

Chapter 2

Integral Field Spectroscopy and Spectral Energy Distributions

A large fraction of this thesis is based on spatially resolved spectroscopy data that were obtained using an observational technique called integral field spectroscopy. These data are used to trace the ionised gas kinematics over kiloparsec scales in the objects studied in Chaps. 3, 4 and 5. This first section of this chapter gives brief details of how integral field spectroscopy works, the instruments used in this thesis and the basic steps required to reduce integral field spectroscopy data. The other main techniques used in this thesis make use of infrared photometric data, either by stacking or fitting spectral energy distributions to multiple photometric data points. These infrared measurements are then used to calculate star formation rates and AGN luminosities. These techniques and calculations are used in Chaps. 3, 4 and 6 and are described in the second section of this chapter.

2.1 Integral Field Spectroscopy

2.1.1 Introduction

With traditional astronomical spectroscopy a single spectrum is obtained for the source that is being observed. However, most extragalactic sources are spatially extended on the sky and therefore it is often desirable to spatially resolve the spectra. In *long-slit* spectroscopy the light from a source is passed through a slit, and then it is the image of this slit that gets dispersed. This has the advantage of providing spatial information in the direction along the slit. However, if you are interested in characterising the spectra for the full source, there are two main disadvantages with long-slit spectroscopy: (1) you only obtain a spectrum of the light that actually passes through the slit (i.e., all other light is lost); (2) all of the spatial information perpendicular to the slit is lost. If the target has a large angular size on the sky

(either intrinsically or due to poor seeing), it can be time consuming to undertake the multiple observations required to obtain spectra for the full source. *Integral field spectroscopy* (IFS) provides the solution.

2.1.2 Integral Field Spectroscopy

IFS is an observational technique that provides three dimensional information of the target being observed. The instruments used are called integral field spectrographs and they produce data in the form of data cubes. These data cubes consist of two spatial dimensions (i.e., $[x, y]$ or $[RA, DEC]$) and a wavelength dimension (i.e., λ ; see Fig. 2.1). Figure 2.1 is a schematic diagram that demonstrates that, with these data, it is possible to obtain images of the target in different wavelength slices and also to obtain spectra at every spatial pixel. These data can thus be used for several different types of analyses, a few examples of which are: (1) creating emission-line images; (2) tracing the velocity structure of emission and absorption lines across the target; (3) measuring emission-line flux ratios across the target. Common scientific experiments that are performed with IFS data of extragalactic objects include:

