Galaxies: The Third Dimension – Conference Summary

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1. Introduction

“Galaxies: the Third Dimension” continues a tradition which started in Marseilles 1994 with the “Tridimensional Optical Spectroscopic Methods in Astrophysics” meeting, followed by “Imaging the Universe in Three Dimensions” at Walnut Creek in 1999. We were both fortunate to attend all three meetings, and this review provides us with the opportunity for retrospect. There have been developments both in instrumentation and in the way astronomy is conducted, and these need to be seen against a broad canvas. As we emphasize below, one of the main reasons for satisfaction is the trend towards talks focused on scientific results rather than on ‘yet another 3D spectroscopic technology.’

2. Cultural change

For the benefit of future chroniclers, we note that the past eight years has seen a number of cultural changes in how astronomy is undertaken. The forces of change include many things:

- the dominance of the web in the life of the modern researcher; the inexorable march of computer power, networking and software development, with the prospect of a world-wide web-driven ‘virtual observatory’ looming on the horizon;

- the researcher is rarely tied to one waveband or observing technique – the researcher has access to many instruments and data bases, and is therefore spoilt for choice, and is less inclined to take on ‘raw data’;

- the burgeoning influence of active and adaptive optics on all large telescopes; the trend towards 3D spectrographs over more traditional 2D spectrographs; the steady rise in detector area and performance which is the starting point of instrument design;

- the commissioning of 8−10m telescopes and the development of large expensive general purpose instruments catering to a broad constituency;
traditional theorists now take far more interest in being involved with observation and data – theorist/experimentalist/observer categories become more mingled to the benefit of more realistic models and fleshier observational papers.

- the changing culture imposed by funding for ground-based astronomy through space agencies, and the stronger connection between space and ground science;

- the weakening role of traditional observatories in producing science papers and the importance of research at universities;

- astrophysics has become the ‘new physics’ due in part to the cancellation of the Superconducting Super Collider in Texas, with the consequence that many particle physicists have moved into astrophysics, an ever increasing number of faculty positions switched from physics into astronomy, and a rising fraction of astrophysics papers are moving to the physics journals;

- the success of the microwave background explorers in determining the world metric has established the importance of the universe as a laboratory – this development has brought studies in galaxy formation and evolution to the top of the agenda (Peebles 2000).

The proceedings of the Marseilles, Walnut Creek and Cozumel meetings show hallmarks of all of these factors. In “Future Perspectives” below, we try to foresee the future cultural trends.

3. Meetings: Past and Present

The Marseilles meeting (Comte & Marcelin 1995) introduced the astronomical community to the integral field spectrograph, first proposed by G. Courtés. In just eight short years, we now find microlens arrays in common use in almost all major observatories. This is quite remarkable. The Conference Summary for that meeting asked why long-slit spectrographs maintain their stronghold in most observatories given that so much of the potential information is thrown away. The instrumentation landscape is very different now. The Marseilles meeting had a decidedly European flavour with a strong focus on local heroes C. Fabry and A. Perot.

Much the largest meeting of the three was held at Walnut Creek, California under the auspices of Lawrence Livermore National Laboratories. Not surprisingly, this meeting had a strong North American emphasis and brought together most of the major instrument developers in the western world. This meeting saw the introduction of tunable filters, the reemergence of image slicers, differential methods based on CCD charge shuffling, energy-resolving 3D detectors, and a dizzying array of enabling technologies for satellites and ground-based observatories.

The overall impression of the Cozumel meeting was the scientific maturity with 3D spectrographs. Some groups have already achieved impressively large survey samples with their devices. The meeting had a much stronger focus on science than in previous meetings. At that time, astronomers seemed
overwhelmed with the problem of data analysis given that optical/IR teams did not make the financial investment of the radio community in software analysis tools. But fortunately this situation has changed with observatories realizing the importance of a reduction pipeline. It is well known that observatories (either in space or on the ground) which deliver calibrated data to the user have the highest publication rates.

4. Instrumentation

“Galaxies: the Third Dimension” brought together speakers from many countries, with the largest contingent from Mexico and Spain. This is an exciting time for Mexican-Spanish astronomy with the Grantecan 10.2m (GTC) due to see first light in late 2003. Many of the science talks, which we review in the next section, showed that the Mexican-Spanish community was gearing up for Grantecan. The first light instruments are the optical tunable filter/multi-slit spectrograph Osiris, and the mid-infrared imager spectrograph Canaricam. In the second phase, the GTC will have a near-infrared imager/spectrograph called EMIR.

