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3D Spectroscopy — a powerful new tool for PN research

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Abstract. Historically, technological progress with detectors and instrumentation has been essential for advances in any field of observational astronomy, e.g. the advent of CCDs being crucial for high dynamic range imaging and quantitative spectroscopy of galactic PNe, faint object spectrophotometry for the discovery of extragalactic PNe to distances as far as 100 Mpc, etc. The emerging technique of integral field (“3D”) spectroscopy, which is being applied quite successfully to extragalactic astronomy, has unfortunately hardly been used so far for the study of PNe. However, 3D spectroscopy has an enormous potential for various observational problems, ranging from high spatial resolution emission line mapping in different wavelengths simultaneously, over extremely high sensitivity spectroscopy of low surface brightness objects like e.g. PN haloes, to accurate 3D spectrophotometry of extragalactic PNe, and many others. As an attempt to encourage PN researchers to make better use of these new opportunities, the presently existing suite of 3D instruments on 4–8m class telescopes is reviewed, highlighting some examples of successful 3D observations for the study of PNe.

Keywords. instrumentation: spectrographs, techniques: spectroscopic

1. Introduction

Integral field (3D) spectroscopy, which was first introduced 2 decades ago and then underwent a phase of experimenting and prototyping, has now become a mature technique, with an impressive suite of facility instruments on 4–10m class telescopes available to the common user. For illustration, Table 1 gives an overview of 3D spectrographs on telescopes with apertures larger than 6m, but many more instruments are operated at

Table 1. 3D Spectrographs at 6-10m class telescopes

Telescope	Aperture	Instrument	λ-range	max. FOV	$\lambda/\Delta\lambda$
Keck	10m	OSIRIS	0.9–2.5 μm	3” × 6”	4000
GTC	10m	*ATLANTIS*	1–2.4 μm	8” × 8”	5000
HET	9.2m	*VIRUS*	0.35-0.57 μm	5’ × 5’	1500
Subaru	8.3m	Kyoto-3D $^{*)}$	0.36–0.9 μm	3.4 ” × 3.4”	1200
Gemini	8.1m	GMOS	0.4–1.1 μm	5” × 7”	3665
		GNIRS	1.0–5.5 μm	3.2” × 4.8”	6000
		CIRPASS $^{*)}$	0.9–1.8 μm	5” × 7”	3665
		NIFS	1–2.5 μm	5” × 7”	3665
VLT	8.2m	VMOS	0.37–1 μm	54” × 54”	2000
		SINFONI	1–2.5 μm	8” × 8”	4500
		FLAMES	0.37–0.9 μm	11.5” × 7.3”	25000
		MUSE	0.46–0.93 μm	1’ × 1’	3000
Magellan	6.5m	IMACS	0.4–0.9 μm	6.9” × 5”	10000
Selentchuk	6m	MPFS	0.39–0.9 μm	16” × 16”	3000

4m class telescopes (instruments under development: slanted font, $^{*)}$: travelling team instruments). Fig. 1 illustrates schematically a datacube resulting from a fully reduced 3D spectroscopy exposure. Depending on the specific application, one can analyse the dataset either in the picture of a *stack of monochromatic images*, or in the picture of *single spectra*, or *groups of spectra*, respectively.

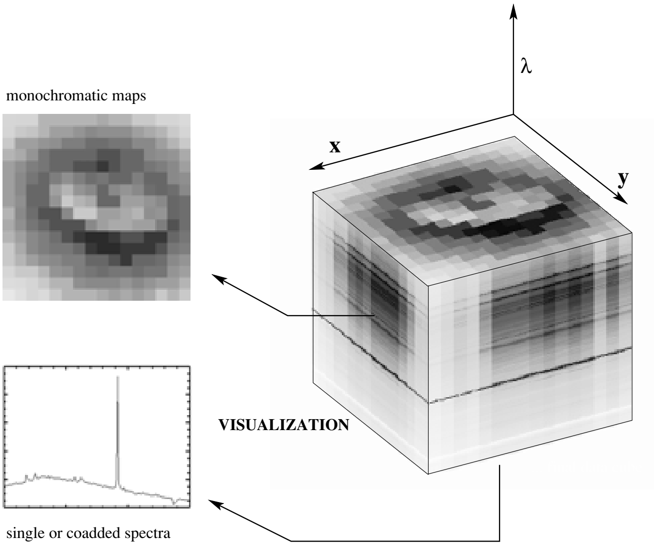

Figure 1. Datacube as obtained with 3D spectroscopy.

Integral field spectroscopy is a well-established and extremely successful technique in the area of extragalactic astronomy, however it is significantly less well-represented in the area of stellar astrophysics and the detailed study of individual objects of the Milky Way — perhaps with the exception of the Galactic Center (Eisenhauer *et al.* 2005), but see also Tsamis *et al.* (these proceedings). This presentation is intended to highlight the usefulness of 3D spectroscopy for the investigation of planetary nebulae and their central stars, with emphasis on two – in a sense *complementary* – applications, namely (1) the study of extremely low surface brightness regions, and (2) to disentangle point sources from a crowded field environment.