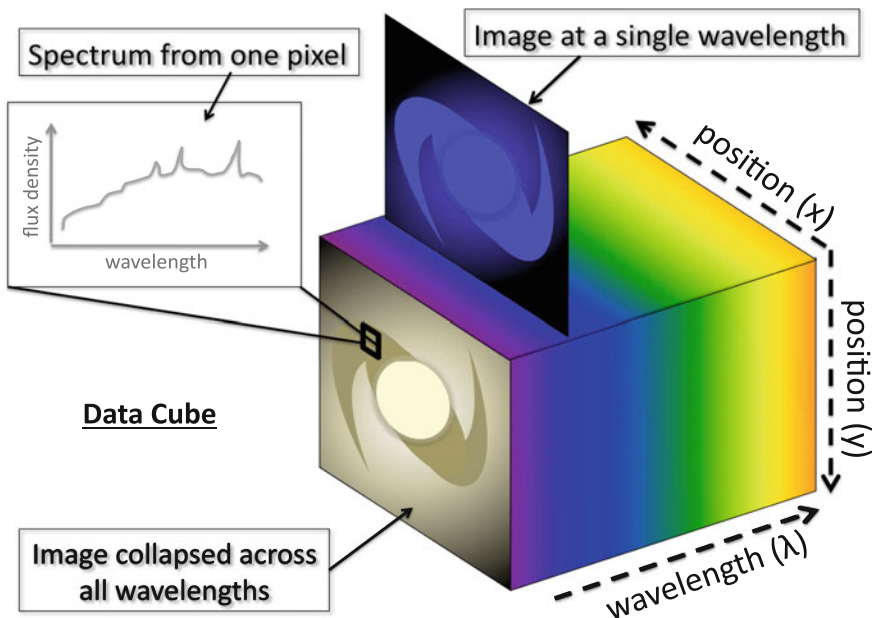


Fig. 2.1 Schematic diagram of a data cube. A data cube provides information in three dimensions: two spatial dimensions (i.e., an image in $[x,y]$) and a third dimension of wavelength. It is therefore possible to obtain an image of the target at a single wavelength or collapsed over wavelength slices. Furthermore, at every spatial pixel of the datacube a spectrum can be extracted

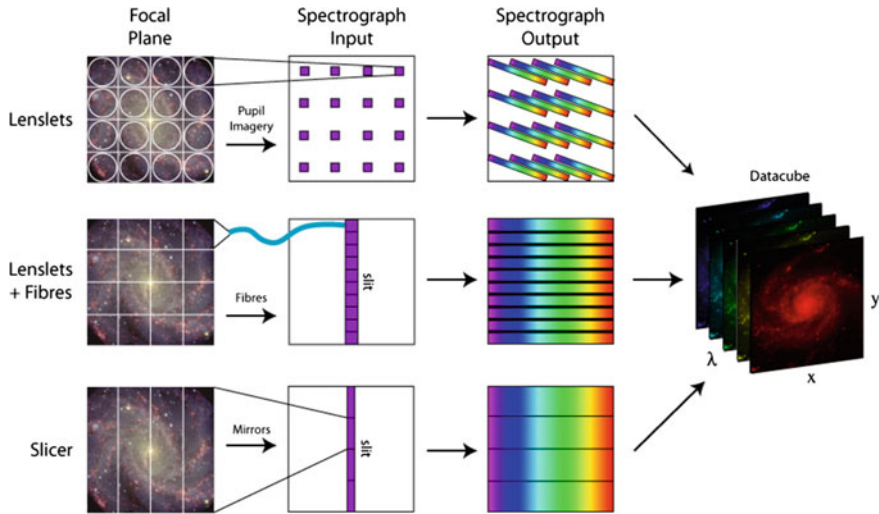


Fig. 2.2 A diagram of the main techniques used in IFS. An IFU samples the light from the focal plane using different techniques (lenslets, lenslets plus fibres and an image slicer are shown here) and then sends the light to a spectrograph to be dispersed. The spectrograph output can then be formatted into a datacube (see Fig. 2.1) during the data reduction process. *Image Credit* M. Westmoquette; Adapted from Allington-Smith and Content (1998)

(1) measuring the dynamical structures of gas and stars; (2) spatially resolving stellar populations; (3) measuring the spatial distribution of on-going star formation; (4) searching for and characterising outflowing or inflowing gas.

IFS is performed with an integral field spectrograph in the optical or infrared wavebands. These instruments consist of an integral field unit (IFU), which samples the light into multiple spatial components, and a spectrograph, which disperse the light. IFUs sample the light by using lenslets, fibres or slicing mirrors. Figure 2.2 illustrates the main methods of IFUs, and they are summarised below.

- *Lenslets arrays* can be used to format the image into several points of light that are then dispersed by the spectrograph. The dispersed light is angled to avoid excessive overlap between the spectra.
- *Fibres* can be used either on their own or in combination with a lenslet array. This technique uses a bundle of optical fibres to sample the image directly or the fibres can be placed behind a lenslet array. The light from the fibres is then aligned to create a “pseudoslits” that is passed to the spectrograph.
- An *image slicer* uses segmented mirrors to split the image into horizontal stripes that are sent in slightly different directions. A second set of mirrors then formats these slices on top of each other into a “pseudoslits” that is then passed to the spectrograph.

