MULTI-WAVELENGTH SPECTROSCOPY REQUIREMENTS

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ABSTRACT

How useful are existing Virtual Observatory standards and models for comparing multi-wavelength data? We outline some science use cases involving spectral energy distributions from radio to X-ray and see whether the VO can provide access to the required data and tools and, if so, whether they are easy to find and use. We look at the requirements for handling radio data in more detail, including data cubes, polarisation, and the use of high-resolution maser spectra to investigate circumnuclear material in distant galaxies.

Key words: Techniques: interferometric; Virtual Observatory.

1. INTRODUCTION

Virtual Observatories should allow astronomers to use data from any source even if they are not a specialist in that area, for example to allow a radio astronomer to compare their data with optical, IR and X-ray data. The resulting Spectral Energy Distributions (SEDs) should at least allow the user to establish quickly which sources are worth persevering with. The minimum requirements are that VO resources should be well-described and easy to find. We test some of the science cases developed by AstroGrid[1] and VOTech[2] (part of Euro-VO) against these criteria. We also look at current topics of interest and tools available via VO to examine and manipulate radio data.

2. ASTROGRID AND VOTECH SCIENCE CASES

2.1. Identifying massive stars

The VOTech Science Reference Mission (Walton et al., 2007) includes investigating the high-mass stellar initial mass function, whilst an AstroGrid science driver involves investigating the Gould Belt, an arc of comparatively recent star formation around the Sun. Hot, massive stars (> 10 $M_\odot$) can be identified by their UV/optical spectral energy distribution and luminosity, which is easy to determine for objects in clusters at known distances. Younger stars may still be embedded in the remnants of star-forming molecular clouds, such as HII regions. The data should have arcsec resolution or better, to avoid confusion and should not have saturation problems since many objects are very bright (conversely, high sensitivity is not an issue).

We used Vizier and AstroScope (Walton & Astrogrid Consortium, 2006) to obtain INT-WFS and 2MASS data for candidate clusters, converted to physical units and displayed using TOPCAT[3] in Fig. 1. AstroGrid is developing a service to allow you to send a list of objects as a series of queries to a catalogue or image archive. Libraries of common band properties are being built up for access via VOSpec[4] (described elsewhere in these proceedings) and STILTS[5]. VOSpec and Aladin provide interactive tools for dereddening and astrometry, respectively. The SVO provides a library of Kurucz and other stellar models (used in Fig. 1) and AstroGrid plans to wrap the Mocassin (Ercolano et al., 2005) radiative transfer code.

VO services make it much faster to find useful data and to display SEDs once constructed in VOSpec or TOPCAT, but some steps have to be performed manually, mostly arising from residual observational peculiarities. The YAFit[6] tool provides a quick way to compare multiple models and constructed SEDs using χ^2 minimisation or other fitting algorithms.

2.2. High-redshift starburst galaxies and AGN

The first VO science paper (Padovani et al., 2004) identified 68 obscured AGN in the GOODS fields. Richards et al. (2007, A&A) followed this up by comparing ra-

[1] http://www.astrogrid.org
[2] http://eurovotech.org/
[3] http://www.starlink.ac.uk/topcat
[4] http://esavo.esa.int/vospec/
[5] http://www.starlink.ac.uk/stilts
[6] http://www.star.bris.ac.uk/ mbt/yafit/

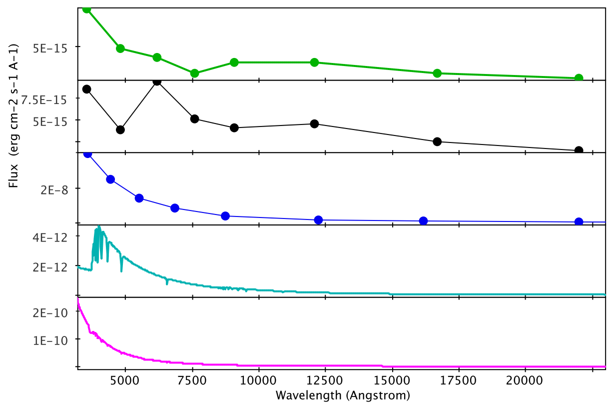

Figure 1. Comparison of SEDs in TOPCAT, obtained by cross-matching SDSS and 2MASS (top 2), from Vizier (Sirius) and from the SVO Kurucz models (bottom 2).

