Ken M. Harrison

Grating Spectroscopes and How to Use Them

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Preface

The development of the spectroscope has contributed more to the science of astronomy than any other telescope accessory. It has been said that 75% of all astronomical discoveries have been made with the spectroscope. If you've just bought, or are thinking of buying, one of the popular filter-sized transmission gratings, then this is the book for you.

The popularity of these gratings as a "first spectroscope" has been growing over the past few years, and these simple devices provide a good entry point for budding amateurs interested in astronomical spectroscopy. They are ideally suited to low resolution stellar spectral imaging.

The basic challenge facing the novice is where to start. What other equipment will you need? How do you process the CCD image? How do you analyze your first spectrum? These questions and more are addressed in this book. It provides up to date information on filter gratings and processing methods available to the amateur, and more importantly, the "how to…".

This book has been written specifically for first time users and keeps the mathematics to a minimum. Where some mathematics is necessary, a worked example or look-up table is provided. It should be possible to image your first spectra on your first night.

The low resolution and lack of an entrance slit limit the type of spectroscopy that can be done, but this should not be seen as a negative. By using the telescopes, mountings and CCD cameras currently available to the amateur, this book will show how, with the addition of a simple transmission grating, we can observe and record spectra that reveal the nature of the stars. Many amateurs have successfully obtained spectra showing the temperature, age and chemical "fingerprints" of the stars as well as recording the elements in bright nebulae and the redshift of fast receding quasars! This is the beginning of a journey into the unknown realms of amateur astronomy.

You should be excited to be among the few who will be able to record the wonders of the universe for themselves and see what stars are really made of.

As you practice and gain experience you may want to increase the resolution of your spectroscope, contribute to the ever-growing list of amateur and pro-am projects, or even construct your own spectroscope. A more complete overview of the theory, use and design of advanced amateur spectroscopes is covered in depth in the companion volume to this one, *Astronomical Spectroscopy for Amateurs*.

This is a new challenging field for amateurs. With even the most basic of equipment your activities can be interesting, thought provoking and most of all fun. Enjoy!

Wezembeek-Oppem, Belgium Ken M. Harrison

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About the Author

An avid amateur astronomer, Ken Harrison was born in Scotland where he trained as a mechanical engineer. He has been designing and building telescopes since the early 1960s and has built a series of spectroscopes for use on medium-sized amateur telescopes. He was Section Director of the Astronomical Society of Victoria, Australia, Astrophotographic Section for 10 years and past president of the society. Harrison's university thesis (and his first publication) was *Design and Construction of the Isaac Newton 98-inch Telescope* (Strathclyde University, 1970). Since then he has published articles on optical design including "*Blink Comparison*" (BAA Journal Vol87, p94) and "*Method of Radially Supporting Large Mirrors*" (Vol. 87, p. 154). He has made contributions to the Astronomical Society of Victoria Newsletter and was for 3 years the Editor of the 'N'Daba' newsletter of the Natal Centre, Astronomical Society of Southern Africa. His first book for Springer, called *Astronomical Spectroscopy for Amateurs,* published in 2010, serves as a useful companion to this volume.

Contents

Quick Start Guide

Reading manuals to get the basic instructions on how to do something is never fun, or easy. Manuals and instructions tend to be most useful when things go wrong.

However, even with a simple grating, there are things you need to know before you can succeed in recording your first spectrum. The following notes and checklist will get you started:

Equipment Needed

- A filter grating
- A DSLR camera body or webcam/CCD camera
- A telescope with a 1.25″ focuser, on a tracking mount (preferred)
- A 1.25″ T thread nosepiece to hold the grating filter
- An adaptor to fit the 1.25″ nosepiece to your camera body (DSLR will also need a T2 to camera adaptor). CCD may accept the T thread as is.

Basic Methods

With a DSLR

Set the camera to M (manual)
ISO setting to 400 or 800
Exposure time to 0.5 s

With a Webcam

Accept the default settings and target to record a video file of 5–10 s. Using the capture software screen find and focus the spectrum as per above.

With a CCD

Set up your image capture software
Use 1×1 binning
Start with exposures of 0.5 s

Set up the telescope and focus a bright star (Vega, Sirius, Betelgeuse, etc.). Remove the eyepiece and insert the grating/nosepiece/camera.

The distance between the grating and the CCD chip is only really important if you're using a webcam. In that case the distance should be less than 50 mm.

Look into the grating and rotate it to align the image of the CCD chip. This will allow the grating to produce the spectrum across the frame (making it easier to analyze the spectrum later).

DSLR

Check the view finder or use the live-view feature (Canon) to confirm the star is in the field of view. Focus on the star image. Look for the brightest spectrum – it should be horizontal to the frame (rotate grating if necessary); position the bright spectrum close to the centre, just keeping the star image visible. Re-focus to get the clearest image of the spectrum (this time ignore the star image).

Webcam/CCD

Take your exposure and check that the spectrum is visible; increase the exposure time if need be.

The above steps will allow you to record your first spectrum on your first night out. It doesn't come much easier than that. If things have gone according to plan, you should see some faint dark lines/marks on the spectrum. These represent the absorption lines of various elements/molecules in the star's atmosphere. Your job now is to decipher this hidden code and reveal all it can tell us about the nature of the star.

The first chapter in this book will provide you with the basic knowledge and understanding of how a grating works and how it produces the spectrum. It also gives some insight into the basic equipment that can be used to help you collect your spectra. Chapter 2 covers in more depth the different set-up options you can use with the grating to record more detailed spectra. Recording your first spectrum is exciting. But the real excitement is yet to come….

Chapter 1

Some Background and Basics

Why Spectroscopy?

The current availability of filter gratings to amateur astronomers has given them the opportunity to become involved in one of the new and challenging aspects of astronomy – spectroscopy. Even with limited time, resources and finances available to him or her, the amateur can still contribute useful data that, although it can't compete with the professionals using large telescopes located in some of the best sites in the world, can complement their work.

How can an average amateur from his/her own backyard with a relatively small telescope do this? Our time and flexibility is our strength. We can observe what we like, when we like and not be locked into some limited observing time slot like the professionals. Our observations can fill the gaps. Amateurs have already made some significant contributions – monitoring dust shells around stars, finding exoplanets orbiting nearby stars and adding spectroscopic data to the traditional variable star observations. Not that you will achieve all this with a filter grating on your first night, but all the necessary skills and knowledge you will need to be able to do that sort of work in the future starts here.

The majority of our knowledge about the universe has come via spectroscopy. We can share that excitement of finding out what is happening around us, how the "star stuff" we're made of came to be and what is going on inside and around the nearby stars. Few amateurs take this opportunity. Think about using the grating as "Spectroscopy 101" – the first small step on the journey.

In this chapter we will briefly discuss the tools to be used – the grating, the telescope and the camera – and answer some frequently asked questions by

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beginners. Once we understand these basics we can quickly move on to the fun part and start obtaining our first detailed spectrum.

What Is a Transmission Grating?

A transmission grating (sometimes called a diffraction grating or a filter grating) breaks white light into a colored spectrum. Sounds simple enough, but a lot of technology has gone into the design and construction of each type of transmission grating. The heart of the transmission filter grating is a section of specially prepared plastic film that has been embossed with a fine series of grooves (called lines).

The shape and spacing of the lines is controlled in a master grating, manufactured under clean room conditions. This master is then used to prepare a number of replica gratings. The replica grating can be produced in a plastic material transparent to light (transmission grating) or subsequently vacuum coated with aluminum to make a reflection grating.

The shape of the groove is important for the efficiency of the grating, and the number of lines per mm (l/mm) defines the ability to separate white light into the various colors. Gratings are available in different l/mm. The Star Analyser grating (SA100) has 100 l/mm and the Rainbow Optics grating (RO200) has 200 l/mm. (Baader also used to produce a 207 l/mm filter grating, but unfortunately this is currently unavailable.) The grating is mounted into a standard astronomical 1.25″ eyepiece filter frame (see Fig. 1.1). The 28.5 mm thread should fit all the 1.25″ filter threads found on eyepieces and adaptors. You'll find other transmission-type gratings up to 600 l/mm readily available.

Fig. 1.1 Filter gratings

Gratings are very delicate. Most of the 1.25″ filter-sized gratings are protected by being sandwiched between glass plates. This makes handling them much easier, but they should be treated like all your optical equipment – with care.

How Does a Grating Work? (The Short Version!)

Early experiments and spectroscopic observations were done using prisms. Isaac Newton first showed that a prism could break white light into a colored spectrum, spreading normal sunlight into a rainbow of light from a deep violet through to a rich ruby red. These are the visible limits of the human eye and is now called the visible spectrum. (A single spectrum is "spectrum"; more than one spectrum is a collection of "spectra.") The ability to separate white light into its colors is called dispersion. Prisms disperse the light due to the type of glass they are made from and the shape of the prism used.

Light is a form of electromagnetic energy and has the amazing qualities of acting both as a particle and a wave. Although the speed of light is fixed and unchanging, the wavelength of light can vary between being very short or very long.

As later investigators found, when analyzing the nature of light, the wavelength of the light defines the perceived color. Short wavelengths appear to us as blue; violet and much longer wavelengths look red. These wavelengths can be extended to cover the whole energy spectrum (the electromagnetic spectrum). Shorter wavelengths lead to X-rays, and the longer wavelengths to the infrared (heat) and radio waves (see Fig. 1.2).

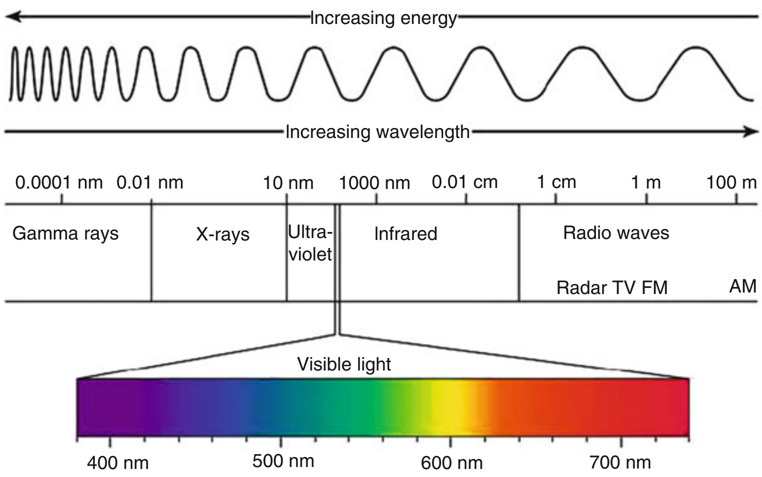

Fig. 1.2 Electromagnetic spectrum

Dispersion

When a spectrum is produced it's made up from a series of "images," one for each wavelength of light. The shape of each of these images replicates shape of the input beam of light. If a circular opening is used in front of a prism (or grating) the resulting spectrum will be a collage of small colored disks – enough to show the various colors but smeared into each other and don't show a lot of detail.

The spread (dispersion) of the spectrum produced by a prism is not uniform. The blue region is much more spread out than the red. This non-uniform dispersion causes problems in accurately measuring the relative positions of features (absorption and emission lines) in the spectrum. The larger the prism (or combination of prisms), the larger the dispersion.

Resolution

The resolution, that is, the ability to separate detailed features within a spectrum is not only linked to dispersion but to the size and shape of the input beam.

Newton and others used a small slit to control the light through the prism; this effectively separated the various colors, thereby improving the clarity and resolution. Each "image" in the spectrum was now a fine line of colored light. This technique is still used today, and most advanced spectroscopes are fitted with a narrow entrance slit that allows the user to observe the absorption and emission "lines," which you see in the usual photographs of spectra. When we use a grating without an entrance slit it is called a "slitless" configuration – for obvious reasons!

The resolution of a slitless spectroscope when used on a telescope/camera lens is therefore restricted to the size of the star image produced by the telescope. A shorter focal length telescope or lens gives a smaller star image; when the grating is used on a telescope/camera lens with a short focal length we get the best detail and resolution in our spectrum. Amateur telescopes with focal ratios of f5 work well, and if your telescope is, say, f8 or f10, you may have to consider adding a reducer to get the optimum performance from your grating.

The other thing to consider is that the spectrum, being produced by multiple images of the star, will only produce a narrow spectral band where the height is the same as the diameter of the star image. Unfortunately, to get maximum resolution in a slitless configuration also means we end up with a very narrow spectrum. This is not a real problem for imaging and subsequent processing (we can expand the height in our processing software) but does limit the visual use of the grating. (Later we'll look at some methods we can use to make the spectrum appear wider.)

To determine the various wavelengths within our spectrum and to allow us to compare spectra, we need a suitable scale. The unit Angstrom (10^{-10} m), symbol Å, was used as a measure of wavelength – violet being around 3500 Å and deep red at 7000 Å. In modern times the standard measure has become the nanometer (nm), with 10 Å = 1 nm. The visible spectrum may now be stated as extending from 350 to 700 nm.

Diffraction Gratings

By the late 1880s an alternative solution was found to the prism – the diffraction grating. With this grating of fine lines and spaces it was found that a series of spectra could be produced by the interference of light waves (diffraction). (The detail of the theory behind this will be discussed in more detail in Chap. 6.)

Gratings also allow spectroscopes to be designed with larger dispersions, without the significant light loss associated with large prisms. The more lines per mm (l/mm) on the grating, the greater the dispersion. Whereas a prism produces a single non-uniform spectrum, a grating produces a whole series of spectra (called orders) on each side of a zero order image (direct image) of the source. When you look through a grating at a bright pinpoint of light the brightest image you see is the light from the source that goes straight through the grating. This image is not deviated and shows the light where it actually is. It will appear slightly fainter than the original, some of the light being deviated into the surrounding spectra. This zero order image comes in very handy for measurements of our spectrum. It lies at a "zero" wavelength, and all other wavelengths can be measured from this point. When you look at the spectra produced by the grating, you see that the spectrum closest to the zero order is shorter and brighter than any of the ones further away. (See Chap. 6.)

Figure 1.3 shows comparison spectra obtained from some gratings and a prism. The exposure used for each spectrum was the same. The zero order image is shown on the left hand side and the spectrum towards the right hand side. Note that the prism produces a brighter spectrum with the red end reversed from that seen in the grating spectra; the red part of the spectrum is less dispersed and appears compressed relative to the blue region.

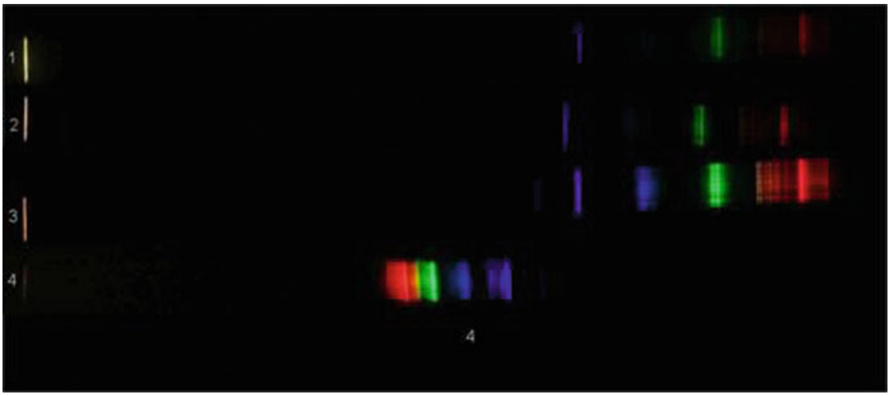

Fig. 1.3 Spectra obtained from gratings and a prism. *Top*: RO200, P-H 200 l/mm, Baader 207 l/mm. *Bottom*: 60°, 25 mm prism

Fig. 1.4 Spectral spread from a grating. Blazed first order spectrum visible towards the *right hand side*

The brightest spectrum produced by a grating is called the first order spectrum. This can contain approximately 20% of the incoming light. To improve the efficiency of the grating it is possible to change the shape of the grooves (blazing) so that 70% of the light is spread into one of the first order spectra. The fainter spectra visible will be the second order, third order, etc., as we move further and further outwards. Notice that these spectra are much longer than the bright first order spectrum. The dispersion increases with the spectral order. i.e., a second order spectrum will have twice the spread of a first order spectrum; with limited amount of light available and spread over a much larger area, the second order spectrum will also appear much fainter. Using the brightest blazed first order spectrum allows us to record the spectrum of fainter objects. When the spectrum is imaged onto a CCD, the dispersion is usually measured in Å/mm or Å/pixel, i.e., 200 Å/mm or 20 Å/pixel.

The angular dispersion of the spectrum produced by a grating is very uniform. A grating with 200 l/mm (RO200) will have twice the dispersion of a grating with 100 l/mm (SA100). The second order spectrum produced by the SA100 would be similar to the first order spectrum produced by the RO200 grating. This uniform spread of the spectrum makes our job of measuring the various wavelengths much easier. This will be seen in the simple mathematics used when we start to analyze the spectrum in Chap. 4.

For normal spectroscopic work we would use the brightest first order spectrum available from the grating. See Fig. 1.4.

The length of the spectrum produced by your camera when mounted behind the grating on a telescope will depend on the number of lines in the grating (l/mm) and the distance between the grating and the camera chip. The larger the distance the more spread out the spectrum will appear. As for operating distances, there are limitations; the optics of the telescope cause distortions in the spectrum and experience shows that distances between the grating and the CCD chip of greater than 80 mm give poor results, a bit like applying too much magnification when viewing the planets. It may make the planet's disk look bigger in the eyepiece, but there's no more detail seen. Tables of distances versus size of spectrum are provided in Chap. 2.

Grating Resolution

The theoretical resolution of a grating is determined by the number of lines illuminated by the image of the target star. With filter gratings used on the telescope the size of the star image at the grating will be determined by the focal ratio of the telescope and the distance to the CCD chip. The size of the star image will be the distance divided by the focal ratio; i.e., when the grating is used in a f5 telescope, with a distance of 50 mm, the image size will be $50/5=10$ mm diameter. Now if the grating used is 100 l/mm, then $10\times100=1{,}000$ lines will be illuminated.

Compare this result with the same grating used on an f8 telescope – the star size would be $50/8=6.25$ mm and the number of lines illuminated only $6.25\times100=625$. This is almost half the theoretical resolution of the first set-up. This clearly shows that the largest star image at the grating is obtained with shorter focal ratios and larger distances between the grating and CCD.

When a grating (28 mm clear diameter) is used in front of a camera lens, the starlight illuminates the full aperture of the grating. The theoretical resolution then increases to $28\times100=2{,}800$ lines – more than double that obtained with the telescope.

Remember, these are theoretical results. The actual resolution you obtain will still be influenced by the seeing conditions and the pixel size of the chip in your camera.

In Chap. 6 we will discuss the performance of the grating in more detail.

Is a Grating Good for Visual Observing?

The SA100 grating is not designed for visual use; the low dispersion of the SA100 is more suited to imaging with smaller CCD chips (i.e., webcams). It can be screwed directly into the front of your eyepiece, just like a normal filter. When you look through the eyepiece at a bright star you will see the zero order image and a bright, narrow spectrum. The length of the spectrum can be increased by moving the grating further from the eyepiece. You can use filter spacing adaptors or fit it to the front of your star diagonal. The use of a cylindrical lens behind the eyepiece (supplied with the visual RO200 kit) when properly aligned with the spectrum, will spread it out vertically to make it easier to see. Figures 1.5 and 1.6 show a typical visual arrangement.

Similar lenses can be found advertised as “line reading lens.” Surplus Shed usually stocks cylindrical lenses. These are available in various sizes. (See Appendix F at the end of this book.)

With the grating fitted to a medium/low power eyepiece, giving around ×40 to ×60 magnification, you will see that the field stars are accompanied by their spectrum. If there are prominent lines in the star’s spectrum these will show up. Likewise, if there is a planetary nebula or a bright emission nebula in the field these

Fig. 1.5 Grating fitted to 20 mm filter extension in front of a 28 mm eyepiece. The cylindrical lens is also shown

Fig. 1.6 Grating with eyepiece and cylindrical lens, ready for use

will only show as small points (due to the fine emission lines of the gases involved) rather than a spread out spectrum. This makes the grating a handy tool for finding faint planetary nebula. (See Chap. 7 for more detail.)

Which Telescope to Use?

With an excellent, well corrected lens or telescope, the spectral band will appear sharp and of uniform height all along this length. Because we are imaging the spectrum from the UV through to the infrared any chromatic aberration in the lens or telescope will affect focus and resolution. The smaller refractors used by amateurs are usually at least of an achromatic (color-corrected) design and have a minimum of two glass elements in the objective lens. These lenses are designed to give good chromatic correction at two wavelengths normally in the red and green. Outside this range it's usual to see the blue and red areas enlarged due to their limited corrections. This is normally noticeable by a distortion of the shape of the spectrum (which can give a loss of resolution) Focusing on different parts of the spectrum, i.e., one exposure for the red area and another for the blue, can improve the results. This is discussed further in Chap. 2.

A reflecting telescope doesn't suffer from chromatic aberrations; all wavelengths of light come to the same focus. Either a Newtonian or an APO (apochromatic, or fully color corrected) – type refractor will give the best results. A short focus refractor or Newtonian will give the smallest star images, hence give better resolution with our slitless grating.

Can I Use Any Camera?

Almost any of the modern CCD cameras, webcams, video cameras and DSLR's can be successfully used for grating spectroscopy. You can definitely use any camera where the lens can be removed from the camera body. It's more difficult – almost impossible, in fact – to use a compact "point and shoot" camera with a grating; this will be discussed later.

The main characteristics of a "good" camera will be the size of the chip (to record the maximum spread of the spectrum), the pixel size (which gives the resolution) and the efficiency of the chip or instrument response (ability to record the various wavelengths of light). These factors are discussed in detail later. Using a modified DSLR, certainly improves the ability to record wavelengths in the red region of the spectrum, but if a UV-IR cut-off filter (i.e., Baader) is fitted, the image is restricted to wavelengths between 400 and 700 nm.

Webcams and similar cameras (i.e., DMK) have relatively small CCD chips. The size of the spectrum that can be recorded is therefore limited. The ability, however, to record a short AVI video, then stack the individual frames (using Registax or similar), can give some excellent results.

All color cameras have a Bayer filter matrix (see Chap. 6). This means that with a DSLR and one-shot color (OSC) CCD cameras, the resolution obtained will not be as good as that achieved by a mono CCD.

When using a DSLR, set the image to save as a RAW file; this records the maximum information and data. Also, ISO settings of 400 or 800 give good results without too much added noise or graininess.

The ultimate solution, when attempting to record faint spectra, is a cooled mono CCD. This gives even greater sensitivity with good resolution.

Camera Resolution and Pixel Size

The size of the pixel in the CCD is an important factor in achieving success in spectroscopy and needs to be considered up front. The best resolution achieved by the grating can still be negatively affected by the choice of pixel size. We'll see later how the Nyquist sampling theory (Chap. 6) comes into play; the main thing to know at this stage is that the best actual resolution you can obtain will be based on the size of two pixels.

A camera with a 6 μm pixel can therefore give 12 μm resolution. This is then applied to the size of the spectrum produced on the chip. If the dispersion is, say, 20 Å/pixel then the resolution will be approximately 40 Å.

What Else Do You Need to Get Started?

To image a spectrum using your telescope you need some way of holding the grating securely at a fixed distance from the CCD chip, then mounting the camera/grating combination into the focuser. Adding the grating to the system will only increase the focus distance by 1 mm; if you can focus an image on your camera, then you will be able to record spectra with a similar setup.

The filter gratings (SA100 and RO200) are usually mounted in a 1.25″ T thread nosepiece. The grating screws in the front of the adaptor and the rear T thread is fitted to your camera. The length of the nosepiece can vary; some examples are only 20 mm long, others 30 mm. When using the SA100 grating on a webcam the standard version (up to 30 mm) 1.25″ nosepiece will work. This will produce a spectrum – from the zero order image to the end of the red region – about 3 mm long. The RO200, with its larger dispersion, requires a shorter version nosepiece to record both the zero order star image and the spectrum on the same frame.

For CCD and DSLR cameras, DSI II, MX916, Canon DSLR, etc., additional T thread spacers and/or T2 camera adaptors (i.e., a Canon EOS T2 to T thread) may be necessary to attach the camera on a lens or telescope, and the larger CCD chip allows the grating to be positioned further from the CCD chip (see Chap. 2).

When you start out, it's better to record the zero star image and the star spectrum in one frame. This makes it much easier for you to calibrate the spectrum for wavelength. By adding spacers and using larger distances with small CCD's you can record the first order spectrum only on the chip. This gives a larger, but fainter, spectrum. Remember, this may increase the size of the spectrum but not the resolution. Table 2.2 gives details of the spectrum size that can be obtained with various distances.

Later we'll discuss some ideas of how the gratings can be modified to further increase the resolution.

Image Capture Software

Just a few words about imaging software. Most users of CCD cameras will be familiar with the different software packages available for controlling their camera and processing their images. Commercial software packages such as AstroArtV5, Maxim DL, CCDOps, etc., are widely used and can also be used to record spectral images. Things are a little different with webcams and DSLR's. For webcams there are commercial packages such as K3CCD, and a few freeware packages, Craterlet, wxAstroCapture, etc. Any of these will control the webcam imaging, and the resulting video file (AVI) can be processed through stacking software such as RegistaxV6 and AVIstackV2 to give a usable final image. (The Imaging Source cameras – DMK series – use their own capture software IC Capture V2.2.)

NOTE: For Philips webcams, i.e., 900nc, the use of the Philips supplied software, Vlounge, is not recommended. It is too basic for our needs, and the AVI format (Codex) is not recognized by other programs such as RegistaxV6.

Some DSLR RAW image formats are now recognized by the more popular CCD programs (AstroArtV5, etc.), and this software can be used to process the images.

Seeing Conditions and Their Effects

When the atmosphere is clear and still and the stars are just hanging in the sky above, no shimmering or twinkling, you just know the conditions are very good for observing!

On nights like that, you can be assured that the seeing conditions – the steadiness and clarity of the images – will be good. The seeing conditions are measured by the size of the star image formed by the telescope, in sec arc. To get the best seeing, astronomers have scoured the globe looking for ideal spots. Places such as Maua Kea on top of the volcanic mountain in Hawaii or La Silla on the edge of the Atacama Desert in the Andes mountains are almost perfect, and the seeing there has been measured at less than 1 sec arc.

Unfortunately we can't all live in such wonderful places, and the reality is that such nights of excellent seeing are far and few between. Light pollution, atmospherics, etc., work against us. When star images appear 4 sec arc or larger the night conditions are below average; 3 sec arc is probably a realistic figure for most of the United States and Europe; 2 sec arc would be a good night seeing, and well, 1 sec arc we can dream about.

For a slitless grating this then means that our spectrum will be formed from "images" of the seeing disk, usually 3 arc sec in diameter. This obviously impacts on the resolution we can achieve with our gratings, and in Chap. 2 we will look at the results in more detail.

Summary

This brief overview will have hopefully helped you understand how a grating forms a spectrum (dispersion) and the factors we can influence and choices we can make to get the best performance from our equipment. In the next chapter we will detail the various different set-ups that can be used to bring the telescope/camera lens together with the grating and camera, and methods of extracting as much detail as possible from that little strip of light we call the spectrum. Let’s get ready to record spectra.

Chapter 2

Imaging a Spectrum with the Grating

Spectroscopy is a three part process. The first part is to obtain a usable spectrum. The second part is to process the spectrum, apply corrections and calibrate for wavelength. The final step is perhaps the most exciting – the analysis and identification of the "fingerprints." The tools and techniques you'll need to carry out each aspect of the work are covered in the following chapters.

We are now ready to record our first spectrum. Here we will discuss the different ways we can connect the grating to the telescope/camera lens, look at the factors that will determine the size, clarity and resolution of the spectrum recorded and equally important describe how to acquire those first spectrum images.

How Do We Use the Grating?

The grating can be used in many different ways to provide us with an image of the spectrum, but the most common ways are:

1. Imaging with a telescope, the grating mounted in front of the camera body ("in the converging beam"). This method uses a telescope or a camera lens to focus the light through the grating onto the CCD. Generally results in a narrow field of view coverage but can allow the recording of fainter star spectra. The resolution obtained is usually 30–60 Å.
2. Imaging the spectrum with the grating mounted in front of a camera lens ("objective grating"). The full aperture of the grating is used in front of a camera lens fitted to a DSLR or CCD. Has the potential of giving maximum resolution, up to <30 Å. Wide field coverage and multiple spectra recorded on each image.

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NOTE: When the grating is used for imaging it's important to align the grating lines with the CCD chip in the camera to get maximum resolution. If the spectrum is placed diagonally across the CCD chip, then five or six inclined pixels may record only one absorption line or feature. When the image is rotated to a horizontal position for processing and analysis, the line will be smeared across two or three pixels with a loss of resolution.

Using the Grating in a Converging Beam

The light from all the stars in the field of view (FOV) passes through the grating, and each individual star will form a zero order image; the spectra produced by the grating will be seen on either side (see Fig. 2.1).

Using the grating in a 1.25″ nosepiece adaptor, mounted on the camera body and inserted into the telescope focuser "in the converging beam" gives good resolution and allows you to record detailed spectra of the stars. See Figs. 2.2 and 2.3.

The distance between the grating and the CCD chip is an important factor. It affects the size of the spectrum recorded and the resolution. You can work out the best distance for your grating and camera by consulting Table 2.1 or by using the TransSpec spreadsheet (see Appendix G at the end of this book).

It's easier to start with the zero order image visible in the frame. This allows it to be used as a zero wavelength reference when calibrating/processing the spectrum. (See Chap. 4.)

The sub-compact "point and shoot"-type cameras are not suitable for this configuration. (In fact, to be absolutely honest, they are not really suitable for any spectroscope work. The fixed lens and the limited control over focusing and exposure times severely limits their ability to record spectra. Later we'll look at one

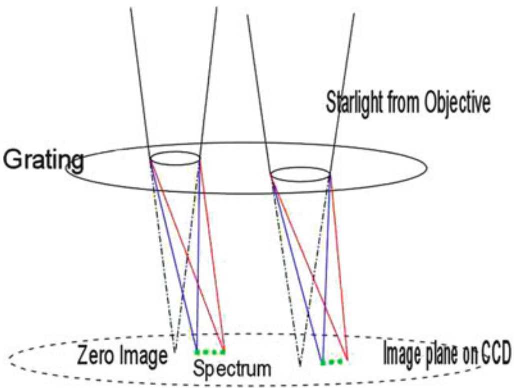

Fig. 2.1 Transmission grating in a converging beam

Fig. 2.2 Filter gratings fitted to a QHY5 camera and Philips SPC900 webcam

Fig. 2.3 Filter grating fitted to a Canon 300D DSLR

Table 2.1 Size of spectrum vs. distance between grating and CCD

Distance (mm)	Zero to red (mm)	Spectrum only (mm)
30	2.1	
35	2.4	
40	2.8	
45	3.1	
50	3.58[a]	
60	4.2	1.9
70	4.9	2.2
80	5.6	2.6

[a] This is the maximum width for a webcam chip

possible alternative setup where they may be used.) Other than that, you can use any camera where the lens can be removed from the camera body.

A DSLR will give a much larger frame to work with than, say, a color webcam, but the resolution obtained in both will be influenced by the built-in Bayer filter used to record the various colors. (See Chap. 6.) With a DSLR, set the image format to RAW. (This should be explained in your camera manual.) This will give maximum definition and the file obtained is uncompressed, containing all the available data needed for further processing.

The spectrum doesn't need to be recorded in color. It may look nice, but it doesn't add any additional data to the image. Once we have obtained the spectral image and have it calibrated, it can be converted to a synthesized full-color spectrum at any time.

Mono cameras have a much higher resolving capability (due to the individual pixels recording every wavelength of light), and when you combine this with a small pixel size, like those found in mono webcams or the DMK series from Imaging Source, you can get some excellent results. Torsten Hansen has obtained some spectacular spectra with the Imaging Source DMK 31 camera, as shown in Fig. 3.7.

Depending on the distance between the grating and the CCD you can also use one of the many astronomical imaging cameras (SBIG ST10, QHY8, etc.). These large format cooled CCD cameras give high efficiency and good spectral response. The pixel size in any of these CCDs also needs to be considered. Large pixels are more sensitive but can result in lower resolution in our spectrum. See later.

How do you know which object is in the field? The field of view through the grating will be similar to the camera/telescope FOV with an eyepiece that has a focal length double the CCD chip width. For example, a webcam with a 3 mm chip shows the same field of view as visually with a 6 mm eyepiece. There are some freeware programs such as Ron Wodaski's CCDCalc, that allow you to visualize the size of the camera image and calculate its size in arc sec, etc. These programs are usually used by astrophotographers to define and frame the image they want to take. Once we know the FOV, it can be used to make overlays for a star atlas or programmed into the planetarium package you use to confirm the target objects. The freeware *Stellarium* star charts and *Cartes du Ciel* software are recommended.

Imaging Your First Spectrum

Set up the telescope as usual and point it towards a bright star above, say, a 45° elevation (this reduces the effects of the atmospheric absorption and should give better seeing conditions). An A-type star (such as Vega) or an M-type star (such as Betelgeuse) provide good starting points, as they both have many absorption features to record. There's a list of possible target stars given in Chap. 3.

Without the grating attached, insert the camera/CCD with its nosepiece into the focuser, then find and focus on the star. Use your normal focusing method,

Fig. 2.4 Zero order image and spectra using a DSLR

inspecting the image on the PC screen, for example, to find best focus. (The final position of the focus will be shifted outward slightly when the grating is attached; so don't worry too much about getting accurate focus at this stage.) We just need it close enough to be able to fine tune the focusing based on the zero star image.

Remove the camera/CCD without touching the focus settings. Insert the grating and rotate it to get the grating lines vertical to the image frame.

HINT: You can look through the grating at the CCD chip in the camera. The grating causes two images of the chip to be seen (due to the dispersion). Rotate the grating until both images appear in line. If you slightly unscrew the filter grating from the nosepiece and wrap a couple of turns of cotton thread onto the grating threads, these can help to give some "fine adjustment" to the grating orientation and allow it to "lock" in place. This will position the spectrum very close to the horizontal axis of the CCD chip. Re-insert the camera/CCD. Each star in the field of view will produce a zero order star image and its pair of spectra, as shown in Fig. 2.4.

Looking at the CCD image on the PC (viewfinder or live-view on a DSLR) you should see your target star image close to the center of the frame and its spectra at either side. If you are using a webcam or a CCD with a small chip, you may have to move the star image off center to see the first order spectra. With a blazed grating, one spectrum will be much brighter than the other. Using the telescope slow motion controls, bring this brighter spectrum close to the middle of the frame. The star image (zero image) will be off to one side.

Keep moving the star image towards the side of the frame to position the spectrum as centrally as possible. Keep the star image just inside the frame.

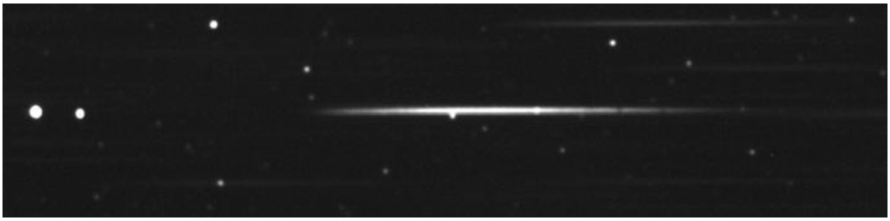

Fig. 2.5 SA100 with background star in spectrum (C. Buil)

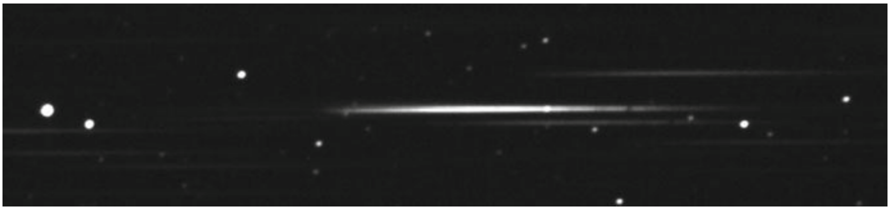

Fig. 2.6 SA100 with rotated grating to reposition the interfering background star (C. Buil)

Now study the star image and the spectrum. As a minimum, the star image should now be brought to focus. Better still is to adjust the focus until the spectrum band is as narrow as possible with clear, sharp edges. Check this focus using an initial exposure of, say, one second and also confirm that the spectrum is lying horizontally across the frame. If you find that secondary star images/spectra are interfering with the target spectrum, try rotating the camera body slightly (without changing the position of the grating in the nosepiece – we're trying to maintain the alignment to the CCD) in the focuser to move the background stars away from the target spectrum. Figure 2.5 shows the zero star images (brightest images at the left hand side of the frame) and the first order spectrum. You can see there is a second bright star just to the right of the target star. The spectrum from this star could interfere with the one we want to record. By rotating the camera slightly, the interfering image has been moved lower in the frame, clearing the spectrum (see Fig. 2.6).

