Developing 3D Spectroscopy in Europe

J.R. WALSH, ESO
M.M. ROTH, Astrophysikalisches Institut Potsdam

1. Background

One of the inherent preoccupations of astronomy is to obtain a three-dimensional view of the Universe and its components. Except for Solar System objects, we are always presented with a two-dimensional view of celestial objects. Spiral galaxies for example could be considered only as flat structures if it were not for the rotational velocity which shows them to be spinning three-dimensional entities. The distance scale is another fundamental aspect of this question – placing astronomical sources in the third dimension. Once their distance is determined, physical parameters can follow such as luminosity, radius and mass. In order to determine this information one could ideally imagine a "maximal spectrograph" which produced the spectrum of the whole sky at some desired spectral resolution and spatial sampling on the sky. The complexity of such an instrument is obviously beyond current technological means and the sheer size of the resulting data set would be prohibitively large. Nevertheless, a small, but significant, step towards this goal is to obtain the spectrum of an area of sky and this is what 3D spectroscopy achieves. With advances in technology the sampled area is becoming bigger.

3D spectroscopy is called integral field (IFS) or area spectroscopy and the principle is summarized in Figure 1. The resulting data have three dimensions – two spatial and one spectral. The spectrum at a spatial pixel (dubbed a "spaxel"), or in an aperture of any desired shape over a substructure of interest, can be extracted or an image over a spectral range can be formed by summing in the spectral direction. A long-slit spectrum can be formed by slicing the 3D data in one spatial and the spectral direction. Such data have very powerful advantages over aperture or long-slit spectra which sample pre-defined spatial regions. With 3D spectroscopy not only can spectra of a whole extended object be obtained, such as a nearby elliptical galaxy to investigate its velocity field, but areas of the sky can be searched for objects which are difficult to detect in wide-band imaging, such as emission line sources with a few, even only one, visible line over the wavelength range of the instrument (such as a search for Lyman-alpha emission from very high-redshift galaxies).

Since there is no slit in the conventional sense, there are neither slit losses nor the problems associated with atmospheric refraction which plague conventional spectroscopy. Most importantly, there is, by definition, no prejudice as to the selection of the region of interest: thus a particular slit pointing and orientation may easily miss a physically important structure which appears to be unassuming on a broad-band image. Integral-field observation can unveil the complete spectroscopic signature within the 2-dimensional field of view of the wavelength coverage of the 3D instrument. A good example is the 3D observations of the stellar kinematics of the nuclear region of the nearby galaxy M31. Whilst the distribution of light shows a double nucleus, the velocity map reveals a structure that is not aligned with the two nuclei and the peak in the velocity dispersion, assumed to mark the location of the supermassive black hole, is also offset from one of the peaks (Bacon et al. 2001a). Orientation of a long slit over the obviously visible features would have missed the essentials of the velocity structure.

