New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000178

Spectroscopic Surveys

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Invited Talk

Abstract. Surveys, surveys, and yet more surveys! During the last decade we have all witnessed a flourishing of imaging and spectroscopic surveys, of different sizes and over different areas of the sky. Although initially set-up for specific scientific goals, they should all share a multi-purpose flavour that can boost their impact and their exploitation by the scientific community. There are, however, fields that need more dedicated observing strategies, coordination and possibly data infrastructure in order to exploit fully these huge datasets. Time-domain astronomy is one of them. In the following, I will review the very recent developments in spectroscopic surveys, and I will report on what ESO has been involved in and has committed itself to do.

Keywords. surveys, instrumentation: spectrographs, techniques: spectroscopic, Galaxy: general, Galaxy: abundances, Galaxy: kinematics and dynamics

1. Introduction

It is not really surprising that astronomy is shifting towards larger and larger projects, involving larger and larger teams. The community has voiced the need to "go big" in several instances. The projects are usually set up to answer specific astrophysical questions, they are granted large amounts of telescope time, and produce an almost overwhelming amount of data. While on the one hand this may mean that telescope time available for small-scale projects is shrinking, on the other hand it usually has the advantage of allowing for the exploitation of a lot of data for other scientific goals. Furthermore, be it a decadal survey or a roadmap exercise, the very top guidelines for future astronomical infrastructures always include some recommendation for surveys and survey facilities.

Back in 2008, the report from the 4$^{\rm th}$ ESA/ESO Working Group† (WG for short) on "Galactic populations, chemistry and dynamics", delivered a set of recommendations heavily clustered around the need for survey facilities (Turon *et al.* 2008). The WG recommended to both organisations that they ensure a leading role for Europe in the exploitation of Gaia data. This was translated into a requirement for spectroscopy of selected samples of Gaia targets before the mission, and specific spectroscopic follow-ups after it. To ESO alone, the WG recommended the investigation of possible ways to build a blue multiplexed spectrograph (>100 fibres, R∼20-30,000, on a 4-m/8-m telescope) and an IR multiplexed spectrograph (>500 fibres, similar resolution) on a 4-m telescope.

When it comes to time-domain astronomy, coordination and complementarity among different instruments/facilities is one of the keys for success. Telescopes and instruments need to be coordinated, to react rapidly to triggers, and to be complementary across the energy spectrum. Most large facilities already have a "Target of Opportunity" observing

† In 2003, following an agreement to cooperate on science planning issues, the European Space Agency and the European Southern Observatory decided to establish a number of working groups that would be tasked to explore synergies in important areas of mutual interest and to make recommendations to both organisations.

schema in place or even a "Rapid Response Mode"‡, and in the literature one can find more and more reports on how successful those multi-site, multi-instrument campaigns are. However, when looking at large-scale surveys, one immediately realises that the observing strategies implemented and/or the access to the survey data may not always be suited to catching the most extreme and unusual phenomena in the universe.

2. On-Going and Future Spectroscopic Surveys

Even if the scientific goals are clear, implementing and carrying out a survey is always a challenging endeavour. The team of proposers/investigators must define well both observing and the analytical strategies: Do we need a dedicated telescope? Can we execute a survey as a large programme (thus applying for general open time at one or more facilities)? Do we have enough manpower to exploit the data set we will be collecting? On the other hand, especially when the survey is executed by Observatory staff on behalf of the team ("Service Mode" in ESO terminology), one faces a different set of challenges: How and when do we schedule it? How do we optimise its execution, especially when competing with other normal programmes scheduled on the same telescope if not the same instrument? Do we have the tools to monitor its progress properly? Which data products do we deliver, and how? Which (advanced) data products do we want to receive back from the team?

Notwithstanding those challenges, many large spectroscopic surveys have already started, and more will start in the near future. The following summary is meant to give a flavour of what has been going on in recent years, but it is certainly far from complete. Observing strategies that provide easier access to time-domain events (such as multi-epoch observations) are highlighted in *italics*.

• SEGUE: the Sloan Extension for Galactic Understanding and Exploration (parts 1 and 2) was carried out at Apache Point Observatory. SEGUE-1 (Yanny *et al.* 2009) obtained spectra of almost 240,000 stars covering a range of spectral types; SEGUE-2 targeted mostly blue horizontal-branch stars, K giants and M giants (∼120,000). Both surveys have been completed; they cover a total of ∼4500 deg^2 in the northern hemisphere and include 360,000 stars in the magnitude range g = 14.5–23.5) at a resolving power R ∼2,000.