Take a couple of exposures to check if the spectrum is over- or under-exposed. On very bright stars (such as Vega) you may find you only need 0.2 or 0.4 s exposure. With a DSLR remember to set to RAW and start with an ISO setting of 400.

These settings should give a usable result. The zero order star image will be seen slightly out of focus towards the edge of the frame and the bright spectrum stretching across the middle. Remember to take some notes of the time and date, your grating distance, camera settings and don't forget to record the name of the star or object you've just imaged! After a few nights of successful imaging you will find you need to develop a system of recording your spectra.

That's it. Our first spectrum has been recorded. Now that you have a spectral image, open it in your usual imaging software, zoom in on the spectrum and see if any dark/bright lines or bumps can be seen. Compare the exposures looking for best focus and clarity. If the focus is good on the spectrum of one star, it will be good for all stars. In the space of one evening it's therefore possible to obtain a whole series of stellar spectra. If the finder telescope is accurately aligned to the main scope you should be able to set up the cross wires in the finder to position the target star in the correct position on the camera frame ready to take an exposure. That way the camera and grating doesn't need to be removed or re-set when going from one star to the next. For the moment, note the setting of your focuser and the best exposure times for future reference.

Depending on the accuracy of focus and the instrument response (see Chap. 6) you may see a spectrum that looks "cut-off" at the blue end and "fishtails" towards the red end. This is normal. These effects are caused by the varying efficiency of the CCD chip across the spectrum and the aberrations in your system. In Chap. 6 we'll look more closely at these issues.

On the brighter A-type stars (such as Vega) the spectrum should show definite dark lines in the region closest to the zero order (the blue end of the spectrum). For an M-type star such as Betelgeuse you'll see dark bands closer to the red end of the spectrum. We'll get more familiar with these features as we start analyzing and calibrating the spectrum in Chap. 4.

NOTE: If the spectrum is recorded on your CCD chip at an angle you can lose resolution and add artifacts to the image when rotating it horizontally. Also note that grating distances above 80 mm tend to be counterproductive, as the benefits of the larger dispersion are outweighed by the increased effects of optical aberrations.

The ultimate resolution obtained from your grating in the converging beam setup is limited by two main problems: field curvature (where the best focus position of different parts of the spectrum varies) and spectral coma (which causes distortion of the spectrum). These can be minimized by re-positioning the CCD plane, i.e., tilting the camera or changing the focus position (field curvature) and by adding a small wedge prism-grism (spectral coma). The effects and improvement options for these aberrations are discussed in more detail in Chap. 6.

Like astrophotography images, short spectral exposures (taken with exactly the same grating settings) can be stacked to improve the image and allow the spectra of fainter objects to be recorded. The freeware program *Registax* V6 will give good results.

As the spectrum of a star is spread over a larger area on your chip than an ordinary star image (some 100–200 times), it requires a far longer exposure than the one you would use to record normal star fields. Depending on the aperture of your telescope you may need a total exposure of 5 min or more, to record a good spectrum of, say, a 7 mag. star with a 100 l/mm grating.

What defines a good spectrum? The resolution obtained is a key factor, as is the signal-to-noise ratio in the image.

Signal-to-Noise Ratio (SNR)

In all images there is good data (the signal – information we want) and bad data (the noise – added interference). The more good data we can obtain the better the quality of the resulting image. Noise can be generated by the electronics of the camera during collection and storage of the image. This is usually called thermal noise, as it varies with exposure time and ambient temperature.

The amount of noise that builds up in an image is directly proportional to the length of the exposure. The longer the total exposure the better the signal-to-noise ratio. Background light from the sky and light pollution can also add to the noise in our spectrum. By removing the background sky signal from the spectrum and using Darks to remove any camera thermal noise, we can improve the SNR. This is discussed in more detail in Chap. 4.

Image Size on the CCD Chip

Depending on the camera and adaptor used, the grating can be positioned approx 30–80 mm in front of the CCD chip. Alternatively the grating can be fitted into a standard 1.25″ filter wheel in front of the camera body. As mentioned earlier, the shorter the focal length, the smaller the star image. On an SCT, it's therefore better to mount the grating behind a focal reducer (for example, an ×0.63 reducer). The final resolution of converging beam arrangement is limited by the seeing conditions, optical aberrations and pixel size of the CCD. The actual resolution obtained will vary from 30 to 60 Å, depending on the grating, etc.

The following tables, based on the 100 l/mm SA100, give some typical results that you can use as a starting point.

NOTE: The RO200 will give double the dispersion. For example, at 30 mm distance, the size of the spectral spread from zero order to red will be 4.2 mm and the scale 1664 Å/mm.

Table 2.1 above (Column 2, Zero to Red) shows the distance between the zero order image and the extreme end of the red region of the visible spectrum. If you know the size of the CCD chip in your camera you can quickly determine the maximum grating to CCD distance, to allow you to get both the zero order star image and the full spectrum on the frame. You will see that for a webcam-sized chip, the maximum distance is about 50 mm. Beyond that distance, you will only be able to record the spectrum on the smaller chips. Note also that for a DSLR, which has typically a 22 mm-wide chip, the whole length of the zero order to red, even at a distance of 80 mm, will only take up 25% of the frame. See Fig. 2.4.

Table 2.2 (Column 2, Plate Scale) gives the dispersion/plate scale of the spectrum (in Å/mm). This tells us is that for a 30 mm distance, the whole of the spectrum from blue to red (approximately 3000 Å) will only take up less than 1 mm on the CCD. If our camera has a pixel size of 5 μm then the whole spectrum will only cover 1,000/5 = 200 pixels on the chip. This works out to roughly 3300/200 = 16 Å/pixel.

Table 2.2 Plate scale vs. distance between grating and CCD vs. resolution

Distance (mm)	Plate scale (Å/mm)	3″ seeing resolution (Å)
30	3327	64
35	2852	55
40	2495	48
45	2218	43
50	1996	38
60	1664	32
70	1426	28
80	1248	28

You should become familiar with the camera/CCD you use and keep the dimensions of the chip and pixel size close to hand. In Chap. 6 you will find details of some of the more common CCD chips. The pixel size determines the best possible theoretical resolution, which is approximately twice that of the pixel, i.e., 32 Å, whereas in real life, due to seeing conditions, etc., it can be double that, at 64 Å.

$$Plate\ scale\ in\ \text{Å}\,/\,pixel = plate\ scale,\ \text{Å}\,/\,mm \cdot\ size\ of\ the\ pixel\ in\ micron\,/\,1{,}000$$

For example, a plate scale of 1248 Å/mm and a camera with 8 µm pixels = 1248 × 8/1000 = 10 Å/pixel.

$$Best\ possible\ resolution, \text{Å} = 2 \cdot\ plate\ scale, \text{Å}\,/\,pixel$$

In the above example the best possible resolution would be 2 × 10 = 20 Å. You can see now the difference between the dispersion/plate scale and the resolution.

When you get up towards the 80 mm distance mark, the resolution is pretty constant, around 28–30 Å – that's about the limit for gratings. (Unfortunately that's not the end of the story. There's an added complication that we'll talk about later that affects the focus and resolution – field curvature.)

Drift Enlarging

The height of the spectrum, as mentioned previously, will be the height of the star image. Sometimes it's good to be able to stretch the height of the spectrum (makes detail easier to see in the image), and this can be done by allowing the star to drift across the field of view at right angles to the length of the spectrum. This increases the height of the spectrum without impacting on the resolution. It's even more important when using a color camera; it allows you to compensate for the effects of the multiple sets of pixels involved in the Bayer matrix. (Details in Chap. 6.)

A drift of, say, 100 pixels across the frame (more than enough to "smooth out" the Bayer matrix) with a camera having a 5 µm pixel would require a "drift" image of 0.5 mm (100 × 0.005) in length.

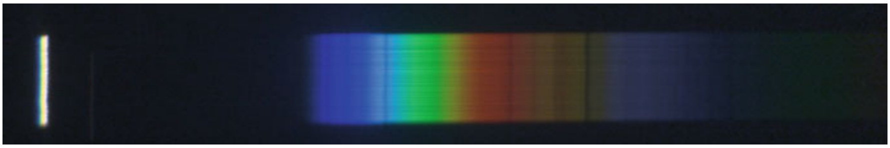

Fig. 2.7 Drift enlarged spectrum (C. Buil)

If the camera and grating are set up on the telescope such that the spectrum is produced along the Dec axis (i.e., north–south) then you can use the RA drive to provide the necessary "drift." The sidereal tracking rate, i.e., when the drive is set up to follow the movement of the stars, is one revolution/day – 360° in 24 h, or 15 min arc per minute of time.

We can use the fact that the image size/scale at the focus is roughly 1 mm per 3.5 min arc per 1,000 mm focal length to calculate the time to give the required drift. This would represent an angular distance (assuming a 1,000 mm fl objective) of 1.7 min arc. With the RA drive off, the drift rate is 15 min arc/min of time, so this represents an exposure of 1.7/15 = 0.11 min = 7 s.

A 7 s exposure with the drive off would give a spread of 0.5 mm on the CCD (= 100 pixels). The star would still be well within the area of the CCD, so switching the drive back on and hand correcting it back to the starting position would be very straightforward. (See Fig. 2.7.)

In crowded star fields, secondary stars and their spectra can cause problems. You may have to re-orient the grating/camera to get good spectra. (See Figs. 2.4, 2.5.)

Summing Up

When the grating is used in the converging beam, the distance between the grating and CCD chip should be matched to the size of the chip and the CCD pixel.

Smaller f ratios/shorter focal lengths give smaller star images and better resolution.

The best resolution obtained will be the result of a combination of the seeing conditions and the size of the pixel. The better the seeing conditions, i.e., the smaller the star image, the better the resolution.

We can now move on to the other popular method of using the grating, and that's mounting it in front of a camera lens as an objective grating.

Objective Gratings on the Front of Your Camera Lens

Using the grating in front of a camera lens as an "objective grating" setup can allow you to record the stellar absorption and emission lines at low resolution. A similar arrangement, but using a prism instead of a grating, was used in the early 1900s to

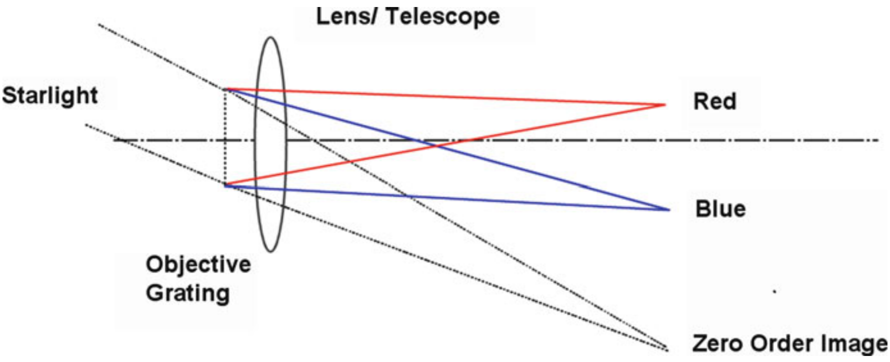

Fig. 2.8 Objective grating arrangement

collect the spectra for the Henry Draper catalogue. This spectral library was fundamental to the development of the star classifications we know today. (See Chap. 7 for details.)

The filter grating is mounted securely on the front of a camera lens. This effectively limits the clear aperture of the lens to only 28 mm, but you'll still be surprised with the results you can obtain. The much wider field of view allows you, on a large CCD chip (i.e., DSLR), to collect the spectrum of many stars (and background objects such as planetary nebula) in one exposure.

In this arrangement the light from the stars (collimated light) enters the grating and is dispersed. The camera lens then focuses the spectrum onto the CCD chip. This configuration uses the whole of the grating surface so the resolution obtained can actually be higher than we achieved in the converging beam. (See Fig. 2.8.)

Ideally, you'll need the camera mounted on a tracking platform or equatorial mounting properly polar aligned or mounted piggyback on your telescope. This arrangement allows the spectrum of fainter objects to be recorded without trailing of the star images.

Fixed focal length lenses are preferred to zoom lenses. Zoom lenses have a tendency to "creep" and change focus. Fixed lenses can be securely taped at infinity focus. Any lens from 50 mm focal length upwards can be used. Set to widest aperture (see Figs. 2.9, 2.10). Figure 2.11 shows a typical wide field "objective grating" image that includes emission stars and background nebulae.

To fit and securely locate the filter grating to the front of the lens you will need a couple of "special" adaptors. The adaptor must hold the grating in place and still allow some degree of freedom to rotate the grating relative to the CCD chip in the camera (we still need the spectrum to be recorded along the horizontal axis of the chip). It must also block out any other light that could get to the lens.

The cheapest option is to buy a spare front lens cover or make a cardboard cap and drill a hole, 28.5 mm diameter in the center (Fig. 2.12). This allows you to "screw" the grating into the cover and then clip the cover on the lens. It's then very easy to position the grating relative to the frame. For a neater job, an empty 1.25″

Fig. 2.9 SA100 mounted on a standard Canon zoom lens

Fig. 2.10 SA100 objective grating mounted on 85 mm telephoto lens (J. Simpson)

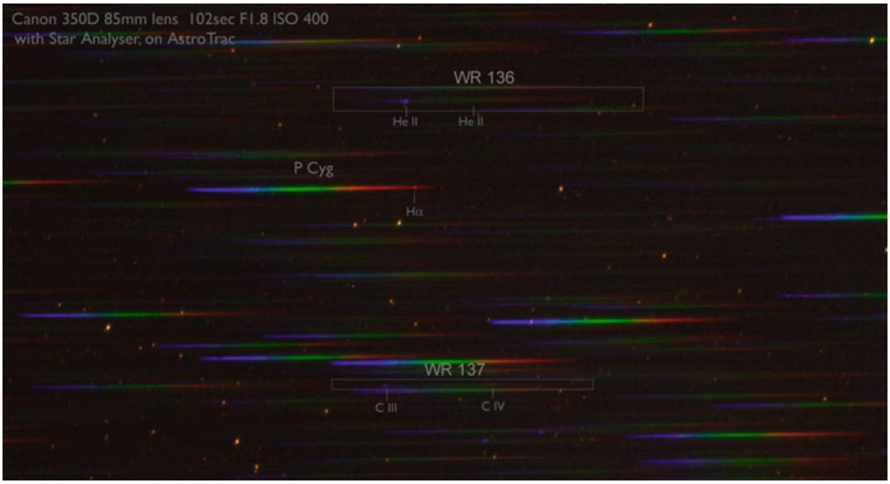

Fig. 2.11 Wide field image of Cygnus (J. Simpson)

Fig. 2.12 A simple lens cap to hold the objective grating (J. Simpson)

filter cell can be glued into the lens cover. Better still, an empty rotating polarizing filter cell can be used to make the positioning of the grating easier.

Baader supplies a T thread to a 48 mm filter thread adaptor. The filter grating mounted in a standard 1.25″ nosepiece can then be fitted to this adaptor. A photographic step-up ring 48 mm to say 55 mm will then allow you to mount the grating plus adaptors in front of the camera lens.

Fig. 2.13 Objective grating mounts. *From the left*: thin disk holding the grating in a 48 mm filter cell, T2 inner ring mounted in a 52–55 mm filter step-ring, Baader T thread to 48 mm adaptor fitted to a 48–58 filter step-ring. A grating mounted in a short T thread nosepiece is shown below

You can also separate the inner T thread section from a T2 camera adaptor; unscrew the three small grub screws on the outer rim and the internal T thread section will fall out. The outside diameter of this insert is almost exactly 49 mm. This is ideal for gluing into the center of a 52–55 mm step-up camera filter ring. Additional stepping rings can then be used to bring this adaptor to the final camera lens size. The distance of the grating in front of the lens is not critical, but using a long nosepiece-type connector (see Fig. 2.13) can cause some slight light loss (vignetting) to the edge of the field of view. Either method is fine.

HINT: If you try this method, do a "dry fit" first, i.e., grating mounted into the 1.25″ T thread adaptor plus the T thread insert sitting in the step up ring, plus any additional stepper rings. Mount them carefully onto the camera lens and mark the position of the T thread insert and the 52 mm adaptor where the grating is dispersing horizontally across the CCD chip. When gluing, use an epoxy-type glue, and line up the marks. This will make it much easier to use the grating at night without worrying about its alignment to the camera.

Leaving the grating in a 1.25″ nosepiece is a safe option and allows the T section base to be used for mounting.

NOTE: If you do use a zoom camera lens, watch for the front of the lens rotating while focusing. This will cause the grating to misalign with the CCD chip. Also, if you're in the habit (a good habit to have!) of leaving a UV or Skylight filter on your lens for protection, this should be removed when you fit the grating. Otherwise the UV part of the spectrum will not be recorded!

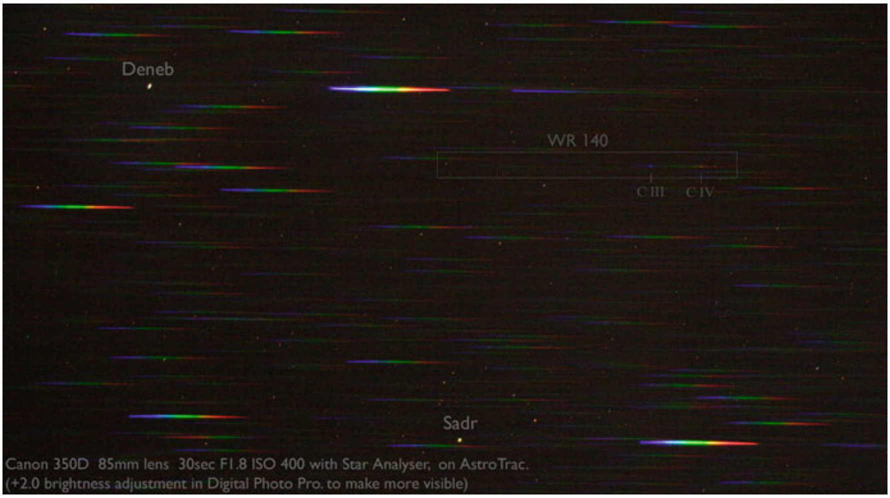

Fig. 2.14 Objective grating spectrum, area around Deneb (J. Simpson)

Objective Gratings with DSLR Cameras

Point the camera lens with the grating attached to the area of the sky or the bright star you wish to record. Make sure the camera is firmly secure and doesn't tend to sag or rotate on the camera support. Set the image format to RAW, set the lens to MF (manual focus) and adjust to infinity focus. Make sure the exposure is set to ISO 400 and M (manual); take a few test images at, say, 2–4 s exposure to check the results. Check the view screen to see where the star images and the brighter spectra are lying (Fig. 2.14).

Rotate the grating relative to the camera body to bring the spectrum horizontal to the CCD (if needed). The closer you achieve this, the better the results. Don't be tempted to try to squeeze the spectrum across the longer diagonal. You may think you are recording more spectrum, but the truth is, by the time you correct this image for processing, any extra detail will be lost. Just stick to the long horizontal axis of the chip. Seeing the zero order star images makes locating targets and initial focusing a bit easier, as well as framing the image to get best results. You can use the data in Table 2.3 to guide you on the size of the spectrum being formed on the CCD chip.

A 135 mm focal length lens and the SA100 grating will give a length from zero image to red of 9.4 mm, just under half the frame width of a DSLR. The maximum length spectrum (to include the zero order) would be recorded on a DSLR with a 300 mm lens. Although this may sound exciting, just bear in mind that the effective aperture is only 28 mm, so the lens will be working at about f5 (135/28 = 5) and the exposure time needed to record this faint spectrum could be pretty long – well into minutes!

Table 2.3 Size of spectrum vs. camera lens focal length

Focal length (mm)	Zero to red (mm)	Spectrum only (mm)
30	2.1	
35	2.4	
50	3.5[a]	
80	5.6	2.6
100	7	3.2
135	9.4	4.3
200	14	6.4
300	21	9.6

[a]Limit for webcam-sized chips

Fig. 2.15 Canon TC-80n3 remote controller

Again, we need to remember that the spectrum will be formed at a different focus from the zero order. Concentrate on focusing around the yellow/green part of the spectrum as a compromise. The zero image may appear out of focus – this is normal. A few trial exposures will quickly guide you to the best focus position. We can also "drift" to make the spectrum a bit more visible. When you find the best focus position tape the lens focusing ring with a piece of masking tape to make sure it doesn't move!! Setting the camera to ISO 400 or ISO 800 and maximum aperture will cause exposures of a few seconds to record the spectra of the brighter stars.

A remote shutter trigger is very useful to reduce vibration, etc. The TC-80n3 remote controller (Fig. 2.15) for Canon cameras is typical of the programmable remotes available; it can be set to give a series of exposures ideal for alt-az type mounts or when a camera tripod alone is used.

CCD-Type Cameras

When fitted to a standard camera lens (see Chap. 5 for details of how to make a suitable adaptor) a CCD camera can be focused and set up similar to the DSLR above. Check the possible width of the spectrum against the chip size using Table 2.3. Cooled mono CCD cameras can give some excellent results. Start with a 1 s exposure on an area containing a bright star; the spectrum should be clear and not overexposed.

Webcams and Video

Standard webcams and video capture devices can also be used. The small chip size limits the field of view, but by stacking the short exposures in an AVI file, it reduces the effects of seeing and can give good results on the brighter stars. The new "industrial" strength mono webcams from Imaging Source (DMK series) can greatly improve your ability to record spectra. The mono chip and the long exposure option makes these cameras ideal.

The RSpec software (see later) can provide live viewing and spectrum capture for these cameras. We'll discuss processing of the spectra later.

Quick Bit of Theory: Dispersion/Plate Scale and Resolution

Many beginners get confused by the terms dispersion, plate scale and resolution. Easy to understand why – these are new terms and not ones you come across every day. They represent important numbers in spectroscopy and allow us to compare different grating set-ups, spectroscopes and their performance. You will come across them very frequently, so you need to know what they mean.

Let's keep it simple at the moment. In Chap. 6 you will practice with the calculations and mathematics involved.

Dispersion

The grating breaks the incoming light into a spectrum and spreads this spectrum out over an angle; the red end of the spectrum is "bent" further from the centerline of the grating (optical axis) than the blue; the angle between them is the dispersion. The more lines on the grating, the greater the dispersion. OK, to be precise this is the angular dispersion.

When we record the spectrum on a CCD chip the length of the spectrum on the chip is related to the distance between the grating and the chip. This is then called the linear dispersion or plate scale.

Plate Scale

The length of the spectrum on the chip can be measured in mm, or in pixels.

Also, as we know the wavelengths at either end of the spectrum (roughly 4000 Å for the blue and 7000 Å for the red end), we can easily come up with a scale for our spectrum. If the spectrum is 3000 Å long (7000–4000) and measures say 3 mm on the chip, the scale would be 3000/3 = 1000 Å/mm. This is known as the plate scale. (Why plate scale? Well, in the early days of photography they used sensitive glass photographic plates to record the image, and scale would have been measured on the glass plate – hence plate scale.)

We can also measure this plate scale in terms of the number of pixels used to record the spectrum. If the length of our spectrum covers 300 pixels in our image, then the plate scale could be said to be 3000/300 = 10 Å/pixel. This is shown in Table 2.2.

Linear dispersion and plate scale are interchangeable names for the same thing. You will see them both used in various textbooks.

Resolution

Like a telescope a grating has a resolution – the ability to record fine detail.

For a grating, if there are two features in the spectrum produced (generally absorption lines) that are *just* separated in the image, the distance between them in Angstroms (or nm) would be the resolution of the grating. The theoretical resolution of a grating is defined by the number of lines illuminated on the grating by the star's image. The actual resolution obtained will be dependent on the seeing conditions and the size of the camera pixel. In spectroscopy we also consider where in the spectrum these two close lines are found. Are they in the blue? Or are they in the red?

A special number has been developed for spectral resolution. R is the standard term used and is equal to the wavelength divided by the resolution. For two lines just seen separated in the red part of the spectrum (say around 6000 Å) say, 30 Å apart, then the R value for that grating would be 6000/30 = 200.

There are more precise ways of calculating the R value, but that's for later.

Summary

For any particular grating, the linear dispersion/plate scale is proportional to the distance from the grating to the film plane. (See Table 2.2.)

A quick rule of thumb for the SA100 grating:

$$\text{Dispersion in } \text{Å} / \text{pixel} = 100 \cdot \text{ pixel size } (\mu m) / \text{ distance to CCD}$$

Table 2.4 Seeing vs. focal length vs. Star size (Micron)

	Seeing conditions (seconds of arc)		
Focal length (mm)	2″	3″	4″
500	4.8	7.3	9.6
750	7.3	10.9	14.6
1,000	9.7	14.5	19.4
1,250	12.1	18.2	24.2
1,500	14.5	21.8	29
2,000	19.4	29.1	38.8
2,500	24.2	36.4	48.5

For a camera with a pixel size of 7.4 µm and a distance of 80 mm we get:

$$100 \cdot\ 7.4/80 = 9.25\ \text{Å}/\,pixel$$

Based on the pixel size, the best possible resolution would be about 19 Å (9.25 × 2). However the seeing conditions can greatly reduce this figure.

The size of the star image effectively becomes the entrance slit of the spectroscope, and obviously the smaller the image the better the resolution. Depending on the system, a maximum of R = 100–200 (i.e., a resolution of 60–30 Å) can be achieved (see Table 2.2). Best results are obtained with smaller f/ratios, which give smaller star images. Like many things in life there are limitations, and experience has shown that f4.5 seems to be about the lowest practical ratio we can use.

The size of the star image formed by the telescope is approximate:

$$Seeing \cdot\ 4.848 \cdot\ focal\ length \cdot\ 10^{-3}\ \mu m$$

For example a 250 mm f6 telescope (focal length = 250 × 6 = 1,500 mm) and seeing of 3″ would give a star image size of:

$$3 \cdot\ 4.848 \cdot\ 1{,}500 \cdot\ 10^{-3} = 22\ \mu m$$

where seeing is expressed in arc seconds. Typical seeing will be between 1″ (excellent!) and 4″ (pretty poor). See Table 2.4.

Short focal length telescopes and small focal ratios are obviously preferred. These still give small star images even in poor seeing conditions. Table 2.4 shows that a 500 mm focal length telescope with 4″ seeing produces star images only 9.6 µm in size, whereas a 2,500 mm focal length gives an image of almost 50 µm – five times the size.

The resolution of this system, based on the seeing conditions (22 µm), with a pixel size of 7.4 µm and a plate scale of 9.25 Å/pixel, would be 22/7.4 × 9.25 = 28 Å which is far greater than best possible. The R value would be approx 214 (6000/28).

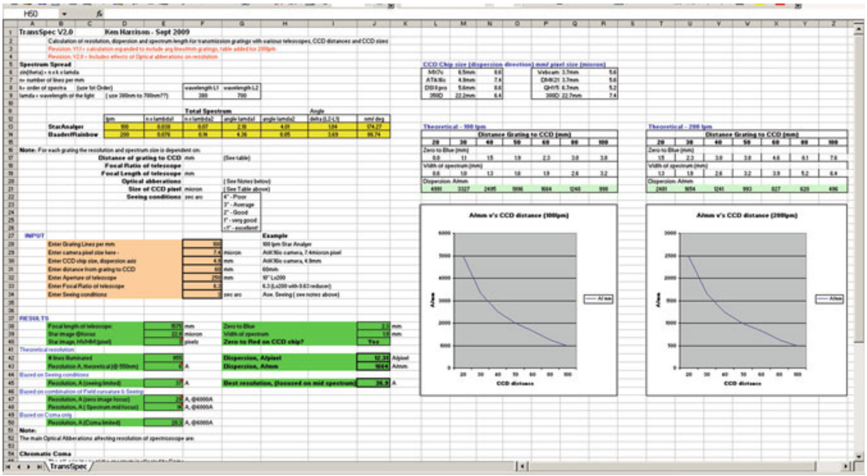

Fig. 2.16 *TransSpec* input screen

NOTE: The spreadsheet *TransSpec* V2 (See Appendix G in this book) is an ideal resource for calculating the various parameters for a filter grating placed in the converging beam or used as an objective grating. See Fig. 2.16.

Chapter 3

My First Spectrum: What Else Can I Record?

By the time you get here you will have successfully recorded your first stellar spectrum. Congratulations!

This pre-processed (raw) image from your camera can be displayed on the PC screen and saved as a RAW, TIFF, or BMP image file for future processing. Using JPEG format is not recommended, it compresses and loses some of the data in the image. These images can then be compared to the spectra published in spectroscopy books and other spectra readily available on the Web.

Quite quickly you can build up a whole series of images that will show the differences between spectral features of the brighter stars. Figures 3.1 and 3.2 show a typical collection of low resolution spectra obtained with a filter grating, cut, cropped and stretched to improve the display. The dark lines, easily seen in the spectra, are absorption lines associated with various elements (mostly hydrogen) in the atmosphere of the star and provide a method of classifying the stars.

As the grating spectroscope is a slitless design, the ability to record useful spectra is limited by the size of the star's image and the spectral spread on the CCD chip. In the case of nebulae we can still record the spectrum but only as multiple images of the nebula in question in the various emission wavelengths. Without further processing and calibration of our spectrum it is still possible to compare our images of different star spectra with others obtained with similar spectroscopes and telescope setups.

There are many satisfying projects that can be undertaken with the basic grating spectroscope. We can record the spectra of many astronomical objects and begin to appreciate the differences seen in them as well as developing our confidence and gaining experience handing the grating, telescope/camera lens and camera. These are only the first small steps on the journey towards understanding and appreciating what spectroscopy can reveal about the universe around us.

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4_3,

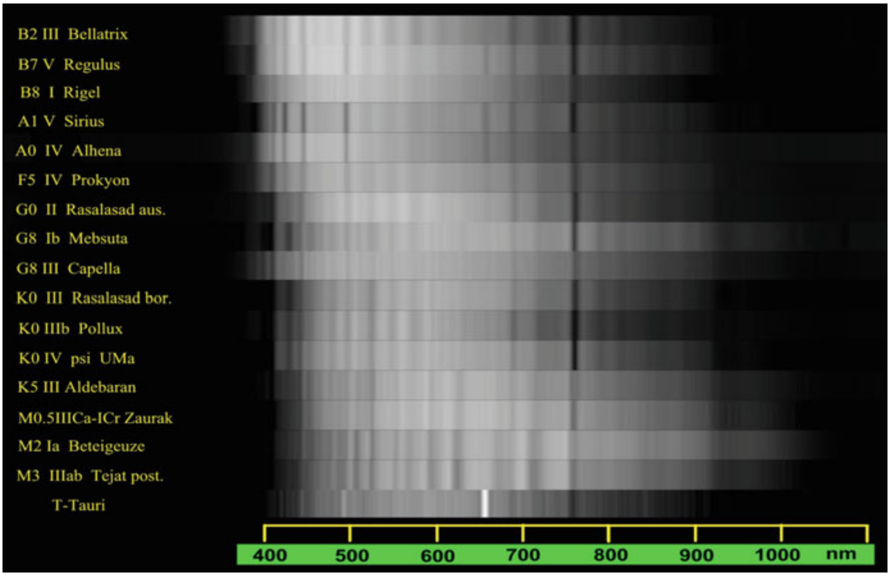

Fig. 3.1 Stellar spectra recorded with an SA100 grating (R. Bahr)

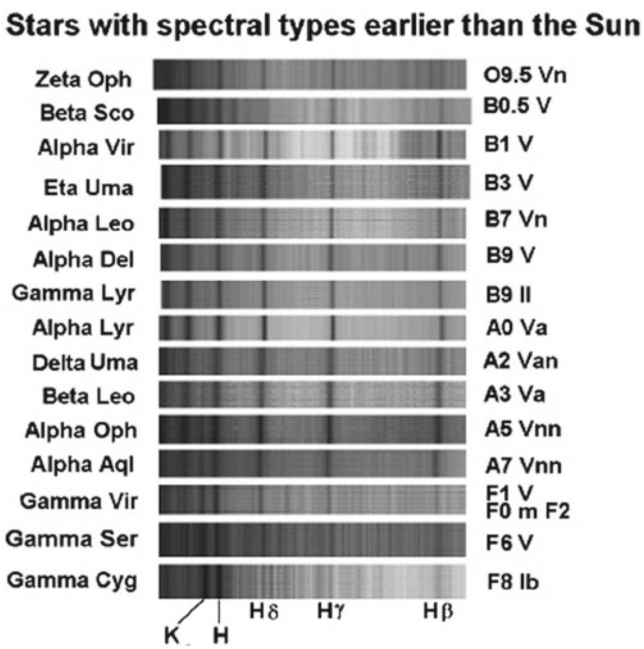

Fig. 3.2 Spectral atlas (R. Hill)

Over the past few years many Internet forums and groups have been established to support the growing interest in amateur spectroscopy. All these groups are open to amateurs interested in astronomical spectroscopy; you'll find that the more experienced forum members are only too willing to share their knowledge and assist the beginner. See Appendix G in this book for more information on these groups.

Let's start by looking at what can be done with star spectra. Each star is different and has its own unique spectral "fingerprint." This can tell us a lot about the star. A photograph of the night sky may show us what stars look like, but their spectrum reveals the star's soul.

A Brief Introduction to Star Classification

With a filter grating, it is possible to replicate the work done by the original team at Harvard and prepare your own detailed stellar classification atlas. (See Chap. 7 for a more detailed explanation of stellar classification.)

A selection of bright stars covering the O/B to M types will provide comparison spectra with an exposure of a minute or so. The spectrum recorded show dark absorption lines superimposed on a broad continuum of light, varying in intensity with wavelength.

The first thing we notice is that although the prominent dark lines may appear in similar positions (on the spectrum), some stars show fainter or wider lines. Other stars show more complex lines toward the red end of the spectrum. Each of these lines is associated with an element or molecule in the star's atmosphere.

The early classification of stars was based on the visibility of the lines associated with hydrogen. Over 75% of the whole visible universe is made up from hydrogen – so there's plenty of it to observe.

Looking at Figs. 3.1 and 3.2, you can see the prominent dark lines in the B through to the F classes; these are caused by hydrogen. There is a whole series of hydrogen lines (Balmer lines) that extend from the red 656.3 nm (hydrogen alpha line) through to the blue 434.0 nm (hydrogen gamma) and beyond.

When we get to the F class, we start to see absorption lines caused by elements such as calcium (H-K lines). There's also a very dark line shown at 760 nm. (This is caused by absorption of the light in Earth's atmosphere, the lines being called Telluric lines).

How do we know this? Which line belongs to which element? Good questions!

When the first experiments in spectroscopy were made way back in the 1860s, laboratory spectra of various chemicals and gases were obtained. It was only later that they identified the same "fingerprint" lines in the spectra of the stars. This then allowed the investigators to establish which elements were present in the individual star.

In preparing the stellar classifications it was also noticed that the absorption lines varied. Where strong absorption lines of, say, calcium, were seen, the lines of hydrogen were weaker and more difficult to measure. Why was this so?

What the Harvard team found was different temperatures influenced the type of absorption (or emission) spectra produced by the various elements. At very high temperatures like 10,000°K the atoms of hydrogen were excited enough to produce definite absorption lines, whereas at 4,000°K the activity of hydrogen was much less than that of calcium. (The quantum theory behind these results is discussed in Chap. 7.)

