Red Supergiant Stars within the Local Group

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Chapter 1

Spectroscopy and the K-band Multi-Object Spectrograph

1.1 Opening Remarks

KMOS warrants an individual section in this chapter as all of the spectroscopic observations used in this thesis are from this instrument. This chapter initially describes the basic design of a spectrograph and outlines some of the more commonly used spectroscopic techniques in Section 1.2. I then move onto to described integral field spectroscopy, a more complex spectroscopic tecnique, in Section 1.3. I then go on to describe KMOS in Section 1.4 and the KMOS data reduction process in Section 1.5. Finally, I conclude the chapter in Section 1.7.

1.2 Introduction to Spectroscopic Techniques

Spectroscopy is the study of the dispersion of light into its constituents and has been at the forefront of astronomy for roughly the last 200 years. Sir Isaac Newton demonstrated the principles of spectroscopy (and coined the term "spectrum") using light from The Sun in his seminal "Opticks" work (**?**). By using the groove spacings on a diffraction grating, Thomas Young first quantified the wavelengths of different colours of light (**?**). The simple set-up of a spectrograph, which has - more or less - been used since the early spectroscopic experiments, consists of five basic elements:

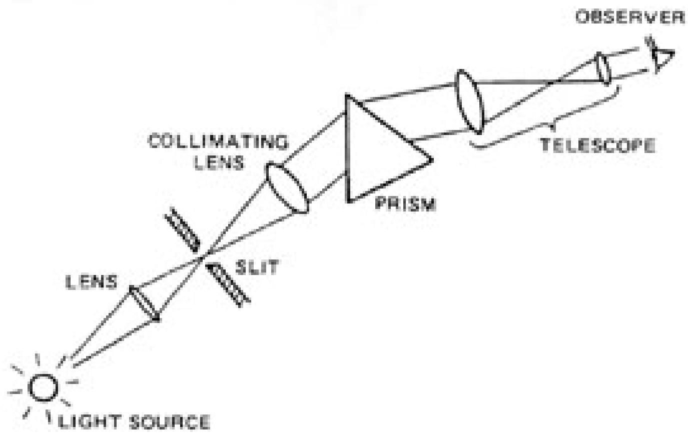

Figure 1.1 *The five basic elements a spectrograph must posess.* ***Placeholder for a figure I will create***

Figure 1.2 *Three panels demonstrating long-slit spectrscopy*

i Slit

ii Collimator

iii Dispersive element

iv Camera

v Detector

A simple spectrograph is illustrated in Figure 1.1. In Newton's demonstration he used a small hole in his window blinds as a slit and a screen as a detector. The slit in modern spectroscopic observations can take various forms. The most widely used type of slit, in modern observations, is long-slit spectroscopy. Using a long slit, a spectrum is taken for each spatial pixel along the length of the slit. This is demonstrated in Figure 1.3, where the final panel shows that each pixel illuminated by the slit produces a spectrum. This can be thought of a 2-dimensional spectroscopy, which is particualrly useful when attempting to take a spectrum of an extended object (rather than a point source).

As an alternative to using a long-slit to remove contamination from other sources, is to use a small hole or fibre to select the target flux. By precisely drilling a hole in a metal plate, a slit is created which can be used to select the target flux. One of the advantages of using this method is that more than one object can be selected for a single exposure. By creating multiple slits within a single plate, spectroscopy

Figure 1.3 *Three panels demonstrating multi-object spectroscopy*

from multiple objects can be obtained where contamination from other sources is minimised. An improvement to this method was to use optical-fibres positioned within the holes. The fibres could then be led to an instrument which was not directly attached to the telescope, which has the advantage that the instrument will not suffer from the changing gravitational force as the telescope moves. In addition, the conditions within the instrument room can be controled. This is particularly important for near-IR spectrographs and detectors.

However, using a plate with several holes drilled into it has some drawbacks. These include the time in which it takes to create the slit mask, the lack of flexibility while observing and the operational costs of creating a new mask each time a different field is to be observed (Parry & Gray, 1986). These reasons, in addition to improved computing power, led to the development of instruments which were able to automatically position fibres (Tubbs, Goss & Cohen, 1982). Most modern fibre-fed spectrographs have automatic fibre positioning technology which is broadly split up into two approaches.

i Each fibre has a magnetic button attached and a single robot is charged with moving each fibre sequentially. This is an effective method to place large numbers of fibres, but does however, take a significant length of time for each configuration.

ii Each fibre is mounted upon a computer controlled arm. This method is generally less time consuming.

As a variant on the five basic elements of a spectrograph, slitless spectroscopy is also a feasible option which is not discussed in detail here. For more information on slitless spectroscopy see Fergus' thesis!

- Some words about the different dispersive elements and their qualities
- Detail the diffraction grating
- Briefly compare gratings and prisms

1.3 Integral field spectroscopy

The overall goal with integral field spectroscopy (IFS) is to obtain a spectrum of everything (targets and their surroundings) within a given field of view. This concept is essentially an extension of the idea that a long-slit spectrograph obtains spectra for targets within the extent of the slit. A natural extension of this technique would be to use a long-slit spectrograph to obtain a spectrum for each pixel within a 2-D field of view on the sky.

