## Part B: Line spectra, chromatic resolution and doppler shifts

### Introduction

The spectrum of light from stars contains many sharp features, light or dark bands called **spectral lines**, that tell astronomers about the chemical composition and physical conditions on its surface. This is done by comparison with simple spectra produced in the laboratory. In this part you will use a diffraction grating to produce the line spectra of a number of elements, and will investigate how close in wavelength two lines can be before they become indistinguishable. This property is called the **chromatic resolution** of the instrument or sometimes, when there is no possibility of confusion with angular measurements (see part A) just the **resolution**. The better the resolution, the more closely one can investigate small wavelength changes caused, for example, by the Doppler effect. Finally, you will measure wavelength shifts in the spectrum of a star system that are actually due to relative motion of the stars.

### The grating spectrometer

In this part you use a diffraction grating mounted on a precision rotating table. A parallel beam of light of wavelength $\lambda$ striking one side of the grating will be **diffracted**, that is, deviated in all directions, as it passes through the apertures between the opaque lines of the grating. The transmitted light will interfere constructively (see exercise 1) at angles determined by $\lambda$ and by the spacing $d$ between the lines. In these directions (the **principal maxima**) the transmitted light intensity is greatest and a telescope set at these angles will see images of the source, a narrow slit parallel to the grating lines, in the colour of the wavelength selected. The expression for the angles of these principal maxima is:

$$\sin\theta_n = \frac{n\lambda}{d}$$

where the number $n = 1, 2, 3, \ldots$ is called the **order** of the principal maximum. The grating you will use has a small value of $d$ so the right-hand side is large; since $\sin\theta_n$ must be less than one, only the first few orders will be visible.

The spectrometer is shown in figure 5. The collimator, which produces a beam of parallel light coming from the adjustable slit source, and the telescope can be rotated around the centre of the table. Vernier scales give accurate measurements of the angular position.

• Place the grating over the centre of the table and perpendicular to the collimator axis. Clamp the table and the collimator firmly, ensuring that the telescope can swing freely on both sides of the straight-through position.
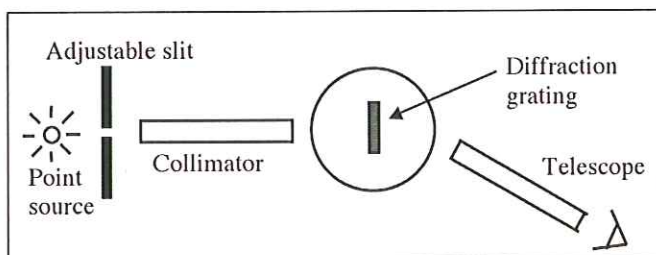


**Figure 5** Grating spectrometer

• In this position observe the direct image of the slit, and adjust the slit, collimator and telescope as needed. You want the slit to be as **narrow as possible** while still appearing uniformly bright, and to be **vertical** (the lines of the grating are vertical). The focusing should be as sharp as you can get it. A useful **hint** is to take the spectrometer carefully into the main lab and adjust the telescope by focusing on a distant object on the horizon. Then adjust the collimator to focus the image of the slit. Record the angle of the telescope in the straight-through position, and subsequently always record the angles of a diffraction maximum on *both left and right sides*. Not only does this give you *two* independent measurements of the angle, but also since the average of left and right readings should be the initial straight-through reading, it also gives you a valuable *check* against blunders *and* an estimate of your measurement accuracy.

• At this point you should check that the grating is accurately perpendicular to the light falling on it from the collimator. Think of a way to do this.

## Observation of spectral lines

• In order to calculate $\lambda$ from measurements of the diffraction angle $\theta$, we first need to know the grating line-spacing $d$. Calculate this from the number of lines per mm (or inch) which is engraved on the grating.

• Using the gas discharge tubes provided, measure a selection of prominent spectral lines of sodium, mercury, cadmium and hydrogen. Observe first, second and (where possible) third orders of principal maxima. Use the following list of prominent lines to *identify* them, and then *calculate their wavelengths*.

| Element | Colour | Intensity |
|---|---|---|
| Sodium | green/yellow | weak |
| | green/yellow | weak |
| | yellow | very strong |
| | yellow | very strong |
| Mercury | violet | strong |
| | turquoise | weak |
| | green | very strong |
| | yellow | quite strong |
| | yellow | quite strong |
| Cadmium | blue | quite strong |
| | blue | strong |
| | green | strong |
| | red | quite strong |
| Hydrogen | blue | weak |
| | deep red | weak |

*Laboratory exercise 7*

• The two yellow lines of the sodium doublet near 589 nm, the famous 'D-lines' of sodium, should be well resolved if you have set up the instrument carefully. Be sure you identify the lines correctly, using the diffraction equation to decide whether the longer or the shorter wavelength is diffracted through the greater angle.

• Finally, look up the *true values* of the wavelengths of all the lines, and *compare* your results with these.