We now have a situation where we can see that each star is made up of different elements. and the absorption lines in the star can give us some indication of temperature. What else? Well, the width of the absorption line is also affected by temperature and pressure (called line broadening). A broad, wide absorption line usually means a hot star is involved. Figure 3.2 shows this clearly; look at the clarity of the lines in the B class spectra, then look at the same lines in the A class. The lines in the A class look fuzzy and less clear. This is not due to problems with the spectrum but a real result of changes in temperature between the two groups of stars.

It was also found that the intensity/brightness shape of the spectrum (and where the brightest area lies) is also affected by temperature. When the data was plotted, a series of curves was obtained. These are represented in the Planck curves (see Fig. 3.5), which show that as the star gets hotter the brightest part of the spectrum moves towards the blue end. That's why hot stars appear blue and cooler star appear red. Astronomers usually measure temperatures in Kelvin (°K) – the temperature above absolute zero (−273°C).

Spectra from our grating can show us all this detail and allow us to estimate the constituents of the star, its surface temperature, and how it compares to its absolute brightness (see Chap. 7) tells us whether or not it's a white dwarf star or a cool super giant.

The concepts and mathematics of the quantum theory, used to calculate which lines are associated with which elements and under which conditions they appear, can be complex and not easy for the beginner to understand. To help, Chap. 7 provides a brief introduction to quantum theory, Planck curves, etc., and at least provides a basis for further reading and investigation.

To make up your own spectral atlas to cover all the main star classifications, a good starting point would be to record the spectra from the following stars:

Star name	Spectral classification
Acrux, αCrucis	B0.5IV
βCentauri	B1III
Adhara, εCanis Majoris	B2II
Spica, αVirginis	B2V
Achenar, αEridani	B3V
Regulus, αLeonis	B7V
Vega, αLyrae	A0V
Sirius, αCanis Majoris	A1V

(continued)

(continued)

Star name	Spectral classification
Castor, αGeminorum	A1V
Deneb, αCygni	A2 Ia
Altair, αAquilae	A7V
Canopus, αCarinae	F0II
Procyon, αCanis Minoris	F5 IV
Sun	G2V
Rigel Kentaurus, αCentauri	G2V
Capella, αAurigae	G5III
Pollux, βGeminorum	K0III
Arcturus, αBootis	K1III
Aldebaran, αTauri	K5III
Antares, αScorpii	M1.5Ib
Betelgeuse, αOrionis	M2Ia
Mira, oCeti	M7IIIe

(The Greek alphabet is shown in Appendix A of this book.)

A more complete table of the brightest stars is presented in Appendix B of this book, and a representative collection of M type – red and carbon stars – is listed in Appendix E.

The data contained in our spectral image can be better visualized when it is converted from an image to a profile. This is a graph of intensity against pixel position (and after calibration, wavelength position). The profile format makes it much easier to see the shape and detail within the spectrum. All spectra are normally converted to a profile before detailed analysis. We'll see how this can be done in the next chapter.

Torsten Hansen has obtained many stellar spectra using the SA100 grating on a 200 mm f6 Newtonian telescope and some of these are shown as profiles in Fig. 3.3. Compare the top profile of the star Vega with the image of the spectrum in Fig. 3.2. We can see that each dark band in the spectrum now shows up as a significant dip in the shape of the curve. It is much easier to measure the exact center of these lines and the distances between them on the profile than on the image. The comparison profiles of the stars θ Lyrae and δ Lyrae show some of the differences visible in stellar spectra. Note also that the position of the peak intensity moves across the spectrum following the Planck curves.

Richard Walker's comprehensive freeware *Spectroscopic Atlas for Amateur Astronomers* is highly recommended. Included is an excellent collection of spectra using a low resolution Baader Dados spectroscope. It contains annotated spectra for all the stellar classes that quickly let you compare the detail and resolution of your results. A representative sample of his spectra (Antares and Rasalgethi, two M class stars) is shown in Fig. 3.4.

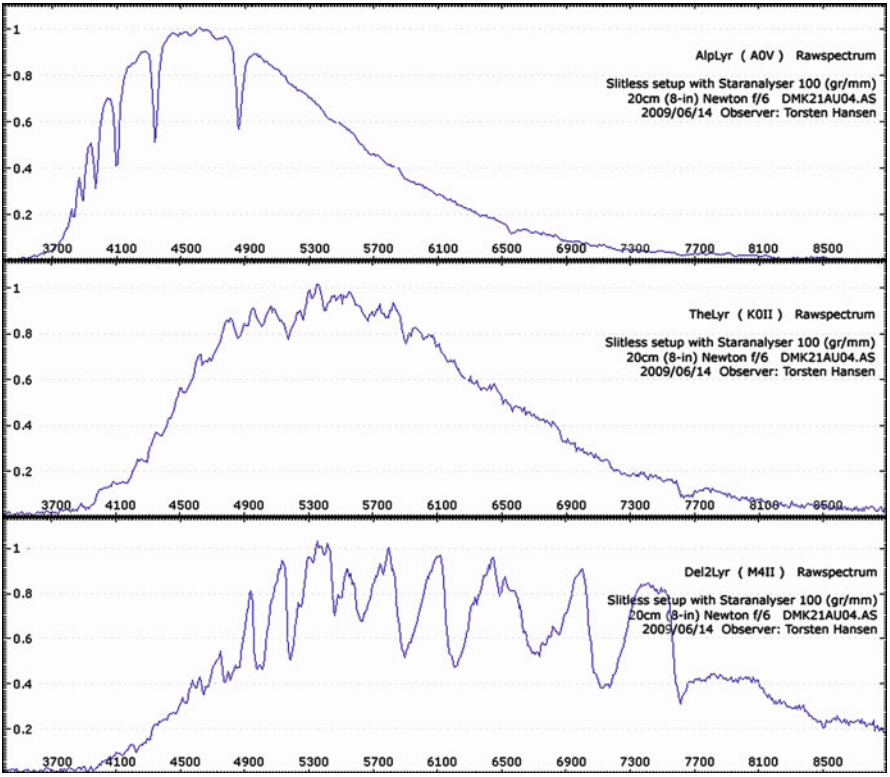

Fig. 3.3 Spectral profiles of Alpha, Theta and Delta Lyrae (T. Hansen)

Stellar Temperatures: Great Balls of Fire!

As was mentioned earlier the shape of the spectrum (the continuum), the Planck curve, (Fig. 3.5) can be used as one measure of the star's temperature. By determining the position of the peak intensity or by comparison with standard star spectra (see Chap. 4) we can easily obtain a first estimate of the surface temperature of the star. For comparison out own Sun is a G2V star with a surface temperature of 5,800°K and the peak wavelength for this temperature is around the 550 nm in the green. (This is the region of the spectrum where the human eye is most sensitive. There may be a connection here??)

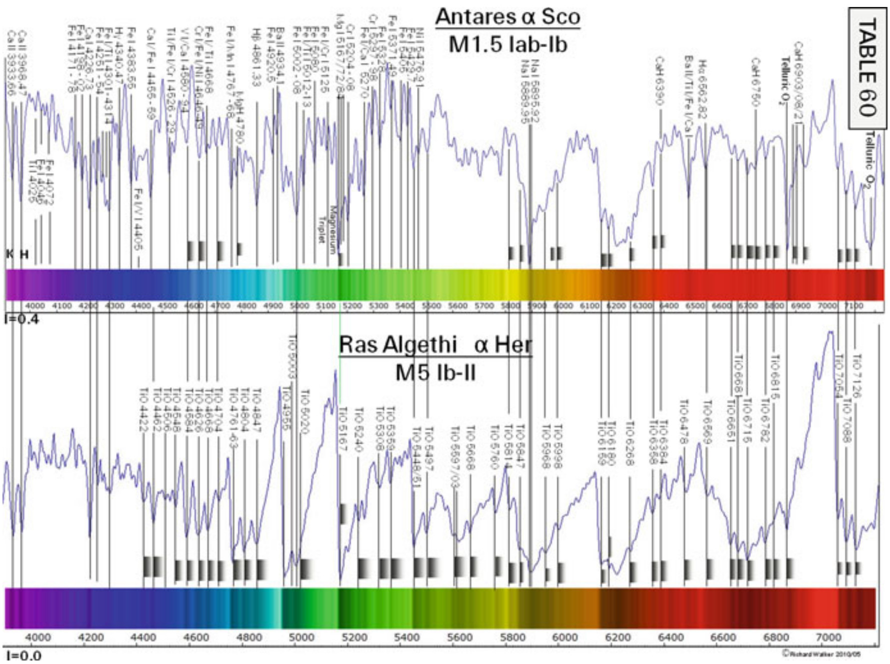

Fig. 3.4 Annotated spectrum M-class stars (R. Walker)

Star Stuff

Carl Sagan used to say we are children of the universe made from recycled star stuff. What did he really mean?

The dominant element in the universe is hydrogen. When you consider the approximate mix is hydrogen 75% and helium is 24%, that only leaves a small amount for all the other elements. But it's that "small amount" that makes a huge difference. Without it we wouldn't be here. All the other elements – carbon, silicon, uranium, etc. – are the result of the nuclear processes that take place in the stars. The hydrogen is converted to helium, then carbon, and then the heavier elements such as iron during the life cycle of a star.

Some stars, when they reach the end of their lives, go nova, exploding and spewing their elements out into nearby space. This has being going on since the beginning of time, and all the elements we now see were at one stage or another inside a star. Thanks to spectroscopy we can accurately determine which elements/chemicals are in the stars. The "fingerprints" are there to be searched out and analyzed. With our grating, hydrogen, calcium, titanium dioxide and many more elements and molecules can easily be found and identified. All we need to help us find these

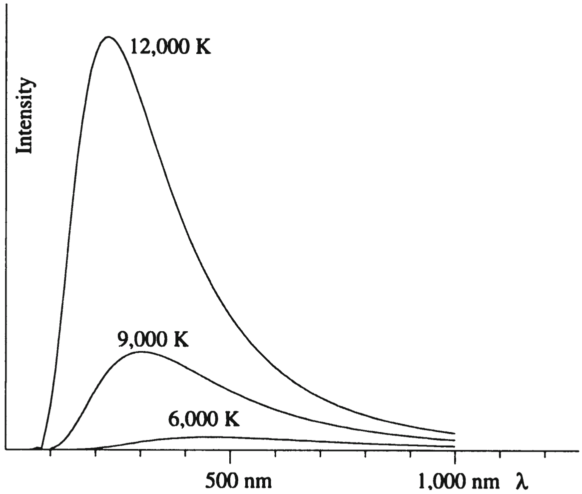

Fig. 3.5 Planck curves of surface temperature (°K) versus peak intensity position

various elements is a "conversion manual" that gives us the key. In the case of hydrogen, the Balmer series of absorption lines gives us the answer. For other elements we can use a series of reference spectra, where the line identification has already been established by professionals, or use a listing of the known emission line positions for the various elements. These lines can then be compared with a calibrated spectrum to seek out matches between our absorption lines and the known lines.

Sounds pretty straightforward and simple. Unfortunately we need to do a bit of work to prepare the data and compensate for instrument response, atmospherics and other effects before we can accurately do the comparisons. Chapter 4 will introduce some of the basic processing methods needed to analyze the spectrum as well as provide a comprehensive source of high quality comparison spectra. This is the exciting part. We have the spectrum and all the facts in front of us; we just need a little knowledge to break the code. A bit like Sherlock Holmes – look for clues and check them against the known facts. As Holmes would say, "Elementary, my dear Watson."

The methods used to determine which absorption line is which and why it is visible (or not visible, as the case may be) is the subject of Chap. 7.

Emission Stars (Be and Shell Stars)

Be stars (class *B* stars with *e*mission spectra) and "shell stars" are hot complex stars where high spin rates eject matter that forms a ring around the star. This ring causes emission lines of hydrogen to be formed that are broadened by a Doppler

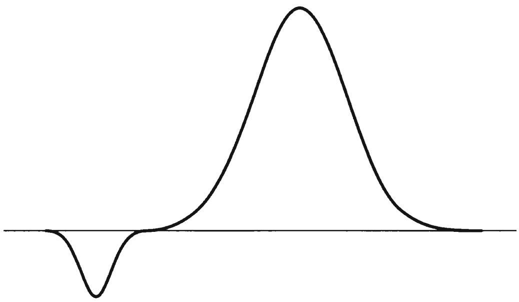

Fig. 3.6 P Cygni intensity profile (K. Robinson)

shift and seen superimposed on absorption lines from the star's atmosphere. The lines therefore appear doubled, with a bluer approaching wing and a reddened receding wing. The Be star γ Cass was the first to be recorded, in 1866, and has been regularly observed ever since. Although astronomers are convinced of the mechanism causing the emission/absorption lines, it is still unclear as to why it occurs. Earlier theories of the ring being formed from material centrifugally thrown out of the star due to the high spin rate have now been dismissed. Continued observations are required to determine both the classification of the underlying star and nature of the circumstellar disk.

All Be stars show signs of variability, and the interaction of the emission/absorption lines is constantly changing. The "wine bottle-type profile" has been used to describe the change in line profile. For amateurs with more powerful spectroscopes (R = 15,000) the regular (daily/weekly/monthly) recording of changes around the Hα line is certainly a very worthwhile project.

With the grating it is possible to at least record the changing emission lines and gain practice in plotting the variations. Some 15% of all O and B type stars show emission spectra.

An extensive catalogue of over 2,000 Be stars and some 46,000 sample spectra (many provided by amateurs) is available at the Be Star Spectra (BeSS) website. This is one area where the amateur can make significant contributions to the knowledge base and assist in the ongoing development and understanding of these important stars. Appendix C in this book gives a listing of the brightest Be stars.

Shell stars also show similar emission/absorption variations. The surrounding material, like that of the Be star, has developed into a shell rather than a disk. ζ Tau is a well-known B shell star, as is Pleione (28 Tau) in the Pleiades.

For amateurs this phenomenon of emission/absorption is more noticeable at the Hα line as a typical "P Cygni" profile shown in Fig. 3.6. (Figure 2.11 also shows the spectrum of P Cygni.)

Wolf-Rayet Stars (WR)

Wolf-Rayet (WR) stars have evolved from extremely hot, massive O-type stars. A typical Wolf-Rayet star can have a mass of up to 25 times that of the Sun. The spectrum shows numerous broad emission bands of hydrogen, ionized helium, carbon, nitrogen and oxygen, associated with the enormous mass transfer going on at their surface. Matter is streaming away from the star, and we only see the spectrum of the lower density outflowing material. It is thought that the WR stars are on the stellar evolution track toward eventual supernova explosion, where their rich supply of chemicals will go on to form the seed of our "star stuff." The WR classification is further divided into WC (carbon emission stars) and WN (nitrogen emission stars).

These stars make great targets for the grating spectroscope. The wide emission lines stand out dramatically against the usual stellar spectra. (Figure 2.11 shows clearly the classic WR spectrum of WR 136/7 among the surrounding stars.) Figure 3.7 shows some typical low resolution spectra of WR stars.

A listing of the brightest WR stars is given in Appendix D of this book.

Variable Stars/Nova and Supernovae

Spectral observations of variable stars and novae can complement the traditional amateur work being done by both visual and photometric observations used to plot the light curves of variable stars. The paper (2010) by Francois Teyssier, although using material from larger amateur spectroscopes, shows clearly the changes seen in the spectrum of the variable star CI Cygni during the recent outburst. It is anticipated that more and more amateur spectral contributions will be made on variable stars and add another dimension to the extensive observational database.

Figure 3.8 shows the resulting spectrum obtained from a stack of 12 × 90 s exposures. A C11, Canon 350D camera and an SA100 grating were used to record this faint nova (11.5mag). The emission lines of hydrogen and helium can clearly be seen. This spectrum was taken some 40 days after the initial outburst.

Variable stars that are of interest to the amateur are the eruptive and cataclysmic-type variable. These are usually surrounded by a gas shell caused by sudden eruptions in the star's atmosphere (chromosphere). Changes in the relative intensity of the emission lines can be seen to parallel the light changes of the stars seen in observations of cataclysmic variables such as SS Cygni. Other stars of interest are η Carinae, HD 34959, V378 And, o Ceti (Mira), R Leonis and R Cygni.

Novae occur (and sometimes recur again and again) when a white dwarf star erupts. The brightness of the star can increase by up to 10 magnitudes over a matter of a day and then gradually decline over a few months. All novae or recurring novae are associated with binary systems. The stars involved are usually a normal star and a white dwarf companion. The spectrum can be very complex; at maximum brightness looking like an A-type supergiant. During decline absorption lines are seen, then a transition to broad emission lines more typical of gaseous nebulae.

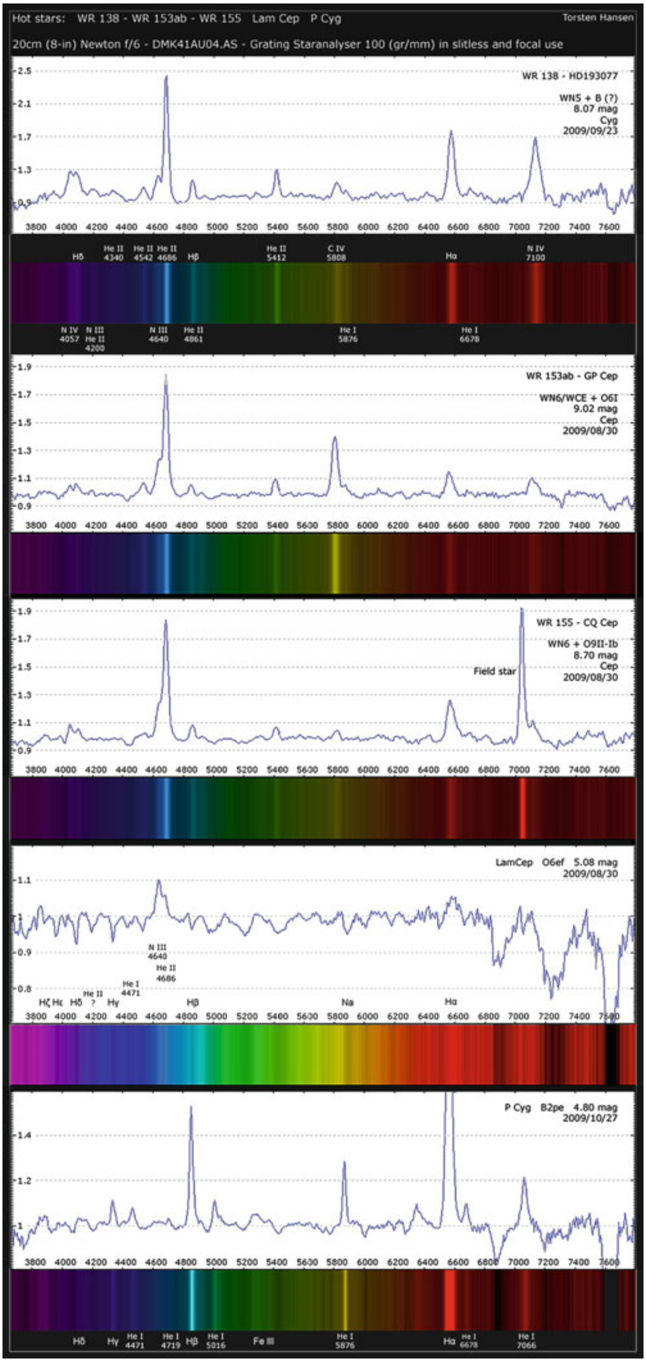

Fig. 3.7 Selection of WR spectrum (T. Hansen)

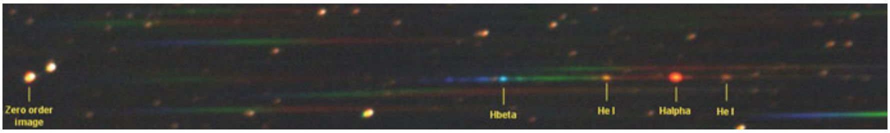

Fig. 3.8 Nova Vulpecula 2007 (V458) (C. Buil)

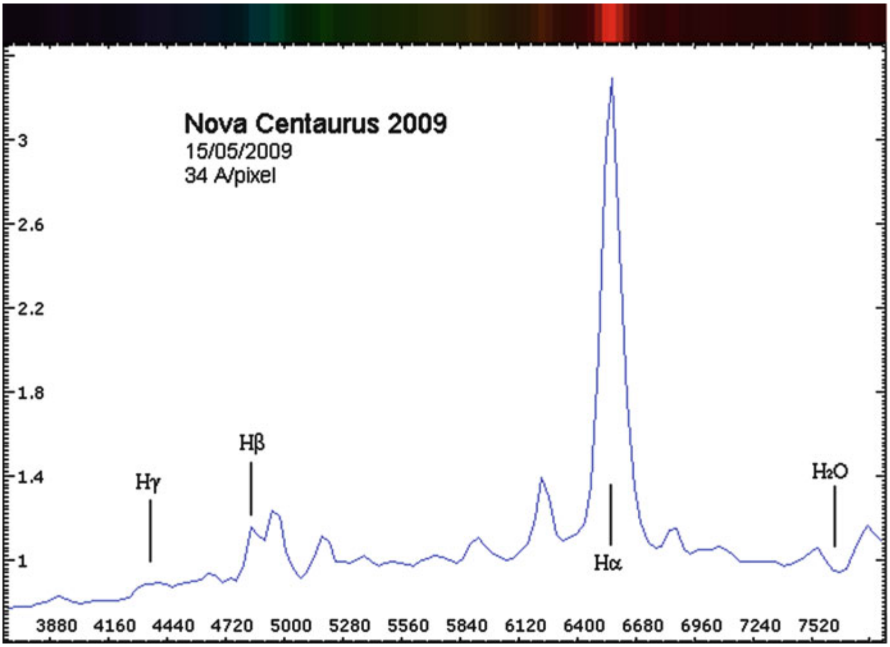

Fig. 3.9 Spectrum of Nova Centaurus 2009, using an SA100 grating (T. Bohlsen)

The classic nova will show emission lines, Fe and H, whereas the recurring variable star-type nova show a much broader continuum. (See Fig. 3.9.)

Supernovae (SN) can appear in any one of the thousands of galaxies visible in amateur telescopes. The typical discovery magnitude of 15 puts them into the difficult category, but Christian Buil and others have successfully obtained spectra with filter transmission gratings.

Supernovae come in different types, the most common being Type 1a and Type II. Type Ia is the classic supernova, where an old low mass star comes to the end of its life and after the explosion will end up as a white dwarf star. Type II is different, being the end point of a single massive star, the remnants of which may become a neutron star or even a black hole.

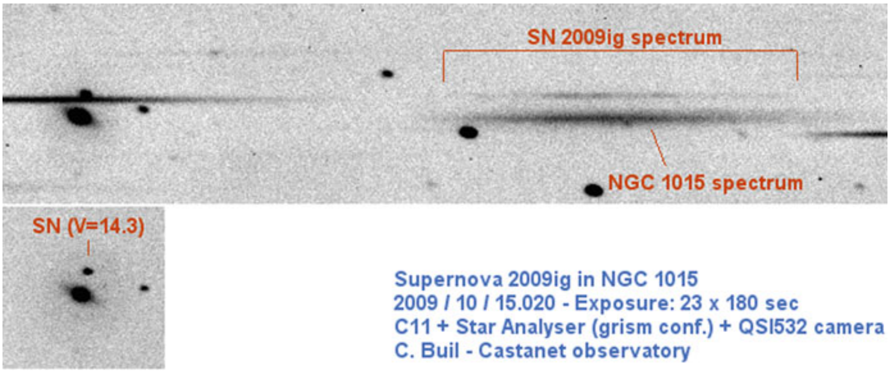

Fig. 3.10 Spectrum of SN 2009ig (C. Buil)

Type 1a has a rapid rise to maximum brightness and a fades slowly over a long period of time. The hydrogen emission lines are not seen during the rise in brightness. The Type II, which stays close to its maximum brightness longer before fading, shows hydrogen emission and absorption lines, widened due to the rapid expansion of the (Doppler shifted) atmosphere. (See Fig. 3.10.)

There are some good web pages which give details of current SN, and their visibility. These are listed at the end of this book.

The Harvard Smithsonian Center for Astrophysics (CfA) maintains a large database of SN spectra (over 700) going back many years. This provides an ideal reference and comparison source for all amateurs.

Nebulae

There are three basic types of nebulae observed by amateurs: bright emission nebulae, such as M42 in Orion; bright reflection nebulae, such as the glow that surrounds M45, the Pleiades; and planetary nebulae such as M27, the Dumbbell. Each one tells us more about the galaxy we live in. They allow us to observer the building blocks of the stars and the interstellar dust that one day will evolve into new stars. Planetary nebulae also give us an insight into the dying days of stars. From womb to tomb, we can see it all. The grating spectroscope is capable of recording these objects and showing the interaction of light and matter.

The high energy levels of bright stars embedded in the emission nebulae excite the atoms in the surrounding nebula just like a fluorescent lamp and causes the nebula to emit light in discrete wavelengths due to the ionized atoms of hydrogen (Hα, Hβ), helium, oxygen, OIII, NII and sodium. The reflection nebula, on the other hand, usually show the continuous spectrum of the nearby stars reflected from

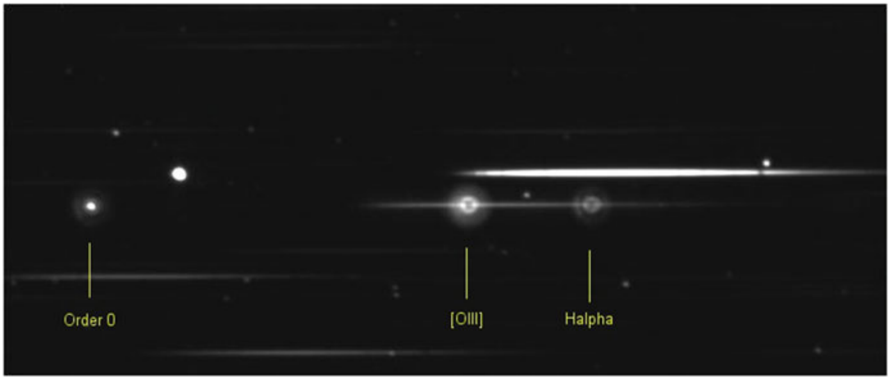

Fig. 3.11 NGC 2392 SA100 + Grism (C. Buil)

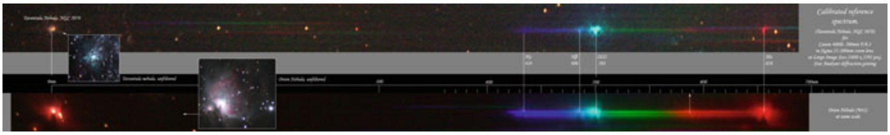

Fig. 3.12 Tarantula and M42 Orion nebula spectrum (R. Kaufmann)

the dust in the region. Some complex regions containing both gas and dust, like M20, the Trifid Nebula, show both emission and reflection nebula.

The planetary nebulae are gaseous remnants of stellar collapse and usually emit OIII, NII, HeI, HeIII, Hα and Hβ light. NGC 6543 was the first non-stellar planetary nebula to be observed, in the mid-1860s. The visible emission lines proved conclusively that it was a nebula and not just another star.

When a grating is used, the emission spectrum shows repeat images of the nebula in the wavelength being emitted (Fig. 3.11). Regions of ionized oxygen can show different images to those of the hydrogen, etc., due to the complex nature of the nebula.

The SA100 spectral image of the Tarantula Nebula in the LMC and M42 in Orion taken with a 55 mm camera lens (Fig. 3.12) clearly shows the differing shape of the emission regions.

To improve the resolution and show the emissions as spectral lines, a slit needs to be used. See Chap. 6 for details.

Redshift/Quasars

One of the first applications of the spectroscope was to resolve close double stars by measuring the Doppler shift of their spectra. As the stars rotate around their common center of gravity they will appear to be approaching or receding from us as they move around in their orbit; this leads to an apparent doubling of the spectral lines. Unfortunately the resolution of our humble grating makes this an impossible task.

However, it is possible to measure and record the higher Doppler shifts associated with the high velocity expansion of supernovae shells and of the expanding universe itself. Distant galaxies and quasi-stellar objects (quasars) have their spectrum red-shifted. This redshift (z) is proportional to the speed of the receding galaxy and is measured by:

$$redshift(z) = \left(\lambda_{observed} - \lambda_{emitted}\right) / \lambda_{emitted}$$

By comparing our spectrum of a distant object with that of a stationary star (well, relatively stationary) we can calculate the speed of recession. It's sobering to think that only a few years ago this type of observation could only be carried out by professionals using large, expensive telescopes, and here we are now, from our backyard, obtaining data that shows the expansion of the universe, using light that may have taken millions of light years to reach us. Such are the opportunities (and challenges) that make spectroscopy so interesting and satisfying.

Maurice Gavin was the first amateur to record the redshift of a quasar, in 1998. He successfully determined the redshift (z) for a 13th magnitude quasar, 3C 273 as 0.16. This is shown in Fig. 3.13.

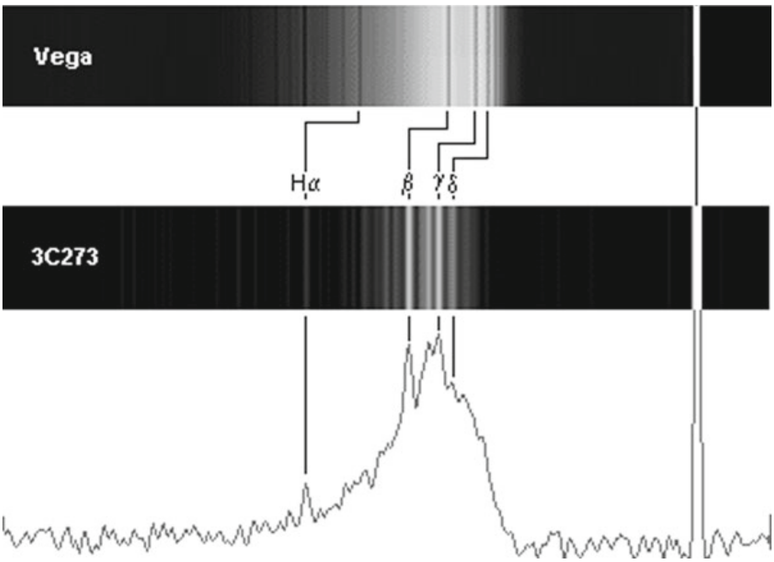

Fig. 3.13 Spectrum of 3C 273 showing redshift compared with Vega (M. Gavin)

In these suggested projects we've moved from nearby stars, calculating their temperature and chemical makeup, looked at the stellar family and how they are related to each other and also how they die. We've also looked at the colorful nebulae that form part of the building blocks of the galaxy and even explored the vast distances towards the edge of the known universe. There is a lifetime's work awaiting you. Every star, nebula and galaxy is different, and courtesy of our spectroscope we can "boldly go where few amateurs have gone before," discovering new information with each observation.

Now let's come back a little closer to home and see what can be done with our grating with Solar System objects. Everything in our Solar System is seen by reflected sunlight, but we can employ some techniques to pull out the subtle details in the spectra and see behind the obvious.

Planetary Spectroscopy

With a slitless grating it's difficult to obtain a clean spectrum of larger objects such as the Sun and Moon (some methods that can be used will be discussed later). It is possible however to obtain the spectra from the planets as they appear starlike at short focal lengths. Planets and their satellites shine by reflected sunlight, so generally we will only record a solar spectrum. By subtracting a typical G2V star spectrum we can highlight any subtle differences between the normal solar spectrum and the reflected spectrum from the planets (and their satellites). This allows us to distinguish some of the gaseous compounds in the atmospheres of the larger planets such as Jupiter, Saturn, Uranus and Neptune. The absorption lines, which form a series of bands (Swan bands) of methane are very prominent and easily recorded with even the SA100 grating. (See Figs. 3.14, 3.15.)

In Chap. 4 we will show how the spectrum can be processed to reveal this data.

Meteor Spectra

Every day Earth's atmosphere is bombarded by foreign bodies from space. Usually these are no bigger than a grain of sand. It is estimated that some 100,000 kg of material arrives each day. These meteor particles are associated with dust orbiting within the Solar System (some of the larger clouds of dust have been linked to old comets). Every year as Earth moves around the Sun it intersects with bands of meteors that can give rise to spectacular meteor showers (shooting stars) – where the particles burn up in the atmosphere. Sometimes, however, a larger piece of debris can hit us – and actually survive the dramatic re-entry through the atmosphere, falling as a meteorite. These larger bodies, called bolides, can be seen as bright flashes, reaching magnitudes of <-2 as they enter Earth's atmosphere. We now know there are two basic types of meteorites: stony meteorites, which make up

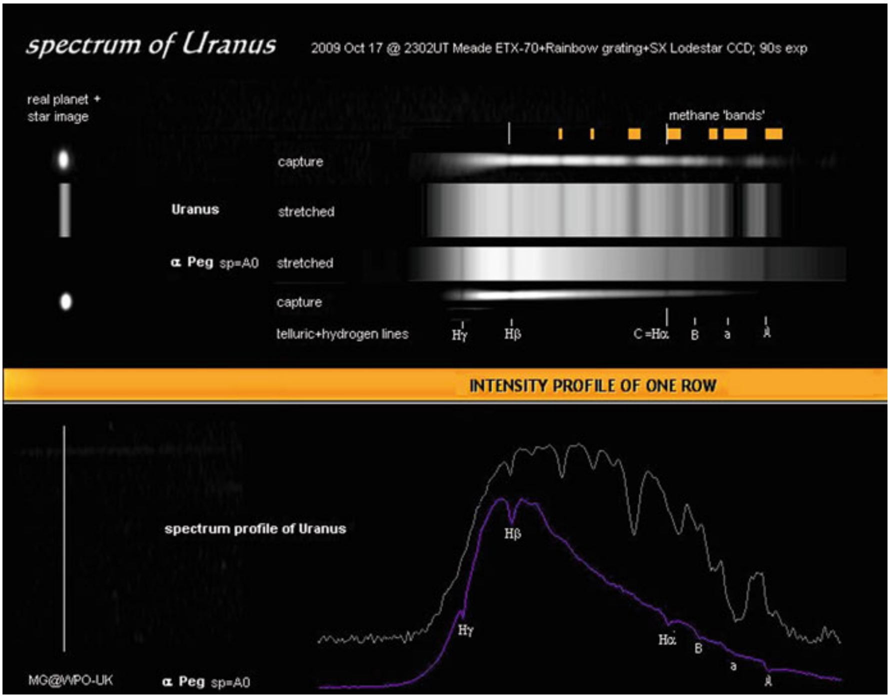

Fig. 3.14 Methane spectrum of Uranus (M. Gavin)

roughly 75% of the meteorites, and the balance being iron (almost pure nickel-iron) meteorites. Some meteorites have been found to have the same composition as our Moon, and some even represent material from Mars.