The formatted light (using the above methods) is collimated and dispersed by the spectrograph before being recorded by the detector. The final output image consists

of multiple lines of spectra, corresponding to different positions in the original image (see Fig. 2.2). Each individual spectrum can then be reformatted into the three-dimensional data cube (Fig. 2.1) during the data reduction process.

2.1.3 The Instruments Used in This Thesis

Five different integral field spectrographs are used in this thesis: (1) The IFU mode of the Gemini Multi-object Spectrograph (GMOS; Allington-Smith et al. 2002) installed on the Gemini-South telescope in Chile; (2) The Near-Infrared Integral Field Spectrometer (NIFS; McGregor et al. 2003) installed on Gemini-North in Hawaii; (3) The Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI; Eisenhauer et al. 2003) on the Very Large Telescope (VLT) in Chile; (4) The VISIBLE MultiObject Spectrograph (VIMOS; Le Fèvre et al. 2003) installed on the VLT and (5) The K-band Multi Object Spectrograph (KMOS; Sharples et al. 2004, 2013) installed on the VLT. This sub-section gives a brief overview of each instrument and their properties are summarised in Table 2.1.

- **SINFONI** is a near-infrared spectrograph which uses an image slicer IFU. The IFU contains 32 slices with three choices of slit height, leading to different pixel scales and fields-of-view (see Table 2.1). In Chap. 3 of this thesis we use SINFONI with slit heights of 250 mas which results in a $8'' \times 8''$ field-of-view. There are four

Table 2.1 Summary of IFS instruments used in this thesis

Name	Design	Pixel scale (milli-arcsec)	Field of view (arcsec)	Wavelength coverage (μm)	Resolution
NIFS	Image slicer	103×40	3×3	0.94–2.40	$\approx 5000\text{--}6000$
GMOS ^a	Fibre + lenslet	200	5×7	0.36–0.94	$\approx 600\text{--}4400$
SINFONI ^b	Image slicer	125×250	8×8	1.10–2.45	$\approx 1500\text{--}4000$
		50×100	3×3		
		12.5×25	0.8×0.8		
VIMOS ^c	Fibre	670×670	27×27	0.370–0.860	$\approx 1440\text{--}3100$
		330×330	13×13		
KMOS ^d	Image slicer	200×200	2.8×2.8	0.8–2.5	$\approx 2000\text{--}4200$

A summary of the properties of the different integral field spectrographs used in this thesis

^aWe use GMOS in “one-slit” mode that provides a field-of-view of 5×3.5 arcsec

^bSINFONI has three different options for spatial sampling and they are all listed here; however, in this thesis we only use the 8×8 arcsec field-of-view

^cFor VIMOS, we only provide a summary of the high resolution grisms as an example (as used in Chap. 5). VIMOS also provides medium and low resolution grisms with different fields-of-view, wavelength coverage and spectral resolutions (see Le Fèvre et al. 2003)

^dKMOS contains 24 identical IFUs

gratings available (J, H, K, H+K) giving an overall wavelength coverage of 1.1–2.45 μm . In Chap. 3 of this thesis we use the H+K grating, which has a spectral resolution of $\lambda/\Delta\lambda \approx 1500$.