• ARGOS: this is a survey targeting 28,000 K giants in 28 "bulge" fields (PIs: Freeman and Bland-Hawthorn). It uses the multi-fibre AAOmega 2dF spectrograph at the Anglo-Australian Telescope and covers two regions of spectra: 5000–5600 Å (at R ∼3000) and 8400–8800 Å (at R ∼11000). It is close to completion (if not now already completed).

• BRAVA: the Bulge RAdial Velocity Assay (already completed) is a large-scale radial-velocity survey of the Galactic bulge. It has delivered spectra of ∼9,000 M-dwarf stars at R ∼4,000 (Howard *et al.* 2008; 2009).

• RAVE: the Radial Velocity Experiment (PI: Steinmetz) started in 2003 and will run until 2012 with the 6dF multi-fibre spectrograph at the 1.2-m UK Schmidt Telescope of the Anglo-Australian Observatory. The survey is dedicated to the measurement of

‡ See `http://www.eso.org/sci/observing/phase2/SMSpecial/TOOObservation.html` or `http://www.eso.org/sci/observing/phase2/SMSpecial/RRMObservation.html` to learn more about how ESO implements those requests.

https://doi.org/10.1017/S1743921312000178 Published online by Cambridge University Press

radial velocities, metallicities and abundance ratios, thus providing a vast stellar kinematic database for all major components of the Galaxy. As of mid-2011 it had obtained 511,000 observations of stars, *20,000 of which have been observed at different epochs*. The complete survey is supposed to cover 20,000 deg.^{2} in the southern hemisphere. To date, three major data releases have been released (Steinmetz *et al.* 2006, Zwitter *et al.* 2008 and Siebert et al. 2011).

• MARVELS: the Multi-object APO Radial Velocity Exoplanet Large-area Survey (PI: Ge) started in 2008, and is one of the four approved SDSS III large surveys. Its main goal is to monitor the radial velocities of 11,000 bright stars with the precision and frequency needed to detect gas giant planets that have orbital periods ranging from several hours to two years. *All stars will be surveyed 15-20 times/year*. The survey is expected to run until 2014.

• APOGEE: the SDSS III Apache Point Observatory Galactic Evolution Experiment (PI: Majewski) uses the high-resolution, near-infrared multi-fibre spectrograph APOGEE to make a detailed survey of the dynamics and chemistry of the Milky Way, especially at low Galactic latitudes. The survey has just started, and plans to target 100,000 stars. Observations cover the H-band NIR at $R \sim$25–30,000, and *each field is to be surveyed three times to detect binaries and possibly other time-domain objects and events*. There is a strong interest in extending it to the southern hemisphere as well, which may prolong the lifetime of the survey to 2019.

• GALAH: The GALactic Archeology with Hermes survey (PIs: Freeman and Bland-Hawthorn) is due to start in 2013 on the Anglo-Australian Telescope, using the HERMES spectrograph. It will observe high-resolution ($R \sim$28,000) spectra of a million Galactic-disk stars (V$<$14 mag), with S/N $\sim$ 100. It is planned to run for 6 years, to cover the full Galaxy.

3. ESO and Surveys

The European Southern Observatory and its facilities in Chile have also been involved in, and have supported, different types of surveys, both imaging and spectroscopic, but there has clearly been an increased emphasis on this specific activity in recent years.

The precursor of today's on-going ESO Public Surveys (PS) is probably the ESO Imaging Survey (EIS; Project Scientist: Luiz da Costa), which was carried out from 1997 to 2002 on the 2.2-m telescope with the Wide Field Imager. That survey was possibly the first attempt by ESO to run large-scale imaging surveys as a service to the community, i.e, planning the observations, carrying them out, assessing the quality of the images, and reducing and releasing them and preparing the associated catalogues.