With an objective grating it is possible to record the spectrum of bright meteors and determine their chemical make-up. A little pre-planning will improve the chances of success. The grating should be oriented at 90° to the anticipated track of the meteor. Meteor showers occur throughout the year, but the richest showers are:

Quadrantids	Jan 1–4
Perseids	July 27–Aug 10
Draconids	Oct 10
Geminids	Dec 6–16

As the meteor burns up in Earth's atmosphere the surrounding air and the material of the meteor emit a spectrum. The oxygen in the atmosphere can be ionized and produce spectral lines at 557.7 and 615.7 nm wavelengths. Depending on the

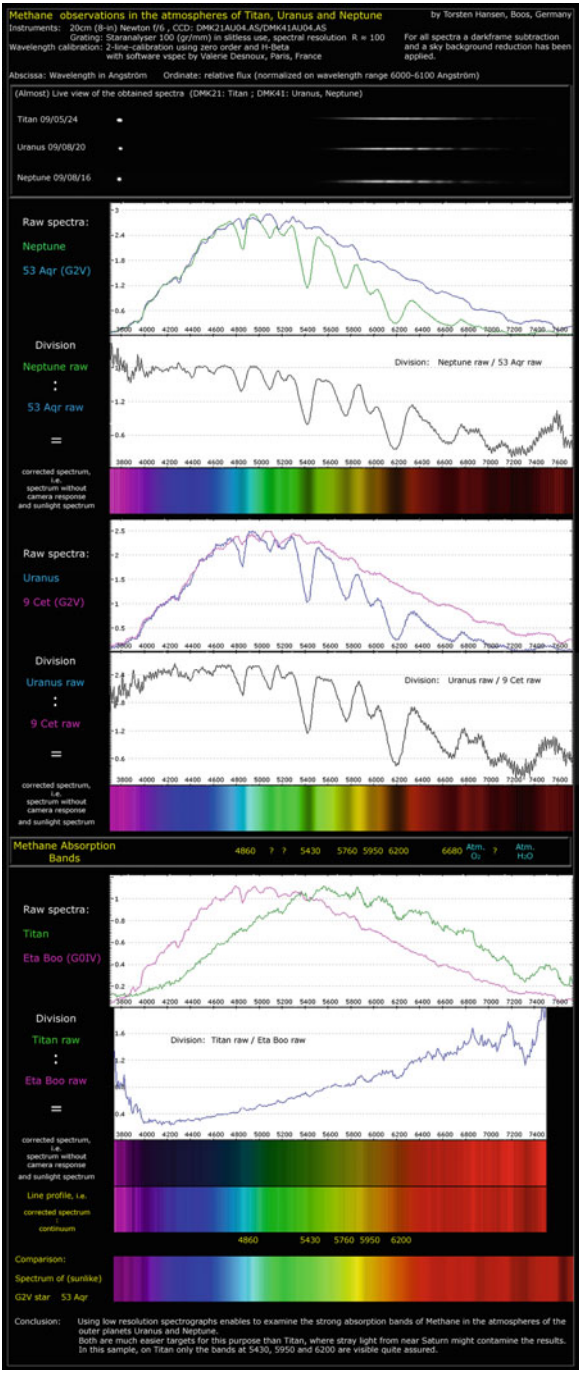

Fig. 3.15 Methane spectra – Titan, Uranus and Neptune (T. Hansen)

Fig. 3.16 Perseid meteor spectrum (R. Leadbeater)

material of the meteor, we may record bright lines from calcium, iron, manganese and sodium. Figure 3.16 shows the spectrum captured from a bright Perseid meteor with an SA100 grating mounted on a 5 mm wide angle lens using a modified webcam.

Recording meteor spectra is a bit of a hit and miss affair. There's no guarantee of success, but wouldn't it be nice to record a spectrum of a visitor from Mars?

What About the Sun?

NEVER LOOK AT THE SUN WITHOUT ADEQUATE FILTER PROTECTION. You can severely damage your eyes as well as your expensive telescope equipment. Don't do it!

Without a slit to limit the light, it's impossible to obtain a spectrum with a grating. (Unless you're lucky enough to see a total solar eclipse!)

Figures 3.17 and 3.18 show the solar spectrum recorded with an SA100 during the eclipse of 2006. Rather than waiting for the next opportune eclipse we can adapt the grating to work with an entrance slit, which then allows us to record the solar spectrum in all its glory.

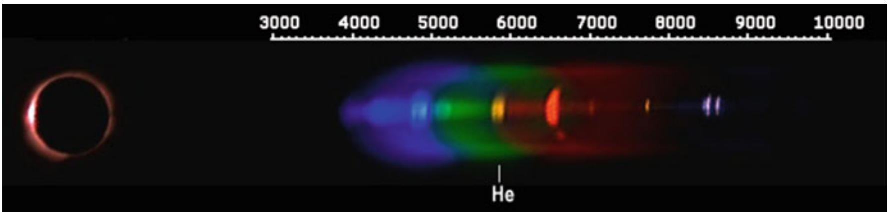

Fig. 3.17 Solar eclipse spectrum (R. Leadbeater)

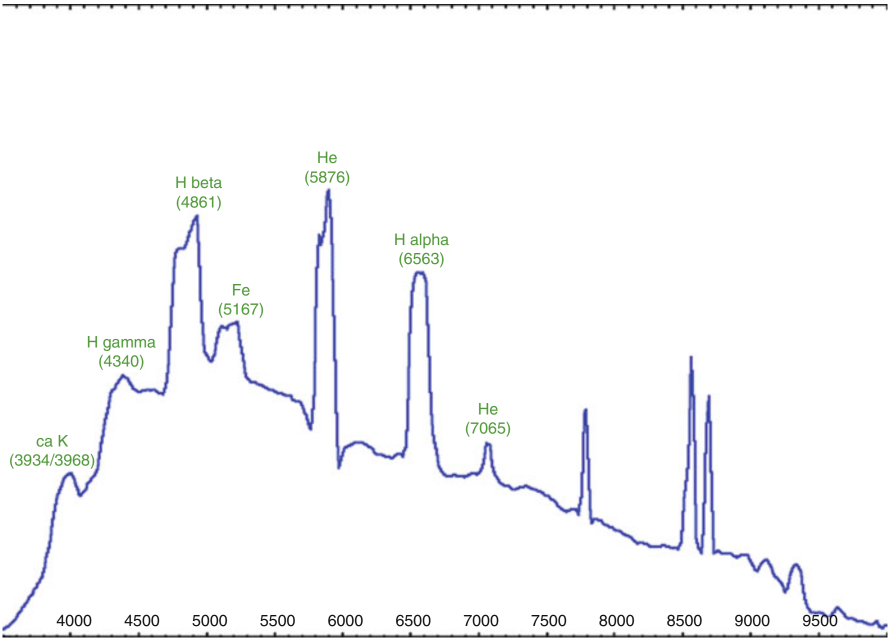

Fig. 3.18 Solar spectrum profile (R. Leadbeater)

Details of suitable slit designs that can be used with the gratings are discussed later (see Chap. 5).

These projects only provide a "taster" of the work that can be done with a spectroscope. Any one of them can keep you busy for a long time, and there's always more and more interesting challenges to attempt. We are only starting….

To extract as much information as possible from our spectrum we need now to come to terms with the next step along the road, and that is processing the spectrum. By correcting, calibrating and preparing profiles we can move forward and start to see more clearly the fruits of our labors. It will require some effort and a bit of discipline, but the results you will achieve will make it all worthwhile.

Chapter 4

Processing Spectra

Getting an image of the spectrum is only the beginning of the adventure.

Looking at the image, cropping and stretching it will reveal the obvious dark absorption/emission lines on the background continuum. You can compare this basic image with others on the web and in books to help recognize some of the prominent features. The collection of low resolution spectra shown in Fig. 3.1 is a good example. Using these raw images doesn't however allow you to analyze the various lines – where they are in the spectrum and what elements may have caused them. This requires some additional investigation. The tools we can use to help us are readily available as freeware software on the web (with a commercial version also available).

We need to be able to better visualize the shape and form of the spectrum, and this is usually done by turning it into a graph, or profile. This profile of intensity vs. pixel position then allows us to measure the spectrum, use some specialized tools to determine wavelengths and compare our data with known and standard spectra of other stars and elements.

You'll be amazed with the information hidden in that small strip of light! With care and the right software it is possible to determine stellar temperatures, chemical constituents and sometimes the physical nature of the star.

Let's look at some of the software and techniques available to help you on your journey of discovery.

Software Overview

Some basic analysis can be done using profile graphs exported from your imaging program and then imported in a spreadsheet (Excel, etc.). This will plot the intensity of the image against the pixel position on the CCD. To be able to use wavelength

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4_4,

calibration and access the various reference and comparison spectra you need to use a dedicated spectroscopic software package.

The most popular freeware programs for pre-processing and analyzing spectra are Christian Buil's *IRIS* and Valerie Desnoux's *Visual Spec* (VSpec). There is also *Sky Spec*, an analysis program by Bernd Marquardt that was specifically developed for processing spectra obtained from gratings. Recently Tom Field has developed his software package *RSpec*; this commercial software allows the real-time collection of a spectrum and displays the results "live" on the computer screen.

There are a series of steps that need to be taken in analyzing the spectrum:

- Preparing the raw image file for processing
- Obtaining a pixel profile graph
- Wavelength calibration
- Correction for instrument response
- Identification of other lines and features

Preparing the Raw Image File for Processing

If you are already doing some astrophotography you will be familiar with the need to apply correction to the image, to improve the SNR and the general quality of the end result. Likewise the spectral image should be corrected using bias, dark and flats before subsequent processing. There's no need to consider any other corrections at this stage. The more you manipulate the original image the greater the likelihood of adding noise and artifacts to the image. To ensure maximum information is retained, keep it simple. In fact, for most filter grating images applying dark corrections is all that is really required. For those who have limited experience in imaging processing, the following explanations will help you understand the basics. (More detail can be found in any of the specialized astrophotography and astro-imaging books available.)

LIGHT: A light (or light frame) is a term used by astro-imagers, and refers to the actual image taken. In our case, it is an image of the target star and its spectrum. Each light contains the noise from the bias (see below) and the light exposure. The longer the exposure the greater the background noise. The part of this noise caused by the electronics in the camera is removed by applying dark frame corrections.

BIAS FRAME: This is a very short exposure with the lens covered (i.e., no light getting to the CCD). Use the shortest exposure setting available (1/1,000 s, etc.). With a DSLR set the ISO rating to the same as you will use to record the spectrum (ISO 400, etc.). It is also sometimes called the system readout noise.

You are effectively recording the noise generated by the camera in preparing the CCD to receive an image, and any noise associated with the electronics transferring the image from the CCD to the memory card (or PC). This bias noise is present in every exposure – dark or light image. The only time it is used independently is when you are using dark frames that were taken at a different exposure from the associated lights. To get the best results 7–10 bias frames should be combined and averaged to become a "master" bias before applying them for corrections.

DARK FRAME: A dark (or dark frame) is an exposure, with the camera covered, using the same settings as the light exposure. For example, if you take a 3 min exposure of the spectrum then you should also take a dark exposure of 3 min. Each dark contains the bias and dark noise. These darks don't have to be taken at exactly the same time as the light. You can have a library of darks pre-prepared for various exposures. The only important requirement is to keep the ambient temperature similar. For example, if the light was taken at 18°C then so should the dark.

The dark exposure contains the thermal noise generated by the camera electronics during the exposure. Again, combining a series of similar darks (7+ recommended) and taking the average suppresses any random noise and gives the best results. This will give you a master dark frame.

Bias frames can be used to compensate where you don't have a suitable dark – for example, your light exposure was, say, 4 min but your available dark is only a 2-min exposure. As each dark will contain the noise from a bias + dark, adding two of them together will give 2 × bias plus 2 × dark, which results in one extra bias frame being added to the correction (1 bias + 1 dark) is (2 bias + 2 dark) = 1 bias. This can be removed by subtracting one of the bias frames prepared earlier. Sounds complicated, but if you understand that each image is a combination of a bias and an exposure the correction required becomes more obvious.

FLAT: The optics of the telescope/camera lens and all the various adaptors between the starlight and the CCD can cause some distortions and shadows to appear on the final image. This is called vignetting. The classic appearance of vignetting is where the central portion of the frame is brighter than the edges. This is very common when focal reducers are used. Dust on the optics close to the CCD chip can also cause shadow marks called "dust bunnies" on the image. These can also be removed with the application of flats.

A short exposure of a uniformly lit background (the sky at twilight, or a white T-shirt, etc.) will record any vignetting/dust in the optical system. This exposure can then be used to correct your light. For added accuracy you can combine and average your flat (and apply dark corrections).

Applying Corrections
SUBTRACT the (master) dark.
DIVIDE by the (master) flat.

Once these basic corrections have been made to the spectral image you can move on to the pre-processing stage.

When using multiple exposures (some faint target stars may require a total exposure of up to 30 min or more), use a stacking program such as *Deep Sky Stacker* (DSS) or *Registax* to combine the images.

Fig. 4.1 Vega spectrum in DSLR frame

Depending on how you set up the grating, the size of the spectrum on your image may be small compared with the CCD frame (for example, when using a DSLR). See Fig. 4.1.

NOTE: It is the convention in spectroscopy that the blue end of the spectrum is positioned at the left hand side of the image. You can mirror your image if necessary to achieve this.

Use your imaging program to correct and align the spectrum horizontal across the image, within 1 or 2 pixels. Save your image in RAW or the highest resolution format available, such as in black and white .fits files

Some sharpening of the spectrum can be done with hi-pass filters, but be very cautious; too much sharpening can add artifacts that will destroy the integrity of the image.

Using IRIS to Pre-process

Taking our image-corrected spectrum and getting it ready for conversion into a profile is the next stage in pre-processing. We need to apply a couple of corrections (or ensure they have already been done) before moving on.

The minimum corrections are:

- Alignment of the spectrum across the horizontal axis of the image. This may already have been done when you obtained the image, but it needs to be double checked and corrected if necessary.
- Removing the sky background, to suppress any light pollution interference and background noise.

The *IRIS* software from Christian Buil is a comprehensive astro-imaging package that is continually being developed and enhanced to meet the needs of spectroscopy. It can be used to do the pre-processing for you and handles both DSLR RAW files as well as all the standard CCD file formats.

The *IRIS* command “File/Load” (or File/Load a RAW file can be used for DSLR images) will bring up your image on its screen. You may have to adjust the threshold numbers (on the pop-up screen) to give a good visual image.

NOTE: This does not change the data in the image, just the way it is presented on the screen.

Your raw image, if in color, needs to be converted to black and white. This can be done by combining the RGB data into a 16-bit .fits file; the drop-down tab “Digital photo/48 to 16bits” converts a color image to a 16-bit black and white file. This can then be saved as a .fits file (or a .pic for VSpec – see later).

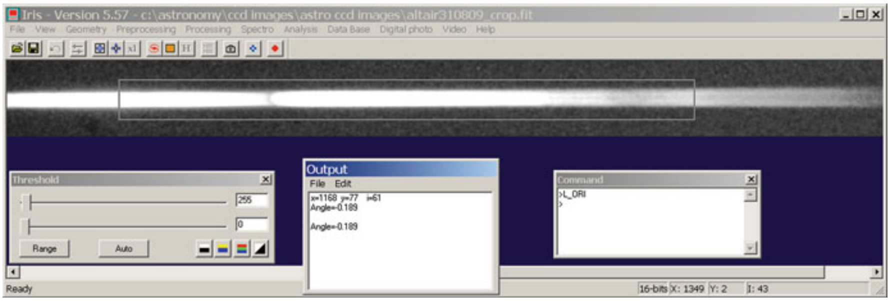

Fig. 4.2 *IRIS* tilt correction screen

IRIS has a couple of commands to help achieve accurate rotation of the spectrum. With the image of your spectrum on the screen use the mouse to select a box (click and drag) around the middle of the spectrum. The size is not critical. (See Fig. 4.2.) Go to the "Command line" tab and a popup screen will allow you to enter "L_ORI" (line orientation) – press ENTER.

This command calculates the tilt angle correction for the spectrum within the selected area. The answer comes up in an "Output" screen. The example in Fig. 4.4 shows a tilt correction required of −0.189°. (NOTE: a positive angle will rotate the spectrum counterclockwise) Alternatively you can use the cursor to check the Y height at the beginning and end of your spectrum. The tab "Spectro/Tilt of a 2D spectrum" brings up a window that asks for the X position of the center of your frame and the correction angle to be applied.

The next significant step is to subtract the background from the image and the spectrum. Under the "Spectro" tab select "remove the sky to a 2D spectra." A pop up screen (subtraction of the sky) will ask which method to use. The default "Median" is usually suitable. Upon clicking this screen, an "Output" screen pop-up will ask you to select four points. You should now point and click on two points above the spectrum followed by two points below the spectrum. One point in each pair should be just above or below the spectrum, with the other at some distance.

When you enter the final point *IRIS* will automatically remove the sky background from the image. See Figs. 4.3 and 4.4.

You can use the command "Geometry/Crop" to define the X-Y coordinates of a box to further reduce the background. Allow a minimum of 10 pixels above and below the widest part of your spectrum image. (This ensures that all the spectral data is captured.) This image is now ready for some serious processing.

The Pixel Profile Graph Using an Image Profile and Spreadsheet

Spectra obtained with a grating are basically linear and can easily be converted from pixels to wavelength if at least two reference points are known. For filter

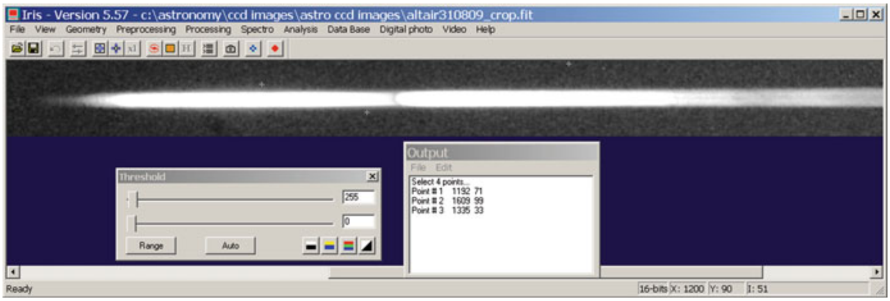

Fig. 4.3 *IRIS* sky removal screen

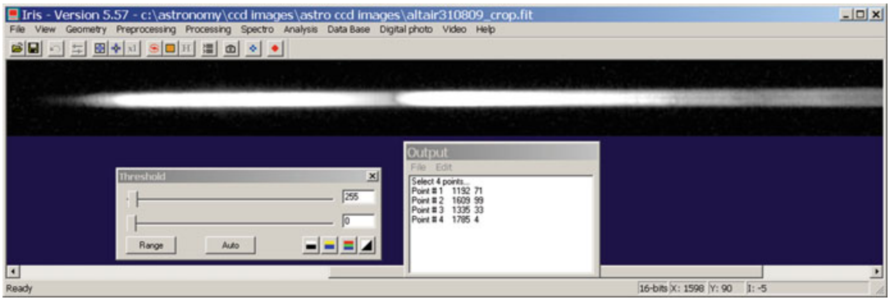

Fig. 4.4 Spectrum after sky background removal

gratings, the zero order image can be taken as one reference; this only leaves a pronounced line feature (one of the Balmer lines, for instance) to be identified (or guessed!) to calibrate the spectrum in Angstrom.

A cursory investigation of the spectrum can be achieved by using a profile taken through the spectrum. All the imaging processing software used by amateurs has the capability of generating a 1D profile graph of an image. Figure 4.5 shows such a profile obtained from the Vega image (Fig. 4.1) in AstroArt V4.

Here you can see the image (from the zero star image at the left hand side to the end of the “tail” of the red region) is approximately 1,800 pixels long.

This profile can be saved as a text file (the format is two columns – the first being the intensity value and the second the pixel number).

Let’s quickly look at the profile. What does it tell us?

You can see the obvious spike of the zero star image at the left hand side, then a long gap (pixel 50 to 900) before the shape of the spectrum appears. (This gap is due to the CCD being unable to record images down in the UV and into the very short wavelengths.) The shape of the spectrum looks a bit odd (compare this profile with the Vega profile shown in Fig. 3.3). The dark lines in the original image show

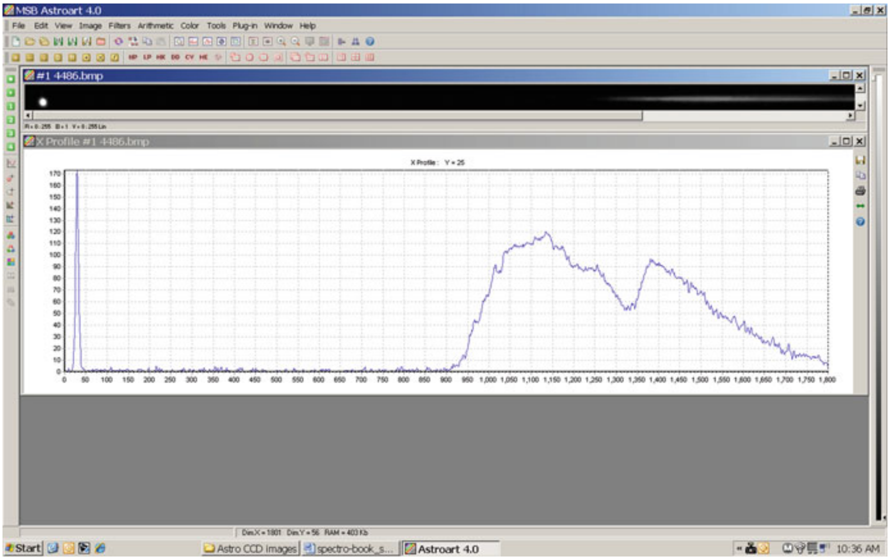

Fig. 4.5 Spectral profile of Vega ex-AA4

up as dips in the general outline of the profile, but why isn't the overall shape smooth and regular?

Some of the "ripple" in the line will be caused by seeing conditions and general noise in the image, but the large dip at pixel 1,350? This is caused by the instrument response efficiency. (See Chap. 6.) The DSLR camera used shows that the efficiency drops off between the green and the red Bayer filters, and this is evident in the profile as a large dip. Can this be fixed or removed? Yes. Later we'll see how to compensate for the instrument response and correct the profile. Note also that the length of the profile that actually contains all the spectral information is only about 900 pixels long. Those 900 pixels contain all the information we can get from this image. Higher dispersions/plate scales will give us a longer spectrum, and if the resolution is maintained (or hopefully improved) we will get more and more information. That's why the professionals keep building larger and larger spectroscopes!

Importing the text/data file from this profile into an Excel spreadsheet allows us to calibrate from pixels to wavelengths. To do a basic calibration we need one of two things – either a couple of definite lines to be identified (see Chap. 7) or one known line and a dispersion (Å/pixel).

Based on the difference in wavelength between the lines and the number of pixels between them on the image you can calculate an Å/pixel calibration factor. For instance if your first line is Hβ at 4861 Å and pixel number is 830, and the second identified line is, say, Hα at 6563 Å and the pixel number is 2,175, the calibration would be (6563 − 4861)/(2175 − 830) = (1702)/(1345) = 1.26 Å/pixel.

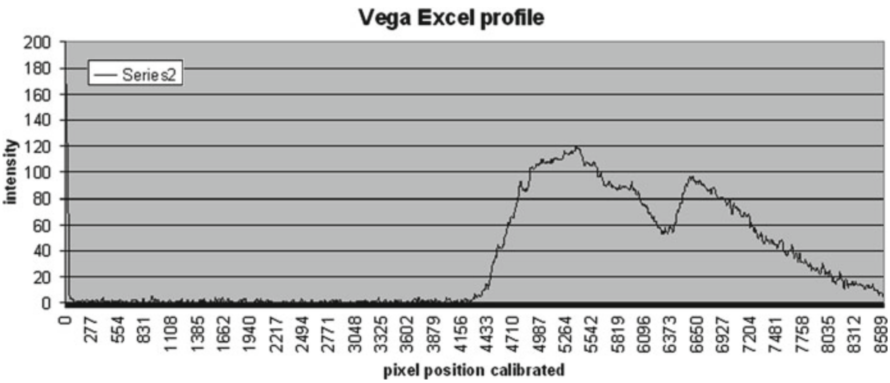

Fig. 4.6 *Excel*-calibrated profile graph

Multiply the pixel number by the calibration factor; for example, pixel 830 would now represent 1046 Å. The scale is now correct; we just need to register an offset for wavelength. The pixel at 1046 Å is actually at wavelength of 4861 Å, so the offset would be +3815 (4861 − 1046). When this offset value is added to each pixel value they will represent calibrated wavelengths in Å. This is shown in Fig. 4.6.

If a zero order image is available in the frame, the calibration is simplified by using only one reference line and the zero order. This can then be used to generate a wavelength calibrated profile graph.

What does this profile tell us? Well, we can see that the camera starts recording the spectrum around 4000 Å and continues through to the red, eventually fading out around 8300 Å. We can see the peak intensity at 5300 Å and that "dip" at 6400 Å.

What about all the other small dips? How do we know what they represent? Patience. All is about to be revealed!

We need a bit of help to identify these dips. That's where programs like *VSpec* (and *RSpec*) come into play.

Preparing a profile as described above is not an ideal way of getting an accurate measurable spectral profile. Yes, it's quick and dirty. It will show the extent of the spectrum recorded, the shape of the continuum, and the approximate position of the more obvious absorption lines. But we really need to do a bit more work to end up with a detailed profile representative of our grating performance.

Spectral Processing Software Options

As mentioned previously there are some very good spectral processing software packages available to the amateur. Here we will describe a few in more detail before moving on to the preparation and processing of a sample spectrum.

Visual Spec (VSpec)

The freeware *Visual Spec* by Valerie Desnoux has become one of the most popular pieces of processing software for amateurs. It takes an input image file and converts it to a profile. The profile can then be calibrated into wavelength, and various reference spectral profiles can be copied to provide line identification. It includes the professionally produced Pickles library of spectrum profiles covering all the stellar classifications, a very complete library of elements and their emission lines and can export spectral data to allow further processing in spreadsheets.

The input file, an image of the spectrum, must be in either a black and white 16-bit .fits format or the proprietary .Pic format. (*IRIS* can convert image files to both.) Pre-processing by applying darks and flats, aligning the spectrum horizontally across the frame and background sky removal should be done prior to importing into *VSpec*. The spectrum must also have the blue region of the image towards the left hand side. The image can be flipped if necessary.

Standard Stellar Spectra

VSpec contains a listing of spectral type for all the stars in the *Bright Star Catalogue*, down to approximately 6.5 mag. Under "Tools/Spectral Type," type in the Bayer letter or the Flamsteed number of the star and constellation. For example, Betelgeuse, α Orionis would be entered as "AlpOri," and this brings up "Spectral Type" – M1-2Ia-Iab. This can then be used to find a suitable comparison spectrum under the *VSpec* library. Open "Tools/Library" and in the drop-down screen look for a matching spectrum, i.e., M2Ia.dat.

Note that *VSpec* uses additional prefixes (1 and 2) to order the listing of spectra. It also uses the following prefixes:

wf – metal weak
rf – metal rich

Standard Element Lines

There is also an extensive listing of elemental lines available for comparison within *VSpec*. These can be accessed through "Tools/Elements."

Element.txt. – based on CRC Handbook
Lineindent.txt – ILLSS catalogue of lines in stellar objects
Sun.txt – astronomical Astrophysics. Suppl. Ser. 131, 431
Hires – a database in 38 sections based on R. O. Gray's "SPECTRUM"
Atmos – Listing prepared by C. Buil from various sources.

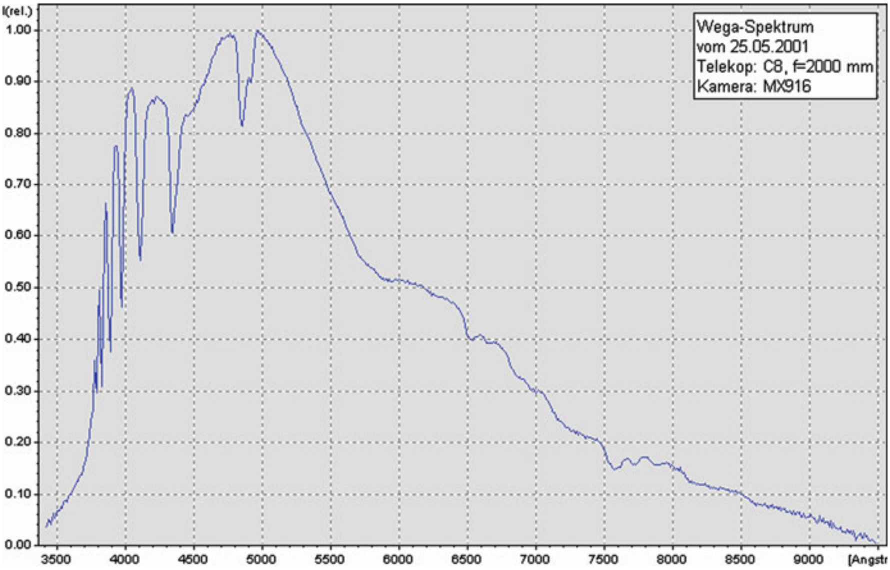

Fig. 4.7 Vega spectrum (B. Marquardt)

In the next section we will use *VSpec* to prepare a sample spectrum image, walk through the various stages of preparing and calibrating a spectral profile and present some basic line identification as well as describing some other useful analytical tools *VSpec* can offer us.

SkySpecV2

Bernd Marquardt's *SkySpecV2* is another freeware spectral processing package. This software is written in German, but the comprehensive manual, translated into English, makes it straightforward to use.

The image input file is again a 16-bit .fits file, and the calibration process is very similar to the one used in *VSpec*. Figure 4.7 shows a typical stellar profile (Vega).

Spectra can be cropped, magnified and merged to make the processing and analysis easier. The software also provides for continuum removal and the application of various Hi Lo filters. A comprehensive collection of standard element lines is available to assist in identification (Fig. 4.8) as well as a full set of sample stellar spectra covering the whole classification series O through to M (Fig. 4.9).

SkySpecV2 is an easy to use basic software package that provides all the processing tools you need and can prepare and label the results into a neat presentation. See Fig. 4.10.

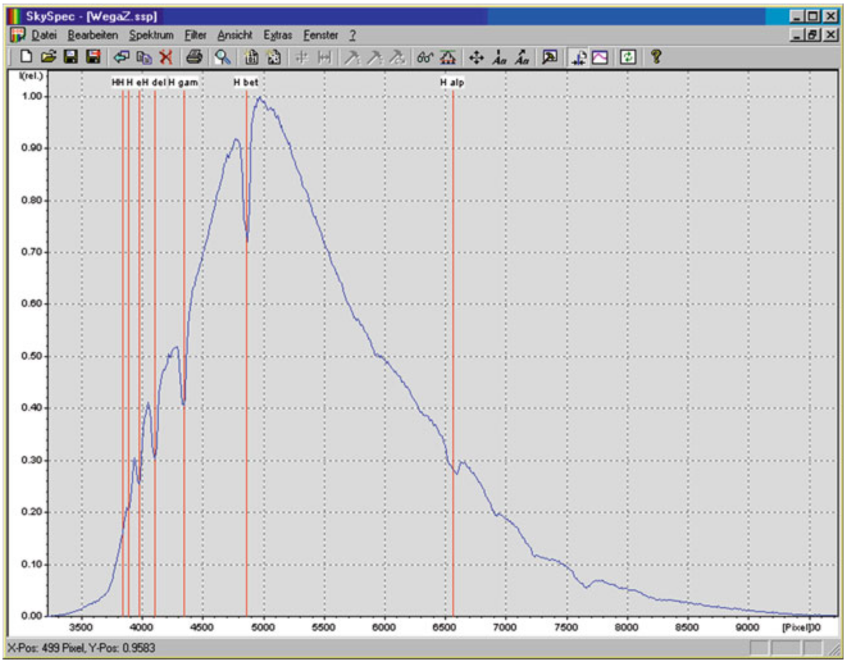

Fig. 4.8 Vega spectrum with element lines (B. Marquardt)

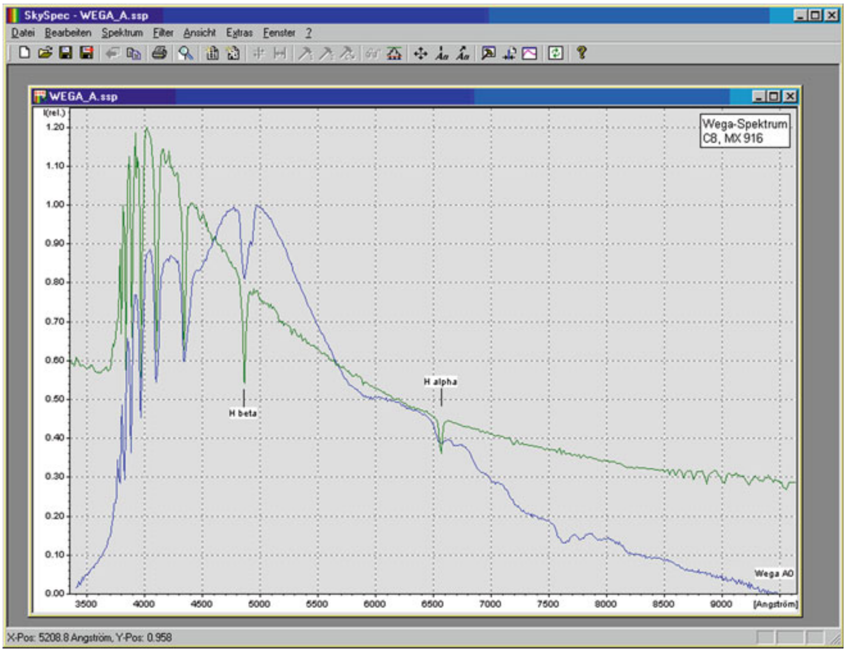

Fig. 4.9 Vega spectrum with reference star spectrum (B. Marquardt)

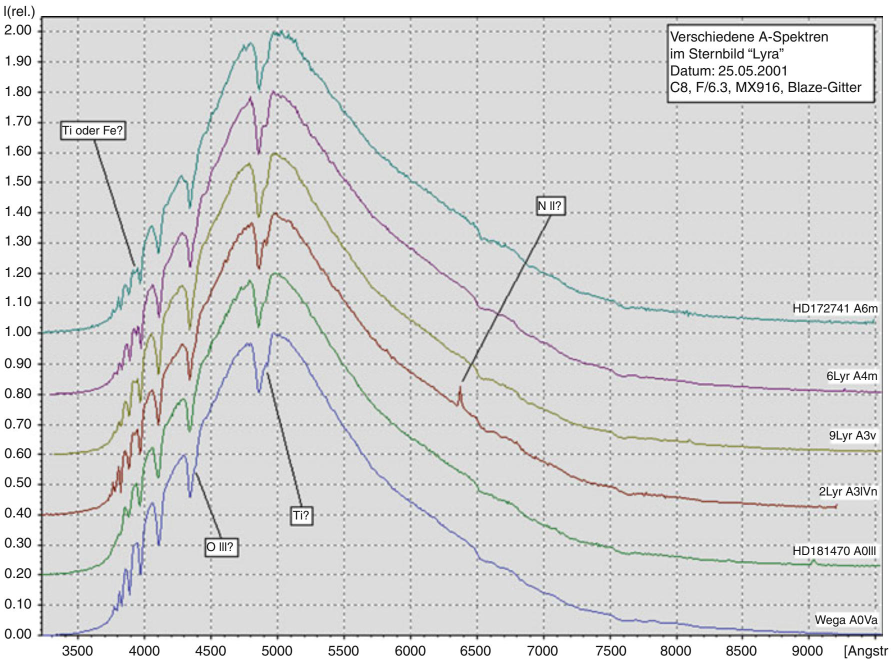

Fig. 4.10 Collection of spectra displayed for comparison (B. Marquardt)

RSpec

Tom Field has recently released his *RSpec* software for processing spectra (Fig. 4.11). This commercial package is interesting in that it can provide a "live view" of the spectrum and its profile as its being recorded with a webcam or other video camera (DirectX). It can handle all the usual image formats and has the added capability of monitoring a selected folder and then automatically displaying the last saved image – very useful when you are imaging the spectrum with a DSLR or CCD.

The online series of video tutorials gently guide you through the learning process and cover all the main features of the program that you need to know.

The program's strength lies in the ease of use for beginners. For video image files it provides an averaging function that takes, say the last 100 frames, and averages the results; this dramatically reduces noise and presents a much "cleaner" spectral profile. You don't even have to worry about slant and tilt calculations – it can all be done on the screen. You can also crop the spectrum image from the frame and automatically remove the background to improve the intensity of the spectral image. See Fig. 4.12.

By viewing the depth of the various absorption features "live" the Focus Tool allows you to re-focus your telescope as necessary to get the best resolution. Great idea.