- **NIFS** is a near-infrared spectrograph which uses an image slicer IFU. There are 29 individual slices with a height of 103 mas. There are four gratings (Z, J, H, K) giving an overall wavelength coverage of 0.94–2.40 μm . In Chap. 3 of this thesis we use NIFS with the J, H and K filters which provide spectral resolutions of $\lambda/\Delta\lambda \approx 5300$ –6000.
- **GMOS** is a multi-purpose optical instrument that can be used for imaging and spectroscopy. For this thesis we make use of the IFU inside the instrument that makes it into an integral field spectrograph. A lenslet array of 1500 elements is used to slice the image into small components. 1000 elements are used to observe the target field and 500 elements are used to simultaneously observe a blank sky field ≈ 1 arcmin away from the target field. Each lenslet is coupled to a fibre that takes the sliced components to the spectrograph in the form of two “pseudoslits”. In “two-slit mode” (i.e., using both pseudoslits) the full field-of-view is sent to the detector (i.e., $5'' \times 7''$). In “one-slit mode” only half of the field-of-view is recorded; however, the extra space on the detector is used to increase the recorded spectral coverage. A variety of gratings are available with different spectral resolutions that are optimised for either blue or red wavelengths. In Chap. 4 we use the GMOS IFU in one-slit mode with the B1200 grating, which has a spectral resolution of $\lambda/\Delta\lambda \approx 3700$, and an effective field-of-view of $5'' \times 3.5''$.
- **VIMOS** is similar to GMOS, in that it is a multi-purpose optical instrument that can be used for imaging or spectroscopy. For this thesis we make use of the IFU instrument that makes in into an integral field spectrograph. The VIMOS IFU consists of 6400 fibres. The scale of these fibres can be changes between 0.33'' per fibre and 0.67'' per fibre. The VIMOS spectrograph contains three spectral resolution modes, high resolution (HR; with red orange or blue grisms), medium resolution (MR; with only one grism) or low resolution (LR; with red or blue grisms). The LR mode provides a field-of-view of $54'' \times 54''$ or $27'' \times 27''$, when using 0.67''/fibre or 0.33''/fibre, respectively. In contrast, The HR and MR modes provide a field-of-view of $27'' \times 27''$ or $13'' \times 13''$, when using 0.67''/fibre or 0.33''/fibre, respectively. In Chap. 5 we use the VIMOS IFU in HR mode and 0.67''/fibre with the Orange grating.
- **KMOS** is a second-generation instrument that contains 24 individual near-infrared IFUs. These 24 IFUs can be individually positioned inside a 7.2 arcmin diameter patrol field. Each IFU contains 14 slices, with 14 spatial pixels along each slice. This results in spatial sampling of $0.2'' \times 0.2''$ and a field-of-view of $2.8'' \times 2.8''$ for each IFU. These IFUs are fed to three separate spectrographs. There are five gratings available (IZ, YJ, H, K, H+K) giving an overall wavelength coverage of 0.8–2.5 μm . In Chap. 8 we present some observations using KMOS with the YJ filter.

2.1.4 Data Reduction

The final image produced by an IFS is in the form of several rows of spectra each corresponding to a different position in the target field (see Fig. 2.2). Just like with traditional spectroscopy these spectra must undergo several calibration steps before they can be used for scientific analyses. The details of the data reduction for the individual instruments are provided in Chaps. 3 and 4; however, a brief outline of the main steps is given here.

Firstly, sky images or “frames” are subtracted from the science frames. Sky frames are observations of a blank-sky field using exactly the same set-up and exposure times as the science observations. This sky subtraction is required because the background sky has a non-zero brightness in the optical and infrared wavebands. Of particular trouble are the large number of infrared emission lines produced by molecules in the atmosphere that need to be removed by this sky-subtraction process. The sky-subtracted science frames must then undergo a series of calibration steps. The steps of calibration are required to correct for imperfections in the telescope and instrument response and also convert the recorded data into physical units (i.e., flux density and wavelength). Several calibration frames are required to perform these steps and they are listed below.

- Bias frames are zero second exposures taken with the detector’s shutter closed. These frames can be used to correct for a non-zero “bias” and/or hot pixels on the detector.
- Dark frames are images taken with the detector’s shutter closed. Several are taken to produce a set of dark frames with exposure lengths to match all of the other calibration and science frames. These dark frames can be used to correct all of the other frames for the average “dark current” (due to thermal excitation) produced during an exposure.
- Flat-field frames are images taken when the detector is illuminated with a uniform source of non-dispersed light. The process of “flat fielding” uses these frames to correct for the non-uniform response of the detector frames due to spatial variations in the sensitivity of the detector or anomalies in the optical path. In the case of IFS this can be done for each slice individually.
- Arc frames are images of the dispersed light from an arc-lamp with a well known set of spectral lines (e.g., Neon and Argon lamps). These frames are used to create the wavelength solution for the science images (i.e., assign a wavelength to each of the pixels in the dispersion direction). These frames can also be used to correct for any spectral curvature on the science frame.
- Ronchi mask frames are images of a grid of perfectly arranged slits or rulings. These frames can be used to correct for any spatial distortions in the images.