2. Low Surface Brightness 3D Spectroscopy

Spectroscopy of low surface brightness regions in emission lines or in the continuum is becoming prohibitively expensive as soon as exposure times of many hours are required, even at 8–10m class telescopes, in order to reach a useful signal-to-noise ratio (S/N). It was first discovered with studies of the kinematics of galaxies, that normally the faint outskirts of galaxies do not contain important information on small spatial scales, and it is thus perfectly justified to use spatial binning for the purpose of increasing the S/N of a measurement, representative for an area larger than a single instrumental resolution element. Capellari & Copin (2003) have developed a sophisticated tool, which uses a Voronoi tesselation to obtain a constant S/N throughout a field with a significant surface brightness gradient ("adaptive binning"). In the most extreme case, one can even coadd the spectra corresponding to *all* spatial elements ("spaxels") of an integral field unit

("IFU") and generate a total spectrum of extremely high S/N as compared to a single spectrum alone, scaling with $\sqrt{N}$, where N is the number of averaged spectra (see Fig. 2 in Roth 2006b). For an IFU with e.g. 256 spaxels, each sampling 1"×1" on the sky, the total S/N gain is a factor of 16. Compared to a longslit spectrograph covering the same field-of-view (FOV), and allowing for spatial resolution in one linear dimension, the gain is still a factor of 4. The example, taken from PMAS at the Calar Alto 3.5m Telescope (Roth *et al.* 2005, Kelz *et al.* 2006), illustrates how spatial binning is equivalent to providing a 4m class telescope with the light collecting power of a 16m telescope.

This method has been used to measure faint haloes of PNe with the goal to determine electron temperature and density, and, ultimately, chemical abundances as a function of radius in order to unravel the mass-loss history of the predecessor AGB star. Fig. 2 shows how "brute-force" binning indeed has enabled the determination of T_e from the [O III] line ratio in the halo of NGC 3242, using the VMOS IFU at the ESO-VLT (Monreal-Ibero *et al.* 2005). There is also an ongoing observing programme with a larger sample of PNe using PMAS/Calar Alto (see Roth 2006a, Roth *et al.* 2006c).

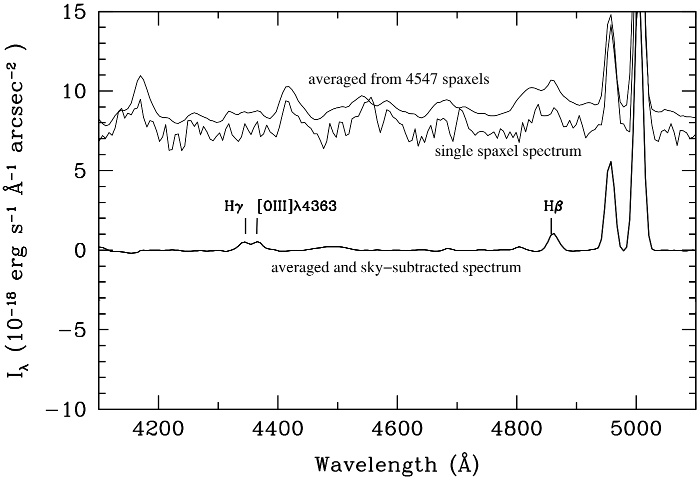

Figure 2. Mean halo spectrum of NGC 3242, averaged from a total of 4547 spectra. Comparison with the middle curve illustrates the S/N gain with regard to a single spectrum (shifted by 1 unit for clarity). The bottom plot is the final sky-subtracted result.

3. Point Source 3D Spectroscopy

While the previous example ignores for a large part spatial resolution across the face of the object under study, "crowded field 3D spectroscopy" is exactly intended to make best use of the full 2-dimensional spatial information in the field-of-view of a point source of interest. The overlapping pointspread functions (PSFs) of stars in binaries, multiple star systems, or densely populated fields, the spatially and spectrally varying background of unresolved stars and gaseous emission in star clusters, star forming regions, and nearby galaxies, etc. make it often very difficult, if not impossible, to disentangle the different components when one has to rely on conventional slit spectroscopy. The application of PSF-fitting algorithms in the spatial domain, however, facilitates this task enormously. A pilot study with PNe near the nucleus in the bulge of M31 (Roth *et al.* 2004) has illustrated the superiority of the 3D method. It eliminates the otherwise unavoidable systematic errors which are introduced by source confusion and incomplete background information, owing to the limited sampling geometry of a slit. In agreement with independent integrated light observations of comparable stellar populations in S0 galaxies (Falcón-Barroso 2006, Roth 2006b), this study has demonstrated that it is indeed possible to model the spatially varying surface brightness distribution of the host galaxy, to accurately model the stellar PSF of the point source, and then finally to extract the emission line spectrum of the PN by fitting the PSF in each monochromatic slice of the datacube, even for very faint emission lines of the spectrum. By contrast, the simulation of a slit extraction yielded significantly deviating results for several critical emission line fluxes, explaining conveniently some discrepancies in the literature (see discussion in Roth *et al.* 2004). More successful applications of PSF-fitting 3D spectroscopy were demonstrated for gravitational lenses (Wisotzki *et al.* 2003), supernovae (Christensen *et al.* 2003), ultraluminous X-ray sources (Lehmann *et al.* 2005), crowded fields in nearby galaxies (Fabrika *et al.* 2005), and others.

4. Future Instrumentation

For more than a decade, the evolution of 3D spectroscopy was rather slow and dominated by team instruments and prototypes. As a second generation of facility instruments has become available on essentially all major large telescopes (Table 1), it is clear that the technique can be considered mature. Presently yet another generation of 3D instruments is being planned, exploring new technologies (KMOS-VLT), adaptive optics and a wide FOV (MUSE-VLT), or space (NIRSPEC-JWST), to name just a few. Without even attempting to review those future developments, it seems to be fair to say that 3D spectroscopy is indeed an established observing technique, and it is now up to the user community to fully exploit its potential.

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