Integral Field Spectrographs

A User's (?) view

Eric Emsellem

(CRAL - Lyon)
If you have to leave just now

- Keep track of the noise pattern
- Characterise the instrument (and data reduction)
- Develop Software on realistic data:
  - Instrument Numerical Model
- 1 SINGLE (evolving) version for the data reduction software
- Develop (and diffuse!) tools to handle the data
- Allow CALIBRATION PROPOSALS

How to optimise the output of this workshop?
Integral Field Specifics?

- IFS (VIMOS, FLAMES, SINFONI, ...):
  - like any spectrograph...

- But:
  - Adding *the issues linked with both Imagers & Spectrographs*
Specifcs - I:
No real Standard (yet)

❖ No good way to deal with the datasets (\textit{but Euro3D})

⇒ Need for more tools to handle the data:
  ✓ Slicing
  ✓ Visualisation
  ✓ Data mining

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>N spatial</th>
<th>N spectral</th>
<th>N total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIGER</td>
<td>1987</td>
<td>572</td>
<td>270</td>
<td>154,440</td>
</tr>
<tr>
<td>OASIS</td>
<td>1997</td>
<td>1,200</td>
<td>360</td>
<td>432,000</td>
</tr>
<tr>
<td>SAURON</td>
<td>1999</td>
<td>1,577</td>
<td>540</td>
<td>851,580</td>
</tr>
<tr>
<td>VIMOS</td>
<td>2002</td>
<td>6,400</td>
<td>550</td>
<td>3,520,000</td>
</tr>
<tr>
<td>MUSE</td>
<td>2012</td>
<td>90,000</td>
<td>4,096</td>
<td>368,640,000</td>
</tr>
</tbody>
</table>

⇒ \textit{Expect blind processes:}
  ◆ No way we can look at individual spectra
  ◆ Accept (and evaluate robust) \textit{errors}
  ◆ Requires robust algorithms
Specifics - II: Maps look GOOD

VIMOS spectrography of clusters in merging systems

The Antennae

WR lines

Gas σ

Bastian et al. 2005
How does this affect our science?

How do we deal with “errors”? 
Specifics - III: Spatial & Spectral

- All spectrographs: mixed spectral + spatial information
- 0D (aperture), 1D (long-slit) spectro:
  - restricted access to the spatial information
- Opening doors with 2D spectroscopy, e.g.:
  - Seeing a posteriori evaluation & correction
  - Atmospheric diffraction
  - (Spatial) Test for artefacts
**Specifics - III:**

**Spatial & Spectral**

- Atmospheric diffraction: images shift with wavelength
  - *Object moving out of the slit?*
- IFS minimise the impact of this effect
  - possible *software* correction (or ADC)

---

Emsellem et al. 1996; Arribas et al. 1999; *Theoretical predictions from e.g. Fillipenko, 1982*
Opening Pandora’s box

- Increasing the number of constraints:
  - Robust global quantities, Modelling,
  - Uncertainties in the modelling ≈ Errors from the data

⇒ Need for a better data treatment

---

Cappellari & McDermid (2005)
Pushing the limits

- Take advantage of the spatial mapping
- **Comparing datasets**
- **Super resolution**
- **Connecting spatial domains (mosaicing)**
- Deep fields (positioning, optimisation): MUSE
- Spectrophotometry !
- Adaptive Optics (& LGS)
Pushing the limits - 1
Connecting spectral domains

FLAMES spectra of NGC 3623

outwards

L3

L4
Pushing the limits - 1
Associating datasets

- SAURON vs OASIS
Pushing the limits – 2
Super resolution

- Follow the barycenter… down to milliarcseconds

Garcia et al. 2000
Implications - I
Need for a better characterisation

- A good, validated, *Calibration system*
- Stability of the instrument & telescope
- Taking into account, e.g. stray light

- Characterisation of the Detectors

- Why is all this needed?

Illustration: zebras...
Implications – I
Better characterisation

OASIS
McDermid et al. 2006

SINFONI data
on NGC 4486a

Nowak et al., submitted

Fringing in VIMOS ➔ see poster 14 by Jullo
Implications - I
Better characterisation

- Spectral (spatial) PSF variations over the field, with $\lambda$?
  - See poster 18 on VIMOS by Kuntschner
- Varying sampling
- Not perfect wavelength calibrations

- Gaussian emission-line
  - Change the sigma by 1 %
  - Change the centroid by 1 % of the sigma
- The lines are barely distinguishable
Implications - I
Better characterisation

- Residuals ~ 0.5-1.0 % of the peak intensity

- Major issue when the sky background ≥ object
  - Deep exposures, near infrared…
  - See poster 24 by Modigliani (SINFONI)
Implications - II

