szokoly et al. (2004), any such source having $L_{\rm x} > 10^{44}$ erg/s will qualify as a type 2 QSO.

### 5.2. Results

Out of the 546 X-ray sources in the GOODS fields, 203 are absorbed ($HR \geq -0.2$). Out of these we selected 68 type 2 AGN candidates, 31 of which qualify as QSO 2 (estimated X-ray power $> 10^{44}$ erg/s). We note that the distribution of estimated X-ray power covers the range $5 \times 10^{42} - 2 \times 10^{45}$ erg/s and peaks around $10^{44}$ erg/s (see Fig. 2). The number of QSO 2 candidates, therefore, is very sensitive to the dividing line between low- and high-luminosity AGN, which is clearly arbitrary and cosmology dependent. For example, if one defines as QSO 2 all sources with $L_{2-10} > 5 \times 10^{43}$ erg/s, a value only a factor of 2 below the commonly used one and corresponding to the break in the AGN X-ray luminosity function (Norman et al. 2002), the number of such sources increases by $\sim 50\%$. We also note that, based on the r.m.s. around the Fiore et al. (2003) correlation, the number of QSO 2 candidates fluctuates in the $13 - 54$ region. The number of type 2 AGN, on the other hand, can only increase, as all our candidates have estimated $\log L_{2-10} > 42.5$.

Our work brings to 40 the number of QSO 2 in the GOODS fields, an improvement of a factor $\sim 4$ when compared to the only nine such sources previously known. As expected, being still unidentified, our sources are very faint: their median ACS $i$ magnitude is $\sim 25.5$, which corresponds to $R \sim 26$ (compare this to the $R \sim 22$ typical of the CDF-S sources with redshift determination). The QSO 2 candidates are even fainter, with median $i$ magnitude $\sim 26.3$ ($R \sim 26.8$). Therefore, spectroscopical identification is not possible, for the large majority of objects, even with the largest telescopes currently available. We have used our estimated X-ray powers together with the observed fluxes to derive redshifts for our type 2 candidates (tests we have performed on the type 2 sources with spectroscopic redshifts show that this method, although very simple, is relatively robust). Our type 2 AGN are expected to be at $z \approx 3$, while our QSO 2 should be at $z \approx 4$. By using VO methods we are sampling a region of redshift - power space so far much harder to reach with classical methods. For the first time, we can also assess how many QSO 2 there are down to relatively faint X-ray fluxes. We find a surface density $> 330$ deg$^{-2}$ for $f(0.5 - 8keV) \geq 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, higher than previously estimated.

Fig. 2 shows the X-ray power distribution for our new type 2 AGN candidates (dashed line), previously known type 2 AGN (solid line), and the combined sample (dotted line). It is interesting to note how the distributions are very different, with the already known type 2 AGN peaking around $L_{\rm x} \sim 10^{43}$ erg/s and declining for luminosities above $\sim 3 \times 10^{43}$ erg/s, while our new candidates are

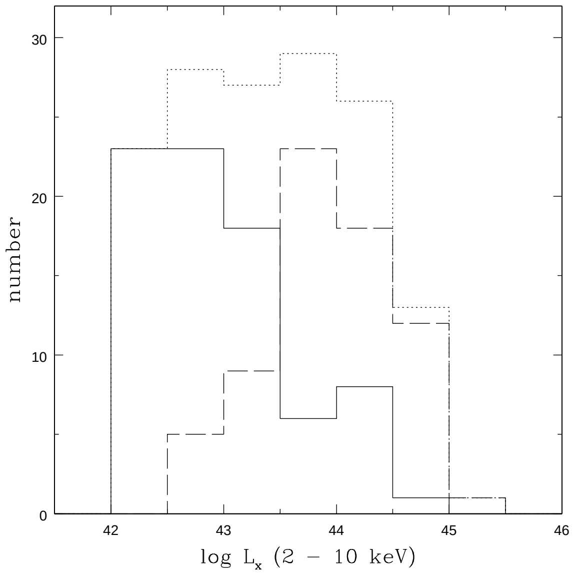

Figure 2. The X-ray power distribution for our new type 2 AGN candidates (dashed line), previously known type 2 AGN (solid line), and the sum of the two populations (dotted line). QSO 2 are defined, somewhat arbitrarily, as having $L_{2-10\mathrm{keV}} > 10^{44}$ erg/s.

