Integral Field Spectroscopy

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Integral Field Units (IFUs) are relatively new instruments in astronomy for obtaining spatially resolved spectra. The largest and most advanced telescopes today are being equipped with IFUs, including plans for future space telescopes.

Taking multiple spectra over large resolvable objects is important for many modern astronomical projects.

IFUs provide a datacube of two spatial dimensions and one wavelength dimension. Thus, various features of a single object (or multiple objects) in the field of view can be studied effectively.

Both spatial and spectral resolution have to be sacrificed for the combination of the two types of data.
IFUs use a similar concept to long slit spectrographs:
- Light from an extended object is passed through a single long slit
- The light is then diffracted with a grating in the direction perpendicular to the slit
- The output is a two dimensional image of distance (along the slit) versus wavelength

Spatial information is constrained along the slit itself, but Integral Field Units aim to add another spatial dimension to provide spectral information over the entire field of view.

Using a single slit spectrograph is an unrealistic method of obtaining a spatially resolved spectrum of extended objects. Long integration times and telescope instabilities inhibits piecing together multiple images efficiently.
IFUs have 3 main designs:

1) **Lenslets** – An array of lenslets focuses the incident light onto a single diffraction grating. The grating is arranged such that the spectra are dispersed at an angle on the CCD to prevent overlap.

2) **Lenslets + Fibres** – The light from the lenslets is sent through individual fibre optic cables and put through a single “slit.” The light is then dispersed perpendicular to that slit, providing the spectrum for each spaxel.
3) **Image Slicer** – This design is the most similar in concept to the single long slit spectrograph:

- The light from the telescope is sent onto a slicing mirror (a mirror with rows to reflect light from the object into different directions)
- These image slices are directed with mirrors onto the same spectrograph slit
- The light is diffracted by a grating, providing a spectrum for each row
### Designs

#### Table 1

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<th>Designs</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Lenslets</td>
<td>- Little light loss</td>
<td>- More lenslets means lower spectral resolution</td>
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<td>- Simplicity in design</td>
<td>- Poor optimization of detector space</td>
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<tr>
<td>Lenslets + Fibres</td>
<td>- Uses full detector</td>
<td>- Optical fibres introduce light loss</td>
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<td>- Easier to convert single slit spectrographs</td>
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<td>- Larger wavelength range</td>
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<tr>
<td>Image Slicer</td>
<td>- High efficiency</td>
<td>- Currently limited to infrared wavelengths</td>
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<td>- High spatial resolution along slices</td>
<td>- Tend to be bulkier than the other IFU designs</td>
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<td>- Low number of spaxels</td>
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During star formation gas is ejected into large outflows. Observations with IFUs provide the intensity for molecular transition lines at different points over the entire outflow.

By comparing the ratio of various transitions of H$_2$ molecules, the temperature and excitation mechanisms of the gas can be obtained using statistical mechanics. We can tell by the line ratio of the intensities of two molecular transitions, whether the molecules are being excited through shocks (line ratio $\sim$10) or florescence ($\sim$2). The temperature can be obtained by comparing the number density (which is proportional to the line emission intensity) of different energy states.
Projects: Luminous Infrared Galaxies (LIRGs)

IFUs are very well suited to studying various aspects of LIRGs. These galaxies are bright and full of star forming regions.

IFUs can help determine:
- The precise locations of star formation in the galaxies
- Position and abundance of large star clusters
- Occurrence of supernovae within LIRGs

Left: Interacting galaxies from the Hubble Space Telescope beside a single wavelength of the datacube from an IFU (SINFONI).

These images illustrate the sacrifice of spatial resolution for spectral information in IFUs.
SINFONI (Spectrograph for Integral Field Observations in the Near Infrared) is a near infrared (1.1-2.45 microns) image slicer IFU on the Very Large Telescope at Cerro Paranal in Chile. Depending on the wavelength band of observation, the spectral resolution ranges from 1500-4000. The spatial resolution is between 0.25”-0.025”, which is a tradeoff for the field of view size (8”x8”-0.8”x0.8”).

The Gemini North and South telescopes have an IFU called The Gemini Multi Object Spectrograph (GMOS). It is a 1500 element lenslet+fibre array operating in the optical and near infrared (400-1100nm). 500 of the fibres are dedicated for observing the sky for removal of background signal. The instrument has a spectral resolution of 630-4300, spatial resolution of 0.2”, and field of view of 5”x7”. 
SAURON (Spectrographic Areal Unit for Research on Optical Nebulae) at the William Herschel Telescope at La Palma, Chile is an optical (450-700nm) IFU composed of a 1577 lenslet array. It has a spatial resolution of 0.27”, 1250-1944 spectral resolution, and field of view of 41”x33”. It’s main goal is to study the formation of elliptical galaxies and the bulges of spirals.

The James Webb Space Telescope (JWST) also has plans to be equipped with two instruments that have IFU components. MIRI (Mid-Infrared Instrument) will have roughly 12-21 slice image slicer, covering the mid-infrared of 5-28 μm. JWST will also have a near-infrared instrument with an IFS mode called NIRSpec (Near-Infrared Spectrograph).
References

General Information
Durham University:
www.dur.ac.uk/cfai/spectroscopy/introductiontointegralfieldspectroscopy/
Integral Field Spectroscopy Wiki: ifs.wikidot.com

Image Credits:
Introduction: Stephen Todd (ROE) and Douglas Pierce-Price (JAC)
Theory: en.wikipedia.org/wiki/File:Longslit_spectroscopy_example.png
Designs: First image from above Durham University link above & examples in table from M. Westmoquette, adapted from Allington-Smith et al., 1998
Stellar Outflows: NASA, ESA, and P. Hartigan (Rice University)
LIRGs: From above LIRGS source
Instruments: VLT image from European Southern Observatory, GMOS-South from Gemini Observatory, SAURON image from project website at www.strw.leidenuniv.nl/sauron/, JWST image from NASA