Integral Field Spectrography

Techniques & Specifics

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Contributions

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- Jeremy Allington-Smith
- Roland Bacon
- Guy Monnet
- James Turner
- Peter Weilbacher
Menu

- Historical perspective
  - 1D – 2D – 2.5D and 3D
- Basics of 3D spectroscopy
  - Techniques and examples
- Specifics
- From sky to cubes
  - Basic principles
- A (short) word on Softwares
- Concluding remarks
3D Spectrography

Historical perspective
From 1D to 2D

- Aperture spectrometry ➔ Long-slit spectroscopy
- Efficient use of
  - 2D photographic plates
  - CCDs
- « Easy » data reduction

NGC 681
Burbidge et al. 1965

\[ V \ [\text{km/s}] \]
\[ R \ [\text{arcsec}] \]

Focal Plane
Long Slit
Collimator
Dispersor
Camera
Detector

IFUs
Why is 2D not enough?

- Morphology of real object rarely follows slit geometry
- Centring on the target
- Light losses
- The slit effect
- Spectral resolution depends on the slit itself
How to squeeze 3D in 2D?

- Modern detectors are 2D (optical, near-infrared)

- We can thus either fix one spatial or one spectral dimension and scan with time:
  - Fabry-Perot interferometers
  - Scanning long-slit spectrographs

- But also:
  - Fourier Transform spectrometers
  - Hadamar Transform spectrometers (masks)
A Fabry-Perot etalon acts as an interference filter:
- Incidence $\theta$
- Wavelength $\lambda$
- Index $n$
- Inter plate $t$

Fabry Perot interferometers

- Tough data reduction (but doable)
- Very efficient for emission lines!
  
  - TAURUS (AAT, WHT), HIFI (CFHT)
  - CIGALE (3D NTT)
  - SAO (6m)

Carranza et al. 1968

Tully 1973

IFUs
Scanning: more space

- FPs limited to single emission lines
- Not ideal to tackle continuum + absorption lines
- Problem of TIME scanning: what about long-slits?

Fourier transform spectrometer

- **Frequency scanning:**
  - Bear at CFHT: 2 arms interferometer

![Diagram of interferometer setup]

- The Galactic center
  *(Maillard, Paumard)*
Problems linked with the scanning:

- Variation of the observing conditions
  - Data characteristics & controls?
- Accuracy of positioning to rebuild the 3D data
- Need of relatively bright objects

Inhomogeneities in the reconstructed datacubes
3D Spectroscopy
The Dawn of Speciation
On the way to real 3D

- 1960’s: aperture photometry to long-slit
  - Wide spectral range

- 1970’s: Fabry Perot interferometers
  - Large field of view, but narrow spectral range

- 1980’s:
  - Advent of modern CCDs
  - New ways to split the field
    - Using Fibers
    - Using micro-lenses
    - …
Advantage of true IFUs

- Large spectral range (but smaller FOV than FPs)
- Multiplex advantage
  - Save telescope time (not necessarily)
  - Homogeneous data (?)
  - Spatial location and PSF can be measured a posteriori
- Spectrophotometry!

Spaxel
Optical/Near Infrared spectroscopy

- The Atmosphere (ground-based instruments)
  - Transparency variations

- Sky Background: emission and absorption

- Spatial resolution: Point Spread Function
  - Typical PSF widths:
    - 0.5 – 2 arcsec in the optical
    - 0.3 – 1 arcsec in the NIR
  - But usually not a Gaussian-like PSF
  - Possibility to fully exploit Adaptive Optics

- Differential refraction
Optical/Near Infrared spectroscopy

- **Specifics:**
  - Spectra with Continuum and absorption lines

- **Resolutions**
  - Spectral = Shannon (Nyquist)
    - Usually FWHM or σ
  - Spatial = SPAXEL shape?
    - Difference between resolution and sampling!
    - Usually FWHM or σ
Splitting the field

- Fibers!
  - Few 100s fibers
  - Possibility of sky fibers
  - 0.3-1 arcsec per lens

Vanderriest, C. (1980), PASP 92, 858
"Fiber-Optics Dissector for Spectroscopy of Nebulosities around Quasars and similar Objects"

"Integral Field Spectrography with optical Fibers at the C.F.H. Telescope"
Fiber fed spectrographs

- INTEGRAL @ the WHT (4.2m)
  - Several configurations
  - Dedicated Sky fibers
Fiber-fed spectrographs

- **Advantages:**
  - Simplified output onto a slit
  - Full use of the CCD for the spectral coverage