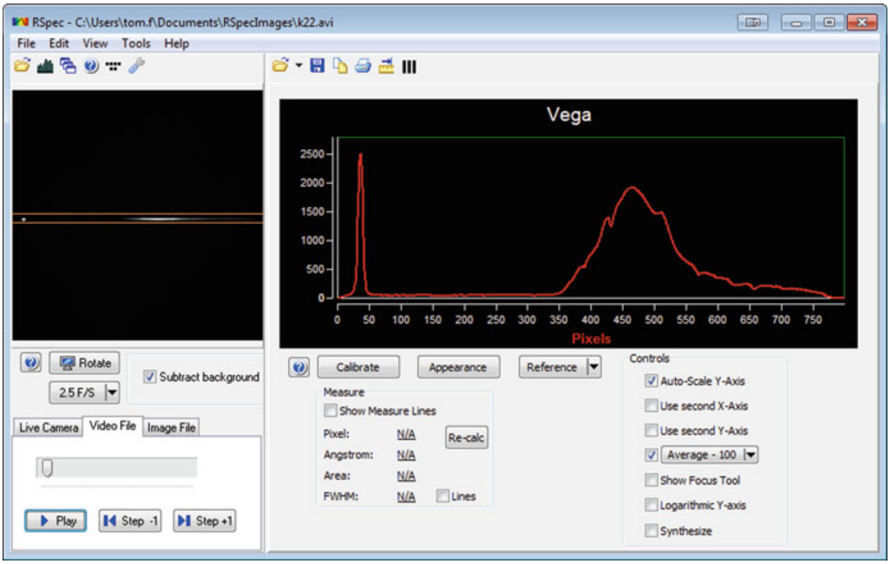

Fig. 4.11 *RSpec* opening screen (T. Field)

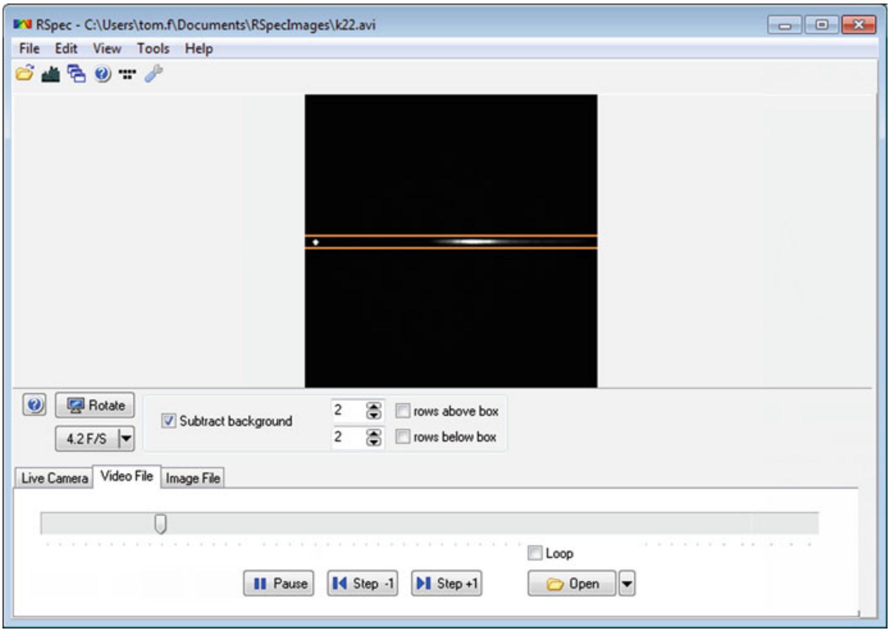

Fig. 4.12 Image screen showing background crop bars (T. Field)

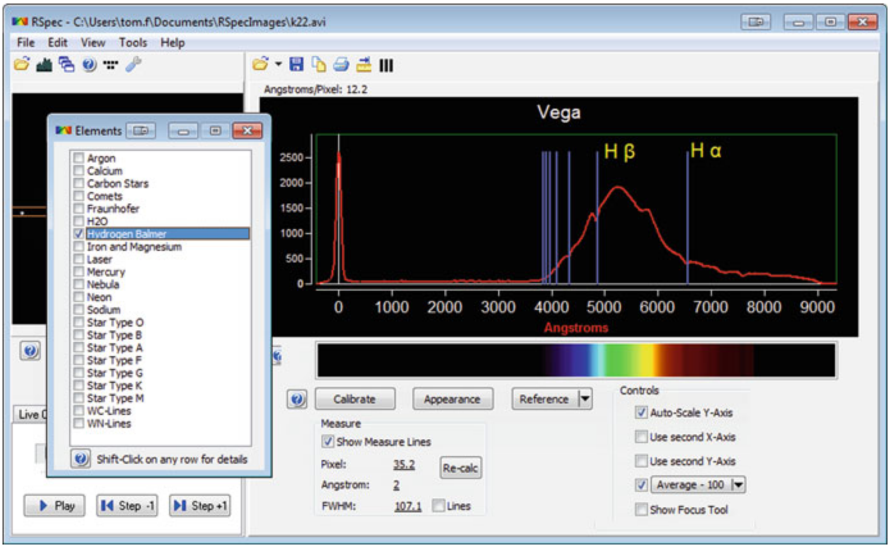

Fig. 4.13 Calibrated profile with comparison elements and stellar reference (T. Field)

For calibration the software has the extensive PICKLES library of stellar spectra as well as a very comprehensive listing of element lines including prominent nebulae lines and light pollution lines. A very useful and complete database.

RSpec not only allows one-point calibration using the zero star image and a known dispersion (Å/pixel); it also has a two line calibration (similar to *VSpec*) and a pretty sophisticated multi-point non-linear calibration. Luckily for the "mathematically challenged" this process doesn't require any more input and thought than a few mouse clicks (Fig. 4.13).

With the built-in menus it is possible to quickly prepare an Instrument response curve from a sample spectrum and the available database. The spline smoothing function makes the process very simple, and the same method can be used to prepare a normalized spectrum (see Fig. 4.14) from a pseudo continuum curve.

All in all, *RSpec* does everything the beginner could ask for and certainly makes the transition to spectroscopy very painless. The output graphics, I'm sure, will please not only you but all those who see them.

ISIS

Christian Buil has also recently (2011) developed a spectral processing software called *ISIS* (Innovative Spectrographic Integrated Software). This new package replaces an earlier version called *Rlhires* and targets users of the more advanced slit spectroscope user but can also be used to process grating spectra. The software will effectively accept a .fits input file (or series of files) and, subject to the correct

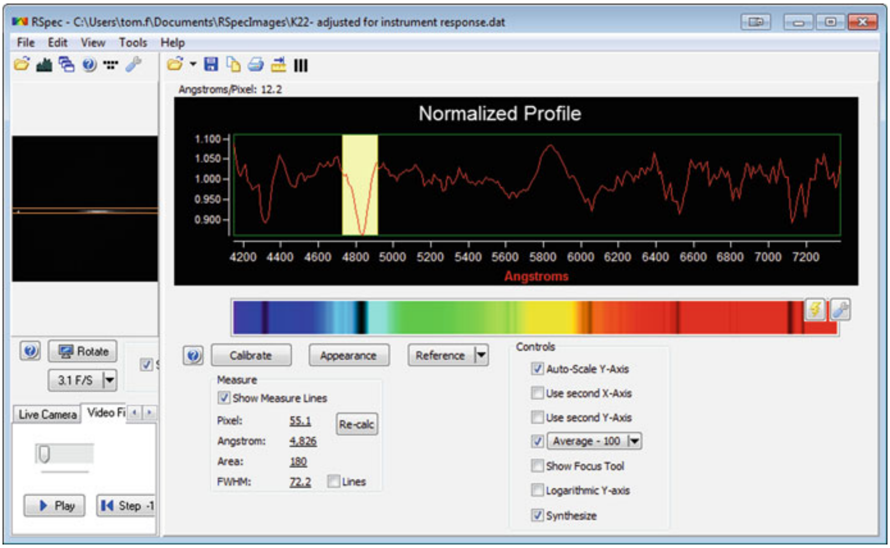

Fig. 4.14 Normalized profile (T. Field)

settings being established, automate the generation and calibration of a profile. This powerful package has the potential of becoming a “one stop shop” for the processing of amateur spectra.

ESO-MIDAS

At the other extreme end of the processing software spectrum (pun intended!) is the professional imaging and spectroscopic processing package used by the ESO (European Southern Observatory) – *ESO-MIDAS*. This freeware package runs under the Linux operating system and is very powerful and comprehensive. It has the capability of processing any spectrum, from any spectroscope, and can access online any of the professional stellar databases, i.e., *Simbad.* Unfortunately unless you already have a Ph.D. in astrophysics or advanced computer science and extensive experience using Linux, you’ll find the learning curve so steep you’ll probably fall off the mountain. It is definitely not the easiest of packages to use (never mind the difficulties of installing it on a PC) and not recommended for the beginner or faint hearted. Having said that, it is the processing package of choice for most professionals, very well supported and held in very high regard by all researchers in spectroscopy.

To allow you to develop an understanding and build experience (and confidence) in the basic processing of the spectrum, we’ll use *VSpec* software to walk you through, and demonstrate, the next series of processing steps. You can use any of the previously mentioned software packages to achieve a similar result.

Obtaining a Pixel Profile Graph Using *VSpec*

The end of our spectrum processing journey is now in sight. The final steps involve converting your precious image into a profile, calibrating it into wavelength and applying corrections for instrument response. When you achieve this, the spectrum can be compared with other reference spectra to reveal similarities (and differences) that provide the clues you need to identify those "fingerprints." This is the most exciting stage of the journey. You get the chance to see what has been lying there hidden in your spectrum and finally expose the information it has brought you. Each spectrum is different and tells its own story. Each has its own delights. Some will show the obvious characteristics of the standard star types and others will reveal exciting new emission lines. This is what spectroscopy is all about!

As you gain practice and experience, more questions will be raised. Why do these particular emission/absorption lines occur here? Why are there no hydrogen lines visible? Some insights into the stellar theory and physics of the spectra will be given in Chap. 7. In the meantime, let's start on the final step and get our profiles prepared.

NOTE: In Chap. 7 you'll find a handy listing of the more common element lines normally found in the spectra. These are very useful to have at hand as you start to practice with calibration of your spectrum.

By importing a black and white 16-bit .fits file (or a *VSpec* .pic file) of our spectrum, we can quickly produce a 1D profile that will show the intensity variations for the spectrum by pixel location.

If the image has been properly pre-processed we can use the "object binning" command. This adds all vertical intensity values in each pixel column across the image. For better accuracy, an area around the spectrum can be selected using the "Display reference binning zone" icon to provide a new binning area. The red lines define the extent of the zone used to generate the profile. The lines should be moved and closed just enough to enclose the height of the spectrum with minimum background. Click the "object binning" icon, and a new screen will be generated showing the profile of your spectrum (note that this also brings up a new file name with a .spc ending). An additional line of icons now appears in the header. The top header panel shows the position of the red cursor line (L) and the intensity value (I) as the cursor is moved across the profile. Note that at this stage the title "Å/pixel" reads 0.

Look carefully at the shape of the profile curve, and see if there are any noticeable dips that could represent hydrogen absorption lines. These are the easiest to use for calibration. Don't worry too much at this stage what the overall shape of the curve looks like – concentrate on the features.

In the example, Fig. 4.15, we have a spectral image and profile of Vega taken with a Baader filter grating and a modified Canon 300D camera (internal filter replaced with a Baader UV-IR filter).

The out of focus zero image is on the left hand side. The spectrum shows some prominent dips (at the cursor position), and we will assume that it is the Hβ line of hydrogen at 4861 Å. With this uncalibrated profile we can move on to the wavelength calibration process.

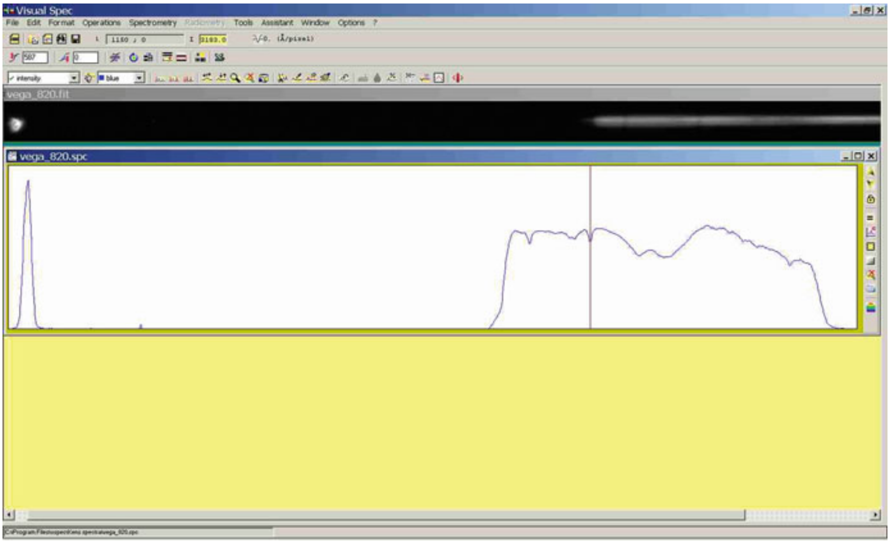

Fig. 4.15 Vega raw image

Wavelength Calibration

There are a few standard methods we can use to calibrate our profile into wavelengths. Here we present a few of the popular methods for the beginner that we can use in *VSpec*.

Wavelength Calibration Using the Zero Order Image

The easiest method to calibrate an unknown spectrum is to use two reference points. One can be the zero image from the filter grating. Click on the “Calibration two lines” icon; a message screen will appear the first time this is used that asks for confirmation to make the profile an Intensity Series. Confirm by clicking Yes. The header portion of the screen now changes to Fig. 4.16.

Position the cursor just to the left of the zero image, press and hold the LH mouse button and drag the cursor to the RH side of the zero image; this will generate two dotted lines and a box containing a number; highlight the number and type in “0000.” This will appear in red and is the wavelength of the zero image. Press ENTER to confirm. The box will disappear, but the dotted lines will remain.

Look up at the header panel, and you will now see against the title “raie 1:” a box with “0000.” This is the first reference line.

Repeat this for the dip in the profile and type in “4861.” The Å/pixel title now shows 4.3774; this is the calibration/plate scale of the profile. Note also as you

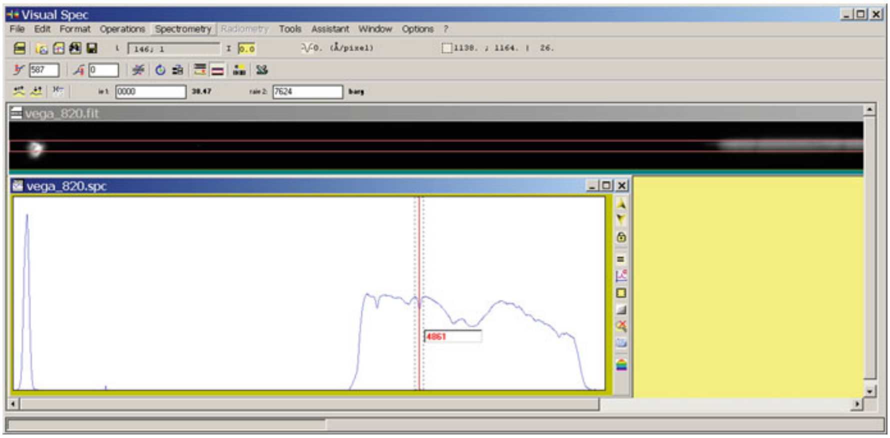

Fig. 4.16 Vega calibration screen

move the cursor over the profile that the number in the L window changes; these changes reflect the wavelength and intensity of the point on the profile below the cursor.

Now we have a calibrated profile, we can note the plate scale 4.3774 Å/pixel. This scale can be used in future to assist in subsequent calibrations using the same grating/camera set-up. We can also use some of the other *VSpec* tools.

Before we go further we can add the scale by clicking on the middle icon on the right hand side of the screen. Doing this will show the intensity value (on the Y axis) and the wavelength in Angstroms (on the X axis). As we really don't need the zero order image any more we can crop the profile to only include our spectrum. Click on the left hand side of the spectrum around 3950 Å and hold and drag the cursor over to the right hand side, say, around 7000 Å. Using the "Edit/crop" command the spectrum will be cropped to the wavelengths chosen. The scale can be added back to the screen.

Let's now normalize the spectrum. If you look at the intensity values you'll see the peak intensity is around 3,720 (This is an arbitrary scale chosen by *VSpec*); now go to the tab "Operations" and click on "Normalize." Look at what happens. The vertical intensity scale now reads from zero to 1.6 with 1.0 close to the average height of our profile. A normalized profile makes it easier to compare with others. See Fig. 4.17.

Under the tab "Tools/Library" a window will open with a listing of stellar spectra from O-types through to M-types. (Note the first 1o5V.dat, etc. is an artificial number to get the listing in order! It's actually an O5V spectrum.)

Click to highlight "a0V.dat" and hold the button down. Drag the highlighted file onto the profile screen and a second profile (in purple) will appear. This is the library spectrum profile of a A0V star similar to Vega. Straightaway you will see the registration between the dips of the original spectrum and those of Vega. See Fig. 4.18.

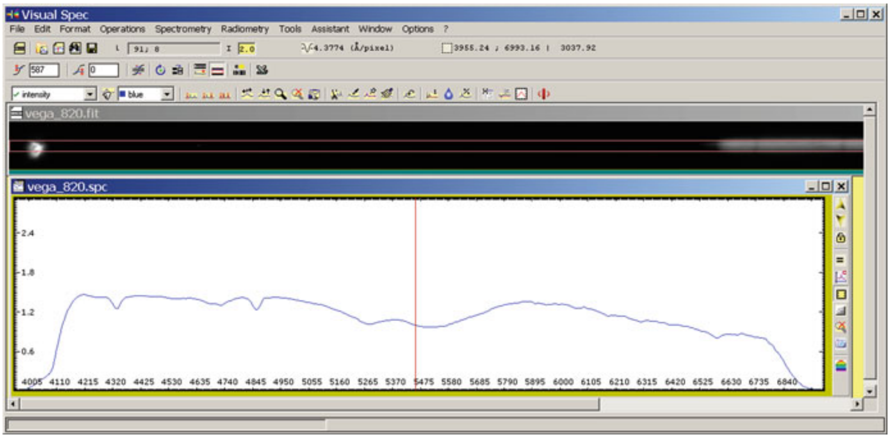

Fig. 4.17 Cropped normalized profile

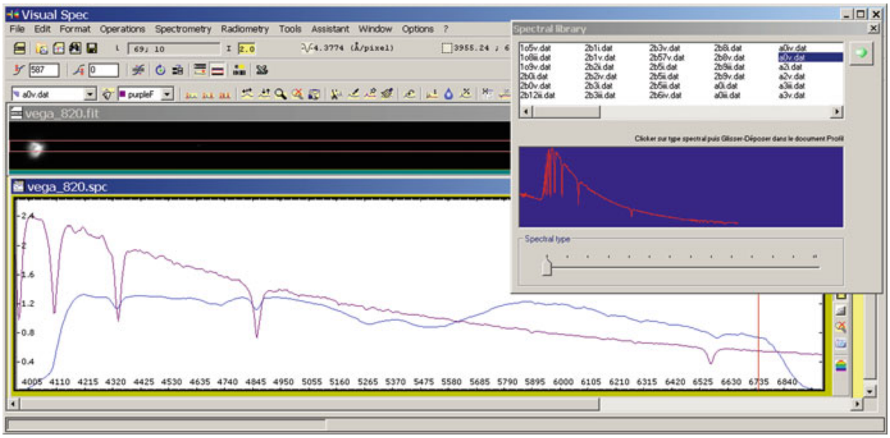

Fig. 4.18 Vega profile with A0V reference spectrum

We now return to the “Tools” and “elements.” In the second window tick “H” for hydrogen and press “sort.” This will list the wavelengths of the hydrogen emission lines in the profile; press “export” and a series of orange lines will appear on our profile. See Fig. 4.19.

Note how these match the dips in the Vega reference spectrum and the dips in the original. We can now confirm the hydrogen absorption lines in the original as Hγ, Hβ, and Hα at 4340.47, 4861.33 and 6562.72 Å. Note also how the profile drops off sharply at 4000 and 7000 Å. This is due to the Baader UV-IR fitted to the camera.

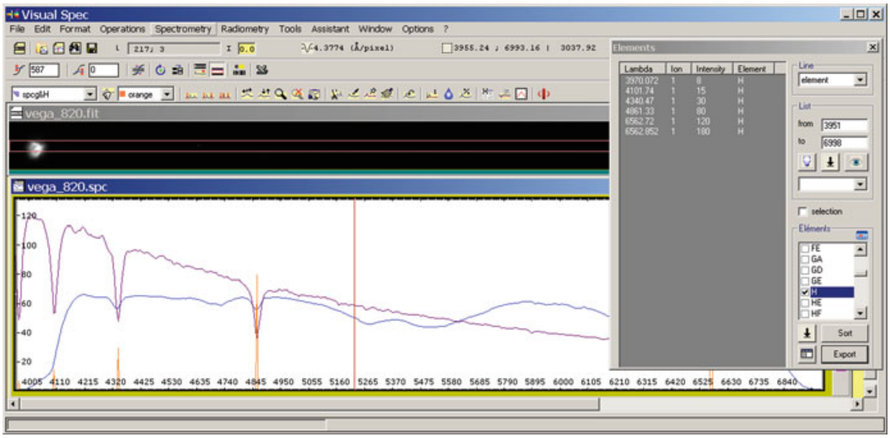

Fig. 4.19 Vega profile with comparison profile and H lines

Wavelength Calibration Using Two Lines

Sometimes we will image the spectrum without the zero order being visible in the same frame. This is a common occurrence when using larger l/mm gratings on small CCD chips. You can use exactly the same methods as those described above, but this time use two "known" lines visible in the spectrum as references.

The hydrogen lines are usually easily found, as are the atmospheric lines. We could therefore calibrate an unknown spectrum using, say, the Hα line at 6563 Å and Hβ line at 4861 Å (or the Telluric lines at 7200 Å).

Wavelength Calibration Using One Line and a Known Dispersion

If you have already determined the dispersion (Å/pixel) of your grating camera setup you can use this information to help calibrate subsequent spectra taken with *exactly the same setup*. The dispersion will not vary. You can use the single line calibration process.

This process assumes at least one line feature can be positively identified in the spectrum. The line can be a prominent hydrogen line or a definite atmospheric/Telluric line. After calibration if you find better features to use for calibration (i.e., additional hydrogen lines become obvious) you can easily re-calibrate by using the "calibration 2 points" icon. Re-calibration can be done at any time.

The first icon in the calibration header will bring up a drop-down screen where you can enter a line center pixel value (Barycenter). (NOTE: If you position the cursor on a suitable line then just press "reset" and it will record the pixel value).

At the bottom of the screen, you then need to enter the wavelength of this selected line/pixel value and finally enter your known dispersion (Å/pixel) in the “sampling” box. After clicking “apply” the data will be used to calibrate the profile.

The accuracy of this method will depend on the pre-processing of the profile (if you have positioned the grating slightly differently to the camera, rotating the spectrum horizontally can cause inconsistency in the scale).

Instrument/Camera Response

In the example Vega profile, it is obvious that the shape of the recorded spectrum profile does not match that of the reference star. The profile is seen below the reference in the blue region and above in the red. The difference is due to the varying response of the optical system and the camera over the wavelengths recorded. It is possible to use the reference star profile to generate an instrument/camera response that can be used to correct future spectra taken with the same setup.

Select a range of wavelengths to be used for the response curve. This will usually be around the 3950–7000 Å, which is close to the QE limits for most cameras. Although there may appear to be data outside these limits, the very low camera response can cause spurious results. It also suppresses atmospheric lines around 7200 Å. Unless you require data from these regions for a specific task it’s best to cut them out of the profile. Save this profile.

Open “Tools/Library/.” Then highlight a0v.dat and drag the file onto the new cropped profile. It will appear as an orange profile. See Fig. 4.20.

We now need to divide the original profile by the reference profile. Select the active profile in the top screen left hand box as “Intensity.” Open “Operations/Divide

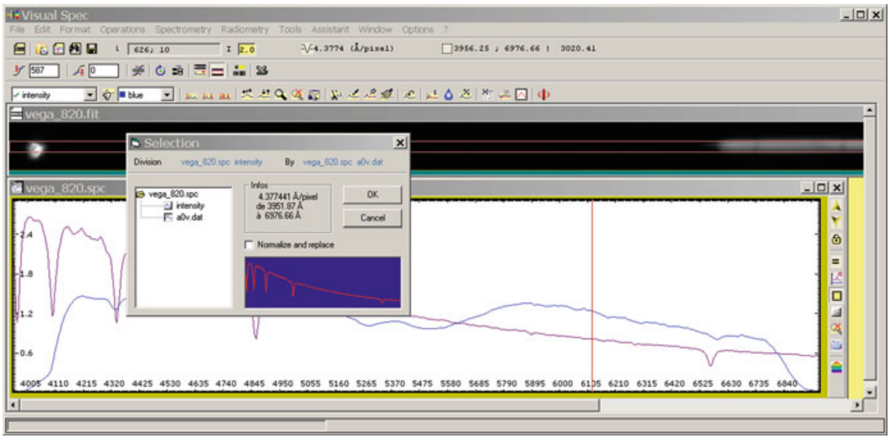

Fig. 4.20 Cropped raw profile with reference profile

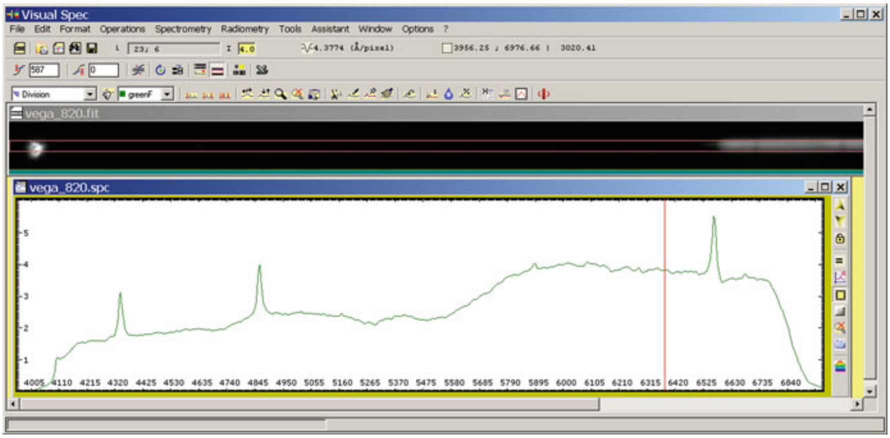

Fig. 4.21 *VSpec* preliminary camera response

profile by profile" and select aOv.dat from the drop-down box. This will generate a new green profile, "Division," as shown in Fig. 4.21.

You will see that the green profile now shows large "emission" lines where the original profile had the hydrogen absorption lines. To make things easier to process click on the "Erase graphic" icon and select "Division" as the active profile from the list. This will clear the profile window and re-load the green profile for further processing. *VSpec* only works with "Intensity" profiles, so the division profile needs to be converted to an intensity profile. This is done by using the "Edit/Replace" command and in the drop-down box. Select "Intensity" and press ENTER. Our green profile will now turn blue and the selection box will show Intensity.

Save this file as xxxxx_division.spc, or something similar.

To convert this profile into a usable camera response curve we need to smooth the curve and remove the "emission lines." This is easily done with the "Radiometry/Compute Continuum"; clicking this option will bring up another line of icons and change the profile from blue to orange. The first icon, "point/courbe," allows the selection of points along the profile which will be used to generate a continuum curve. Using this command we can suppress the "emission" lines (and any other line features) to get a consistent curve. See Fig. 4.22.

Click on as many points as you need on the profile, obviously missing the lines, then press the "execute" icon. This will open the drop-down screen "Continuum – coefficient" and show a new orange profile corresponding to the points selected.

The continuum co-efficient should be selected to give a smooth continuous curve and can be altered by editing the initial value "20" to around 2,000; the slider then will show a value of 0–2,000 as it is moved down the scale. Very high values (experiment with a value >5,000) will make the curve too smooth and will not accurately reflect the camera response curve. When you're satisfied with the result click OK on the drop-down screen, and the profile window will change to show the

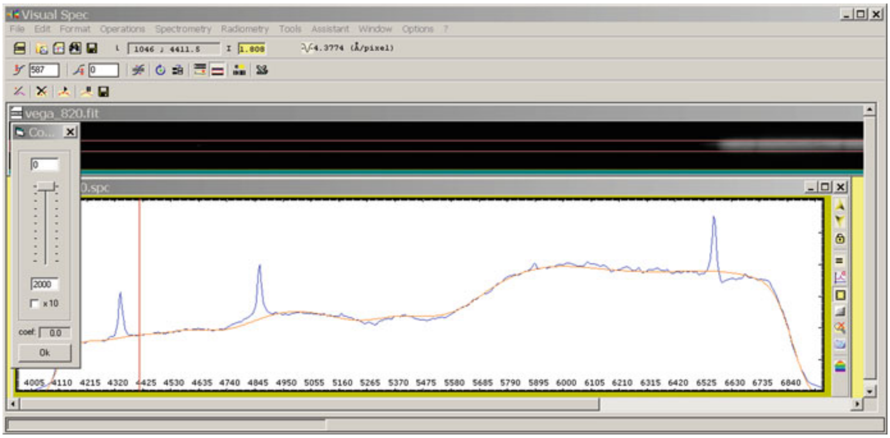

Fig. 4.22 *VSpec*-smoothed camera response curve

final result. Delete the contents of the display window and bring up the "fit.intensity" profile. Use "Edit/Replace" to make it an active profile and save as a response .spc (Choose a name to suit your camera and setup).

NOTE: *VSpec* saves only the current active profile.

Correcting Spectra Using the Instrument/Camera Response Curve

This response curve can be used to correct spectra taken under similar conditions, i.e., the same telescope/grating/camera. With a new profile open, select a similar spectral region to that recorded on the instrument/camera response, open the response profile and use "Edit/Copy"; click on the new profile window to use "Edit/Paste" to place it on the new profile. You should now see the new profile in blue and the response curve in purple. Click on the profile box and select "Intensity" as the active profile using "Operations/divide profile by profile"; select the response intensity curve. The new green profile will show the result. Again the star spectrum and element lines can be copied from the library to show the calibration. The results are shown in Fig. 4.23.

Identification of Lines and Features

As we saw when calibrating our spectrum, we can access the comprehensive library of element lines and the standard PICKLES stellar spectra database.

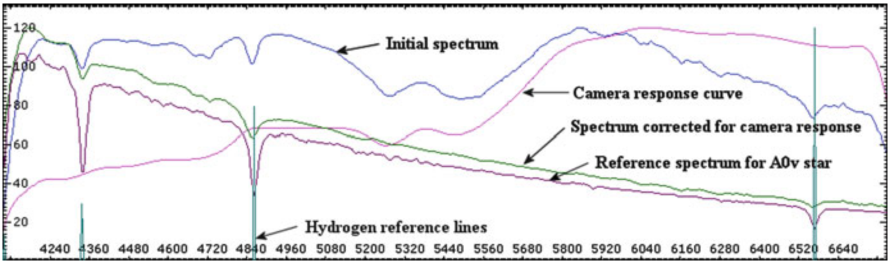

Fig. 4.23 Profiles showing raw profile, camera response, reference spectrum and corrected profile

Now that we have a calibrated, corrected spectral profile to work with, we can use these tools (and others) to investigate those "fingerprints" in the spectrum. The basic object of the exercise is to determine what lines might be associated with the various elements. In Chap. 7 we will discuss in more detail what may cause these lines to be formed and what can be inferred from the line position and line shape. As this stage you should practice with the element lines database and look for "matches" to the features seen in your spectrum. Can you positively identify the hydrogen Balmer series in our A-type star spectrum? Does the calibration you have achieved give the correct result for the various wavelengths? By answering these questions, you can be assured that the data you have recorded is accurate.

Further experience gained by reviewing comparison data on the Internet, in reference books and via the various user groups will quickly make you more comfortable with your data and confirm your ability to analyze the spectrum. It's not easy for the beginner to see all the patterns and linkages between the various spectra, but with practice, and some perseverance, you can make the spectrum give up its secrets.

You can also use the profile to determine the resolution and signal to noise ratio of your spectrum, which provides a useful comparison with other spectra you may obtain in the future, or when comparing your spectra with others.

Resolution

One method of estimating the resolution of the grating is to measure the full width half maximum (FWHM) of an emission/absorption line in the spectrum. *VSpec* can do this calculation automatically based on a smooth continuum on either side of the line (or better still after the spectrum has been normalized). Select the "Spectrometry/computation preferences/" tab and click the FWHM box. A note of caution – the inherent width of an absorption or emission line may make this measure inaccurate. Measure many line features and take an average figure – remember it is only an estimate.

Normalized Spectrum

This rescaling function, "Operations/Normalization," is used when comparing profiles, or when stacking profiles for display and visual analysis. The resulting profile shows the relative intensities with the average continuum as the base, equal to one. (See Fig. 4.9.) Note that this is not the same as normalizing to the continuum – see continuum removal.

Continuum Removal

Also called normalizing to the continuum or rectification. This process makes line features easier to see by removing the continuum from the profile and effectively "flattening" the curve.

First normalize the profile by using a similar process to that described for camera response; points are selected on the continuum line, a profile generated, smoothed, then divided into the target profile.

Creating Additional Stellar Reference Profiles

The star spectrum you've just recorded is a B7 type, and there's not one in the PICKLES library. Where do you find one? You can make your own.

Using two reference profiles, one on either side of the type you want (i.e., a 2b6iv and a 2b8i), you can drag and drop them onto a calibrated normalized spectrum (they will appear as purple profiles), and using the "Operations/add profile by profile" command join them to form a composite reference that will appear as a green profile. Clear the display window and bring back the "addition" series only. Then use the "edit/replace" to make it a blue intensity profile. Finally, save with a suitable name.

NOTE: This new profile doesn't need to be divided by 2 to give an average – that only changes the scale, not the content. It can be added to the *VSpec* database for future reference if required.

Signal to Noise Ratio (SNR)

VSpec can provide an approximate value for the SNR in a spectrum. This is based on the ratio of standard deviation to the average. For best results this should be done on a number of line free sections of a profile that has been normalized to the continuum. For example, on a level section of the continuum. An SNR of above 50 is good; for a ProAm contribution a SNR of >100 would be acceptable.

This is just a brief introduction to the capabilities of *VSpec.* You should watch the videos and read though the various tutorials that cover processing in much more detail than the above examples.

We have now reached the end of our first journey in spectroscopy. We have developed the skills with our telescope/camera and grating to obtain a quality image of a spectrum, made corrections to reduce the noise and improve the quality and finally converted it into a profile, calibrated and corrected for instrument response. As you have probably guessed this is really only the beginning. Fully understanding the significance of the various lines in our spectrum can keep you occupied for a lifetime. There are many good books available to help you along the way. J. Kaler's *Stars and their Spectra* and Keith Robinson's *Spectroscopy – The Key to the Stars* are highly recommended. See the appendices of this book.

The following chapters provide additional information on how to improve the grating spectroscope to achieve the maximum resolution, more detailed explanations of the grating theory and formation of spectra and finally a brief introduction to the world of quantum physics – the driving force behind the spectrum.

Chapter 5

Improving Your Grating Spectroscope

Once you've collected a few spectra of the brighter stars it's only natural to ask – can I improve the resolution? Can I do more with what I have? The answer is yes!

The performance of the basic filter grating can be improved by incorporating an entrance slit into the optics. The addition of a slit produces a line source that can be used to produce measurable spectra. We can then use these lines to prepare a calibrated reference. The slit also allows us to observe objects (such as the Sun and nebulae) that otherwise would not be possible. For the RO200 and other high dispersion gratings we can also add a "grism" (*gr*ating pr*ism*), which can reduce the optical aberrations and improve resolution.

NOTE: An Excel spreadsheet has been prepared to assist in the design of transmission grating spectroscopes. TransSpec.xls provides all the necessary calculations to evaluate a transmission grating in a converging beam. (See Appendix G of this book.)

Adding a Slit for Solar Spectrum/Reference Lamps

Adding a slit in front of the grating gives us the opportunity to record the spectrum of extended objects like the Sun, moon and various light sources. A slit tube is handy for very bright sources (i.e., the Sun) whereas a more compact system is needed on the telescope. Both are discussed below.

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4_5,

The Slit Tube

For solar spectrum observing, you can make a simple tube/box arrangement to hold a slit far enough away from a camera lens fitted with a grating to allow focus. For convenience, sunlight can be reflected from a small mirror into the slit. If the slit is positioned parallel to the direction of the grating lines, a "line spectrum" will be produced.