There are many intrinsic advantages, however, to having a specifically designed instrument to perform this task rather than simply repeating observations with a long-slit spectrograph. These advantages include,

i slit-losses are eliminated,

ii accurate target acquisition is not required,

iii target position can be recovered from data,

iv radial velocity errors from positional issues in slit when comparing target and reference object,

v velocity field is recovered without biases,

vi IFS always optimally samples object point spread function (PSF).

In addition, the potentially most compelling argument (from a purely romantic perspectively) is that to perform IFS with a long-slit spectrograph one is required to take N exposures all of length t_{exp}, however, using IFS, a spectrum for each spaxel is obtained with a single exposure.

1.3.1 Techniques of integral field spectroscopy

IFS may be achieved using a variety of different and novel methods. Potentially, the simplest of these is (and most cost effectively in the short term) is to take multiple exposures using an existing spectrograph over a small field of view. Another, conceptually, simple approach is to take photometric data of the same field using multiple narrow-band filters which can be stitched together to create effectively low-resolution spectroscopy of a field of view (e.g. TAURUS, ref!).

Figure 1.4 *Three diagrams demonstrating the techniques of IFS*

There are three main techniques which are more commonly used to generate spectra over a 2-dimensional field of view. An spectrograph specialised for integral fields adds an additional element to the five basic elements of a spectrograph outlined previously. This additional element is an integral field unit (IFU) which acts to split up the image obtained by the telescope into elements or slices which are constructed into a slit and dispersed by the dispersive element. The difference between the techniques is in the way in which they split up the image. In this section I will detail each of these techniques in turn and conclude by providing a comparison between the techniques.

A lenslet array splits the input image using a tight array of small lenses (Bacon et al., 1995). The lenses then focus the light which are then dispersed. This technique limits the length of the spectrum measured on the detector. To improve this the spectra are tilted about the optical axis to minimise overlapping of spectra, which leads to inefficient packing of the resulting spectra on the detector.

Fibre arrays use a tightly packed bundle of fibre-optic cables to split the telescope image (ref). The fibres are then reposition the image onto a linear slit. Figure 1.4 shows a cartoon of this process. As the fibre cables are intrinsically cylindrical objects, much light is lost between fibres. To minimise the light lost this technique can be improved upon by using an array of lenses to focus the light from each element into the fibre, effectively combining this technique with the previous described.

The final technique is to use an image slicer to split the image from the telescope (Content, 1997). Figure 1.5 shows an image slicer used in the KMOS instrument. An image slicer is a type of segmented mirror where each linear segment reflect light in a slightly different direction. A second segmented mirror then arranges the images into a pseduoslit where it is then dispersed. As Allington-Smith (2006) demonstrate, this method is intrinsically efficient as complete slices of the field are imaged by the detector. In addition, this method is also particularly applicable for IR studies as the optical system consists mainly of mirrors which are easily cooled to low temperatures. Drawbacks with this technique include that a large and complex optical system is required with a surface roughness (σ) of $\sigma \leq 10\,\mathrm{nm}$ in the IR.

Allington-Smith (2006) perform a detailed theoretical comparison between these

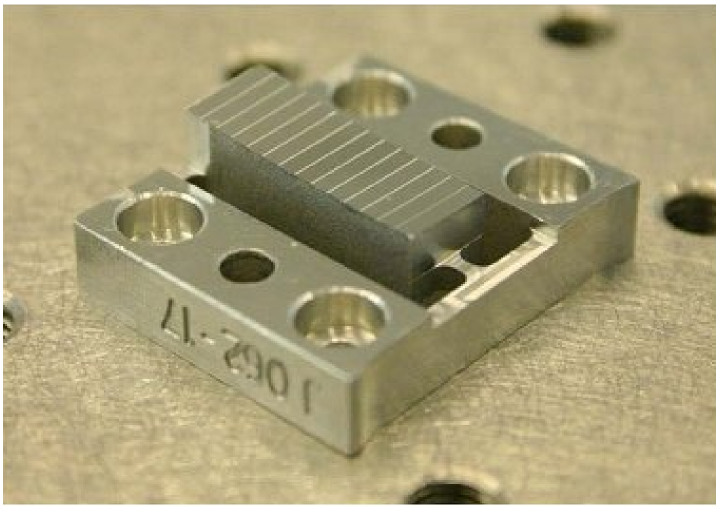

Figure 1.5 *An image slicer from one of the arms used in the KMOS instrument. An image slicer is a type of segmented mirror which, in this case, slices the image into 14 different segments where each segment focuses the light in a slightly different direction. KMOS has 24 of these image slicers. Note: Image retrieved from the ESO website: https://www.eso.org/sci/facilities/develop/instruments/kmos.html*

three techniques and conclude that using an image slicer to split up the telescope image is the most efficient, by a considerable margin. Using fibres or lenslet arrays give similar performances, although, lenslet arrays are easier to construct. Image slicer instruments, however, are the most complicated to construct owing to their complex optical systems.

1.4 The K-band Multi Object Spectrograph

KMOS is a second generation instrument on the Very Large Telescope (VLT), Chile. KMOS multi-object spectgrograph with a multiplex of 14. Each of these 24 pick-off ars

1.5 Three Dimensional Data Cubes

1.6 Reduction of Spectroscopic Data

1.7 Conclusions

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