Since then, ESO has executed several "Large Programmes", i.e., programmes that are submitted to the time-allocation committee (aka OPC, Observing Proposals Committee) and which require a minimum (though large) number of nights and run over multiple semesters. Apart from sample sizes, the main difference between a Public Survey and a Large Programme is the time-scale over which the raw data are released to the community at large; in the case of a Public Survey the data release is immediate, while in the case of Large Programmes it is usually 12 months after the observations were made. Most of the latter have so far used the FORS and VIMOS instruments, thus combining imaging and multi-object spectroscopy capabilities, but it is certainly worth mentioning the HARPS

https://doi.org/10.1017/S1743921312000178 Published online by Cambridge University Press

Table 1. ESO Public Surveys with a potential for time domain science.

Survey	Area (deg^2)	Depth Measure	Filters and depth
VVV	520	5σ, Vega	Z=21.9, K_s=18.1
VMC	184	10σ, Vega	Y=21.9, K_s=20.3
VHS	20,000	5σ, AB	Y=21.2, K_s=20.0
VPHAS+	1800	10σ, AB	u′/i′=21.8, g′/r′=22.5, Hα=21.6

spectrograph (Mayor *et al.* 2003), which is almost fully dedicated to the search for extra-solar planets.

3.1. *Public Surveys on Survey Telescopes*

As of 2010/11, ESO is operating two survey telescopes on Cerro Paranal: VISTA and VST, equipped respectively with VIRCAM and OmegaCAM imagers. Although these facilities do not offer any spectroscopic capability at the moment, a couple of the public surveys that have been approved for execution over the next years† may have some relevance for exploiting time-domain phenomena. They are the the VISTA Variables in the Via Lactea (VVV) survey (PI: Minniti), and the VISTA Magellanic Survey (VMC, PI: Cioni). VVV targets mainly the Galactic bulge and a part of the adjacent plane, and is *multi-epoch: each "tile" will be covered more than 100 times, spaced over the entire lifetime of the survey.* Its product will be a catalogue of 10^9 objects, of which 10^6 are expected to be variables. VMC focuses on the Magellanic Clouds system, and its observing strategy also includes some *multi-epoch observations to determine the mean magnitude of short-term variables.*

Among the others, the VISTA Hemisphere Survey (VHS, PI: McMahon) and the VST Photometric H-α Survey of the Southern Galactic Plane (VPHAS+, PI: Drew) should be mentioned because they represent an important source of information. VHS will cover the entire Southern Sky, reaching 4 mag—deeper than DENIS and 2MASS. Its final catalogue will offer the possibility for studying low-mass and nearby stars and the merger history of the Galaxy. In contrast, VPHAS+ will map the entire Southern Galactic Plane in order to reconstruct the star-formation history and detailed structure of the Galactic disk. It will produce a catalogue of around 500 $\times 10^6$ objects, which will include greatly enhanced samples of rare evolved massive stars, Be stars, Herbig and T Tau stars, post-AGB stars, compact nebulæ, white dwarfs and interacting binaries. The main characteristics of these surveys in terms of area and depth of measurement are summarised in Table 1.

3.2. *Public Spectroscopic Surveys*

Owing to a strong demand from the astronomical community, the ESO Scientific and Technical Committee made a clear recommendation to ESO back in 2010 April to explore possible ways to implement spectroscopic surveys. In 2010 August, ESO published a Call for Letters of Intent (LoI) regarding all instruments available at the La Silla Paranal Observatory. 24 proposals were received by the deadline (mid-October 2010). A Public Spectroscopic Survey Panel composed of international experts evaluated the 24 LoI, and recommended two of them, which were then invited to submit a full and detailed observing proposal at the Period 88 deadline (end of March, covering the semester 2011 October to 2012 March). After an eventual approval by the Observing Programme Committee, the finalisation of the implementation of these two spectroscopic surveys could commence. The two projects are:

† `http://www.eso.org/sci/observing/policies/PublicSurveys/sciencePublicSurveys.html`

https://doi.org/10.1017/S1743921312000178 Published online by Cambridge University Press

• The Gaia–ESO survey (PIs: Gilmore and Randich), approved on the VLT Kueyen telescope. It will use the multiplex FLAMES instrument (GIRAFFE and FLAMES/UVES modes) for 4 years, with approximately 30 nights allocated per semester. The survey will produce a large database of high-resolution spectra of more than 10^5 stars across the Milky Way galaxy. Among the deliverables, all the spectra will be classified, not only in terms of spectral type and stellar population but also as far as their stellar parameters and chemical characteristics are concerned. The survey will start in January 2012, and will be carried out in classical Visitor Mode.