Typically camera lenses can focus down to a distance of 1.5 m or less, so if a suitable tube is cut approximately 1,500 mm long and a slit placed at one end, the camera can focus on the slit and the incoming light. Such an arrangement is shown in Fig. 5.1 below. The slit can be made from a couple of pencil sharpener blades or disposable razorblades, or using the Surplus Shed adjustable slit. Even a stiff card can be used. See Fig. 5.1a.

By setting up the grating as an "objective grating" on our camera lens (as per Chap. 2) we can focus our lens onto the slit. The resulting "line" spectrum will record details of the solar spectrum. The *Liege Solar Atlas* – see later – gives all the reference data you'll need to identify the various features.

The same setup can be used to obtain line spectra of astronomical filters and various reference lamp sources. See Fig. 5.2. (This arrangement was used to prepare the comparison spectra shown in Fig. 1.3.)

Alternative Solar Slit: The Reflective Needle

The reflection of the Sun from a needle gives a bright, narrow image that can also be used as a "reflection" slit or a small ball bearing to produce a point "star-like" image. It should be mounted on a suitable post/tripod with a dark card or sheet as a background (see Fig. 5.3a). Mount the grating on your camera as per the details given in Chap. 2.

Set up the needle or ball bearing so it is illuminated by the Sun and reflects the glitter point back towards you. The Sun should be shining from behind you and the needle inclined to about half the altitude of the Sun. Point the camera towards the needle (no drive required!), and you should pick up the zero order reflection (Fig. 5.3b). The bright first order spectrum should be visible at one side of the frame. Bring this to the center and focus; the prominent dark bands should be visible. A short exposure, around 1/1,000 of a second is usually enough to record the spectrum.

Figure 5.4a, b shows the results obtained using a Baader 207 l/mm grating on a 135 mm lens and a DSLR. Set to ISO 200 and a 1/1,000 s exposure. The plate scale was 2.05 Å/pixel. The blue line shows the solar spectrum recorded, and the purple line is a comparison reference spectrum of a G2V star. The similarities are obvious.

Fig. 5.1 Slit tube, showing surplus shed adjustable slit fitted. From the left: Pencil sharpener slit, disposable razorblade slit and paper slit

Solar Spectrum

Telluric lines of atmospheric oxygen and H_2O bands are evident at the extreme red end of the visible the spectrum, just beyond the wide and obvious Hα line at 656.3 nm. At sunset and sunrise these bands become more obvious due to the

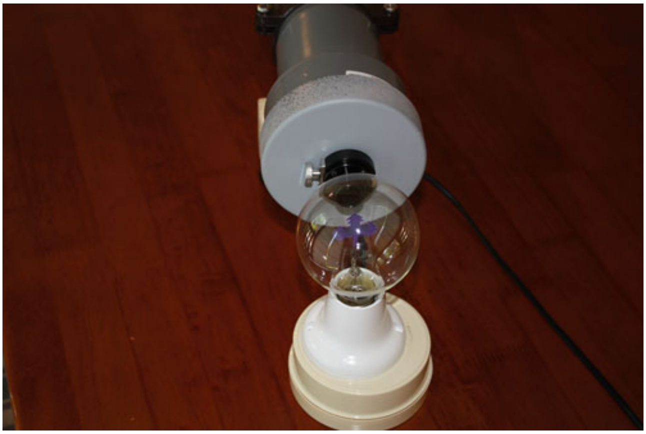

Fig. 5.2 Slit tube arrangement. A Filly argon reference lamp is seen in front of the slit

Fig. 5.3 (**a**) Reflective needle setup; (**b**) grating fitted to a DSLR and telephoto lens imaging the needle

longer atmospheric path. (Noting their positions will help when analyzing stellar spectra, as they obviously occur in them as well.) Imaging the solar spectrum with your grating will not add to our knowledge of the Sun, but it will allow you get practice in using your spectroscope – setting it up to the telescope, focusing, calibration and estimating plate scale and resolution. Analyzing the solar spectrum will

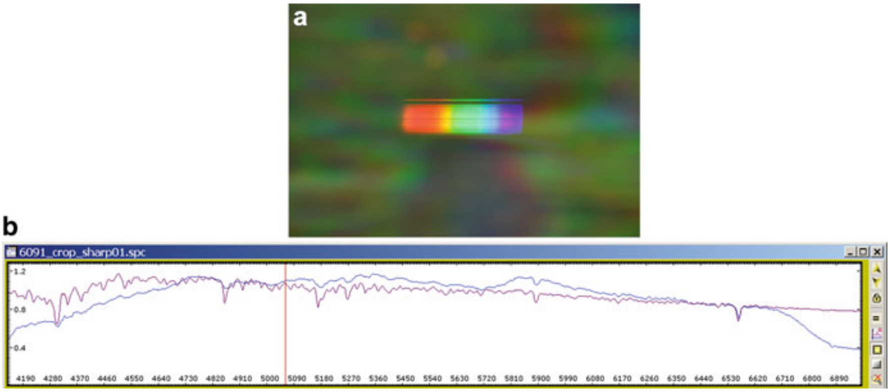

Fig. 5.4 (**a**) Solar spectrum reflected from a needle; (**b**) profile of solar spectrum (blue) compared with a G2V star (purple)

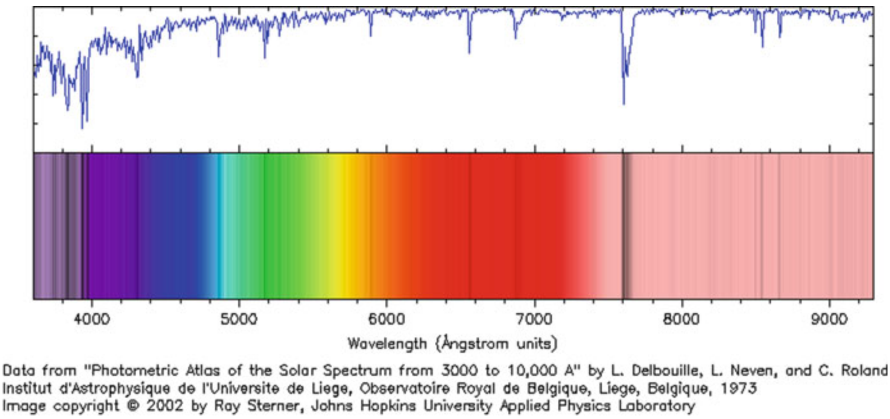

Fig. 5.5 *Liege Atlas* – full solar spectrum

also show the effects of the instrument/camera response curve, and the changing focus position between the blue and red regions.

Indentifying lines in the solar spectrum is made easier by referring to the collection of solar spectral data available on the web. (See the web page links at the end of this book.) The *Liege Atlas* (Fig. 5.5) is recommended, as it allows various wavelengths to be seen in detail and provides a fully annotated identification of lines.

Using a slit can obviously help us to record the spectrum for other bright lamps such as a neon or fluro reference lamp. Adding a filter between a uniform light source (a halogen lamp) will quickly show the transmission characteristics of the filter.

Astronomical Filters

The bandwidth and transmission factors for all the available astronomical filters can be measured using a grating and slit. First take a sample spectrum with the slit illuminated by a "flat" spectrum source, i.e., a quartz halogen lamp (or even the Sun, for this type of experiment); this will provide an instrument response profile. The filter to be tested should then be placed in front of the slit. When the filter spectrum is corrected for instrument response (Chap. 4) the bandwidth of the filter will be obvious and the shape of the spectrum will clearly show the transmission wavelengths. See Fig. 5.6. For more precise measurements a calibration spectrum of a neon reference can be used. After calibration, various elements and their lines (i.e., hydrogen, oxygen, mercury, sodium, etc.) can be brought in for comparison.

Another easy way of checking the effectiveness of the light pollution rejection type filters is to set up the telescope and grating pointing towards a light pollution glow (or street lights) and take a couple of spectral images; put the filter in front of the grating and retake an image. The differences are obviously due to the bandwidth and efficiency of the filter!

Key emission lines are listed in Chap. 7.

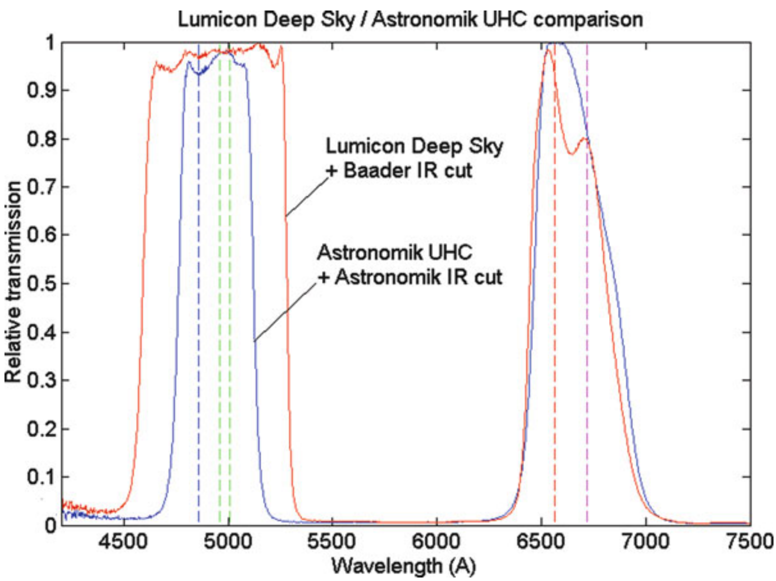

Fig. 5.6 Comparison spectral profiles for Lumicon and Astronomik filters – *dotted lines* from the left are: Hβ, OIII (doublet), Hα and SII (C. Buil)

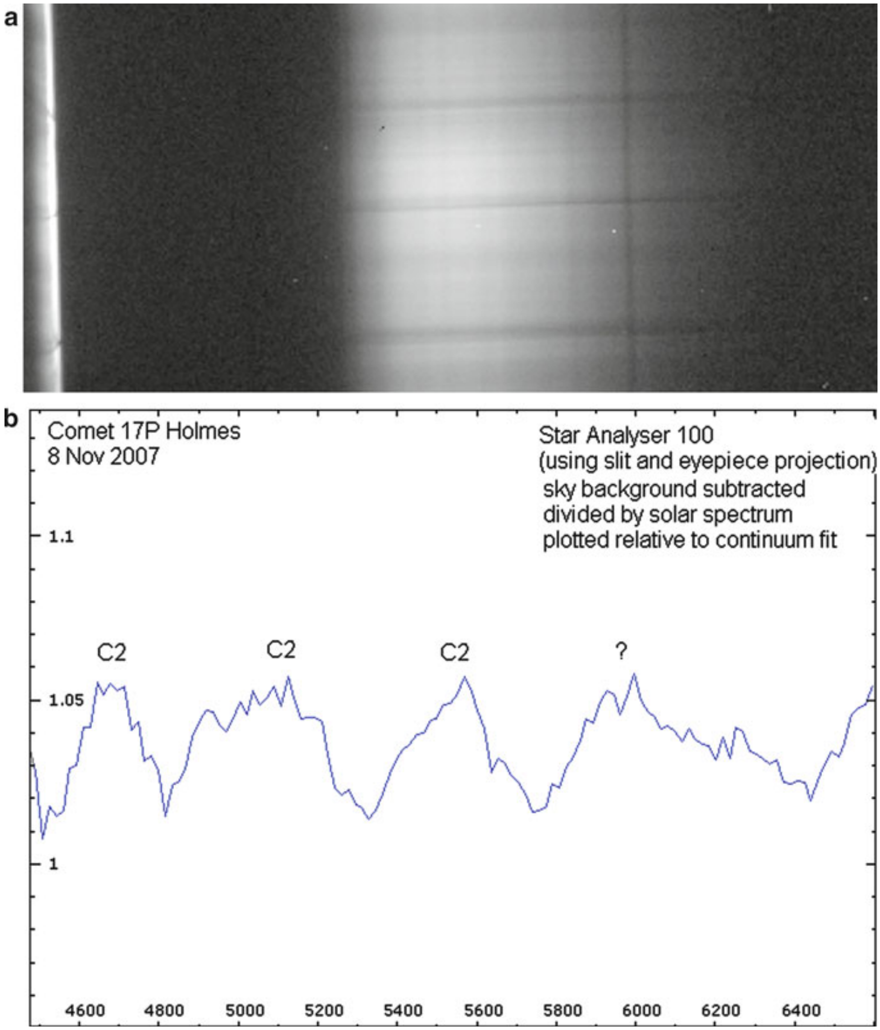

Fig. 5.7 (**a**) Spectrum of Comet Holmes 2007 (R. Leadbeater); (**b**) annotated profile of Comet Holmes spectrum (R. Leadbeater)

Adding a Slit for Deep Sky Objects

By adding a slit in front of the filter grating you can record spectra from extended objects such as comets, nebulae and galaxies. This was originally suggested by Robin Leadbeater (as the Slit Eyepiece Projection Star Analyzer – SEPSA).

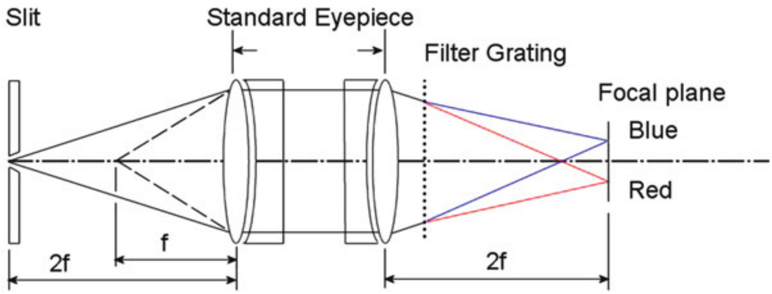

Fig. 5.8 Showing arrangement of the slit mounted at twice the focal length of the eyepiece (f) and the position of the spectrum image

Fig. 5.9 Components for a transmission grating slit

The concept is to focus an eyepiece onto a slit at a distance of twice its focal length and then projecting the image of the slit through the eyepiece, through the filter grating and onto the CCD. See Fig. 5.8. Note that the grating is still working in the converging beam and this will limit the resulting plate scale and resolution.

We can use standard adaptors to position a slit in front of the eyepiece. For a 25 mm eyepiece at a 1:1 projection, this distance is 50 mm. See Fig. 5.9.

Using a thin card or sheet metal we can quickly and easily make a slit diaphragm (two pencil sharpener blades) that can be positioned at the front of a filter ring.

Fig. 5.10 Grating with slit assembly

An adjustable slit can also be used (see below). Using off the shelf adaptors, they can be configured as shown:

– 1.25″ to T thread adaptor, holding the slit assembly
– Cheap camera adaptor (eyepiece projection) with clamp screw for eyepiece (female T thread at telescope side and male T thread at camera side), holding an 25 mm eyepiece
– T thread to 1.25″ adaptor
– 1.25″ to T thread nosepiece to hold the filter grating.

By positioning the filter grating into the nosepiece of the webcam/CCD, etc., and then screwing the slit into the 1.25″ T thread adaptor at the front of the camera adaptor, we can get a projected image of the slit onto the CCD, etc. (The slit obviously needs to be aligned with the grating.) See Fig. 5.10. For a smaller CCD, like a webcam, it may be necessary to offset the centerline of the slit to bring the spectrum onto the chip.

NOTE: The Surplus Shed adjustable slit mechanism (# 1570D) can be fitted into a 15 mm wide T thread spacer. A suitable slot has to be cut to provide clearance for the adjusting screw, and the inside diameter needs to be slightly increased (using a small drum sander). Figure 5.10 shows such an assembly fitted to the front of the camera adaptor. A similar result can be obtained using an Afocal camera adaptor to hold the camera body and grating behind the eyepiece.

This technique was used to obtain a spectrum of Comet Holmes in 2007. A 200 mm f6 telescope, with 20 × 3 min exposures was needed (Fig. 5.7). The resolution is approximately R = 40 and the plate scale 17 Å/pixel. The dark Swan bands can be seen against a continuum of the solar spectrum.

Eric Sarrazin has also used the SEPSA concept to record emission spectra of M57 and M42.

Using the Grating Behind an Eyepiece (Point and Shoot Camera?)

Transmission gratings can also be used behind a low power eyepiece using a standard camera with its lens. The eyepiece provides a collimated light beam to the grating, and the camera lens focuses the resulting spectrum.

Unfortunately there are few off-the-shelf adaptors available to hold the grating onto the eyepiece, and as the grating l/mm increases so does the required angular off set of the camera and lens. But there are a couple of DIY options available: The grating can be mounted in a 1.25″ nosepiece T thread adaptor and the camera held it place with an Afocal camera adaptor. (These adaptors are usually used to image through the eyepiece with "point and shoot" cameras.) A low power eyepiece with long eye relief gives best results. One benefit of this method is the opportunity to set the camera at the deviation angle and improve the focus. Drape a dark cloth over the focuser and camera to keep out extraneous light. Alternatively, the grating can be positioned behind the eyepiece in an eyepiece projection adaptor and a T thread- filter ring adaptor used to mount the camera lens. This is suitable for 100–200 l/mm gratings where the deviation angle is only a few degrees. See Figs. 5.11 and 5.12.

This afocal arrangement has the potential to increase the resolution of the grating. It is still limited by the size of the star image and the optical aberrations.

Rigel Systems supplies a 600 l/mm grating, mounted in a holder as their "RS Spectroscope," which fits over many of the popular standard eyepieces (Televue, etc.). They also supply a camera adaptor that allows a DSLR with its lens to be mounted securely to image the spectrum.

The limited exposure times available with "point and shoot" cameras and the lack of a manual focus option make them only suitable to record the spectra of

Fig. 5.11 Eyepiece projection with filter grating, showing the components

Fig. 5.12 Final assembly of eyepiece projection with filter grating

the brighter stars. Check your camera and see if it has a setting called "night landscape" or "candlelight" – these settings usually provide the longest exposures.

Other Types of Transmission Gratings

Our focus so far has been on the readily available filter gratings, but there are others available.

A word of caution. Many of the diffraction gratings advertised are not of an optical quality suitable for spectroscopy. Some of the "educational"-type gratings are usable but are not blazed, so the efficiency is very low. They can be used on the brighter stars, but that's about their limit. Cokin has a 55 mm "specialty" camera filter, the "B-40 Cosmos," which actually is a low efficiency 250 l/mm transmission grating! See Fig. 5.13.

A simple way of comparing gratings is to look at the brightness of the zero order image. This light is not being directed into the spectrum. A bright zero order image means a low efficiency grating. Only use optical-quality blazed transmission gratings if you can.

All the major optical suppliers stock transmission gratings of different sizes and l/mm. Some of these are shown in Fig. 5.14.

The commercial transmission gratings, in 35 mm frames, can be mounted (and used with a grism) in a suitable adaptor. This gives the flexibility of using different l/mm gratings.

NOTE: The 35 mm framed gratings usually have a smaller grooved grating surface; the mounting adaptor should form an aperture stop to prevent extraneous light from getting through and contaminating the spectrum.

Fig. 5.13 Cokin Cosmos filter mounted on a 135 mm lens

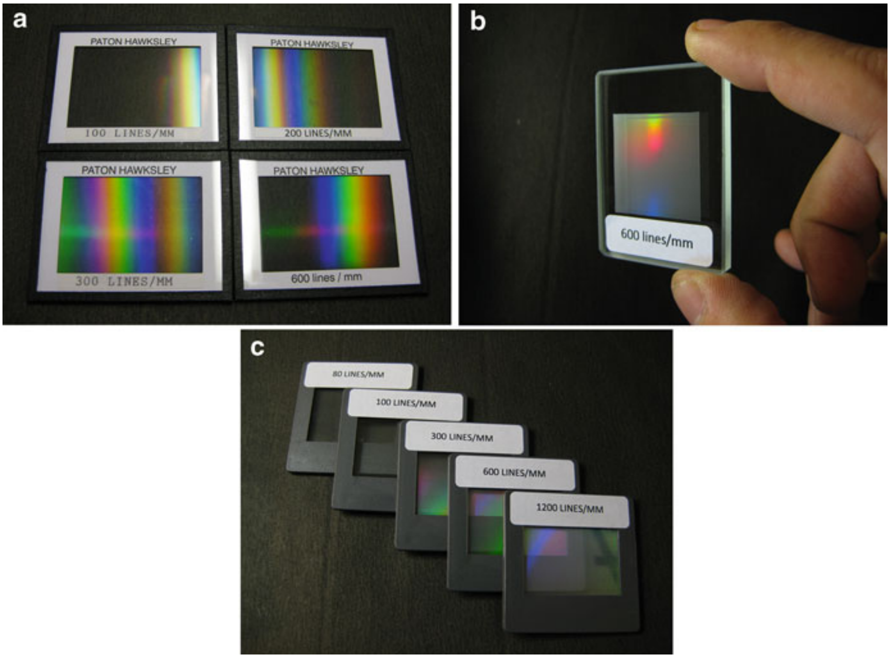

Fig. 5.14 Selection of transmission gratings (Paton-Hawksley)

Fig. 5.15 A 35 mm objective filter mounted in a lens hood

Fig. 5.16 A 35 mm objective grating mounted in a Cokin filter holder

These gratings can be mounted on the camera lens or the front of the telescope as objective gratings. See Fig. 5.15.

A Cokin filter holder can be used to align the grating with the camera (Fig. 5.16).

The 35 mm slide sized gratings can also be used on the telescope in the converging beam. A typical mounting frame is shown in Fig. 5.17 below. This was

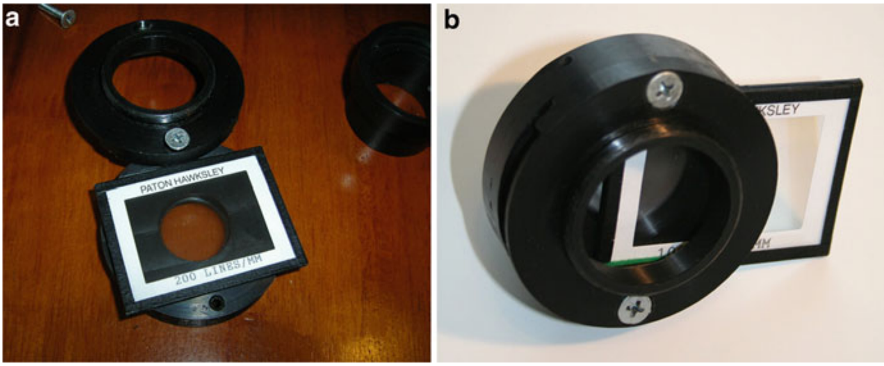

Fig. 5.17 (**a**) Mounting frame showing location slot and recess for grism; (**b**) grating/grism DIY adaptor

machined from structural nylon (Delrin) and has a T thread at the front, a pocket for a 25 mm diameter prism (grism), provision for a slide gap to accommodate the grating and a T thread at the rear. Standard nosepieces and T adaptors can be fitted to suit the telescope and camera.

Making a CCD Adaptor for a Camera Lens

Being able to use old camera lenses with a CCD camera is very handy. Old Pentax, Olympus and Canon lenses can be found very cheaply nowadays. The fixed focal length versions, i.e., 135 mm f2.8, 200 mm f4, etc., offer good performance. These can be used with an objective grating to collect wide field spectra. You can modify a "camera macro extension tube" and add an adaptor plate; this plate can be machined to allow 1.25″ fittings to be used, or incorporate T thread adaptors.

Most CCD cameras have a back focus (distance from front flange to CCD chip) of about 10–12.5 mm. A DSLR normally requires 44 mm (55 mm if you include a T2 adaptor). A standard camera lens therefore needs a distance of 44 mm to focus on infinity, but the inner element of the lens may be further back and reduce the "clearance" to less than 22 mm. The normal length of a 1.25″ to T thread nosepiece is around 30 mm. These variations need to be taken into account. See Fig. 5.18.

Whatever method is used, it must hold the camera/CCD square and secure and still allow some rotation to align the spectrum with the horizontal axis and provide some means of adjusting the focus.

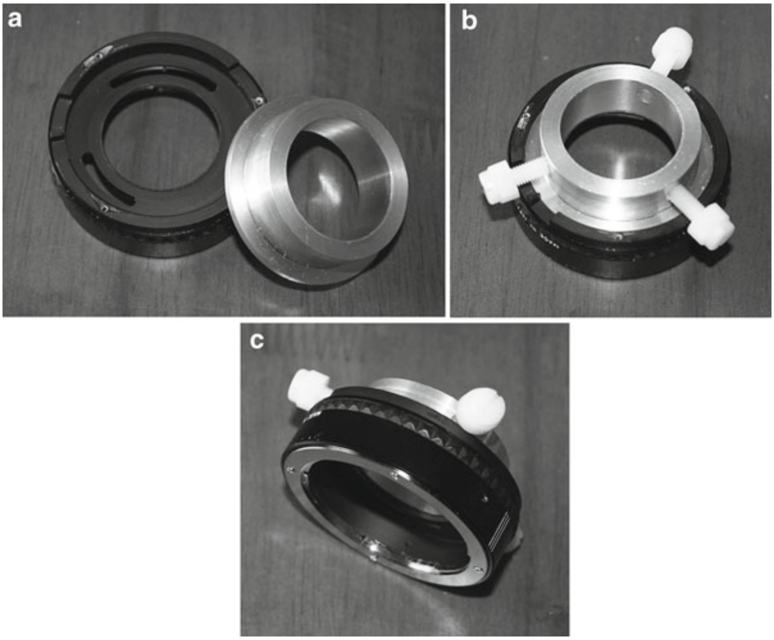

Fig. 5.18 Camera lens adaptor

Other Grating Spectroscopes

It is possible to build a full transmission spectroscope using filter gratings (as well as other transmission gratings) to improve the performance of the grating. As we have seen in Chap. 2, when the grating is used as an objective grating, the collimated (parallel) light from the star(s) illuminates the whole grating and gives the potential of maximum resolution.

Obviously the final resolution will be determined by the seeing conditions, as before. We can build on this concept further by using a collimating lens in front of the grating with a camera lens and a CCD behind it and mounting it on the focuser of the telescope. Figure 5.19 shows the arrangement where a star image is focused by the telescope onto a wide slit gap. This also brings the star image to the focus of the collimating lens, which in turn illuminates the grating. At the other output side of the grating, the spectrum is formed at a deviation angle and imaged onto a CCD. Note that the focal plane is curved. This field curvature means that the camera must be tilted relative to the optical axis and refocused for the blue and red regions of the spectrum.

There are a couple of design issues that need to be considered.

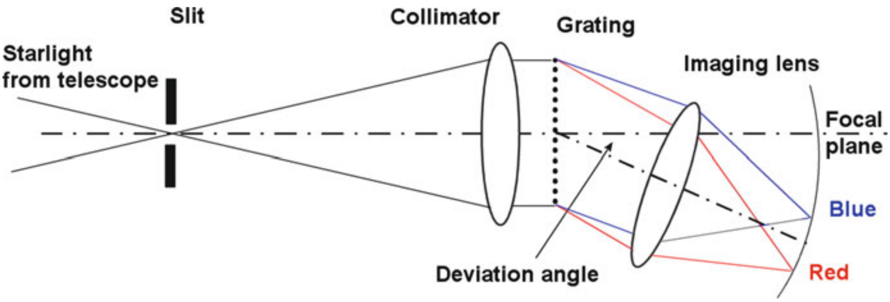

Fig. 5.19 Collimated transmission grating spectroscope

Weight and Length

The added weight of the collimator with the camera lens has to be supported by the telescope focuser. If there is any "slop" in the focuser mechanism, the spectroscope will "droop" and be misaligned. You may need an additional bracket to securely support and hold it in place. The overall length of the instrument will be determined by the focal ratio of the telescope and the focal lengths of the collimating/camera lens. All this additional hardware can result in a setup where the length of the spectroscope can be around 250 mm! That's a lot of overhang on your focuser and can cause vibration and balancing problems.

The Size of the Collimator Lens

The beam of light entering the spectroscope will be at the same f ratio as the telescope itself, i.e., 200 mm f5, etc. This cone of light then expands behind the focus point and eventually reaches the collimator. The collimator can be a lens or even a spherical/parabolic mirror. Its job is to collect all the incoming light and turn it into a collimated (parallel) light beam.

The focal ratio of the collimator must obviously match the telescope. For instance, if the telescope is, say, f5, then the collimator should be at least f5 to "catch" all the light. A smaller f ratio (i.e., f4) will just mean that the beam is vignetted (blocked down) by the telescope optics, and the diameter of the emerging beam from the collimator will be smaller. Likewise, if the collimating lens has a focal ratio greater than the telescope, i.e., f8, then the lens diameter will be smaller than the illuminated area from the telescope and the excess light will be lost; once again the emerging beam will be at the telescope focal ratio – there's no way around it! It is best to match the size and focal ratio of the telescope and collimator.

The Size of the Grating

If we use the standard filter gratings then the size will be restricted to 28 mm diameter. Other commercial gratings will allow you to use sizes up to 50×50 mm. To prevent the loss of light (and efficiency), the collimator lens diameter should match the size of the grating.

The grating size and focal ratio have now determined the minimum size of the collimator lens:

Diameter of lens – 28 to 30 mm for a standard filter grating
Focal ratio of lens – to match the telescope (say f5)
Focal length of the lens – (for f5) 140 mm (28×5)

(If we used a 50 mm square grating on the same telescope, the lens would have to be 50 mm diameter and have a focal length of 250 mm!)

Any good achromatic lens can be used for the collimator. Suppliers of suitable lenses are given in Appendix F of this book. In fact, you can sometimes find old camera lenses that meet the specification, i.e., 135 mm f2.8 lens; these can also be used.

Depending on the grating used and the number of lines per mm, the bright first order spectrum produced will lie at some deviated angle (see Chap. 6). A good rule of thumb to remember is 3.15° for every 100 l/mm.

For the SA100 grating this means the camera lens should be inclined at 3.15° to the optical axis (6.3° for the RO200). Although not mandatory, incorporating this angle into your design will improve the focus of the spectrum and keep problems such as field curvature to a minimum.

Like the collimator, the aperture of the camera lens used must match the size of the grating. The focal length of the camera lens, however, can be different.

Camera Lens

If you work on the collimator being 140 mm focal length, then using a camera with a similar focal length, i.e., 135 mm, there will be no (or very little) magnification or reduction of the star image (and hence the resolution) on the imaging CCD. The size of the image projected onto the CCD chip can be reduced by using a shorter focal length camera lens (you almost never want to increase the size of the image – that would just spread the same amount of light over a larger area with a reduction in brightness and resolution).

The final image size will be reduced by the ratio of the focal lengths:

$$\text{Final image size} = \text{original star size} \times \text{camera focal length} / \text{collimator focal length}$$

For example, a 20 μm star image with a 140 mm collimator and a 50 mm camera lens would appear (20×50/140) as a 7 μm image.

How do we make a choice then for the camera lens focal length?

The answer lies with the CCD chip you will use. Look back at Table 2.4. The seeing conditions and the focal length determine the size of the star image at the prime focus. For typical seeing conditions of 3″ arc and a focal length of 1,000 mm the size of the star will be 14.5 μm. When the collimator and camera focal lengths are matched this will give a image/line size of 14.5 μm in the spectrum on the CCD chip. The Nyquist sampling theory (Chap. 6) says we need at least 2 pixels illuminated by this "line" to get maximum resolution. If your camera has, say, 10 μm pixels then the "minimum" resolution would be 20 μm. With a 14 μm image you are "under-sampling" and will lose detail. Reducing the camera focal length won't improve matters; in fact it would make the outcome worse!

If you have a camera with, say, 5 μm pixels, however, the sampling is OK (10 vs. 14 μm), and you could even squeeze a bit more resolution by reducing the image to around 10 μm. This could be done by using a 100 mm camera lens with a 140 mm collimating lens.

The best answer is always achieved when the final image size is at least twice the CCD pixel size.

There we have it. A design for a slitless collimated spectroscope, based on a 200 mm f5 telescope, using a SA100 grating:

Collimating lens – 140 mm f5
Grating – SA100
Camera lens – 135 mm f2.8 standard lens, ideally inclined at 3.15° to the optical axis.

Fitting the various parts together and getting a robust assembly may require a little ingenuity. Figure 5.20 shows a 600 l/mm grating assembly. Note the angle of the camera lens to the collimator!

Is all this effort worthwhile? Will the benefits be noticeable?

We saw in Chap. 2 that the best possible resolution with the SA100 grating on the telescope was around 30 Å. A slitless collimated spectroscope design, if well constructed, can improve this to about 20 Å. Depending on the size of the CCD chip, the zero order image may still be visible to assist in calibration. The real performance benefits are found when we start to incorporate larger l/mm gratings. A 300 l/mm will give results close to 6.5 Å resolution.

Summary Points

Match the collimator to the telescope and grating size.
Match the camera lens to the pixel size of the CCD.

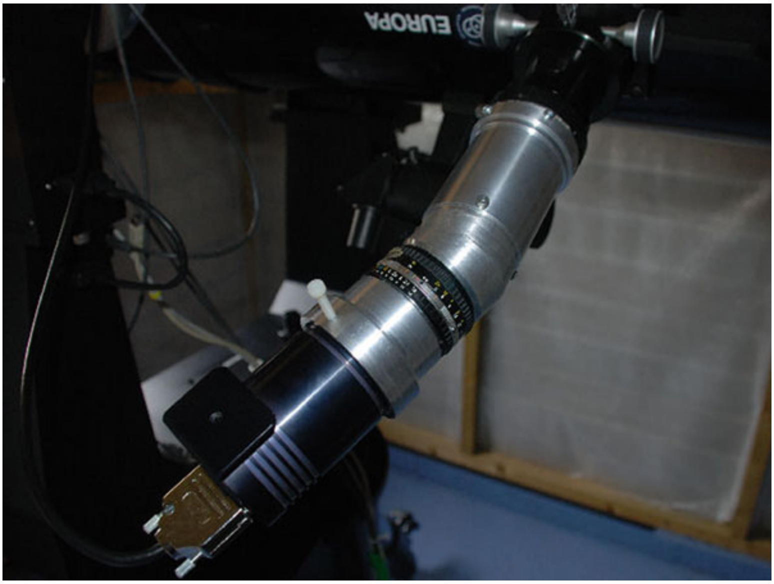

Fig. 5.20 Transmission grating spectroscope (I. Baker)

Adding a Slit

By incorporating an entrance slit at the focus of the collimating lens you can further improve the resolution and the ability to do more serious spectroscopy. Using the data above, if you incorporated a slit into the design, the resolution with the SA100 would be improved to 5 Å – a significant improvement!

One of the major differences between using the grating slitless design and using a slit spectroscope is that the target star must be focused and guided on the entrance slit. As the width of the slit is very narrow, around 20 or 30 μm, this can present a challenge to the amateur. Many homebuilt spectroscopes fail to perform due to the lack of understanding and not properly addressing this problem. The design and construction of any spectroscope must have good provision for acquiring the target star, focusing it on the slit and guiding. Some workable solutions you can apply to the problem of guiding will be discussed in detail later.

When mounted onto the telescope focuser the entrance slit must be placed precisely at focus of both the telescope and the collimator lens. The width of the slit gap will depend on the focal length of the telescope. The width of the slit gap must be calculated to give maximum resolution with minimum light loss. A slit gap with a width of approximately 80% of the star diameter is a good starting point.

Table 2.4 gives typical star sizes for different seeing conditions. An ideal way of starting out with slit spectroscopes is to use the Surplus Shed adjustable slit

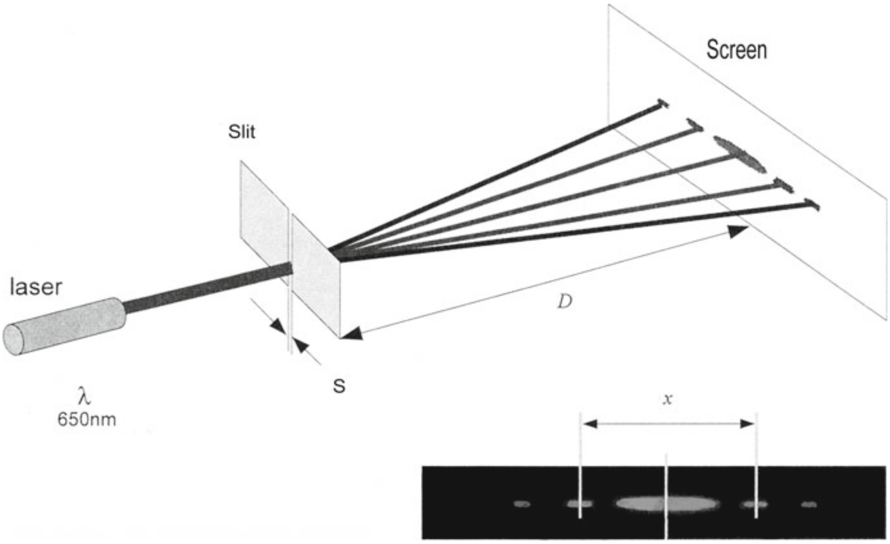

Fig. 5.21 Using a laser to measure the slit gap (After C. Buil)

assembly (see Appendix F in this book). This allows the slit gap to be varied from almost 2 mm down to 20 μm.