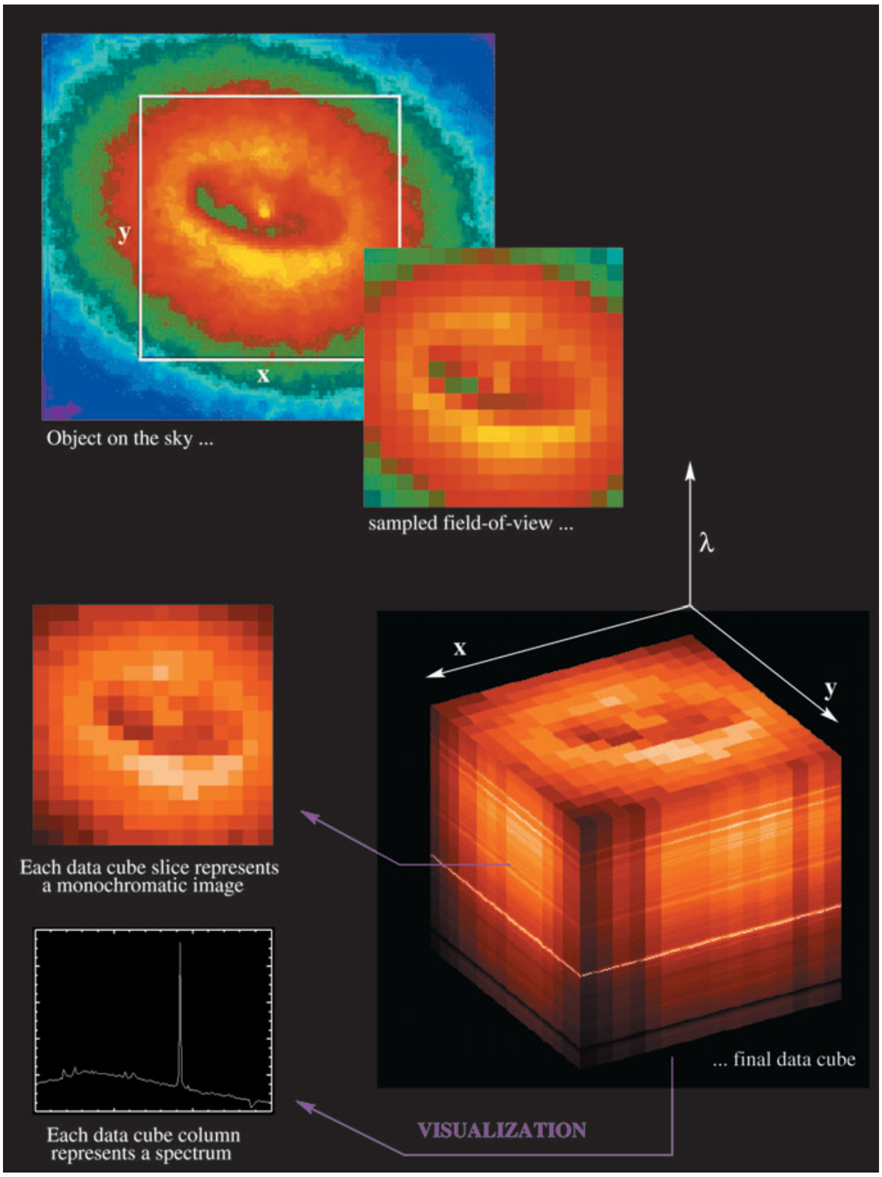

Figure 1: The principle of 3D spectroscopy is illustrated. An area of interest on the sky is sampled on a discrete grid of spatial elements, using techniques such as a fibre bundle, lenslet array, slicer, etc. The light collected in each spatial element is dispersed into a spectrum. After extracting the family of individual spectra from the detector image, they can be rearranged to form a data cube. Spectra of individual spatial elements, or defined regions on the sky, can be extracted from the data cube. Slicing the data cube over a range of wavelengths allows a narrow-band or broad-band image of the sky to be formed.

The process of data-taking sounds simple – point at a target of interest (high-precision pointing is not required), obtain spectra at many spatial positions (currently hundreds to thousands). The removal of the instrument signature and the assembly of the data into a 3D data cube proceeds similarly to spectroscopic reduction with long slits except for the much larger volume of data. However, it is the analysis of those thousands of spectra which provides the greatest hurdle. Integral-field spectrometers in various forms have been available for decades but the publications resulting have in no way been proportional to their data volume, or allocated telescope time. The sheer scale of the data analysis and the need to do justice to the quantity of spectra has deterred many, and even the 3D spectroscopy pundits have to admit that they cannot analyse their data cubes fast enough. The lack of adequate data-analysis tools is becoming more acute with the installation of new common-user instruments offering IFS modes on 8–10-m-class telescopes, such as VIMOS, FLAMES and SINFONI at the VLT, and GMOS at GEMINI.

In order to try to ease this "data jam", all the European groups working in 3D spectroscopy came together in a working group launched by OPTICON – the Optical and Infrared Coordination Network for Astronomy. A proposal for a Research Training Network (RTN) in the 5th Framework of the European Commission was made in which young post-docs would be enabled to work on science projects with 3D spectroscopy. User tools would be developed and shared to increase the scientific exploitation and productivity of the data. The RTN, entitled "Promoting 3D Spectroscopy in Europe" was awarded and began on 2002 July 1. Post-docs are now being sought in ten European institutes. This article provides a brief overview of the 3D spectroscopy and a flavour of what can be expected from the RTN over the next few years.

2. Growth of 3D Spectroscopy

The first attempts at imaging spectroscopy used scanned Fabry-Perot interferometers to observe the velocity fields of emission lines in gaseous nebulae. Groups at Marseille and Manchester used photographic and image-tube recorders to obtain multiple narrow spectral band maps which, when stacked, allow the line profiles over an area to be mapped. With the advent of piezo-scanning Fabry-Perot spectrometers coupled with photon-counting detectors, rapid sampling of the spectral range could be achieved. The effect of transparency variations in the atmosphere would be reduced by the fast scanning and many scans could be averaged. The TAURUS instrument, used at many 4-m telescopes, was the most advanced realization (Atherton et al., 1982) and emission line maps of many extended targets were observed.