## Chromatic resolution *[This section is optional; do it at the end if you have time]*

Diffraction theory shows that the angular separation of two nearby wavelengths is increased by (i) going to higher orders, as we have seen above, and (ii) increasing the *total* number of lines on the grating which contribute to the diffraction. If the Rayleigh criterion for angular resolution (see part A) is used, then it can be shown that the minimum wavelength difference that can be resolved is

$$\delta\lambda = \lambda/Nn$$

where $N$ is the total number of lines and $n$ the order. It is convenient to define the **resolving power** as the ratio $\lambda/\delta\lambda$ between the wavelength itself and the smallest difference that can be measured at that wavelength. The larger the resolving power the better the chromatic resolution. From the expression above, the resolving power equals $Nn$.

• The sodium D-lines should be well resolved when you use the full width of the grating. A simple way to vary the illuminated width is to clamp vernier callipers just in front of the grating and adjust the opening of the jaws. Find the narrowest opening that still allows you to resolve the D-lines with confidence. Evaluate the quantity $Nn$ and compare with the value of $\lambda/\delta\lambda$. Repeat this several times for both orders. Do the experimental and the theoretical estimates of resolving power agree? Remember that the Rayleigh criterion is somewhat arbitrary.

*[End of optional section]*

## Doppler shift of spectral lines

A change in wavelength occurs when a source of light moves towards or away from an observer. The change, $\Delta\lambda = \lambda' - \lambda$, where $\lambda$ is the normal wavelength and $\lambda'$ is the changed wavelength, is proportional to the relative velocity $v$:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where $c$ is the velocity of light. This is the Doppler shift. When source and observer are moving apart, $v$ is positive, $\lambda'$ is larger than $\lambda$ and the light becomes redder. If they are approaching, $v$ is negative and the light becomes bluer. The effect is very small but can be detected in the light from some stars and galaxies.

• Figure 6 is a photograph of part of the spectrum of iron, taken by focusing diffracted light from iron vapour onto a long strip of film. The principle maxima appear as bright lines, some of which are labelled $A$–$H$. Their wavelengths are well known, and are tabulated below. Superimposed across the centre of the spectrum of iron is that of a star, taken by directing the light from a telescope onto a spectrometer fitted with a camera. Some faint dark bands labelled $a$–$f$ can be discerned; these are known to be lines of the elements hydrogen and calcium, whose wavelengths are also well known and tabulated below. However, because the star is moving relative to the Earth its light is Doppler shifted, so these stellar spectral lines do not appear at exactly the wavelengths measured in the laboratory. From the information below, and careful measurements of the positions of the stellar lines relative to the iron lines, find the apparent wavelengths of the lines $a$-$f$, deduce whether the star is moving towards or away from us, and estimate the relative velocity.
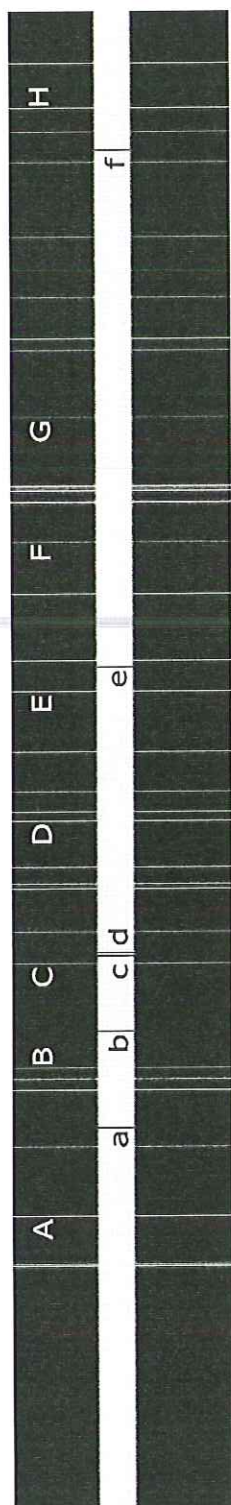
**Stellar lines:**

| Line | $\lambda$ (nm) |
|------|----------------|
| $a'$ | 388.90 hydrogen |
| $b'$ | 393.38 calcium |
| $c'$ | 396.86 calcium |
| $d'$ | 397.01 hydrogen |
| $e'$ | 410.17 hydrogen |
| $f'$ | 434.05 hydrogen |

**Iron lines:**

| Source Line | $\lambda$ (nm) |
|-------------|----------------|
| $A$ | 388.71 |
| $B$ | 395.67 |
| $C$ | 400.52 |
| $D$ | 407.17 |
| $E$ | 413.21 |
| $F$ | 420.20 |
| $G$ | 426.05 |
| $H$ | 440.48 |

The lines a'-f' given in the table above are unshifted and correspond to the shifted lines a-f in figure 6.



**Figure 6** Doppler-shifted spectrum