When used wide open, and the gap is much wider than the size of the star image, we have effectively a slitless configuration. This has the benefit of allowing the target star image to be seen in the zero order (subject to the size of the CCD chip or by repositioning the spectrum – see below). We can use this image to verify focus and position the star image onto the edge of the slit in readiness to close the slit gap.

Measuring the Slit Gap

The easiest way to measure the slit gap is by using the diffraction pattern generated by shining a laser penlight pointer through the slit (see Chap. 6). By measuring the pattern of light and dark images formed on a distant screen or wall, we can determine the size of the gap to within to 1/10 the width of a human hair! Amazing.

Figure 5.21 shows the setup. We need to know the wavelength of the laser, usually mentioned somewhere in the documentation/manual. (Red lasers are about 6500 Å and green about 5320 Å.) The projected image on the screen will show a bright central spot with a series of fainter spots on either side. The brightest image is the zero image, formed by the laser beam, the fainter spots being the diffraction images produced by the interference of the light waves.

Table 5.1 Slit gap vs. fringe spacing for various screen distances

Slit gap	Screen distance (D)			
(μm)	0.25 m	0.5 m	1.0 m	2.0 m
10	48 mm	96 mm	195 mm	395 mm
20		48 mm	98 mm	210 mm
30		33 mm	66 mm	129 mm
50		19 mm	39 mm	80 mm

The formula is

$$S = 3D \times \lambda / 10X$$

Table 5.1 shows the relationship between the slit gap (S) in microns, the distance to the screen or wall (D), in meters and the measured spacing between the first two fainter dots (X), measured in mm.

Here's an example. Using a red laser (6500 Å) and a distance to the screen of 1 m, we measure the gap between the two faint dots as 98 mm. What is the width of the slit?

$$S = 3 \times 1 \times 6{,}500 / 10 \times 98$$

$$S = 19.9\ \mu m$$

The slit gap will be almost 20 μm. This agrees with the results in Table 5.1.

Living Without a Zero Order Image

The first order spectrum is produced at a deviation angle relative to the grating, which depends on the l/mm. As we increase the grating l/mm to further improve the resolution, compensating for the deviation angle becomes more and more of a problem. The spectrum will suffer from field curvature and the zero order image will appear further and further away from the spectrum. On smaller CCD chips it's impossible to image all of the spectrum and the zero order image in the same frame.

We have to either incline the camera axis, as per the previous example, or find some other method of compensating. If we ignore the need for the zero image, then adding a "grism" (see Chap. 6) will bring the spectrum back on-axis. We can also rotate the grating around a vertical axis aligned with the grooves to re-position the spectrum in the field of view. In fact, by rotating the grating through a large enough angle we can access the zero order image and then move onwards to image the spectrum. Presented below are a couple of design ideas that may help you determine a final design.

The other aspect of working without a zero order image is that of calibration. We saw in Chap. 4 that it was easy to use the zero order image as a 0000 Å reference and then identify one other line in the spectrum (a prominent hydrogen line or even a Telluric line) to provide a linear two point calibration.

What do you do if there's no zero order image? Check out the sections "Wavelength Calibration Using Two Lines" and "Wavelength Calibration Using One Line and a Known Dispersion" in Chap. 4.

Watkis Transmission Spectroscope

Back in the 1970s C. J. Watkis was challenged to come up with a basic slit spectroscope design that could be used on amateur telescopes. Over the years there have been other similar designs, but the sheer simplicity of the original design still shines through. The instrument was housed in a small plastic project box and when completed only weighed 650 g. See Fig. 5.22.

It uses an aluminum spring tab as an adjustable slit, a couple of old binocular lenses for collimation and imaging, and two or three small front surface mirrors (depending on the configuration). These simple components allow the instrument to function initially in slitless mode and by rotating the second mirror, access the

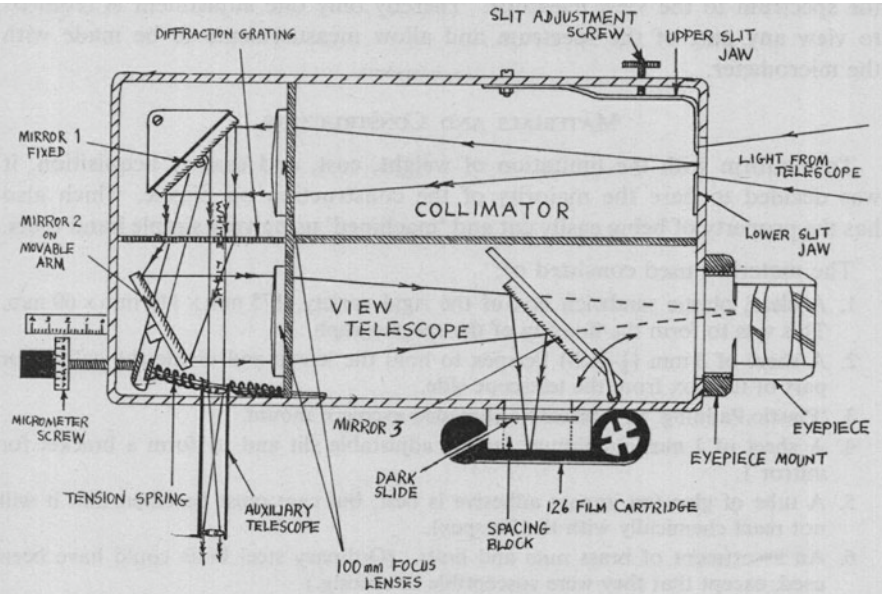

Fig. 5.22 Watkis spectroscope, general arrangement (BAA)

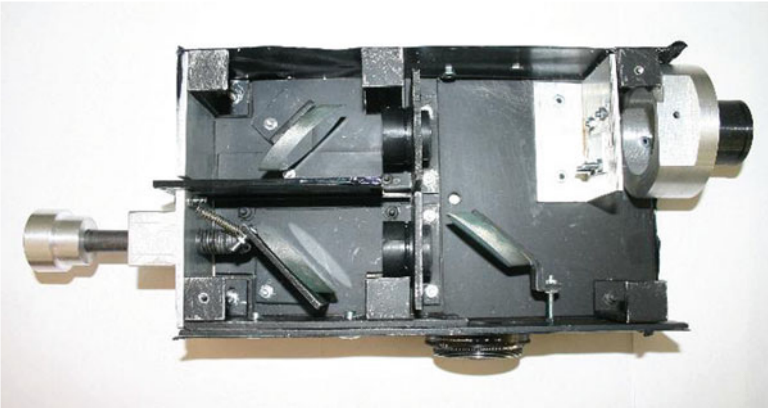

Fig. 5.23 Watkis spectroscope, final design (J. Nott)

zero order image for focusing. The slit can then be closed down to a suitable gap and the mirror rotated to pick up the spectrum. Very simple, very functional.

Nowadays, using the Surplus Shed adjustable slit may be easier to incorporate than filing and polishing the original slit jaws. The basic design parameters outlined above still hold regarding the size and focal ratio of the lens. The only thing to watch out for is that the rotation axis of the mirror support must be square to the grating and able to be "locked" after adjustment. This basic design can be adapted to for use with any of the filter gratings available and even some of the commercial transmission gratings up to 600 l/mm. It does require some means of mounting to the telescope and additional hardware to locate and focus the CCD camera. (Not many people still have #126 film cassettes around!)

If the size of the second mirror is chosen wisely, the zero order star image, which goes directly through the grating on the optical axis, can be viewed and focused using a small finder telescope. This then allows the target star to be positioned in a wide slit, making it easier to focus the spectroscope. By altering the angle of the mirror the full spectrum can be directed to the camera lens and the imaging CCD.

Figure 5.23 shows a recently built Watkis instrument using 30×6 binocular objectives, elliptical secondary mirrors (as used in a small Newtonian telescope) and the Surplus Shed adjustable slit. The gratings used in this construction were "Educational" gratings similar to those normally used for school projects.

Other Transmission Spectroscope Designs

On Christian Buil's excellent website, he shows various homemade spectroscopes. One is specifically designed for transmission gratings – LORIS (Low Resolution Imaging Spectrograph). The layout is similar to the basic concept outlined earlier.

He uses a couple of standard camera lenses, a 50 mm f1.8 as the collimator and a 35 mm f2 lens for imaging. This combination of lenses gives a reduction ratio of ×0.7. A 30 μm entrance slit will project as a 21 μm image on the CCD. The Nyquist sampling requirement would be satisfied using a CCD chip having a pixel size of 9 μm.

The team at CAOS (Club of Amateurs in Optical Spectroscopy), a group of experienced engineers and scientists, have developed many spectroscope designs suitable for amateurs. Their transmission grating spectroscope – TRAGOS (Transmission Grating Optical Spectroscope) – is a very robust and sophisticated design. To faithfully follow their design would require some serious (and expensive) machining work. However, the basic elements could be used in a DIY construction. The design has a fixed entrance slit that is reflective. This provides, via a secondary mirror and lens, an image of the target star onto a guide camera. A Baader 207 l/mm filter grating is used for dispersion and standard Edmund Optics achromatic lenses for the collimating and imaging elements – 25.4 mm, 80 mm fl. for the collimator and a 25.4 mm, 60 mm fl. for the imaging. To bring the deviated spectrum beam back onto the optical axis, a "grism" wedge prism (see Chap. 6) is incorporated.

Guiding Slit Spectroscopes

As mentioned at the beginning of this chapter, many amateur slit spectroscope designs and projects fail to perform in the real world due to the lack of good provision for guiding the target object onto a very narrow slit.

There are three basic design challenges for the three different basic designs: slitless spectroscopes (filter gratings, wide slit applications), adjustable slits (where the target object can be found in a wide slit opening, then the slit closed down to obtain a spectrum) and the fixed slit design (where the visibility of the sky and the target objects is severely limited by the narrow slit gap).

For slitless applications, a guide telescope fitted to the main telescope will do the job nicely. The Skywatcher ST80 (80 mm aperture, f5) combined with a QHY5 guide camera has proved itself as a winner. Orion in the U. S. market sells a similar product known as their StarShoot autoguider. A guide software package such as *PHD* (freeware) will allow you to position the target in the field of view of the camera and send guide correction signals to your telescope mount.

When using adjustable slits, the above method can still work, but adding a moveable crosswire overlay to the *PHD* screen gives very accurate positioning of the target onto the entrance slit. Al Sheeny has developed his freeware *Al's Reticule* specifically for this purpose (The latest version is available in the files area of the Y! group astronomical_spectroscopy). The double crosshairs can be made any width and height to replicate the physical size of the entrance slit and moved in X-Y and rotated so you end up with a "virtual" slit on the guide screen. It only takes a few moments to position the target on the virtual slit, and you are almost guaranteed it will be sitting on or very close to the actual slit.

Even more precise acquisition and control can be achieved using a beamsplitter in front of the spectroscope. A typical arrangement would have a 70R/30T beamsplitter plate (this reflects 70% of the incident light and only transmits 30%) positioned at 45° before the entrance slit. The brighter beam is directed into the spectroscope and the other to a guide camera. Modified flip mirror bodies (i.e., Vixen, Brightstar, Meade, etc.) have been used to support the beamsplitter.

This configuration is a bit like using an off-axis guider (OAG) for astrophotography but with many fewer problems! The whole field of view is visible in the guider. This makes selecting and focusing a target much easier. *PHD* and *Al's Reticule* do the rest.

Using a beamsplitter where 30% of the incoming light is diverted away from the slit and the final spectrum may sound dramatic, but when you consider that this is only equivalent to a loss of less than 0.4 of a star's magnitude, it's a small price to pay for easy acquisition and focusing of your target. (See Chap. 6 for details of the star magnitude scale.)

Finally, the fixed slit option. This IS a challenge. Remember you can't really see anything through a 20 or 30 μm slit gap. Finding and positioning your star image on the slit can be a very time-consuming affair (as well as very frustrating!). Yes, the beamsplitter method detailed above can still be used but is still unfortunately a hit and miss operation. Consider a star image of say 20 μm in diameter sitting squarely on a slit gap of 15 μm. The central portion of the star image will "disappear" into the gap, and only two small "wings" of starlight – the overflow from each side of the slit – will be visible. (The entrance slit gap, if set correctly, will only appear in the zero order as an image 2 or 3 pixels wide. In this window of opportunity we must position a star image that itself is only 5–6 pixels in diameter. Not easy.)

The tried and proven solution is to a use reflective slit (see Fig. 5.24 as an example). This can be made from highly polished stainless steel or aluminum. The professional versions use laser-engraved slit plates where the entrance slit is etched on a background of chromed glass. Besides being highly reflective, they provide very accurate and even slit gaps. When this slit plate is inclined slightly to the optical axis (along the height of the slit) the slit can be viewed by a guide system and the image of the starlight "overflow" used for precise guiding.

That's about as far as we can take the filter grating concept. We have gone from the basic objective grating and mounting it in front of a camera in your telescope to adding simple slits for solar or bright light spectra (and brighter DSO's) and a fully functional transmission slit spectroscope. We have covered a lot of ground and shown that the filter grating provides an ideal platform for amateur spectroscopy.

The next stage on the spectroscopic learning curve is to move into more complex and higher resolution designs. Most of these advanced designs are based on reflection gratings due to the higher dispersion efficiency. Some of the more basic designs can be successfully constructed by the avid amateur who possesses a reasonable amount of DIY skills, and such instruments are being used around the world to carry out some ProAm astronomy projects. The details of the components required and layout of these designs are beyond the scope of the current book but

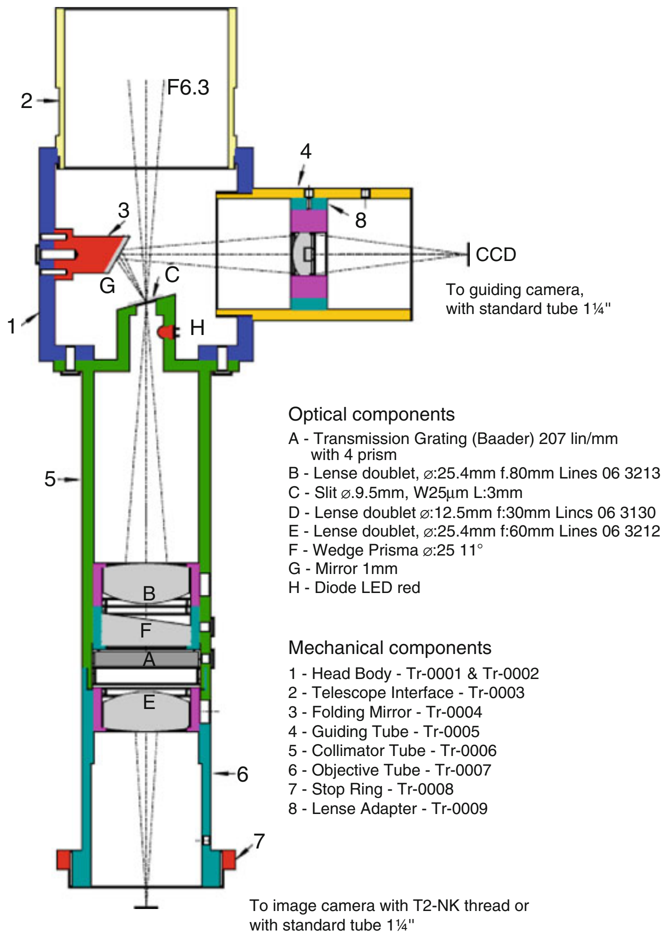

Fig. 5.24 Tragos spectroscope, general assembly (CAOS)

are well described in the companion book *Astronomical Spectroscopy for Amateurs* by Springer.

Now is the opportune time to return to some of the important theoretical aspects of spectroscopy – star brightness, camera and pixels and how they interact with the spectrum we want to record. We will also look at the details of how the grating actually produces the spectrum and how it interacts with the telescope optics. This is good foundation knowledge for the future.

Chapter 6

Some Technical (Nice to Know) Stuff

This chapter brings together some additional material, which although not strictly necessary to know or understand before using a filter grating, will add to your knowledge and give you a better appreciation of some of the more important aspects of amateur spectroscopy, the equipment and instruments we use.

Star Magnitudes and Star Brightness

Way back in the distant past early observers of the sky couldn't help but notice that some stars appear brighter than others. By the time of the ancient Greeks around 800 stars had been accurately recorded and given a rough scale of brightness.

The brightest stars, such as Sirius and Vega, were called "first magnitude stars," slightly fainter stars "second magnitude," etc. On this arbitrary scale the limit of the naked eye was sixth magnitude. This system of allocating stars to brightness magnitudes worked well for a couple of 1,000 years, and it was only when the telescope was invented that fainter and fainter stars began to be recorded. How then do we extend what was basically a visual brightness scale down to fainter and fainter stars? Good question!

The early telescope observers invented their own scales. You will see in some of the older texts on astronomy where comparisons of star brightness are discussed. "Mr. X saw this star as a ninth magnitude star, whereas Mr. Y according to his observations said it was tenth magnitude." In some books a look up table for the various astronomers was provided – Herschel, Struve, Piazzi etc. – who all had their own star magnitude scale. It wasn't until the mid-1800s that a rigorous investigation was carried out by Norman Pogson, who determined that a sixth magnitude star was 100 times brighter than a first magnitude star.

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4_6,

The ratio of apparent brightness by magnitude is therefore the fifth root of 100, which is 2.512; a third magnitude star is 2.512 times brighter than a fourth magnitude star.

The star Vega was chosen has the 0.0 magnitude reference star, and all other star brightnesses were measured relative to it. It was found that stars such as Sirius and Arcturus were brighter than Vega, so the scale was extended to accommodate them. Sirius is now classified as having a magnitude of −1.46. This scale can be further expanded to include the Moon (−12.74) and the Sun (−26.74). At the other end of the scale the faintest object recorded by the Hubble Space Telescope is about +30 magnitude.

The formula used to relate brightness (B) to apparent magnitude (m) is:

$$m_2 - m_1 = 2.5 \, log \, (B_2/B_1)$$

or

$$B_2 - B_1 = 2.512 \, (m_2 - m_1)$$

where $m_2 - m_1$ is the magnitude difference and B_1 and B_2 the brightness of the star.

For example, if Sirius has a magnitude −1.46 and Capella a magnitude of +0.08, what is the difference in brightness between these stars?

$$m_2 - m_1 = 0.08 - (-1.46) = 1.54$$

$$B_2 - B_1 = 2.512^{(1.54)} = 4.13$$

Therefore, Sirius is 4.13 times brighter than Capella.

In spectroscopy we can use the same formula to calculate the effects of a beamsplitter and slit gaps. If we used a 70/30 beamsplitter to assist in guiding our spectroscope (30% of the incoming light being diverted to the guide camera), what would be the effective loss of light to the spectroscope?

Using the above formula, (B_2/B_1) would be 0.3 (30/100). Hence,

$$m_2 - m_1 = 2.5 \, log \, (0.3) = 0.38$$

The loss of light to the spectroscope is equivalent to 0.38 magnitudes.

A similar calculation can be used to evaluate an entrance slit by estimating the light lost when a narrow slit width is used. (CAOS has a spreadsheet that can be used. This is available on their website.)

So far we have been considering *apparent magnitude* (m). To be specific, when we observe visually the brightness of the star we give a *visual magnitude* (m_v). When specialized filters are used we can obtain photometric magnitudes. These are widely used by variable star observers and professional astronomers. The standard filters are the UBVRI series (UBVRI – Ultra violet, Blue, Visual, Red, Infrared). Figure 6.1 shows the typical bandwidths of the photometric filters.

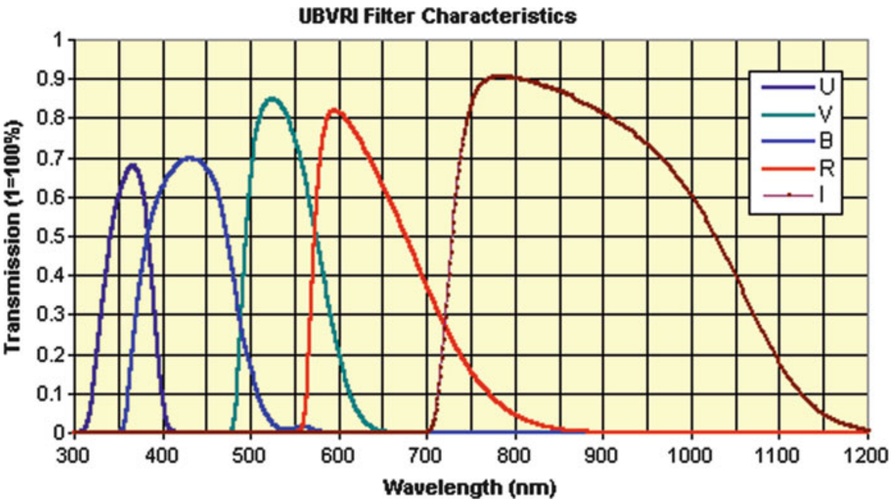

Fig. 6.1 UBVI filter bandwidths (Astrodon)

Note that the bandwidths covered by these filters are different from the RGB (Red, Green, Blue) filters used by amateurs for color astroimaging.

The V – visual – filter allows the starlight in the green region to be recorded. This matches the peak sensitivity of the human eye, and the magnitude recorded is called the *photovisual magnitude* (m_{pv}). You may therefore find star magnitudes defined as either apparent magnitude (m), visual magnitude (v) or photovisual magnitude (m_{pv}) – they all give the same result.

By measuring the star brightness (energy flux) with the other filters we are actually sampling the energy from the star along the blackbody curve. (See Chap. 7.)

A hot white star will emit more energy towards the blue end of the spectrum than a cooler red star. The hot star will appear brighter in the B filter and the cooler star brighter in the R or I filter. These differences are used to generate a *color index.*

When the B magnitude is subtracted from the U magnitude we get a U-B index, and B minus the Visual gives the B-V index. Like the apparent magnitude scale these indices have been standardized on an A0 star (similar to Vega).

By comparing the U-B and the B-V indices we can quickly determine if the star is more red (and hence probably cooler) than another star. Our Sun has a U-B = 0.1 and B-V = 0.62, typical of an orange G-type star.

These magnitudes don't tell us about the actual brightness of the star. It could be a faint star close by, or a really bright star far away, and they will have the same apparent magnitude. We need to consider the distance to the star. There are many ways of measuring distances – parallax or association with a known cluster that has a pre-determined redshift (see Chap. 7) – and once we have an estimate of distance (r) an *absolute magnitude* (M) can be calculated.

Based on the apparent brightness (or luminosity) being proportional to the square of the distance, i.e., apparent magnitude (m) ∞ $1/r^2$.

A standard distance of 10 pc (a parsec is equivalent to a distance of 3.26 light years) has been adopted, and the magnitude of the star converted to this standard gives the absolute magnitude. The resulting equation is:

$$M - M = 5 \log r - 5$$

When photometric filters are used the absolute magnitudes become M_U, M_B and $M_{V.}$

The absolute magnitude of a star is an important number to know. It allows us to determine the actual luminosity of the star and helps us recognize the relationships between luminosity, size and age of the various stars. The H-R diagram is based on these relationships.

Our Sun has an apparent magnitude of −26.74 (because it's so close to us), but an absolute magnitude of only +4.82 – certainly just an average star.

Aldebaran (αTau) has an absolute magnitude of −0.6, much more luminous than the Sun. The most luminous stars can reach magnitudes of −9.2 (S Doradus), and some super nova can be as bright as −20. The least luminous stars can be very faint; Van Biesbroeck's Star (V1289 Aql) is only +18.6.

Magnitudes of the brightest stars are given in Appendix B.

Harry Nyquist, Claude Shannon and Bryce Bayer

Who are these guys? Why mention them here? Nyquist and Shannon did a lot of research while working at Bell Labs and developed a theory known as "Nyquist-Shannon Sampling theory" while considering the effective transmission of information. In simple terms, as applied to spectroscopy (and astroimaging), the Nyquist sampling theory states that we need information from at least two pixels to resolve the information in our image. The minimum resolution of your camera will be roughly twice the pixel size; for example, a 6.4 μm pixel camera will give a resolution of 12.8 μm. If the star image is less than two pixels it's said to be "under-sampled"; likewise if we had a star image covering say five or six pixels it would be "over-sampled" and again the opportunity to improve resolution is lost.

OK, what about Bayer? Well, he was the guy who probably brought about the revolution in digital cameras. He invented a method of using a series of colored filters in front of the CCD pixels where the information could be subsequently combined ("De-bayered") to provide a full color image. Pretty neat! This is used in all the DSLR cameras and one shot color (OSC) CCD cameras.

The Bayer filter matrix consists of a series of red, green and blue filters (RGB) or cyan, magenta, and yellow (CMY) placed in a matrix over the CCD pixels. Usually its 50% green, 25% red and 25% blue. All the DSLR cameras use the RGB as well as the color SBIG cameras, such as Starlight H8C, H9C and M25. The DSI,

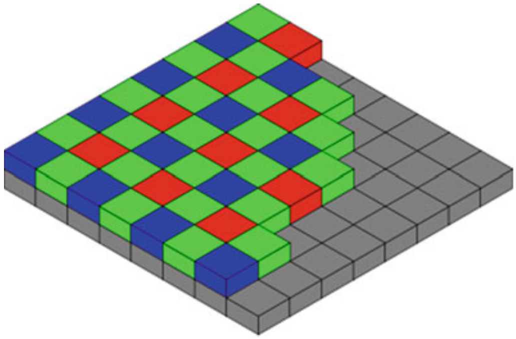

Fig. 6.2 Bayer matrix (WIKI)

DSI II, and Starlight MX7C use the CMY. Effectively each pixel records a monochromatic intensity signal of the incident light.

So whereas a mono chip collects data from the whole of the spectrum on each pixel, a colour CCD will only collect the color(s) associated with the Bayer filter on the pixel. See Fig. 6.2. The final resolution of a OSC is approximately 60–70% of an equivalent mono camera.

Various de-bayering algorithms have been developed. It should be noted that none of the physical pixels on the camera chip are displayed on the computer screen! Each pixel shown on the screen is a "virtual pixel" made up from data in the surrounding pixels. (If this were not the case, you would only see red, green or blue pixels on a highly magnified image…this is obviously not what you see.) The positioning of the spectral image on the Bayer matrix can significantly affect the resolution and response of the CCD. It's recommended that the spectrum always be positioned as close to the horizontal axis of the chip as possible. Images saved as RAW files give the maximum dynamic range.

Pixel Size

Based on the Nyquist sampling criteria of a minimum two or three pixel images, the final resolution of the spectroscope can be limited by the size of the pixels in the imaging camera. For instance, if the telescope you are using produces a star image of say 8 μm (see Table 3.1). What would be the best CCD pixel size? Answer – around 4 μm. What if I only have a pixel size of 11 μm available? Then you'll be under-sampling and the end resolution in the spectrum will be about 22 μm. This is almost 2.5 times the size of the star image.

To record faint spectra using 2×2 binning may help to improve the sensitivity, but at the cost also of reduced resolution. Try and match the pixel size to the star size/plate scale and camera lens capabilities.

Table 6.1 CCD chips

CCD chip	QE (%age)	Pixel size (μm)	Pixel array	Chip size (mm × mm)	Resolution Nyquist (μm)
ICX098BQ	–	5.6	640 × 480	3.6 × 2.7	11.2
ICX249AK	70	8.6 × 8.3	752 × 580	6.5 × 4.8	17.4
KAF-0401E	50	9	768 × 512	6.9 × 4.6	18
ICX085AL	50	6.7	1300 × 1030	8.7 × 6.9	13.4
KAF-0261E	–	20	512 × 512	10.2 × 10.2	40
KAF-1602E	50	9	1536 × 1024	14.0 × 9.3	18
KAF-3200ME	60	6.8	2148 × 1472	14.8 × 10.2	13.6
EOS 300D	30	7.1	3072 × 2048	22.7 × 15	14.2
Nikon D40	60	7.8	3032 × 2016	23.6 × 15.7	15.6

CCD Chip Size

Sizes vary from 3.6 mm × 2.7 mm (typical webcam) to the APS-C, 22.7 mm × 15 mm. When used with different plate scales obviously the larger CCD will allow more of the spectrum to be recorded. Some CCD data is presented in Table 6.1.

Use Table 2.2 to match the spectrum (with or without the zero order star image) to the size of the CCD chip. The table shows that a webcam with a 3.6 mm chip size can record the zero order through to the red at a distance of 50 mm. Working beyond that distance, to record the spectrum alone, you'll need to reposition the spectrum on the chip. A DSLR, however, with its much larger chip (22.7 mm), will continue to record both the zero order and the full spectrum up to distances of 80 mm.

NOTE: that even at the maximum recommended distance (80 mm), with an SA100 the length of the spectrum (blue to red) is only 2.6 mm – about 10% of the width of the DSLR frame.

Quantum Efficiency (QE)

Each camera has a unique efficiency curve, sometimes called a sensitivity curve or quantum efficiency (QE) curve. This is a measure of the ability of the chip to convert the incoming light (photons) to electrons, which are then used to generate the electrical signal (ADU) required to record an image. The ADU (analogue to digital unit) is the smallest signal that the CCD chip can resolve. Each pixel has a capacity (well depth) to store a limited number of electrons. This limit is determined by the bit depth of the camera. CCD cameras usually have 16-bit capacity (2^{16} bits) and can hold up to a maximum of 65,536 electrons; the actual value found on most cameras will be around 56,000. DSLR cameras can be 14-bit (Cannon 450D), 16,384 maximum, or 12-bit (Cannon 1000D), 4,096 electrons maximum. Webcams with their 8-bit capacity only give 256 electrons. The range of brightness in the final image will depend on the total electrons collected by each pixel, and the cameras ability to convert them into ADU's. Higher bit cameras give more brightness levels.

When a pixel collects all the electrons it can (full well) any additional photons striking the pixel will be lost and not recorded. The pixel is then said to be saturated. For our purposes we want our image to stay below this maximum brightness. The intensity of the image is then proportional to the photons received.

DSLR cameras have a built in multiplying/amplifier system via the ISO settings. The conversion ratio of electrons to ADU is changed depending on the ISO setting. This is called the "gain." For example, let's assume that with an ISO setting of 100 the conversion is one electron, giving one ADU, and with a ISO setting of 200 we get one electron giving two ADU, and the gain would be ×2. This gain allows fainter detail to be more easily seen in the image.

Some cameras use specialized CCD chips that are designed to record light from different parts of the spectrum. For example, they are more sensitive to the UV region than the green. All CCD's seem to be sensitive to the infrared (beyond the visible red), and this can lead to "star bloat" in astrophotography. An IR blocking filter is usually the solution.

For spectroscopy we want to record as much data as we can across as wide a spectrum as possible. Some chips will give a usable efficiency (say, above 20%) from the UV through to the IR, with a peak in the green around 550 nm. Most chips show a maximum quantum efficiency below 60%. (Note: Some literature shows the curves as "Relative response". These can be misleading inasmuch as they do not give an actual QE figure but rather a percentage of the maximum. When in doubt, assume a maximum of 60%.)

In the case of one-shot color (OSC) chips (or DSLR's) the RGB response curves can show significant dips in efficiency between the various color filters used in the Bayer matrix. When using a DSLR, always save images in RAW format. This maximizes the information in the image and avoids compression artifacts.

Figure 6.3 shows a typical QE curve for a mono chip. Note the scale is "relative response." We have to assume the actual maximum will be approx 60%, so the values given need to be multiplied by 0.6 to get an approximate absolute efficiency figure. At the UV (400 nm) it has an efficiency of 30% (0.6×0.5). The curve shows a gradual rise to a maximum of 60% around the green at 500 nm, and then shows a slow decline down into the infrared (1,000 nm), where it reaches 2%. For the normal range, from 370 to 700 nm (UV-infrared), the overall efficiency is above 30%. This means that only 30% of the photons received by the chip are converted into the final image. Not a high number.

If you looked at a spectrum taken with this chip what would you see? Well, the blue end would be pretty bright, the middle of the spectrum around the green would be much brighter, and the red end would fade out into the sunset. You need to remember this when you start analyzing your spectrum.

Figure 6.4 shows the curves for an OSC chip. Straightaway you can see a few differences.

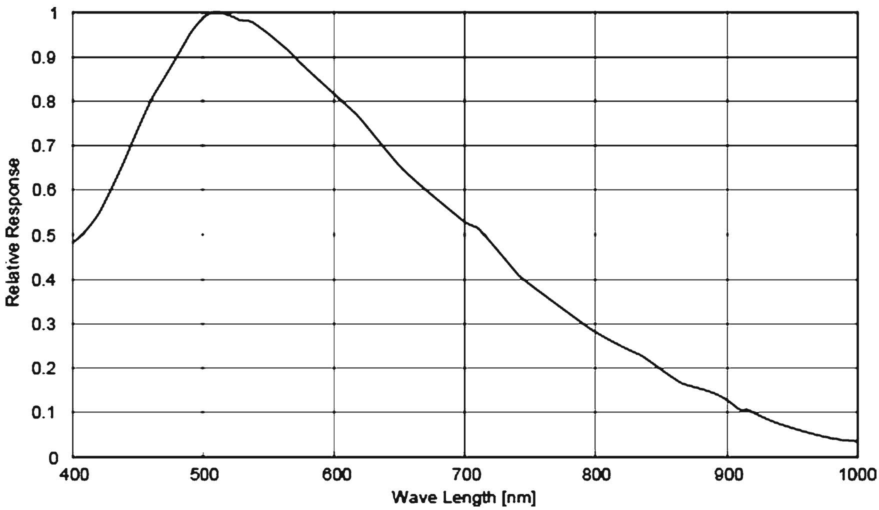

Fig. 6.3 QE curve for ICX098BL-DMK (Sony)

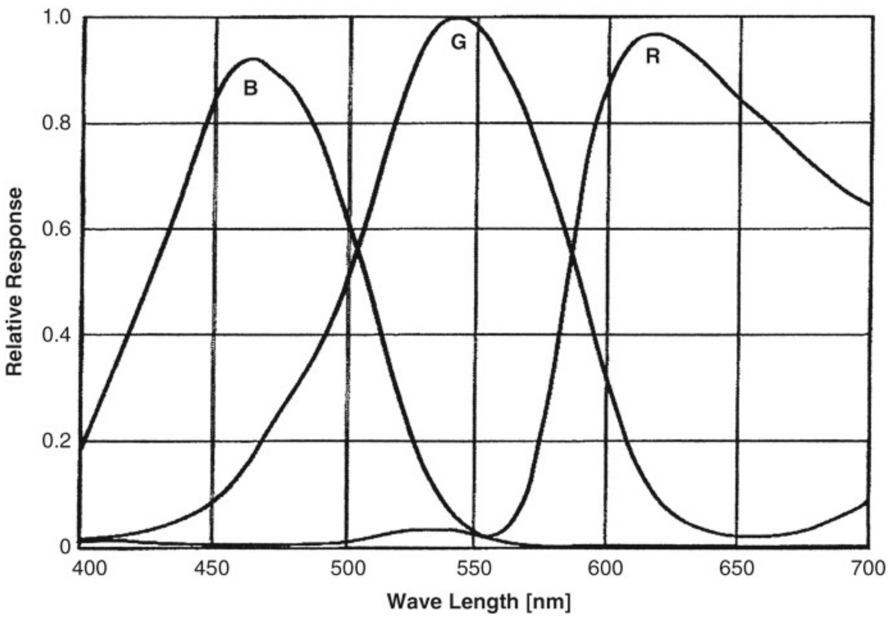

Fig. 6.4 QE curve for ICX098BQ-color webcams (Sony)

If we assume the same actual maximum of 60% then the efficiency in the UV (400 nm) is only 12% – less than half of the mono chip shown in Fig. 6.2. The peak efficiency in the green (550 nm) is similar at 60%, but look at the dips in the combined curves on either side. At 500 nm and again at 580 nm you can see the crossover from one filter to the other. The efficiency drops to around 30%. Notice also the extended efficiency (sensitivity) out into the far red – infrared. This chip is more sensitive to this region than the mono.