rising in this range and peak around $L_\mathrm{x} \sim 10^{44}$ erg/s. To be more quantitative, while only $\sim 1/5$ of already known type 2 AGN have $\log L_\mathrm{x} > 43.5$, $\sim 3/4$ of our candidates are above this value. This difference is easily explained by our use of the X-ray-to-optical flux ratios to estimate X-ray powers and by the fact that our candidates are on average $\sim 3$ magnitudes fainter than previously known sources. Our method is then filling a gap in the luminosity distribution, which becomes almost constant in the range $10^{42} \lesssim L_\mathrm{x} \lesssim 3 \times 10^{44}$ erg/s. This also explains the fact that the number of QSO 2 candidates we find is $\gtrsim 3$ times larger than the previously known ones.

The identification of a population of high-power obscured black holes and the active galaxies in which they live has been a key goal for astronomers and will lead to greater understanding and a refinement of the cosmological models describing our Universe. The paper reporting these results has been recently published (Padovani et al. 2004).

The AVO prototype made it much easier to classify the sources we were interested in and to identify the previously known ones, as we could easily integrate all available information from images, spectra, and catalogues at once. This is proof that VO tools have evolved beyond the demonstration level to become respectable research tools, as the VO is already enabling astronomers to reach into new areas of parameter space with relatively little effort.

The AVO prototype can be downloaded from the AVO Web site[10]. We encourage astronomers to download the prototype, test it, and also use it for their own research. For any problems with the installation and any requests, questions, feedback, and comments you might have please contact the AVO team at twiki@euro-vo.org. (Please note that this is still a prototype: although some components are pretty robust some others are not.)

## 6. Near Future AVO Science Developments

The AVO is promoting science with VO tools through two further developments: a Science Reference Mission and the next science demonstration.

### 6.1. The AVO Science Reference Mission

The AVO team, with input from the Science Working Group, is putting together a Science Reference Mission. This will define the key scientific results that the full-fledged EURO-VO should achieve when fully implemented and will consist of a number of science cases covering a broad range of astronomical topics, with related requirements, against which the success of the EURO-VO will be measured.

### 6.2. The next AVO Science Demonstration

The next and last AVO science demonstration is to be held in January 2005 at the European Space Astronomy Centre (ESAC; formerly known as VILSPA). Preparations are still on-going so the details are not fully worked out yet but it is firmly established that we will be dealing with two scenarios. The first, on star formation histories in galaxies, will revolve around the European Large-Area ISO Survey (ELAIS), which covers five different areas of the sky over $\sim 10$ deg$^2$. The second, on the transition from Asymptotic Giant Branch to Planetary Nebulae, will be the strongest one on the science side and should produce a new list of stars in this very interesting transitional phase.

On the technical side, the science demonstration will see the rollout of the first version of the EURO-VO portal, through which European astronomers will gain secure access to a wide range of data access and manipulation capabilities. Also, we will demonstrate the use of distributed workflows, registry harvesting, and the wrapping of sophisticated astronomical applications as Web services.

The AVO demonstration will also mark the transition from the AVO to the EURO-VO. Funding for the technology part of the EURO-VO, VO-TECH, has been secured from the European Community at a level of 6.6 million Euros, which will translate into 12 Full Time Equivalent (FTEs). Twelve more FTEs will be provided by the partners, which include Edinburgh, Leicester, and Cambridge in the UK, ESO, CDS, and INAF in Italy.

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[10] `http://www.euro-vo.org/twiki/bin/view/Avo/SwgDownload`

## 7. Summary

The main results of this paper can be summarized as follows:

- The Virtual Observatory is happening because it has to! If it does not, we will not be able to cope with the huge amount of data astronomers are being flooded with.
- Astronomy can and *is being* done with Virtual Observatory tools, which are now mature enough. Real science results are being produced and papers are being published.
- The Astrophysical Virtual Observatory, soon to be EURO-VO, is committed to the pursuit of science with Virtual Observatory tools through scientific demonstrations, science papers, and a Science Reference Mission.

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