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3D SPECTROPHOTOMETRY WITH PMAS

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Abstract. Although the method of optical 3D spectroscopy has become more popular in astronomy with the availability of new integral field units (IFUs) for instruments like FLAMES, SINFONI, and VIMOS for the VLT in Chile (ESO), or GMOS at GEMINI North, it has not really become a common tool yet. The main reason for the apparent reluctance in the astronomical community of using IFUs is the difficulty of handling the data.

Here we present the integral field spectrograph PMAS (Postdam Multi-Aperture Spectrophotometer) together with the IDL software tool P3d, developed especially for the reduction of PMAS data. However, with some minor adaptions it is also very useful for the reduction of data taken by other IFUs like VIMOS. We show the capabilities of PMAS with its standard lenslet IFU and its new wide-field IFU module called PPAK, a further development for the observation of low surface brightness objects. Apart from technical details about the instrument and the software, some preliminary scientific results are shown from the observations of Planetary Nebulae.

1. THE PRINCIPLE OF 3D SPECTROSCOPY

3D Spectroscopy (sometimes also called Imaging Spectroscopy, or even more commonly Integral Field Spectroscopy = IFS) is an observational technique to obtain spectra for each point of a 2-dimensional field-of-view in the following way (Fig. 1):

1. the 2D field-of-view on the sky is sampled into discrete spatial elements (so-called SPAXELS) of round, square, hexagonal, ..., shape (depending on the special application of the used IFU instrument)
2. individual spectra are created *simultaneously* for each spaxel over the whole field-of-view
3. the generated set of spectra can be rearranged in a computer to form a 3-dimensional data cube of two spatial coordinates, and one wavelength coordinate

Any column of the data cube represents an individual spectrum at a certain spatial position and any slice corresponds to a monochromatic image at a certain wavelength. Coadding of several columns provides e.g. background or object spectra, and coadding of slices leads to quasi-broadband images.

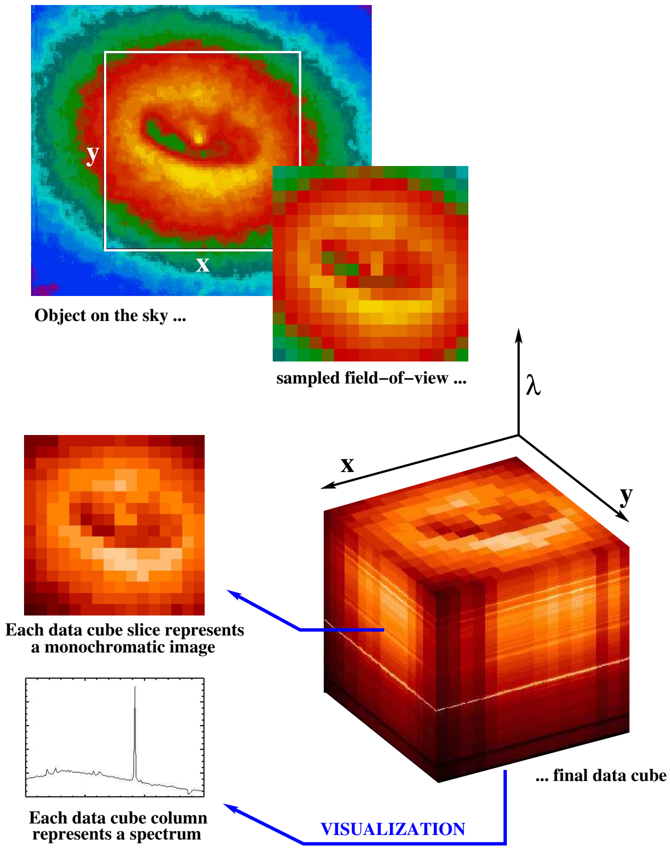


Figure 1: Principle of 3D spectroscopy with square spaxels. In reality, the data cube becomes a *rhomboid* in the presence of atmospheric refraction because of spatial shift as a function of wavelength.