After the calibration process the sky-subtracted science frames (see Fig. 2.2) will have been corrected for the telescope and instrument imperfections and have a good wavelength solution. The datacube now needs to be constructed by extracting each row of spectra on the frame, and placing them into the appropriate spatial position

(see Fig. 2.1). Finally, each spectrum needs to be flux calibrated. This is done using observations of “standard stars” that are observed and calibrated in the same manner to the science targets. The chosen stars have well known intrinsic luminosities and spectra in the wavelength bands being observed and their spectra have few features beyond the continuum. The standard star observations are used to create a model of the correction between observed intensity units (i.e., counts) and flux density units as a function of wavelength. This model is then applied to each spatial pixel of the science data cube. Standard stars can also be used to correct for telluric absorption by the atmosphere which can be particularly troublesome in the infrared waveband.

2.2 Spectral Energy Distributions

Throughout this thesis we make measurements of the star formation rates and bolometric AGN luminosities of our targets. To do this, we primarily make use of infrared photometric data.¹ The most direct tracer of star formation is through the ultra-violet and optical light produced by the youngest stars and supernovae. However, this emission can be significantly absorbed by obscuring dusty material around these areas, making it very challenging to observe. Fortunately this obscuring dust can be used to *indirectly* trace the star formation because it is re-emits the stellar light it absorbs at mid infrared (MIR) and far infrared (FIR) wavelengths, typically peaking at rest frame wavelengths of $\approx 80\text{--}100\mu\text{m}$ (e.g., Mullaney et al. 2011). The total infrared emission (rest frame wavelengths of $8\text{--}1000\mu\text{m}$) is arguably the best tracer of ongoing star formation, particularly at high redshifts, providing that the conversion factors between FIR luminosity and star formation rate have been well calibrated. Fortunately, detailed studies of galaxies in the local Universe have provided these calibration factors, incorporating supernovae rates to measure star formation rates and multi-wavelength photometric data.

In Sect. 1.2.2 it was shown that AGN produce emission at MIR wavelengths, due to them begin surrounded by a dusty structure (often being described as a “torus”). This dust is heated by the central source and then re-emits at these wavelengths. This dust is predicted to be relatively hot resulting in a emission that peaks at $\lambda \approx 20\text{--}50\mu\text{m}$, with a steep fall-off at longer wavelengths (e.g., Schartmann et al. 2008; Nenkova et al. 2008; Mullaney et al. 2011; Fig. 1.2). If a measurement of the infrared emission produced by the dust-heated AGN is available it is then possible to estimate an AGN bolometric luminosity using the relevant bolometric correction factors (see Sect. 1.2.4). In summary, when observing the infrared emission produced by galaxies that host AGN, it will be produced by a combination of dust heated by the AGN (peaking at MIR wavelengths) and cooler dust heated by star formation. In summary, if sufficient infrared photometric data exists (i.e., the infrared spectral energy

¹We note that we use emission-line luminosities and X-ray luminosities as a tracer of AGN bolometric luminosity in Chaps. 4 and 6, respectively. These tracers are discussed in Sects. 1.2.2–1.2.4.

distribution [SED], is well sampled), it is possible to decompose this emission and obtain measurements of both the star formation rates and AGN bolometric luminosity.