Need for new tools

- Mosaicing, Binning
- *Optimal* summation, normalisation, positioning
- Smoothing (spatially & spectrally)
- Deconvolution

7 exposures of 30 to 45-min each on the bow shock of NGC 4258 (obtained with OASIS at CFHT). P. Ferruit
Implications - II
Need for new tools

- Mosaicing and binning with IFS!
  - 36 fields, more than 30 000 independent spectra
    (and only 1/24 of MUSE data volume for 1 expo)
  - Optimal summing, binning \(\Rightarrow\) requires noise propagation

Jourdeuil et al., in preparation; Binning scheme: Cappellari & Copin
Implications - II
Need for new tools

- DRIZZLING:
  - Improving the sampling of poorly sampled images (HST era)
  - See e.g. *Hook & Fruchter, 2000, ADASS #216* and references therein

- A natural extension to 3D spectroscopy
  - Handling data cubes as stacks of monochromatic slices?

*Figure 2:* Illustration of how the drizzling method transforms an input pixel onto the selected output grid and showing the pixel shrinkage and general geometric distortion which can be included.

Additional corrections (distortion, atmospheric refraction) to be applied at the same time
Implication - II
Need for new tools

- Deconvolution:
  - Guided or not
  - To be adapted to 3D
Implications - III
Need for a good calibration plan...

- What is a science data product?

- Example:
  - FLAMES pipeline: amazingly good
    - But...

- Where are the flux standards?
  - Archive?
  - Which standard? *(spectral resolution, calibration!)*
  - UVES calibrated spectra? (secondary…*)
Implications – III
A good calibration plan

FLAMES/ARGUS mode: 2 domains (Hβ, Mgb, Fe5270, Fe5335)

R=12000

⇒ Stellar population study

& link with the dynamics

Emsellem, et al., in preparation
Aging Stars

FLAMES/VLT – ARGUS mode (L3)

Emsellem, et al., in preparation

5-7 Gyrs?

10-12 Gyrs?

2 H\(\beta\) cuts

Flux correction
Noise propagation and you...

- Keep track of noise propagation
- Required for any optimal stacking, binning, etc
- Published measurement should include error bars…
  - Keeping track of noise along the analysis
  - Easy to say, hard to do
  - Covariance?
  - Monte Carlo

→ Euro3D data cube to store this information together with your data

→ see *poster 11 on X-shooter (and also poster 10 by Grado)*

The COBE data analysis = good example of how the noise and bias levels can tracked when conducting an analysis of a dataset
The fear of resampling...

- Resampling a data set is seen by many as EVIL!
  - Usually not much choice in the spectral direction:
    - most datacubes are resampled spectrally during the wavelength calibration

- Spatial resampling can usually be avoided (and usually is)

- All this is due to the problem of
  - Spreading the artifacts over several spaxels
  - Following the noise pattern (correlation)
    - The spectra are not independent anymore
    - Summing /averaging a resampled dataset: lower gain?
Propagation of artefacts

- New sampling points
- Artifact has been
  - spread
  - attenuated: less likely to be identified
The all-in-one 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?

Diagram:
- Raw 3D data
  - Flux-calibrated data cube with the instrumental signature removed
    - Physical quantities
      - A LOT OF THINKING, MODELING...
        - The path to the holy Graal...
        - Paper...
Data Analysis Software Tools for MUSE

- Extract the best science products from MUSE cubes
- Volume, complexity…
Data analysis software tools for MUSE

DATA ANALYSIS TOOLS (non-exhaustive list !)

- Sky subtraction tools
- Image reconstruction tools
- Deconvolution tools
- Atmospheric refraction correction tools
- Mosaicing tools
- Visualisation tools
- Crowded-field spectro-photometric tools
- Generic image and spectrum analysis tools
- Model-fitting tools
  - Stellar-continuum fitting tools
  - Emission-line fitting tools

**Tools for data processing / reduction**

**Tools for data handling, preparation and visualisation**

**Tools to extract physical quantities from the data**
Conclusion

- Development of the (automated ?) tools to analyse the huge data sets of the next generation of instruments.

- Keep track of noise and systematic errors (tricky but good for scientific health).

- Characterisation of the instrument (+ reduction software)

- Adapted calibration plan + CALIBRATION PROPOSALS

- Need for a good (parametric ?) model

- Most statements not specific to IFS
Perspectives

- Software on realistic data: *Instrumental Numerical Model*
- Data Reduction Software + DAST

- Coordination!

**Diagram**

- Community
- ESO
- Data Reduction Software
- Consortium
- DAST