dio (MERLIN+VLA) and X-ray (*Chandra*) data, finding that most of the radio counterparts are high-redshift starbursts. VO services such as Vizier, AstroScope, TOPCAT VOSpec and Aladin were invaluable in finding, cross-matching, applying algorithms to and displaying tabular data, and qualitative comparisons of images. The PLASTIC[7] protocol enables you to transfer data between tools or select points simultaneously. The full goal is a VO service to construct the full radio-IR-optical-X-ray SED including upper limits and to provide template fitting for high-redshift galactic classification and distance estimates. An image cutout service (at user-specified resolution) for MERLIN+VLA HDF(N) images will be published this Autumn and a radio source extraction service is under development.

3. FINDING TOOLS AND DATA

3.1. IVOA metadata standards

The IVOA Resource Metadata standard (Hanisch , 2007) summarises how publishers should describe data collections, tools and services, including the coverage along spatial, spectral and temporal axes and a self-assessment of the calibration status. Unfortunately, most of the data published to the VO is not described adequately even by the simplest Registry standards. The Euro-VO is investigating how best to offer support and motivation, through Data Centre Alliance (DCA) initiatives such as this conference. The IVOA also provides standard protocols for retrieving spectra, images and so on, including the Simple Spectral Access Protocol (Tody & Dolensky 2005; see also Tody, these proceedings).

[7]http://plastic.sourceforge.net/

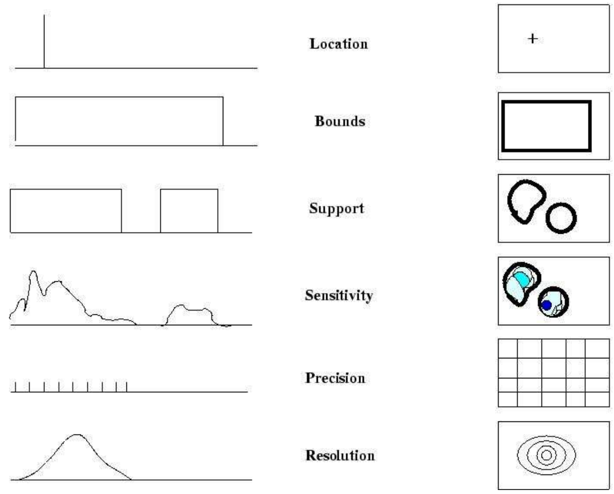

Figure 2. The IVOA data models provide for increasing (optional) levels of detail to allow all kinds of spectral data to be described (courtesy McDowell).

3.2. Development of data models

More detailed models are under development such as the Spectrum Data Model (McDowell , 2007), which are designed to allow intelligent tools to, for example, associate relevant calibration tables or manipulation tools with specific data. The Characterisation model (McDowell et al., 2007) is hierarchical and extensible; increasing levels of detail for spectral or spatial coverage are illustrated in Fig. 2. It can be used to describe complex data, for example, radio interferometry visibilities which could be used to produce images at a range of sizes/resolutions, spectra or even time series from the same calibrated data set. Most astronomers do not naturally think in *uv*-plane spatial frequencies, so the observation is described in terms of minimum and maximum beam sizes, spectral resolution and so on, illustrated in Table 1. These form part of the family of IVOA data models which should eventually be able to provide an astronomer (or an intelligent tool) with the location not only of the data, but of tables of appropriate line rest frequencies and a method to convert these to velocities in the required convention.

The better the data are described, the more effectively a science user should be able to track down data they may not even have known existed. This can be problematic, as the quantity of astronomical data generated increases exponentially with time and a query to AstroScope with a search radius of less than an arcmin can return hundreds of matching datasets. The AstroGrid VOExplorer (Fig. 3) solves this by offering pre-selection by several metadata fields and data types before retrieving the data or sending them to tools.