Photon-counting detectors could also be employed in rapid slit-scanning techniques where the positioning of a long slit on the sky was synchronized with the readout of the detector. The ASPECT system at the AAT (Clark et al. 1984) using the IPCS (Boksenberg & Burgess 1973) was successfully used for a number of projects from kinematic mapping of elliptical galaxies to spatial abundance mapping of spiral and starburst galaxies. The data volumes were modest with typically ten long slit positions. Scanning techniques suffer from changing seeing and transparency, which also produce line profile variations for Fabry-Perot spectrometers.

The first attempts to measure simultaneously spectra over a 2-dimensional field were made in the 1980's with fibre bundles packed into an area at the telescope focal plane and aligned onto a common "pseudo-slit" of a conventional spectrometer. Each fibre generated a single spectrum on the detector of one position on the sky. Several prototype instruments have been developed, and some of them are still in use today. The application of microlens arrays to astronomy brought a revolution in this field. An area of sky could be divided up by a monolithic microlens array. The beams from the microlenses could then be fed to a spectrometer and many spectra recorded on the same detector. The spectrometer design can ensure that the many individual spectra are packed on the detector so that there is minimal overlap. The Tiger, subsequently Oasis, instruments used for many years on the CFHT was the most successful example of this design principle and much science was achieved from resolving the kinematic components of galaxy nuclei to the jet structure of PMS stars (Bacon et al., 1995). Using the micropupil principle, the coupling of lens arrays with fibre bundles allowed more flexible designs even with several spectrometers. The integral field mode of the Gemini GMOS instrument uses this design, as does the VLT FLAMES facility; in VIMOS, currently the largest IFU unit in operation (80 × 80 elements), the fibres feed four spectrometers. There is no reason in principle for not extending the number of spatial elements towards that of the maximal spectrometer and two propos-

OBITUARY GUILLERMO DELGADO (1961–2002)

Guillermo started his career in radio astronomy in 1983 when he participated in the activities and development of the Maipu Radio Astronomy Observatory.

In 1986, at the time when Onsala Space Observatory and ESO embarked on the SEST project, Guillermo went to Sweden to become involved in the project. Upon his return to Chile he took an active part in the commissioning of the SEST. His contribution helped greatly in the early readiness of the SEST operations. Later on, he was responsible for the instrument maintenance and upgrades, including the installation of receivers and the design of their control system.

In 1989 Guillermo graduated as Electrical Engineer from the Universidad de Chile. In 1992 he went to Sweden to work on his doctorate at Chalmers University of Technology. He returned to Chile and the SEST in 1995 where he completed his Ph.D. thesis.

In 1997, health problems obliged him to be based in Santiago, where he was, essentially, dedicated to support the ALMA site testing and development campaign, including the maintenance of its equipment, the interpretation of the atmospheric transparency data from Chajnantor and the modelling of phase correction methods. His efficient work under difficult health conditions was impressive. Above all, Guillermo had an extraordinary capacity to handle a large spectrum of skills, ranging from electronic designs and opto-mechanics to software development and data analysis. He taught at the Universidad de Chile and encouraged students towards the world of astronomy. ESO and Onsala Space Observatory are deeply grateful for his contribution to ALMA and the SEST.

Guillermo was a first-rate colleague whose generosity and dedication was highly appreciated by all who worked with him. Until his very last weeks at the hospital he was actively involved in his tasks with an energy and will power only to be defeated by his physical condition.

Our expression of condolence goes to his wife, Alejandra, and their sons.

DANIEL HOFSTADT
LARS-ÅKE NYMAN

als for VLT wide-field (1 × 1′) 3D optical spectrometers are under consideration (see Monnet, 2002).

One other technique has found application for dividing up the field subsequent to feeding the spatial elements to a spectrometer and that is a development of the image slicer. Originally image slicers were used to increase the throughput of slit spectrometers for a point source by stacking slices along a narrow slit. Applied in two dimensions mirrors can be used to reformat a square field onto a long slit which is then packed on to the detector (e.g. for the MPA instrument 3D, Weitzel et al., 1996, which is the fore-runner of the VLT instrument SPIFFI). In common with all methods the limitation is detector area, and as CCDs have grown larger so have the areas encompassed by 3D instruments, whilst the sampled size on the sky has remained relatively constant. A survey of the commissioned and planned 3D instruments, or instruments with an integral-field capability, around the world showed the astonishing number of 26. Truly, this is a burgeoning field and many integral field instruments are planned for the large telescopes, and for NGST. Within two years there will be three IFU-capable instruments on the VLT – VIMOS, FLAMES and SINFONI.