2. PMAS DESIGN AND CHARACTERISTICS

The instrument PMAS, designed and built at AIP, uses a fiber-coupled lensarray to divide the field-of-view into spaxels. A magnified image of the telescope focal plane is projected by foreoptics onto the front surface of a quadratic array of microlenses. Each lens creates a tiny image of the entrance pupil of the optical system (= main telescope mirror), several tens of micrometers in diameter. Optical fibers are attached to the lensarray at the location of these spots, thus providing coupling to a spectrograph at the other end of the waveguides.

The flexibility of fibers is used to rearrange the square format of the input field-of-view into a linear pattern to form a pseudo-slit at the input of the spectrograph collimator. The light from each fiber is dispersed by the grating and is projected as a

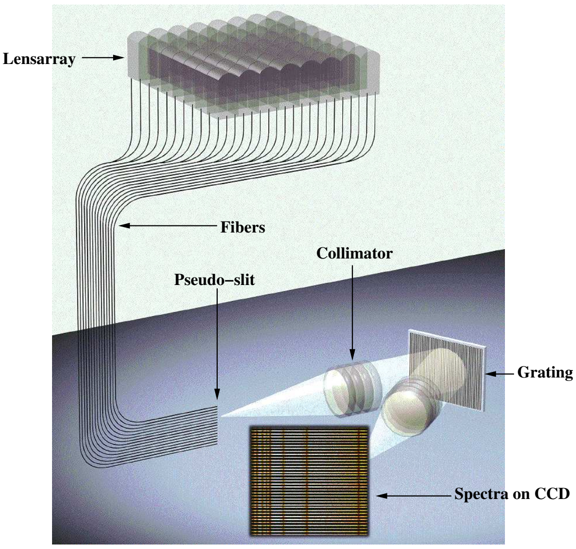


Figure 2: Principle of fiber-coupled lensarray IFS (excluding foreoptics) for a 8×8 lensarray. The recent configuration of the PMAS standard IFU is 16×16 lenses, producing 256 spectra per exposure.

single spectrum on the detector. Since there are many fibers at the pseudo-slit, a family of spectra is generated simultaneously on the CCD, i.e. one exposure produces one CCD-frame containing one set of spectra (Fig. 2).

Apart from the spectrograph CCD, PMAS has a second cryogenic CCD camera for target aquisition and guiding, which can be equipped with up to 4 broad- or narrowband filters.

PMAS was built as a travel instrument that can be mounted to different telescopes with little modification. It has a total weight of roughly 1.5 tons. PMAS has had First Light in 2001, and since 2002 it has been available to the German and Spanish astronomical community and their collaboration partners as a common user instrument at the 3.5 m telescope at Calar Alto Observatory (Spain).

For a complete technical overview of PMAS see Roth 2002, a summary is given in (Tab. 1).

3. P3d – THE PMAS REDUCTION SOFTWARE

There has been an enormous progress in the construction of IFU instruments during the last two years. Large IFUs like GMOS for GEMINI North with 1500 (1000 science, 500 sky) spectra per shot, FLAMES, SINFONI, and VIMOS for the VLT, the last one with 80×80 = 6400 spectra per exposure, have come into operation. Nevertheless, the difficulty of handling the complexity and amount of spectra in a proper and effective way has prevented many astronomers from using these powerful instruments. One needs dedicated data reduction software to automatically extract several hundreds spectra and remove instrumental signatures in order to create the final data cube.