Osiris is modelled on the Taurus Tunable Filter (TTF) at the AAT, having very similar parameters in all respects, although of course the instrument will be mounted on a telescope with a sevenfold increase in light-collecting power, and on a first rate observing site. The entire optical spectrum will be covered by a blue TF and a red TF. Furthermore, volume-phase holographic gratings will allow multi-slit spectroscopy at low to mid resolutions. Another feature carried over from the TTF is that all observing modes will be coupled with charge-shuffling which allows for differential measurement \(\text{e.g.}\) perfect sky subtraction with nod & shuffle, perfect continuum subtraction with straddle shuffle, etc.). Osiris will also allow for time series readout in either spectroscopic or imaging modes.

We are at the dawn of an era for 3D spectrographs. All 8-10 meter class telescopes will have such a device. The first ones are already active or are being commissioned as we write (VMOS/VLT): the Gemini suite with GMOS of course (Allington-Smith) but also the soon to come GNIRS and NIFS (Miller), GIRAFFE/FLAMES on the VLT (Chemin) with its 3 different modes, the double FP etalon on SALT (Reynolds). Most of these instruments are expected to open up scientific niches.

In an age of 3D spectrographs on the largest telescopes, it is important not to forget that similar facilities on 4m class telescopes are alive and kicking, and will continue to deliver excellent and sometimes surprising science \(\text{e.g.}\) LIFTS, OASIS, SAURON, INTEGRAL, PMAS, various FP systems; examples provided by Wurtz, Arribas, Bacon, Roth, Veilleux and many others). For the foreseeable future, the largest survey samples are going to arise from medium sized telescopes. A particularly interesting combination was demonstrated with GRIF (Clenet), which advantageously combines the high spatial resolution attainable in the NIR with a 4m aperture (see also Le Coarer), and the traditional scanning Fabry-Perot technique. A related technique has been discussed in detail by Baldry & Bland-Hawthorn (2000).
A memorable exchange brought out the extremes of astronomy. Taylor wowed the audience with the layout for the Californian Extremely Large Telescope (CELT), and the proposed instrument suite – ‘a billion here, a billion there; soon this will start to add up to real money.’ He showed how HIRES could be rescoped for a 25m telescope. Not to be outdone, in a charming talk, Parry presented England’s answer to the CELT, the Cambridge Extremely Little Telescope, a 2 cm aperture telescope with a fibre feed to CIRPASS, a spectrograph soon to see first light on Gemini. The English CELT was observed to be ‘the largest telescope in operation below sea level.’ Remarkably, Parry was able to obtain the same sky flux per pixel as could be expected at Gemini, and in the process demonstrate the excellent sky subtraction possible with CIRPASS.

3D meetings are a good time to pause and consider the progress made in the R&D of true 3D detectors in the optical. With de Bruijne’s captivating talk, we heard of actual astrophysical applications of superconducting tunnel junctions (4D detectors, adding a time resolution of 5 µs), conducted at the WHT with a 6 × 6 elements system. The spectral resolution is very low ($R \sim 10$), but already the reduction and analysis of the data flowing out of this instrument is demanding. A larger format device will require a revolution in pipeline processing techniques. Talks by Charles and Javier emphasized the importance of time resolved imaging and spectroscopy.

5. Science with 3D spectrographs

Multi-object studies have wide-ranging application, in particular, star forming galaxies in clusters, around quasars, in QSO-identified absorption line structures, and so on. The tunable filter studies provide accurate photometry and object morphologies over the widest possible field. The integral field studies provide broad spectral coverage over a limited field. The compromise between spatial and spectral field, or resolution, was nicely summarized by Boulesteix: ‘it is now clear that astronomers do dig more freely into the large bag of instruments available depending on the scientific goal they wish to reach.’

Tunable filter, Fabry-Perot and integral field spectrographs together then provide a powerful arsenal for going after a wide range of science cases. These can be broadly divided into two categories: detailed studies of individual extended sources in absorption and emission; multi-object spectroscopy of compact sources over a wide field. We provide a brief overview of some of these topics before taking a closer look at a few particularly promising areas.

There is a wide range of energetic processes which are expected or known to produce detectable diffuse optical/IR line emission. These include (in order of decreasing energy): colliding clusters; cooling flows; gamma ray bursts, quasars (QSOs), radio galaxies and ultraluminous IR galaxies (ULIGs); galaxy mergers; QSO/ULIG jets and winds, AGNs and starbursts, hypernovae, supernovae, compact x-ray sources, and so on. There exists a wide class of exotic possibilities including flash photoionization events, galaxy bow shocks and so forth.

Many of these topics were covered by participants at the conference (e.g. van Breugel, Veilleux), with a strong emphasis on objects with complex emission line distribution such as in interacting systems: these are natural targets for spectrography covering a two-dimensional field of view. Fabry-Perots are best
suited to studies of a few spectroscopic lines over a large field, e.g. Hα to map the gas distribution and kinematics (Puentecarrera, Planas, Melo, Veilleux), although true IFS have also been extensively used to probe merger remnants or galaxies with spatially extended bursts of star formation (Arribas, Monreal-Ibero, Garcia-Lorenzo).