Table 1. IVOA data model describing the spectral products available from calibrated visibility data for Markarian 273.

Axis	Spatial	Temporal	Spectral	Observable
Frame/Units	ICRF, deg.	MJD	MHz	Jy/beam
Location	13.12 +55.98	50613.5	1600	undef
Bounds	12.92, +55.58, 13.32, +56.38	50613.0, 50614.0	1592, 1608	0.0002, 0.5
Support	12.92, +55.58, 13.32, +56.38	(URL for scan listing)	1593, 1607	undef
Sensitivity	f(support, primary beam)	undef	(URL for bandpass table)	1
Fill Factor	1	0.7	0.93	undef
Resolution	0.2, 2.0, 0.2, 2.0 arcsec	5 m	125 kHz 0.05, 0.1	
Sampling	0.04, 0.625, 0.04, 0.625 arcsec	16 s	125 kHz	undef

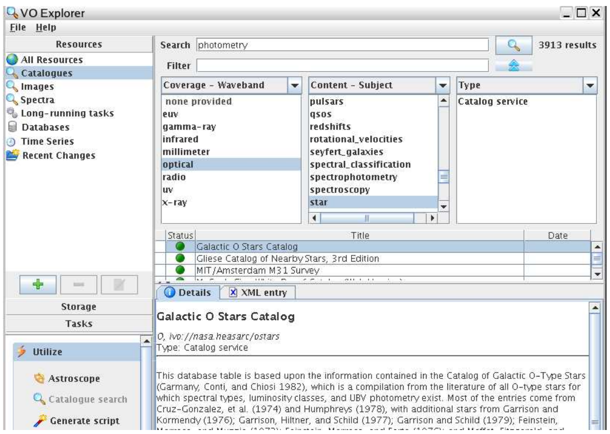

Figure 3. The AstroGrid VOExplorer

4. FORTHCOMING MASER SCIENCE CASES

Hydroxyl masers show Zeeman splitting in the presence of a magnetic field. This is well-resolved in Galactic star-forming regions but the first extra-galactic measurements have only just been reported (Robishaw & Heiles, in prep.). OH mega-masers are too weak to be simultaneously spatially and spectrally resolved. The observations of Markarian 273 described in Table 1 have a spatial resolution equivalent to ≈ 85 pc, but a spectral resolution as coarse as 23 km s^{-1}. Single-dish observations using the Arecibo telescope are sensitive enough to achieve spectral channels < 1 km s^{-1} at the expense of spatial resolution. Both types of data must be compared to decompose the spectrum into spatially distinct components and this to investigate the magnetic field as a function of distance from the galactic nucleus. The VO has an obvious rôle to play in locating high spatial resolution data to go with future detailed spectra.

Miyoshi et al. (1995) discovered water masers orbiting in a sub-pc Keplerian disc around the AGN in NGC 4258 (Fig. 4). Maser proper motions were measured with μ-arcsec accuracy with Very Long Baseline Interferometry; coupled with high spectral resolution acceleration measurements, this lead to very precise measurements of the central mass (such that it could only be a black hole) and the distance to the galaxy. Many years later, new candidates have been identified (Braatz et al. in prep.; Darling & Giovanelli 2002). A full analysis requires multi-wavelength continuum observations (radio VLBI, *HST*, *Spitzer* etc.) in order to investigate the distribution of mass (since the AGN core is often embedded in dense star-formation), the accretion-jet ejection relationship (black hole feeding) and other exciting phenomena.

5. GETTING AT RADIO (AND OTHER) SPECTRAL DATA AND PRODUCTS

VO tools to manipulate 1-D spectra have been well described elsewhere in these Proceedings. Radio and (sub-) mm data are often in the form of 3-dimensional cubes. These can be viewed using Aladin or Gaia, both PLASTICised tools but the full range of operations (e.g. creating moment maps) are not available or not fully suitable. Such generic tools are invaluable for a quick look at data, but interferometry data cubes are best handled by specialised software.