Table 1: PMAS characteristics at Calar Alto Observatory

primary mirror diameter	3.5m
focal station	cassegrain
principle of operation	lensarray + fiber-coupled spectrograph
spectrograph type	fully reflective f/3 collimator and f/1.5 camera
wavelenght range	350 – 900 nm (CaF2 optics)
gratings	1200, 600 and 300 gr/mm reflective gratings
linear dispersion	≈ 0.35, 0.8 and 1.7 Å/pixel, resp.
detector size (standard mode)	2048×4096, 15μm pixels, 2048 spectral pixels
detector size (mosaic mode)	2×2048×4096 mosaic, 4096 spectral pixels
standard field size	16×16 square elements ($8'' \times 8''$ FoV)
spatial sampling	$0.5'' \times 0.5''$, $0.75'' \times 0.75''$, $1'' \times 1''$

PMAS data can be reduced with the IDL-based modular data reduction package P3d, developed by Thomas Becker in parallel with the construction of PMAS. All P3d tools provide graphical user interfaces (GUI) for the comfortable, interactive operation plus an active IDL window for the implication of your own commands.

Apart from the full data reduction package there are tools for quick online reduction, data cube visualization, and mosaicing of data cubes (offset exposures).

3.1. THE FULL REDUCTION PROGRAM P3D

P3d is a data reduction tool which offers an automatic reduction of raw images with photometric accuracy, provided all the necessary calibration data are taken. All the several reduction steps like bias and dark subtraction, cosmic removal, spectra tracing and extraction, wavelength calibration and flat fielding can be run for a complete stack of images either as a whole (after dedicated parameter settings), or step by step.

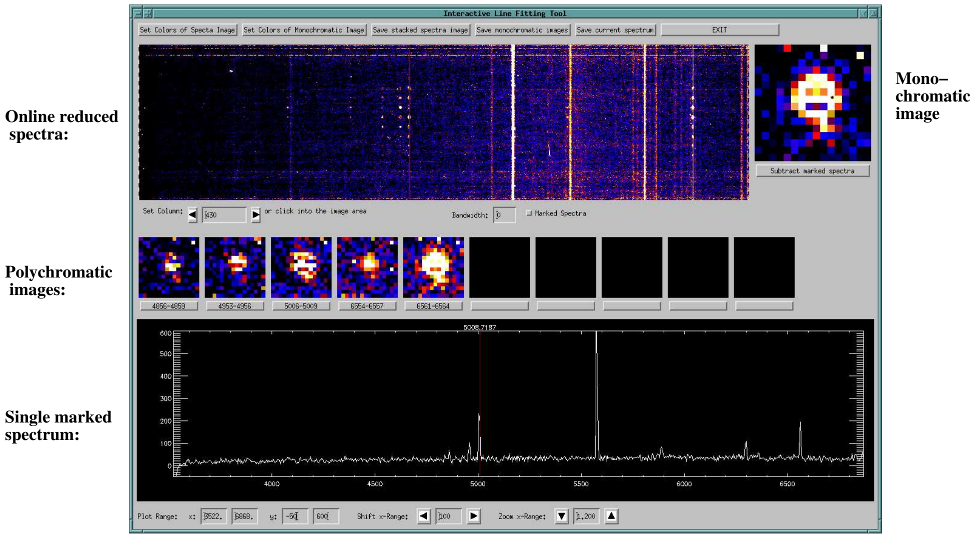
3.2. P3D ONLINE REDUCTION

As an aid for the observer at the telescope, there is a fast program for the online reduction, in order to have a quick look to the data just observed for immediate observing schedule decisions. To use P3d Online one needs to have

(1) one lamp flat exposure (Halogen) to create the trace mask
(2) one bias exposure for bias subtraction (optional)
(3) one calibration lamp exposure (Neon, Mercury, Thorium/Argon - depending on wavelength range) to create the dispersion mask (optional)
(4) one dome or better skyflat exposure to create the fiber flat mask (optional)

Provided the calibration frames were taken prior the science exposure, the extraction of spectra is performed as a matter of a few minutes after CCD readout. It can be seen immediately, if the target is centered, if the exposure time is sufficient, and if the spectrum shows the expected features.