Another trend we are seeing is the realization of the importance of detailed astrophysical studies of nearby sources. This is not as obvious a statement as it sounds. Until recently, many astronomers would have preferred to keep the objects as simple as possible by viewing them at the highest possible redshift. But important physical processes are now evident in pixel-pixel comparisons over several spectral diagnostics. A superb example is the bipolar wind in M82. The individual emission line maps are extremely complex and most observers would dismiss this information as weather, i.e. unimportant detail. However, Shopbell & Bland-Hawthorn (1998) show that the ratio of, say, [NII]/Hα reveals a very well organized bipolar fans where the UV radiation is escaping from the galaxy core.

3D spectrographs provide detailed information on more than one physical measurement at a time and are thus efficient at delivering the key diagnostics over a spatial region freed from simple geometrical assumptions. It is then critical to understand how the spatial averaging on our target affects our observational data. Talks by Points, Rosado, Silich are clearly telling us that this is a complex issue, specially when dealing with the ISM and star forming regions. The multi-wavelength approach is certainly a key here, but without the two-dimensional spatial coverage, such spectroscopy would look like a list of street names without a city map.

‘Feedback’ is probably one of the most overused words in this context, probably because it seems to include a subset of physical processes depending on the author and the field. Winds and radiation from celestial sources provide the mechanisms for feedback, but wind energetics are notoriously difficult to measure directly. A courageous attempt to map the impact of winds due to star formation was presented by Hidalgo-Gáméz, who scanned the dwarf but starbursting IC 10 with long-slits. But this was not counting on the power of their galactic (super)versions, beautifully illustrated by Veilleux’s review, who convincingly argued for the need of 3D spectrographs but with high spatial resolution.

We have also seen quite a number of detailed studies on bright nearby galaxies, again mainly dealing with the gas distribution and kinematics (Cairós, Puerari, Relañ Pastor, Valdez-Gutierrez). As we move towards the central cores of these galaxies, more irregularities, asymmetries and overlapping physical states were revealed (García-Lorenzo, Mediavilla, Moiseev).

The success of 3D spectroscopy in obtaining absorption line maps of galaxies shows us how to open a large window on the study of stellar populations and kinematics in extended and sometimes remote objects. As shown by many contributors (Sil’chenko, Moiseev, Bacon, Emsellem, González, Bureau, Cretton, Wernli, Falcón Barroso), the real difficulty is to reconstruct the link between the stellar kinematics and underlying populations. State of the art dynamical models are required (Cretton, Pichardo, Martinez), but we still need a ‘coloured’
version of these models if we really wish to build a good scenario for the forma-
tion and evolution of these objects.

As mentioned above, survey science with 3D spectrographs is now of in-
creasing importance. This is typified by the GHASP (FP, Amram), WHAM
(FP, Reynolds) and Sauron (IFS, Bacon) surveys.

The Sauron team (Bacon, Bureau, Cappellari, Copin, Cretton, Emsellem,
Falcón Barroso, Wernli) presented integral field results for a large sample of
elliptical, lenticular and spiral galaxies divided between clusters and the field.
Fully one third of these show evidence of nuclear sub-structure. Some show
evidence for triaxility, including nuclear bars as judged from Athanassoula’s bar
simulations. The group emphasizes caution in the analysis and derivation of
black hole masses from long-slit measurements.

Some of the most impressive conclusions were those derived from the age and
abundance information coupled to new stellar synthesis models (Vazdekis). The
new models, which have a fourfold increase in spectroscopic resolution compared
to the Lick system, show that the isochrone or isochemical grid lines overlaid
on a plot of two Lick indices are more orthogonal than the Worthey models.
Thus, galaxies like NGC 4365 that exhibit no age gradient in the Vazdekis
models (Davies et al 2001) appear to show an age spread in the Worthey models.
Interestingly, NGC 4150 exhibits an abundance spread with constant age.

It will probably take time before astronomers can fully exploit the potential
of such data sets. But one thing is clear from the Sauron talks: axisymmetry
in early-type galaxies is the exception rather than the rule – these are not quite
the simple systems the community was led to believe.