Fig. 5 shows a VO interface for radio image extraction (Richards et al., 2006a,b). A similar service, also using non-jargon inputs, will be developed for spectral data products. These services are possible thanks to parselTongue Kettenis et al. (2006), a python-based scripting language developed by RadioNet[8] which runs classic AIPS. As python-based interfaces to more and more astronomical packages are being developed (e.g. CASA[9], GILDAS and MIRIAD (Pety et al., 2004), Pyraf[10]), interoperability will improve.

6. SUMMARY

Many of the most important questions in astronomy today require the use of either high resolution spectral line

[8] http://www.radionet-eu.org
[9] http://aips2.nrao.edu/daily/docs/casa.html
[10] http://www.stsci.edu/resources/software_hardware/pyraf

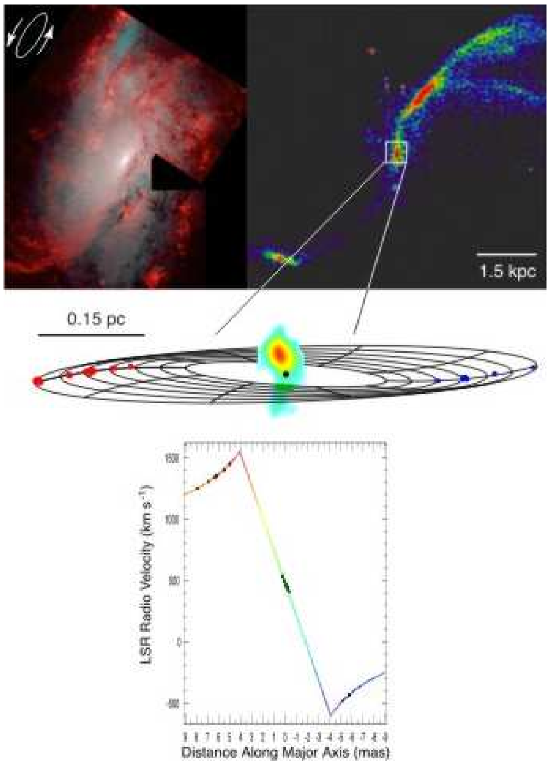

Figure 4. Optical, IR, radio continuum and water maser emission from NGC 4258 (NRAO/L Greenhill.)

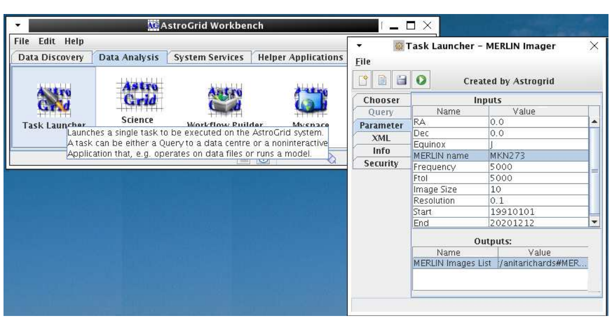

*Figure 5. The MERLINImager in the AstroGrid workbench. This provides a non-jargon interface to a parselTongue/*AIPS *pipeline.*

observations, or spectral energy distributions from radio to X-ray wavelengths. Other papers in these proceedings describe the wealth of data which are potentially available. The development of AstroGrid and the Euro-VO is driven by science cases, many of which require spectral data, such as refining the IMF of massive stars. Recent developments in radio interferometry and spectroscopy include the possibility of measuring the magnetic field within a few hundred pc of active galaxies where the OH masers show Zeeman splitting, and very accurately constraining the mass, distance and other parameters of black holes in AGN using water maser data. Both scenarios require comparisons between data taken at multiple wavelengths and resolutions. We encourage the publication of data using IVOA standards, and the development of VO-interoperable tools to construct SEDs and compare data with models.

Current problems and possible solutions include:

- Data providers need easy tools to help publish properly-described data, with the help of the DCA.
- Some data are in domain-specific formats (for example optical magnitudes), requiring special tools to convert to physical units.
- The VO should be able to provide flexible or on-demand data products – for example extracting spectra in given apertures from a data cube, and friendly interfaces to specialised software maintained by specialised data centres.

This meeting has been a step towards solving these problems by establishing the needs of spectral data providers and users.

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