- **Disadvantages:**
  - Light losses, performances
  - Stability of the instrument
  - Spectrophotometry?
The TIGER concept: The trick

Uniform illumination at the entrance of the array

The array samples the field and focus the light into micro-pupils

The array is rotated to avoid overlapping between the spectra

The micro-pupils are dispersed via a classical spectrograph

A filter limits the Y range
OASIS Raw Exposures

Flatfield exposure

Micropupil exposure

Object exposure

Neon Calibration exposure
Lens Array - Raw Data

Micropupil

Arc

SAURON - WHT

Continuum

Galaxy
TIGER-like spectrographs

- TIGER (CFHT), OASIS (CFHT/WHT)
  ... SAURON (WHT), SNIFs (UH 2.2m)
- OSIRIS (Keck) in the NIR

- Advantages:
  - Spatial & spectral information
  - No light loss (in principle)
  - Spatial scale can be easily changed

- Disadvantages:
  - Complex data format
  - Requires clean separation of spectra on the CCD
    - Not optimal use of the CCD pixels
Fiber + Lenses

- PMAS, CIRPASS
- VIMOS, FLAMES, GMOS

**Advantages:**
- Separation of spatial and spectral information
- No light loss
- Reconfiguration of SPAXELS on the detectors
- Better controled stability (?)

**Disadvantages:**
- Fibers…
- Spectrophotometric properties?
IFU Techniques: Optical Fibres

Pros:
- Flexible design
- Optimise CCD area

Cons:
- Poorer throughput
- Calibration-heavy

PMAS – Calar Alto
GMOS-IFU

- 0.4 - 1.0μm
- Hexagonal - contiguous
- 5 x 7 arcsec @ 0.2 arcsec
VIMOS-IFU

- 0.4 - 1μm
- 54x54/27x27 arcsec @ 0.7/0.3"
- 4 x EEV CCDs
VIMOS Raw Data
IFU Techniques: Optical Fibres

FLAMES - VLT
### IFU Techniques: Principles of a Slicer

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IFU Techniques: Image Slicer

Pros:
- Compact design
- High throughput
- “Easy” cryogenics

Cons:
- Difficult to manufacture
From MPE-3D to SINFONI / VLT

SINFONI / VLT – Eisenhauer et al.
The MUSE / VLT Slicer
Image Slicer - Raw Data

SINFONI - VLT

Wavelength

Slice
IFU Zoo: How to map 3D on 2D

Telescope Focus

Image Slicer

Spectrograph Input

Spectrograph Output

Final Output Data Cube

Lens Array + Fibers

Pure Lens Array

mirrors

fibers

lens image

IFUs ESO 08
To first order: all 3D methods are equivalent

⇒ same number of Detector pixels = same Data volume
But it is **NOT** equivalent

- Efficiency of packing on the CCD $\Rightarrow Q_{\text{max}}$
- Noise issues
- Separation of spectral versus spatial information:
  - better handle on spectrophotometry
  - But low packing efficiency
- **Slice = spatial continuity**
  - Continuous variation
  - High packing efficiency
  - But the 2 spatial dimensions are not on a similar ground
Best technique?

- lenslets
- fibres
- slicers
- microslicers

→ Slicers .... but difficult to make
From Sky to Datacubes

We wish to retrieve the full 3D information from an observed astrophysical object

❖ Issues

❖ Atmosphere
  - Transparency, PSF, refraction, time variations

❖ Optical path (telescope/instrument)
  - distortions, achromatism, diffraction, …

❖ Splitting the field, sampling issues

❖ CCD signatures
  - dark current, bias, artefacts, non linearity, irregularities, CTE

❖ An Inverse problem with knowns and unknowns:
  - HOW to recover the best signal out of a given exposure
  - HOW to robustly estimate the quality of the data
How to un-map 2D to 3D?

- Standard = to ‘extract’ 2D data into 3D (x,y,λ) ‘data-cube’
- Cubes are then resampled to linearize the 3D
- Initial extraction ➔ extra resampling step
- Very difficult to retain the original sampling during extraction
- Assumption of smoothly-varying properties across a CCD?
How is the 3D data mapped?
How is the 3D data mapped?