Eight reduced object files can be displayed in one P3d Online GUI in parallel as monochromatic images. Additionallay, raw images can be displayed, the trace mask can be inspected in comparison to the raw image, and the active data cube can be



Set Column: 430 or click into the image area

Bandwidth: 0

Plot Range: x: 3522. 6868. y: -50 600

Shift x-Range: 100

Zoom x-Range: 1.200

Figure 3: P3d online reduction software, spectra viewer. The object shown is a planetary nebula in LeoA with emission lines in H_β, [OIII], and H_α.

checked by Spectra Viewer and Cube Slider. Last but not least one can display and evaluate telescope focus series taken with PMAS. For more detailed information about the P3d Online tool, see Becker 2003.

3.3. SPECTRA VIEWER

The Spectra Viewer (Fig. 3) displays the extracted 256 spectra of one data cube in a stacked 2D format one by one as lines (dispersion direction) starting from bottom to top (crossdispersion direction). The stacked spectra format gives a first overview of the spectral features in a data cube, and also provides hints to regions of interest in the spatial domain. For example, a distant pointlike planetary nebula appears as emission dots in the spectra of the object spaxels, i.e. in the middle of the y-axis, if the object is centered (upper panel).

A monochromatic image is selected simply by mouse-click onto the column of interest. So-called polychromatic or broadband images are displayed in the middle panel by selection of a certain wavelength region in the panel above.

Clicking onto a certain spaxel in the monochromatic image (upper right) produces the corresponding spectrum plot in the lower panel. The spaxel is marked in the monochromatic image by a black dot. Sky spaxels can be easily recognized by eye, marked on the monochromatic image by mouse-click, and subtracted from the object spectrum.

Although developed especially for the PMAS IFU, the P3d Online software has been successfully adapted for the reduction of VIMOS data.

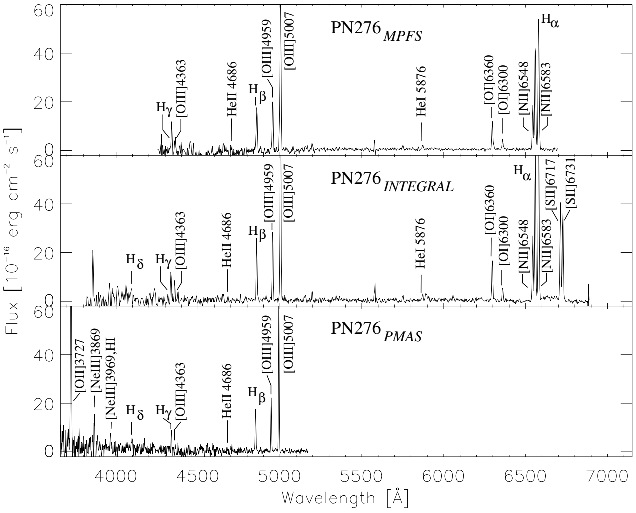


Figure 4: Spectra of the XPN candidate PN276, observed with the 3 IFU instruments MPFS, INTEGRAL, and PMAS. (Roth et al., 2004, Fig. 11).

4. SPECTROPHOTOMETRY OF PLANETARY NEBULAE

The improvement of IFU instruments in comparison to classical slit-spectroscopy is the ability to perform crowded-field spectrophotometry, useful for the study of resolved stellar populations in nearby galaxies. A pilot study of five extragalactic planetary nebulae (XPNe) in M31 of Roth et al. (2004), observed with three different IFU instruments including PMAS, demonstrated the major improvement in the accuracy of background subtraction.