• The Transient Universe survey (PI: Smartt), approved on the La Silla New Technology Telescope (NTT). It will make use of EFOSC2 and SOFI. The survey aims to *follow-up ∼150 optical transients by securing high-quality, time-series optical and near infrared spectra*. It will cover the full range of parameter space: luminosity, host metallicity and explosion mechanisms. One of the survey deliverables is the *ESO Transient Database* (ETABASE), which will allow the astronomical community to access these extensive datasets of transients.

3.3. *Forward Look*

Today's best strategy for tackling at least some of the top open questions in astrophysics seems to require the availability of moderate to large multi-object spectroscopic facilities (MOS), especially when the requirements are for fundamental Galactic astronomy. Both the Astronet Roadmap (Bode & Monnet 2008) and the ESO/ESA Working Group #4 (Turon *et al.* 2008) explicitly listed the need for MOS capabilities among their top recommendations. It is therefore not surprising that ESO was recently asked by its Scientific and Technical Committee to look into future MOS capabilities. ESO followed the same outline as in the case of the launch of Public Spectroscopic Surveys (Call for Letters of Intent, evaluation of the proposals received and pre-selection of most interesting projects), and selected two projects which are now carrying out their Phase A studies:

• 4MOST, the 4-meter Multi-Object Spectroscopic Telescope, which focuses on the follow-up of very large surveys such as Gaia and eROSITA, and is expected to observed 7×10^6 objects over more than 10,000 deg^2. The initial proposal plans for an installation on the Vista or NTT telescopes. The facility would allow a wavelength coverage of 3700–10000 Å (with some gaps in between), for a multiplex capability of at least 1,500 fibres and a resolution of 3000–5000 or 20,000 (the latter, of course, achievable only with 10-20% of the total fibres).

• MOONS, the Multi-Object Optical and Near-infrared Spectrograph, which focuses on galaxy formation and evolution, large scale structures, high-redshift and Galactic archaeology, though its rather small field of view may be not efficient for Gaia follow-ups. The original proposal is for installation on any of the VLT Unit Telescopes, with a wavelength coverage of 0.8–1.8μ, a multiplex capability of 250 (up to 500) fibres and a resolution of 3000–5,000 or 20,000.

The final decision is expected in 2013.

4. Concluding Remarks

It is hard to believe that today's astronomical community will ever suffer from lack of data! Several large-scale surveys have already been completed, or are on-going, or will start soon. They are usually tailored to answer specific astrophysical questions, but we all agree that it would be a big loss if we were not given the opportunity to exploit those immense datasets for other scientific goals besides the original ones.

https://doi.org/10.1017/S1743921312000178 Published online by Cambridge University Press

In order to achieve that, the fundamental requirement for realising such a goal is a user-friendly interface which makes the data available to the public at large, preferably in a co-ordinated way (e.g. through the Virtual Observatory). Some of the surveys mentioned in this report were (or are) indeed *not* public, but were (or are) carried out by a consortium or collaboration of institutes (such as SDSS). However, in those cases a huge effort has been already made to ensure releases of data to the public at regular intervals.

ESO's approach is slightly different, because its surveys are public, meaning that raw data are made available to the community as soon as observations are made. Furthermore, ESO has also fully recognised the importance of making ready-to-use (advanced) data products (such as calibrated catalogues) available, to ensure maximum involvement by its community. ESO has recently introduced the concept of Phase 3, to follow naturally after Phases 1 (submission and evaluation of observing proposals) and 2 (implementation and optimisation of strategies and programme execution). Phase 3 defines the "closing the loop" phase, during which high-level data products are submitted to ESO by the PIs of Large Programmes and Public Surveys (i.e., those with the best expertise to provide them), and ESO then releases them to the community after some detailed consistency checks. For that purpose, a new Phase 3 query interface has recently been released (Arnaboldi *et al.* 2011). More information can be found at: `http://www.eso.org/sci/observing/phase3.html`

Yet this may not be sufficient for time-domain astronomy. The large volume of data to be searched for transients and the associated real-time decisions that need to be taken argue strongly in favour of a more automated retrieval and distribution of time-critical information. It is hoped that the concept of a common facility like the Virtual Observatory for integrating a vast variety of astronomical archives and computational tools around the world will offer a robust infrastructure for this field of research. But a lot of work still lies ahead of us.

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