In Chaps. 3 and 4 of this thesis we make use of a technique, that was initially presented in Mullaney et al. (2011), that simultaneously fits an empirically derived AGN model (parameterised in an analytical form) and empirically derived host-galaxy templates to the infrared photometric data. We show an example of this in Fig. 2.3. We simultaneously fit these data with the five star-forming galaxy templates (“SB1”–“SB5”) and the mean AGN model, originally defined in Mullaney et al. (2011) and extended to cover the wavelength range $3\text{--}10^5\ \mu\text{m}$, by Del Moro et al. (2013). To derive the AGN luminosities and SFRs (Table 4.2) we use the star-forming template plus AGN template combination that gives the lowest overall χ^2 value. For the sources where we have no detections in the far-infrared bands, we are unable to measure reliable SFRs and we therefore calculate conservative upper limits by increasing the normalisation of the star-forming templates until the photometric upper limits were reached. We emphasise that our method decomposes the emission due to an AGN and star formation, therefore removing the need to assume the relative contributions from these two processes. Furthermore, we find that, for targets that we have observed which have archival MIR spectroscopic measurements (e.g., Menéndez-Delmestre et al. 2009; Valiante et al. 2007), there is a good agreement between the strength of the AGN component calculated from our SED-fitting procedure and the strength of the AGN derived from the mid-infrared spectroscopy (also see Del Moro et al. 2013 for more tests of this method).

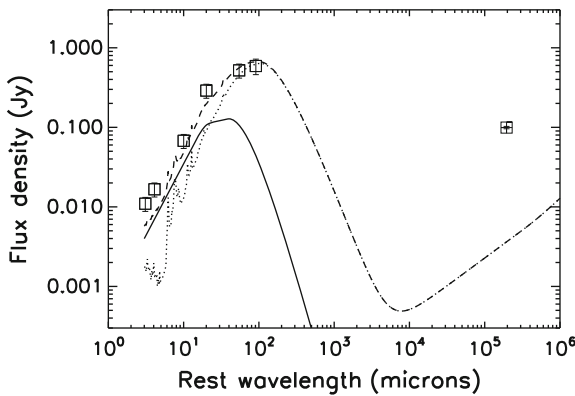


Fig. 2.3 An example infrared SED, where we have decomposed the emission from star formation and AGN. The *squares* show the photometric infrared data (with the addition of a 1.4 GHz radio measurement at $\approx 10^5$ GHz). The *dotted curve* shows the best-fit star formation template and the *solid curve* shows the AGN template described in Sect. 2.2. The *dashed curve* shows the total fit from the combined processes. The AGN emission dominates at MIR wavelengths (i.e., $\lesssim 20\ \mu\text{m}$) and the star formation dominated at FIR wavelengths (i.e., $\gtrsim 20\ \mu\text{m}$). We can use these best fit solutions to estimate a SFR and AGN luminosity for our targets

In Chap. 6 we measure SFRs for a sample of $z = 1\text{--}3$ X-ray detected AGN. However, due to the limited photometric data available, it was not possible to reliably perform full SED fitting for these targets. Instead, we make the simplifying assumption that at FIR wavelengths, the emission is dominated by star formation heated dust, with little contribution from the AGN. This assumption has been shown to be reliable in numerous studies (e.g., Netzer et al. 2007; Mullaney et al. 2011) and is discussed further within Chap. 6 itself. For these targets we make average measurements of the total infrared luminosities using average FIR fluxes from stacked *Herschel* data and assumed SEDs (see Sect. 6.4).

2.3 Calculation of SFRs and AGN Luminosities

We calculated the SFRs for each source by measuring the infrared luminosities of the star-formation components from the best-fitting SED solutions ($L_{\text{IR,SF}}$; integrated over $8\text{--}1000\mu\text{m}$) and using the conversion factor from Kennicutt (1998).² To determine the bolometric AGN luminosities for each source, we first calculated the AGN continuum luminosity at $6\mu\text{m}$ from the best fitting SED solution and converted this to an AGN bolometric luminosity using a correction factor of $\times 8$ (Richards et al. 2006; see Sect. 1.2.4).

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²We note that in Chap. 4 we convert the SFR calibration of Kennicutt (1998) from a Salpeter IMF to a Chabrier IMF by dividing by a factor of 1.7 (Chabrier 2003).

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