Four of the five candidates were confirmed as XPNe, but with significant differences of the resulting line ratios when compared to other authors, e.g. Jacoby and Ciardullo (1999), or Richer et al. (1999). It was argued that 3D Spectroscopy is the superior method in comparison with classical slit spectroscopy for the spectrophotometry of faint background-limited objects, in particular with regard to systematic errors arising from emission or absorption line features from the background surface brightness distribution. One XPN candidate was found to be a misidentification, and classified as a supernova remnant (SNR) instead, based on the following arguments (Fig. 4):

- the [S II] doublet $\lambda\lambda$6717,6731 line ration of 1.03 implies an electron density of $\approx 400\, e\,\mathrm{cm}^{-3}$, rather low for a typical PN
- $\mathrm{T}_e \approx 55000\,\mathrm{K}$, derived from the [O III] line ratio $[\mathrm{I}(\lambda4959)+\mathrm{I}(\lambda5007)]/\mathrm{I}(\lambda4363)$ is too high
- the spatial extension of $\approx 5'' \times 4''$ is incompatible with the typical angular size of an XPN at that distance.

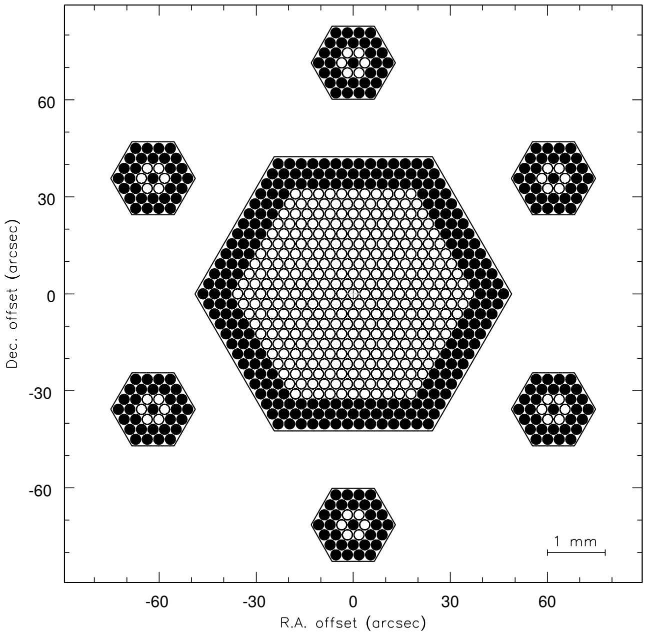


Figure 5: Wide-field IFU PPAK with 331 science fibers (open circles in the center), 36 sky fibers (open circles in the 6 mini IFUs), 15 calibration fibers (not shown because of different location), and 302 buffer fibers (filled circles). The overall FOV is $65'' \times 74''$, with spaxel sizes of $2''.7$ per science fiber core diameter.

5. THE NEW WIDE-FIELD IFU PPAK

For the observation of objects like XPNe, luminous stars in nearby galaxies, QSO host galaxies, gravitationally lensed QSOs, or other pointlike sources a FOV of $8'' \times 8''$ is sufficient. However, for the observation of extended low surface brightness objects it is far too small. Having in mind projects like the determination of galaxy disk masses by measuring the stellar velocity dispersions in the outer disks of spiral galaxies, or for the H_α velocity fields of LSB galaxies, an IFU concept with sparsely packed fibers in a wider FOV was proposed (Verheijen et al., 2004).

In 2003, the new wide-field IFU PPAK was designed and built, providing a FOV of $65'' \times 74''$ from a total of 331 science fibers, forming a bare hexagonal bundle in the focal plane without microlenses (Fig. 5). Additionally, 6 mini IFUs (sky fibers) provide a proper background sampling, and 15 fibers can be illuminated simultaneously by internal lamps for calibration purposes (Kelz et al., 2004).

Commisioning and First Light for PPAK was achieved in January 2004 (Kelz, 2004).

6. OBSERVING TIME PROPOSALS

PMAS is available at the 3.5m telescope of the German-Spanish Calar Alto Observatory, to the north of Almeria (Spain). Applications for observing time have to be sent as electronic proposals till March, 15th, for the autumn semester, and September, 15th, for the spring semester, respectively. For detailed description, LaTeX template and style files see http://www.mpia-hd.mpg.de/Public/CAHA/Applications/.

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