6. Software

A traditional argument used against 3D spectroscopy was simply that ‘the data
are too complex, too difficult to model, and impossible to calibrate.’ Most in-
stitutes carrying out the construction of 3D spectrographs were well aware of
the importance of software and more specifically of semi-automated reduction
pipelines. The Cozumel meeting was an opportunity to witness the results of
these efforts. Dedicated IRAF tasks have been developed for the GMOS IFU
on Gemini and presented by Miller. Garcia-Lorenzo focused on IDA, an IDL
based soft tool to view and analyse INTEGRAL/WHT data, and the OASIS
& SAURON teams showing some examples of reduction and analysis via the
corresponding (C-based) XOasis and XSauron. We have also seen various ap-
lications and extensions such as 3D deconvolution or 2D binning (Cappellari).

The GHASP survey (Amram) is a good illustration of how Fabry-Perot Hα
velocity fields can now be produced in reasonably large numbers. We are thus
starting to really explore the techniques which will truly exploit the full three-
dimensional data at our disposal. But more importantly, astronomers are getting
used to the concept of datacubes. In this context, Brinks is right to remind us
that radio astronomers have been tackling 3D data for a few decades already.
Some new developments are and will certainly be inspired from existing tools,
like the analysis of two-dimensional maps with the newly baptised “kinemetry”
(Copin). We however feel that the current trend really goes one step beyond,
since it appears to be providing new algorithms and tools for a much wider net of applications than before.

Although the existing software packages make use of a zoo of different languages and platforms, the community is actively engaged in establishing a solid and common basis for future developments. The advent of a European format for spectroscopic datacubes perfectly illustrates this point. The Euro3D network is just starting, so we are looking forward to harvest the fruits of these collaborations at the next 3D meeting.

7. Future Perspectives

It continues to surprise us that so little attention has been paid to the ‘diffuse light’ universe. We know that there must be a lot of activity at low surface brightness which is not seen in contemporary images. A customized machine would be demanding to build. An off-axis telescope would bypass the problem of the diffraction pattern. The mirror needs to be kept clean of dust and the optics well specified and AR coated. This leaves the not insignificant problem of atmospheric scattering. A 5th mag star can be detected a degree or more away. This of course can be bypassed from a satellite platform.

Surveys drive astronomy at any wavelength. We have seen a gradual trend towards field widening of telescopes and instruments. This raises the problem of how to sustain diffraction limited imaging or spectroscopy over a wide field. Gemini has invested much effort in multi-conjugate adaptive optics, and the second generation of VLT instruments will certainly address this too. An alternative approach might be deployable adaptive optics correctors connected to deployable IFUs or microIFUs.

The strategic initiative of the Next Generation Space Telescope has provided the impetus for numerous enabling technologies relating to multi-object spectroscopy. Complex fibre positioning systems would be far too risky for a remote space observatory. Some of the ideas under consideration are transmissive spectrographs which use $2000 \times 2000$ micro-shutters and would allow for fully programmable electronic object selection keeping the number of moving parts at a low level.

We predict that there will be a complete blurring of the traditional wavelength boundaries. It will however take time before we can digest the wealth of information contained within the flowing stream of 3D data. This adaptation will certainly represents a higher number of generations for astronomers than for computers. Another prediction, or rather a strong wish, is to reach the state of fully automated data analysis more or less directly linked to virtual observatories. A first step is being taken to obtain a standard (and optimized) format at the output of the 3D spectrographs.

The rising cost of future telescopes and instrumentation carries the risk that astronomy will price itself out of existence. We may see the return of specialist ‘niche’ instruments which target a specific science question. The Dazele instrument (Cambridge/AAO) is an example of this may change. The instrument is entirely optimized for high redshift Lyα imaging, and shares an expensive camera with the CIRPASS spectrograph. The camera is a modular unit with
handles and can be ferried back and forth between the instruments with little fuss.

Both software and instrumentation developers will need to be mindful of spiralling costs. Large survey machines like the Sloan Telescope were almost undone by the enormous expenditure involved in pipeline reduction. Huge massively multiplexed spectrographs offer many more features than are likely to find effective use in the ten to fifteen year lifetime of the instrument. Now more than ever, if in doubt, astronomers really must focus on a particular science niche, where all other scientific considerations are secondary, and remain that way until the instrument sees first light. Even if the instrument is intended for the general community, there must be unique terrain for the instrument to explore if it is to avoid the fate of being ‘yet another 3D spectroscopic technology.’

Acknowledgments. We would like to thank the conference organizers for arranging an excellent meeting at such a resplendent venue in Cozumel just a short distance from the Yucatan peninsula. Quite apart from hearing about the latest developments in astronomical 3D instruments and observations, this afforded the opportunity for some wonderful diving. We would both like to thank Drs. Bureau, Cretton, Miller, Relaño-Pastor and Veilleux for the memorable shared experiences among the gardens and canyons 80 feet below. And then there were the endless ‘happy hours’ at the pool or on the beach, dance parties till sunrise, all in the interests of international relations.