- Example: SAURON mask
  - Flexures ➔ reference exposure
  - Critical blends
  - Sampling of the spectral PSF
- Detailed optical model:

  To know where each $x, y, \lambda$ lie on the CCD!!
Within a slice, CCD pixels are neighbouring in \((x,y,\lambda)\) - no de-blending

- Slices are independent
- No common wavelength axis

- Spatial axes can be arranged arbitrarily
- Fibres may need de-blending
- Wavelength axis is common to all fibres
- Fibres usually treated as independent

- Both spatial and spectral axes re-arranged
- CCD pixels fully decoupled from \((x,y,\lambda)\)
- Deblending is critical
- Each lens is independent
The Noise issue

- Noise from the instrument
  - Detector noise
    - Read-out noise, shot noise from the dark current
  - Noise introduced during the data processing
    - E.g., due to the finite S/N of calibration exposures

- Noise from the undesired backgrounds
  - Shot noise from the backgrounds will remain even after a perfect subtraction of the undesired background

- Shot noise from the signal itself

- S/N of a dataset = key element for the analysis

*How real/robust are features you will detect / use?*
Propagation of artefacts

Artefact has been:
- spread out - more data loss
- attenuated - less likely to be identified
**Cosmic Rays**

- CCD coordinates are decoupled from data-cube coordinates
- Cosmics have high contrast in image planes
- Real features follow smooth/PSF distribution
- But better to do before resampling
Common data reduction steps

- Linearity correction
- Dark current subtraction
- Detector flat
- Bias subtraction
- Extraction
- Spatial calibration/tracing
- IFU flat
- Flux correction
- Wavelength calibration
- Instrumental background removal
- Atmospheric dispersion correction
- Sky subtraction
- Telluric correction
- Binning
- Dithering/mosaicing
- Bad pixel identification/removal
- Spatial calibration/tracing
- Bias subtraction
- Dark current subtraction
- Detector flat
- Extraction
- Spatial calibration/tracing
- IFU flat
- Flux correction
- Wavelength calibration
- Instrumental background removal
- Atmospheric dispersion correction
- Sky subtraction
- Telluric correction
- Binning
- Dithering/mosaicing
- Bad pixel identification/removal
The all-in one (magic!) solution?

- **Minimise** the number of steps including a resampling
- **Associate data analysis tools with data reduction software**
  
  The “ultimate” solution: to keep working with the detector pixels
  
  → real nightmare (and a 3D one!)

  “less” true for densely-packed fiber systems and image slicers?

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IFU Issues: Atmospheric Refraction

- Atmospheric refraction = image shifts as function of wavelength
- Shifts largest at blue wavelengths
- Can be corrected during reduction by shifting back each $\lambda$ plane

© R. McDermid
Fringing from bad flat fielding

OASIS
McDermid et al. 2006
Variations in spectral PSF across field
Need to homogenize before merging
Measured using twilight sky
Co-Adding Data Cubes

Two approaches:

1. Dithering by non-integer number of spaxels:
   - Allows over-sampling, via ‘drizzling’
   - Resampling introduces correlated noise
   - Good for fairly bright sources

2. Dithers by integer number of spaxels
   - Allows direct ‘shift and add’ approach
   - No resampling: better error characterisation
   - Assumes accurate (sub-pixel) offsetting
   - Suitable for ‘deep-field’ applications
IFU Issues: Spatial Binning

Unbinned S/N map

S/N map After binning

Voronoi tessellation

Target S/N

Cappellari & Copin 2003
# IFU evolution

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<tr>
<th>Instrument</th>
<th>Type</th>
<th>N Spat</th>
<th>N Spec</th>
<th>Domain $\mu$m</th>
<th>Spaxel arcsecond</th>
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<th>AO</th>
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**IFUs**
IFU papers

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## IFU (biased) evolution

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<th>Year</th>
<th>N spatial</th>
<th>N spectral</th>
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Data reduction and analysis challenges

Data complexity:
- Optimal extraction ➔ Good data model
- 2D mapping of 3D data
- Data characteristics: noise and systematics

Lack of robust tools:
- Each instrument has different characteristics
- Observing strategy can condition the data reduction
- Lack of manpower
- Community ?
  - Success !: Euro3D
  - Failure : Euro3D
Data reduction and analysis challenges

- **Data volume, for example MUSE:**
  - One exposure is > 1Gb (360 million resolved elements)
  - One night = a few 100 Gb of raw data
  - One 3D deep field will take 10 nights (> 1 Tb…)

- **Such instruments and applications require:**
  - A parallel data-reduction pipeline
  - Control the systematic to reach the required limiting magnitude
  - Optimal summation of 100 data cubes obtained under different sky conditions
  - Mining the final data cube to search for Ly$\alpha$ emission