3. The Euro3D RTN

Europe currently has the lead in the development of integral-field devices and many of the instruments currently in use, or planned, are for telescopes in which European institutes, including ESO, have strong participation. The need to foster good communication and interchange between these groups, which represent all the different 3D methods sketched above, led to the formation of an OPTICON 3D Spectroscopy Working Group. This group identified that, whilst individual instruments are diverse and the responsibility for removal of the instrument signature must rest with the instrument builders, there existed a lack of instrument-independent data analysis software. The Euro3D RTN was proposed and planned by this group.

A 3D data format for the exchange of 3D data and a software platform for the development of analysis tools form two of the cornerstones of the Euro3D effort. A draft format for a Euro3D format has been issued and the essence of the format, which is FITS, is a stacked spectrum image with a table to reference each spectrum to its position on the sky plane. For the data analysis tools, it was decided to write individual applications in C and to use a scripting language such as Python, Tcl/Tk or IDL for analysis scripts. The I/O library would be adapted from the extensive Lyon Oasis libraries for the Euro3D format.

The RTN consists of a network of eleven institutes – Astrophysikalisches Institut Potsdam, Institute of Astronomy Cambridge, University of Durham, Max-Planck-Institut für Extraterrestrische Physik, Garching, Leiden Observatory, CRAL Observatoire de Lyon, Laboratoire d'Astrophysique de Marseille, Istituto de Fisica Cosmica "G. Occhialini" of the Italian CNR in Milan, Observatoire de Paris section de Meudon, Instituto de Astrofísica de Canarias, ESO – all of which have active involvement in 3D spectroscopy projects. Full details of the RTN are available on the Web at: http://www.aip.de/Euro3D/ and there are also links to detailed descriptions of the 11 3D instruments with which the RTN members are involved. The coordinator of the network is Martin Roth at AIP Potsdam (mmroth@aip.de) and questions about participation or interest in the scientific or software activities should be directed to him.

References

Atherton, P.D., Taylor, K., Pike, C.D. et al., 1982, *MNRAS*, **201**, 661.
Bacon, R., Emsellem, E., Combes, F., et al., 2001a, *A&A*, **371**, 409.
Bacon, R., Copin, Y., Monnet, G., et al. (The Sauron Project), 2001b, *MNRAS*, **326**, 23.
Bacon, R., Adam, G., Baranne, A., et al., 1995, *A&AS*, **113**, 347.
Boksenberg, A. Burgess, D. E., 1973, in Proc. Symp. TV type sensors, eds. Glaspey, J. W., Walker, G.A.H., 21.
Clark, D., Wallace, P., Fosbury, R. F., Wood, R., 1984, *QJRAS*, **25**, 114.
Monnet, G., 2002. *The Messenger*, No. **108**, 2.
Weitzel, L., Krabbe, A., Kroker, H., et al., 1996, *A&AS*, **119**, 531.

Forty Years ESO – Public Anniversary Activities

C. MADSEN, ESO

Readers of *The Messenger* will be well aware of ESO's 40th anniversary in October this year. This is most certainly a reason for ESO's friends to celebrate. Beyond the professional astronomers, engineers and other people with direct links to the organization, this includes many people all over Europe, e.g. amateur astronomers, science teachers, and people with a general interest in science. At the same time, the European Intergovernmental Research Organizations constitute fine examples of how, through collaboration, European countries can interact and achieve ambitious goals. Thus the success of ESO reaches beyond the confines of professional Astronomy.

Taking account of this, ESO's Education and Public Relations Department has worked intensively with partners in the publishing world and planetaria to ensure that the 40th anniversary will also become a visible event in the public arena.

Among the activities and products that will be ready in the autumn are a major book, a CD-ROM, a video and a planetarium show.

Geheimnisvolles Universum – Europas Astronomen entschleiern das Weltall is the title of an 'anniversary book', published by the German Kosmos Verlag. Comprising 208 large-format pages with more than 150 colour pictures, the book is written by science journalist Dirk Lorenzen, known from German Radio and author of *Deep Space* and *Raumsonde Galileo*. The original version of the book is published in German, but other language versions are planned.

Although published on the occasion of the 40th anniversary of ESO, the book

is a forward-looking book, dealing with some of the hottest topics of contemporary astronomy. It looks at the technology and, by means of interviews with both ESO staff and visiting observers, offers a very human account of the people now engaged in front-line astronomical research. A chapter describes an observing night at Paranal and provides an outlook to the future, in particular the ALMA and the OWL projects.

For readers who are interested in the past, the book includes a chapter with some historical aspects and milestones in ESO's development, and a fascinat-