What would the spectrum look like with this chip? Bright UV, getting bright in the violet dipping in the blue green, brighter in the green dipping again in the orange and then pretty bright all the way out into the red. A complex intensity curve!

Instrument and Camera Response Versus Recorded Spectra

All the spectra you obtain will show the effects of the camera CCD response curve. All CCD's as we have seen, have an efficiency curve that normally peaks in the green region of the spectrum. This is made even more complex due to the absorption of the shorter wavelengths (below 400 nm) by the optics. This, together with the low CCD response in this region, may limit the extent of the spectrum. Non-chromatic lenses also cause a focus shift across the spectrum. When all these factors are taken into account they cause the spectrum to appear "cut-off" in the blue and "fish tail" towards the red. The spectrum will also vary in brightness across its length. The combined effect of the camera response and the telescope optics can be determined and is called the "instrument response." During pre-processing, the instrument response curve can be calculated and corrections made to the spectrum image. (See Chap. 4.) For example, a DSLR modified with the Baader-type UV-IR filter will pass light with high efficiency at Hα (656 nm) but will limit the spectral response to between 400 and 700 nm.

Colored images of the spectrum may look nice, but monochrome images contain as much (if not more) useful data. For RBG one-shot color cameras (or DSLRs), convert the image to black and white and save the image as a 16-bit .fits file. (This format is required if you wish to do further processing.)

In your imaging processing software, after rotating the spectrum horizontal (if necessary), crop around the zero order image and the spectrum, allowing, say, 10–20 pixels above and below the spectrum.

Use pixel binning in Y axis to "spread" the spectrum; then re-crop a section 10–20 pixels high. Slight processing with a high pass filter will bring out more detail. Be cautious – over applying filters can add artificial detail and ruin the integrity of the original.

A quick look at the X profile will show the dips in the spectrum caused by the Hydrogen Balmer series. See Fig. 6.5.

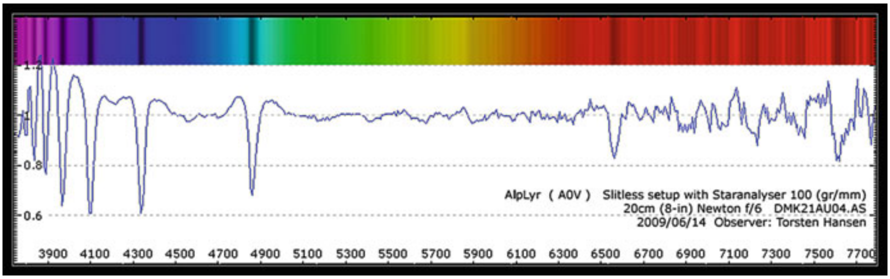

Fig. 6.5 Typical spectrum – Vega (T. Hansen)

Signal to Noise Ratio (SNR)

Like conventional astrophotographs, the image of the spectrum will also contain spurious data (noise) from the CCD chip. As the final spectrum is usually a few pixels wide any noise or hot pixels can distort the analysis.

The majority of noise signals in the CCD image are generated by temperature (thermal noise) and hot pixels. There will also be distortions introduced by the optical system – vignetting, internal reflections, dust, etc.

We can apply dark and flats to our image to correct for the majority of these problems and also compensate by using the surrounding sky image to reduce the interference from light pollution on our spectrum (discussed in Chap. 4). These corrections should be applied to your spectrum before any analysis is carried out.

The ratio of the signal to the noise background (SNR) is an important factor in determining the accuracy and resolution of our spectrum. For example, if the signal is 1,000 and the noise is 50, the SNR will be 1,000/50 = 20. The calculation of the signal to noise ratio (SNR) in a spectrum is sometimes difficult. Areas of the spectrum that look ragged and noisy may in fact be the result of numerous absorption features. Caution needs to be the watchword.

We have mentioned the noise generated in and around the CCD chip (bias and dark frames being used for corrections), but we also have the random noise in the image itself. This is called the "shot noise."

Each image we take contains shot noise. It's the result of a random distribution of the photons that reach our CCD. Statistically the shot noise is equal to the √ signal. For example, a signal of 10 would have a noise of $\sqrt{10} = 3.16$, and the SNR would be 10/3.16 = 3.16. Compare this with a signal of 1,000; the shot noise would be $\sqrt{1{,}000} = 31.6$ and the SNR = 1,000/31.6 = 30. There's nothing we can do about reducing the shot noise, but we can increase the signal to improve the SNR. Longer exposures always give the lowest SNR.

When we combine a series of short exposures (subs) the noise will always be greater than with one longer exposure and hence the SNR will always be lower. For example, if a single 10 min exposure gives a SNR of 30, a combination of 10 × 1 min exposures will probably give a SNR around 20–25. The best solution is to expose the subs for as long as your mounting and guiding will allow and use as many images as you can in the stack.

Grating Theory (The Heavy Bits!)

If we consider light as being an electromagnetic wave, the wavelength (or frequency) of the light determines the perceived color, as we saw in Fig. 1.3. The individual "wavelets" can interact, like ripples on the surface of a pond. This is also seen when a collimated monochromatic light (i.e., single wavelength of light such as a laser beam) beam goes through a narrow slit (or pair of fine slits). The light waves causes both diffraction and interference effects. The expanding waves, as they move outwards from the slit, like on the pond, interact at varying angles from the slit to generate a series of interference patterns; where the crest of one wave reinforces the crest of the other a bright line is formed (maximum), or no light (minimum) where the crests oppose each other. See Fig. 6.6.

The angle (θ) at which we get a maximum is determined by the wavelength of the light (λ) and the width of the slit (a) (or the distance between two very narrow slits).

$$Sin\theta = \lambda / a$$

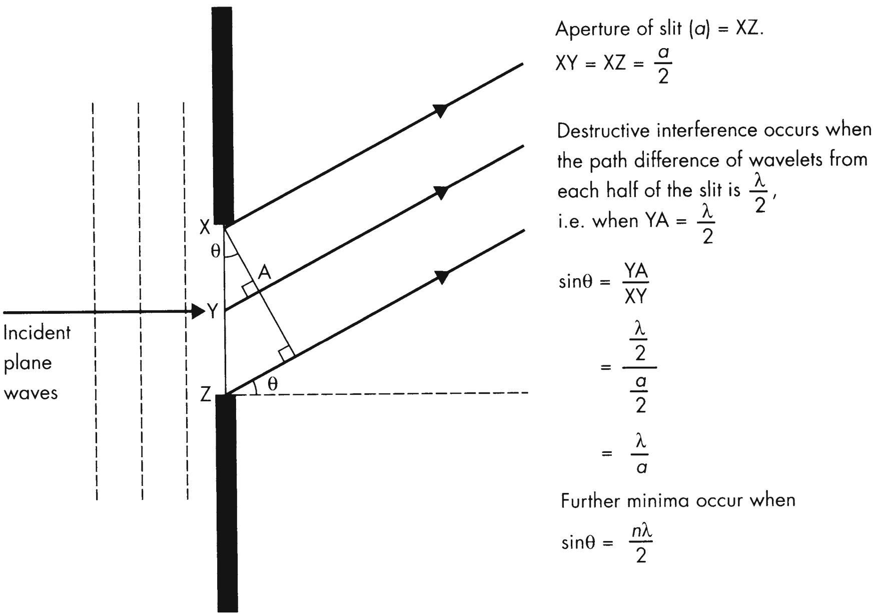

Fig. 6.6 Grating – path length difference (S. Tonkin)

These diffraction effects were well demonstrated in Fig. 5.21, when we used a laser to calibrate a slit gap.

(Note that the bright maxima get fainter the further we move from the bright zero order image.) The first, brightest diffraction images (closest to the zero order) are the first order images, the next, the second order, etc. The series continues until they become too weak to see.

When we add all the different wavelengths of visible light to the model, the maxima, from the above equation, for each wavelength (from blue through to red) will be formed at slightly different angles (deviation angle). The end result is a spread of colored light which we call a spectrum. The angular spread between the blue and the red ends of the spectrum is called the angular dispersion.

This dispersion, for every order generated by a grating, is very linear. This makes it easier to measure the wavelengths of the various colours (and any absorption/emission features in the spectrum).

Dispersion, Plate Scale and Resolution (The Long Answer)

All spectroscopes are designed to separate light into various wavelengths and spread it into a colored band called a spectrum. The blue light is “bent” (deviated) the least, away from the optical axis, the deviation angle for the red light being much more. The difference in these deviation angles is called angular dispersion. When the spectrum image is focused by a lens onto a CCD, the size of the spectrum recorded is measured by its linear dispersion, or plate scale (not to be confused with resolution) and is usually measured either in Å/mm or Å/pixel (nm/mm or nm/pixel), when using an imaging camera. A low dispersion system would be 200 Å/mm (20 nm/mm) and high dispersion <10 Å/mm (1 nm/mm). As the amount of available light, say from a star, is limited and not all this light ends up in the first order spectrum, the lower the dispersion the brighter the spectrum will appear.

NOTE: For any configuration the dispersion will be constant. If the grating and its distance to the CCD remains unchanged the dispersion will always be the same. This can be helpful when imaging new spectra and calibrating without a zero image. We can select only one prominent line and apply a single point calibration. See Chap. 4.

Depending on the size of the CCD sensor more or less of the spectrum will be recorded on the image. Like telescopes, the measure of the detail seen in the spectrum is limited by its resolving power. In the case of a grating spectroscope, this is the ability to detect differences between very close features in the spectrum, like absorption bands.

The theoretical spectral resolution (R) is defined as:

$$R = \lambda / \Delta\lambda$$

where $\Delta\lambda$ is the minimum wavelength distance between two features in the spectrum that are resolved. Sometimes this is called the Rayleigh limit. For example, a

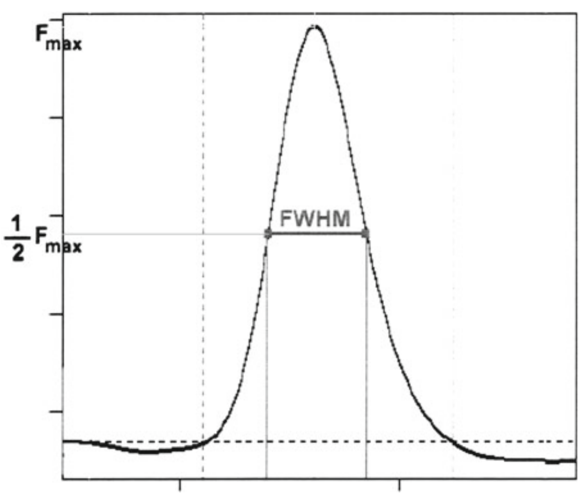

Fig. 6.7 FWHM

spectroscope where two fine lines around the blue end of the spectrum (say at 4000 Å), 10 Å apart, are just seen separated would have an R value of 4000/10 = 400. A low resolution spectroscope would have an R = 100 (resolving 6 nm at 600.0 nm), whereas a high resolution one can be at R = 10,000 to 20,000 (0.06–0.03 nm at 600.0 nm). To get a high resolution generally means using a high dispersion system.

If you look closely at the intensity distribution of an emission line formed by the grating you will see it actually takes the form and shape of a curve. The emission line originally may have been a precise tight line source, but the seeing conditions and optics distort the image, and you end up with a curve. A useful method of determining the size of the curve is to measure its width at a point equal to 50% of the peak intensity; this result is called the full width half maximum (FWHM). This result can also be taken as a measure of resolving power. See the example in Fig. 6.7.

The spectral resolution can be influenced by factors such as:

- Size of the star image
- Distance from the grating to the camera/CCD
- Number of lines on the grating
- Width of the slit (when used)
- Focal length of the camera lens (when used)
- Pixel size of the CCD.

For a transmission grating, some of the light is un-deviated as it passes through the grating and gives a "zero order" image. Spectra are formed symmetrically about this zero order image at various angular distances, the first order being the brightest.

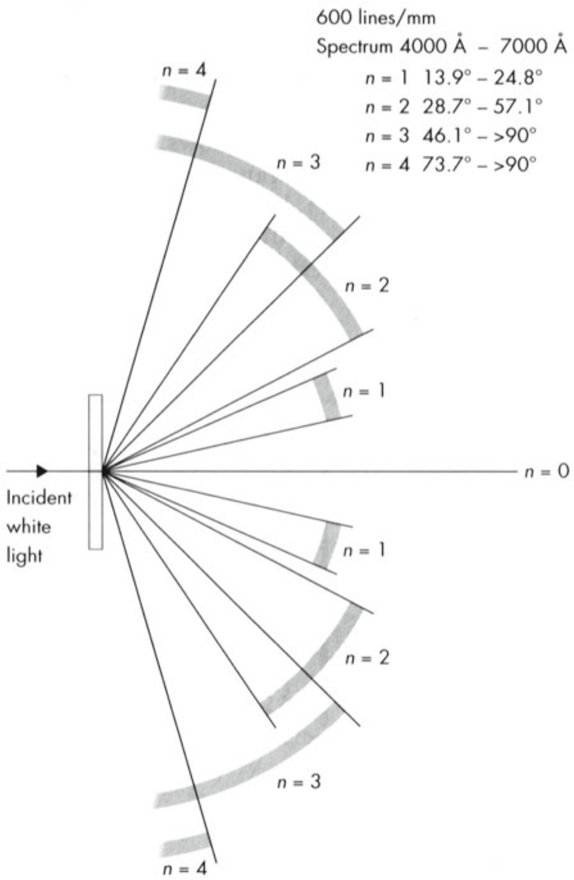

Fig. 6.8 Spectra spread from a 600 l/mm grating (S. Tonkin)

The grating equation gives the formula for the deviation angle for various wavelengths of light:

$$nN\lambda = sin\alpha + sin\beta$$

This equation defines the relationship between the angle of the incident beam (α), the angle of the exit beam (β), the spectrum order (n), the grating l/mm (N) and the wavelength of the light (λ).

Due to the linear dispersion of gratings, the second order spectrum is twice the length of the first order and can overlap on the red portion of the first order. (The 400 nm in the second order will be produced at the same point as the 800 nm in the first order.) The non overlapped length of the spectrum defines the free spectral range of the grating. See Fig. 6.8.

The interference in the red portion of the first order spectrum by the blue region of the second order spectrum can be easily suppressed by using a red filter. (A Wratten 29A filter will allow imaging of the Hα (656.3 nm) region without second order interference.)

For a grating positioned square to the incoming light (α = 0), the spectral deviation of the first order spectrum (n = 1), a 100 l/mm grating (N) based on 550 nm (λ) is:

$$Sin\beta = nN\lambda$$

$$Sin\beta = 1*100*550*10^{-6}$$
$$\beta = 3.15^{\circ}$$

The deviation angle for filter gratings with low l/mm is small, and this allows them to be used inline with the camera.

For green light (550 nm) the deviation angles for the common filter gratings are:

100 l/mm	3.15°
200 l/mm	6.3°

Due to the changing deviation angle with the wavelength, the spectrum is spread out over a wide angle. This spread of wavelength or spectral dispersion is given by:

$$d\lambda / d\beta = N\,Cos\beta / n$$

For small angles, cosβ tends to 1, giving the dispersion as approximately:

$$d\lambda / d\beta = N / n$$

When the spectrum is recorded on a CCD, we have to take into account the distance between the grating and the CCD chip. The size of the spectrum image on the CCD is measured in Å/mm and called the linear dispersion or plate scale. The conversion from angular to linear dispersion is given by:

$$linear\ dispersion\ or\ plate\ scale = 10^7 cos\beta / nNL\ Å / mm$$

where L is the distance from the grating to the CCD.

For a 100 l/mm grating and first order spectrum at a distance of 80 mm this gives:

$$plate\ scale = 10^7 cos(3.15^{\circ}) / 1*100*80Å / mm = 1248Å / mm$$

NOTE: The dispersion of the second order is twice that of the first; a 100 l/mm grating working in the second order will have the same dispersion as a 200 l/mm working at first order.

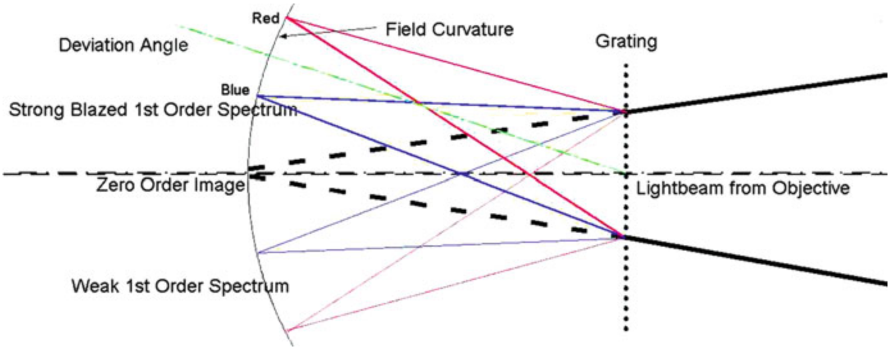

Fig. 6.9 Deviation angle and field curvature for a filter grating in a converging beam

The spectral resolution, based on the Rayleigh criteria is:

$$\lambda / \Delta\lambda = nN = R$$

More illuminated lines on the grating give a higher theoretical resolution; hence using the maximum l/mm and the largest distance between the grating will maximize the theoretical resolution. This theoretical maximum is never usually achieved in practice due to the optical aberrations present in the converging beam arrangement. See below.

The light distribution across the zero image and subsequent spectra is approx 50% in the zero image, 15% in each of the first order, 5% in the second and so on. This is very inefficient, and to improve this distribution most professional gratings are now "blazed". Blazing is where the shape of the groove in the grating is tilted to preferentially deviate the maximum amount of light into one of the first order spectra. This can dramatically improve the efficiency, and up to 70% of the incoming light can be directed into the first order.

The various wavelengths in the spectrum are formed at different deviation angles, and unless the camera is correctly re-adjusted between the blue and red, some of the spectrum will be out of focus. Focusing on the zero order image will not give a good focus on the spectrum. See Fig. 6.9.

Reducing Aberration: Adding a Grism

There are two significant optical aberrations that affect the resolution when the grating is used in the converging beam – field curvature and spectral coma.

Field Curvature

The image of the spectrum is formed along a cylindrical curve with a radius equal to the distance between the grating and the CCD. Therefore the zero order image, the blue and red regions, will be focused at different distances along the optical axis. This is shown in Fig. 6.9.

You can see, with a zero order image focused on the optical axis of the telescope that the preferred blazed spectrum lies off to the side. The blue region is closest to the zero image and comes to a focus some small distance in front of the zero order image. The out of focus condition gets worse towards the red end of the spectrum. In a setup where the camera/CCD is mounted square behind the grating, the effect of the field curvature can be minimized by focusing the CCD on the spectrum rather than the zero image.

For maximum resolution, however, a particular area (or line feature) should be focused rather than a "nominal" mid-point on the spectrum. To calculate the difference between the zero order focus and wavelength λ we can use the following formula:

$$\Delta L = 3\,L(tan\beta)^2 / 2$$

where β is the deviation angle for the target wavelength.

For Hα (6563 Å), (β = 3.76°), a 100 l/mm grating and a grating distance of 80 mm, this gives:

$$\Delta L = 3 * 80 * (tan(3.76^{\circ}))^2 / 2 = 0.52mm$$

This means that the red Hα light would be brought to a focus 0.52 mm in front of the zero order image. Or, in other words, the zero image should be positioned *out of* focus by 0.52 mm to bring the Hα *into* focus…

If the camera/CCD can be tilted/rotated relative to the grating (or the grating itself tilted), then the effects of field curvature can be further reduced by setting the angle of the grating to the deviation angle of the spectrum.

Spectral Coma

This aberration (sometimes called chromatic coma) is similar to that seen in fast optical systems where "seagull" like distortions are evident towards the edge of the field of view and affects all wavelengths of light. Figure 6.10 shows the coma spread for various wavelengths (based on a SA100 and a distance of 85 mm between the grating and the CCD).

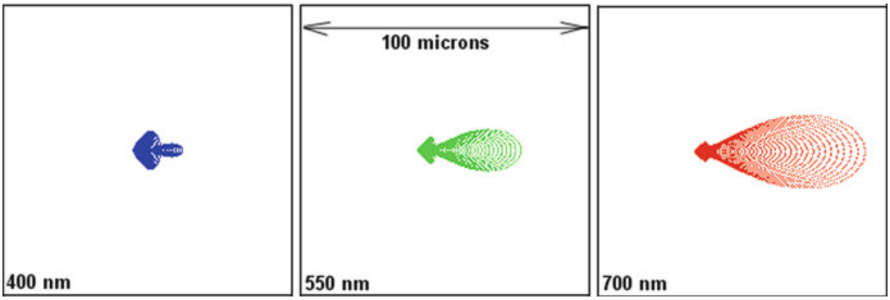

Fig. 6.10 Spectral coma images (C. Buil)

The formula for the spectral coma aberration is:

$$\Delta\lambda = 3\lambda / 8f^2$$

As the distorted image contains 80% of the light in 50% of the image, we can safely use half of the above result. Note that the coma varies both with wavelength and the inverse square of the focal ratio (f). A faster focal ratio therefore gives smaller star images but more spectral coma.

This coma has a negative effect on the resolution:

$$linear\ coma\ image\ size = 3L\ tan\beta / 16f^2$$

$$spectral\ coma\ resolution, R_c = 16f^2 / 3$$

For an f6.3 system, again looking at Hα (6563 Å) and distance between grating and CCD of 60 mm, we get:

$$coma\ resolution, R_c = 212$$

and a coma image of 31 Å.

The effects of spectral coma can be reduced by adding a small prism just in front of the grating to compensate and apply a reverse deviation (Fig. 6.11), bringing the image of the spectrum back onto the optical axis. This configuration is called a "grism," (*gr*ating pr*ism*), or Carpenter prism. The required deviation angle of the prism should be calculated to match the deviation angle of the grating at some nominated wavelength.

Based on the properties of the prism, the refractive index (n), we can calculate the prism angle required. The prism deviation angle (θ) is calculated from:

$$\theta = nN.\lambda_0.n_o / \left(n_o^2 - 1\right)$$

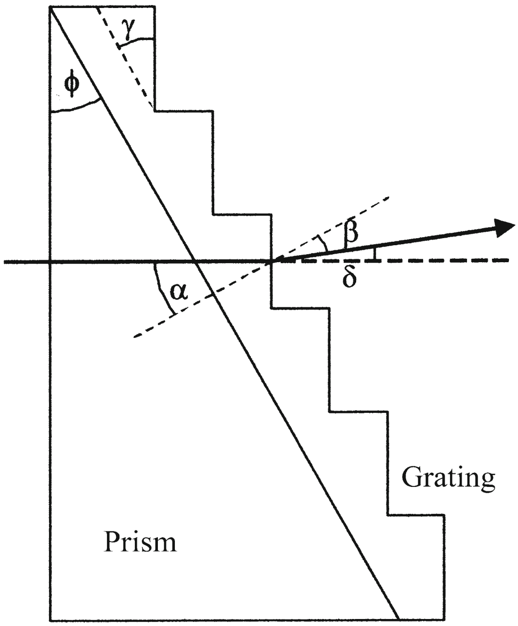

Fig. 6.11 Grism optical arrangement (J. Allington-Smith)

For $n_o = 1.5$, and a first order spectrum (n = 1) using a 100 l/mm grating (N = 100) this gives:

$$\theta = 120\lambda_0 Radian$$

So, for 550 nm wavelength, the prism deviation angle would be:

$$\begin{aligned}\theta &= 120 * 550 * 10^{-7}\,Radian\\ &= 0.066\,Radian\\ &= 3.78^{\circ}\end{aligned}$$

This gives a prism deviation angle of approximately 3.8° × l/mm/100

Suitable 25 mm diameter wedge prisms (Fig. 6.12) are available from most of the optical suppliers. (See Appendix F in this book.)

Using this prism will bring the 550 nm wavelength back onto the optical axis and significantly reduce the spectral coma. Any remaining field curvature can be reduced by refocusing on the target wavelength.

The wedge angle of the prism must be aligned to the direction of the grating grooves to achieve the necessary chromatic corrections, the thickest part of the prism wedge being positioned towards the zero order image. (See Fig. 6.13).

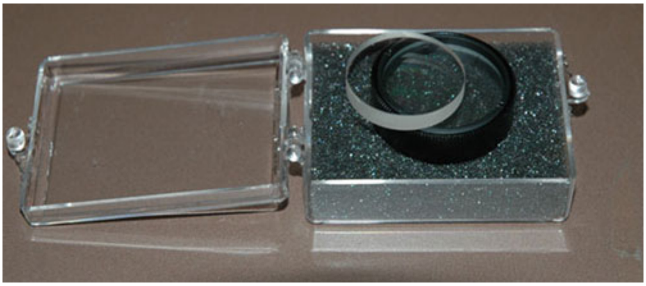

Fig. 6.12 Wedge prism and grating (Blackwell)

Fig. 6.13 Grism mounted to an SA100 grating (C. Buil)

Although using a grism can improve the resolution on the SA100 (by up to 20%); it gives better results when applied to gratings with 200 l/mm and above.

Non Linearity of the Spectrum

Unfortunately, adding the prism also introduces some slight non-linearity into the spectrum. This means that the dispersion and hence the plate scale and calibration of the spectrum doesn't follow a linear relationship between position and wavelength (i.e., wavelength = ax) but needs a "correction" equation to be prepared based on at least three points along the spectrum (generally in the form of wavelength = $ax + bx^2 + cx^3$). Both VSpec and RSpec software have built in methods to do this.

For completeness, you should also be aware that notwithstanding the earlier comment, the spectrum from a grating is not perfectly linear either! The grating equation given at the beginning of this chapter shows the dispersion to be a function (Sin) of the incoming and outgoing angles (α and β). For small angles this effect is minimal, but for larger l/mm gratings where β can reach 20° the effects are noticeable. This is also complicated by the effects of spectral coma, which tends to spread the red part of the spectrum more than the blue. These factors all add up and when preparing detailed wavelength calibrations need to be considered. Sorry about that.

Chapter 7

Spectral Analysis: A Bit of Theory

As was mentioned in the introduction, most of the knowledge we have today about stars has come from observations made with spectroscopes. In fact the term "new astronomy" was coined in the late 1800s to reflect the major changes in our understanding of the universe caused by the spectroscope. We can continue to contribute to this new age of astronomy – even with our humble grating spectroscope. In this limited introduction to spectral analysis, quantum theory and star classification we will see the opportunities and challenges available to the amateur and his/her spectroscope.

It's not difficult to obtain spectra, calibrate spectra and determine most of the significant information it tells us. We can determine the temperature of a star and the likely classification based on the absorption lines of the elements. From that we can position the star on the H-R diagram and consider its age and probable path through to destruction.

We must remember that the science of spectroscopy, like that of photography, is a relatively modern science. There was little understanding of what a spectrum really was and what it could tell us. The early experimenters had to feel their way along the dark corridors of ignorance before they could emerge into the bright light of understanding. It was only in the early to mid-1800s that the basic principles of diffraction and the first tentative steps of spectral analysis were carried out.

Kirchhoff's Laws

The first absorption lines were recorded in the Sun's spectrum by observers in the late 1790s, but it wasn't until 1815 that the German optician Joseph Fraunhofer accurately mapped the more prominent lines. He found that the positions of the

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4_7,

dark lines never varied, and he successfully used them to test and produce different types of quality glass, a method still used today to calibrate the color correction of optics. We still refer to Fraunhofer's listing to identify lines such as Hα (C line), sodium doublet (D1 and D2), etc. The nature of these lines was unknown, and it became a challenge to the scientists of the day to determine what they were and why they existed. There were many theories but no conclusive evidence, and it was only in the 1830's that the early German investigators Kirchhoff and Bunsen managed to find that the bright spectra produced by heating elements (sodium was the first) in the laboratory matched the wavelength of particular dark lines when a bright spectrum was viewed through vapors of the same gas. This proved to them that each element had a signature absorption/emission wavelength. They also carried out a series of experiments to determine the effects of pressure on gases in the laboratory spectra they were investigating. This gave rise to Kirchhoff's laws:

1. An incandescent solid or a gas under high pressure will produce a continuum spectrum.
2. An incandescent gas under low pressure will produce an emission line spectrum.
3. A continuous spectrum viewed through a low-density gas at low temperature will produce an absorption line spectrum.

When these laws are applied to astronomical spectra they allow us to understand the nature of stellar atmospheres.

A star is generally a collection of very hot gas under tremendous pressure and will produce a continuum spectrum (Law 1).

The light from the star, as it travels through the cooler outer layers of the star's atmosphere, will show the various elements as absorption lines (Law 2).

Law 2 then allows the astronomers not only to determine the elements in the star but their concentrations.

A series of emission lines (the emission spectra) are seen when a gaseous nebula is excited by nearby stars and provide a unique fingerprint of the gases, i.e., hydrogen, oxygen, etc. (Law 3).

Some stars, notably Be stars, also show emission features due to a local transfer of matter to a surrounding darker dust/gas cloud.

Nowadays almost every element on the Periodic Table has been identified in stellar spectra, not just as a single line per element (life is just not that simple!) but as a series of lines that depend on the conditions (pressure, temperature, etc.) within the star. We need to use some quantum physics to unravel this jungle of information. See later.

Blackbody Radiation

Kirchhoff also proposed his blackbody theory of thermal emission. This theory states that the intensity distribution of light emitted by a body (i.e., a star) will follow a regular shape dependent on its temperature. This is the blackbody curve.

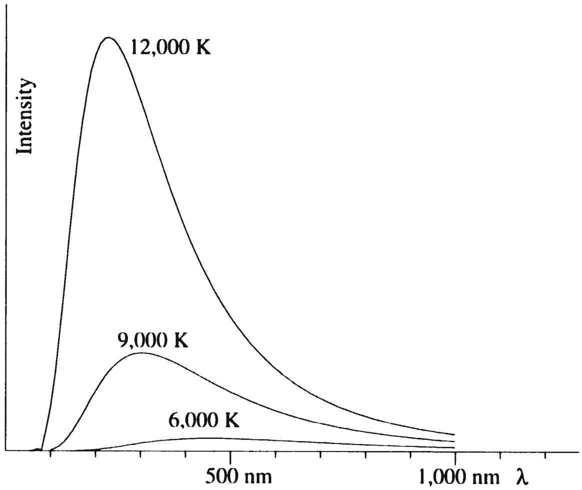

Fig. 7.1 Planck curves (From H. Karttunen et al., *Fundamental Astronomy*, 4th edn. Springer, 2003)

When a body is heated, the peak wavelength of the light emitted varies, peaking initially in the infrared and moving towards the UV. A dull red is normally visible when material (such as steel) is heated to around 800°; as the temperature increases, the color becomes orange and eventually white (white hot). Wein and Planck later developed a mathematical model to give the peak wavelength for a blackbody.

$$\lambda_{max} = 2{,}897{,}820 / T$$

where T is the temperature in Kelvin and λ_{max} the peak emission wavelength in nm. A series of Planck curves (Fig. 7.1) can be drawn up for various temperatures.

The shape of the continuum spectrum reflects the surface temperature of the star. The Planck curves show the position of the peak energy as the star moves towards the blue/UV region with increasing temperature. The Sun, a 5,800° star, peaks in the green, around 500 nm, whereas a hotter star such as Vega (10,000°K), peaks in the blue around 350 nm. The shape of the spectral continuum can therefore assist in determining the surface temperature of the stars. This, together with information of element absorptions, allow the accurate classification of a star to be determined.

Quantum Theory

Once we've obtained a spectrum, we want to analyze it and extract as much information from it as we can. The limited resolution of grating spectra can sometimes make this difficult. Whereas in larger spectroscopes it's easier to determine which

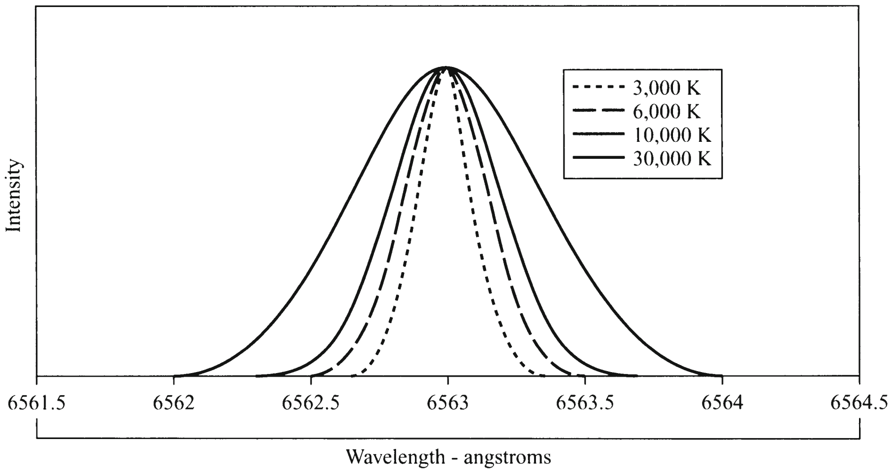

Fig. 7.2 Broadening of the Hα line due to temperature (K. Robinson)

absorption or emission feature belongs to which element, in a grating spectrum they can appear blended, and a number of very close lines can appear just as a large dip rather than individual lines. It is possible, however, to learn a lot and even determine the temperature and chemical composition of the star.

It helps to understand how the various lines are formed, and this can sometimes give a clue as to which lines may or may not be visible. Welcome to the world of quantum physics.

As per Kirchhoff's laws, the bright continuous spectra of a star will be overlaid by absorption and emission features from the surrounding stellar atmosphere. Each element will absorb/emit in a unique series of wavelengths dependent on temperature. These lines can also be modified by temperature, pressure and electromagnetic fields.

Figure 7.2 shows the effects of temperature in the Hα line. You can see it's much narrower at lower temperatures (3,000°) than it is at 10,000° or above. This is very noticeable when you take a series of stellar spectra. Using this knowledge we can now determine the temperature of a star either by interpretation of the shape of the Planck curve or by comparison of the broadness and visibility of the hydrogen absorption lines.

So far so good. But how are these spectral lines formed? How do we know which line belongs to which element?

Quantum mechanics is the answer. An atom of any element is made up from a nucleus and a surrounding collection of electrons. These electrons normally move in stable orbits, and the amount of energy they have is determined by (among other things) the position of the orbit. When an atom is subjected to pressure or temperature, the electrons can absorb (or give up) some of their energy. Planck (yes, the same guy) found that the energy changed in small “packets” called “photons.” Each time the energy level changes one or more photons are absorbed (or given up). The release or absorption of these photons can be seen in the light absorbed or emitted. Planck also found that energy and wavelength are related.Here is Planck’s constant:

$$\Delta E = h\nu$$

where ΔE is the change in energy, ν, the frequency of the radiation (photon) emitted/absorbed and h, Planck’s constant = 6.6256×10^{-34} Js (joules second).

When energy is added to the atom – through heat, collision, electromagnetic fields, etc., the electron(s) move to stable orbits further from the nucleus. In absorbing this energy, the photon equivalent is seen as dark absorption lines in the spectrum. Similarly when photons are emitted during energy loss, emission lines are seen.

As each atom has a different number of electrons (well – usually!) there are limited options to the number of orbits and the number of electrons in each. In fact, if the energy change is very high, electrons can be stripped away from the atom entirely.

The various energy levels of the electron movements are shown in Grotrian diagrams. See Fig. 7.3.

As hydrogen has only one electron, the available energy levels can easily be mapped, giving rise to the Balmer series of absorption lines in the spectrum.

The Hα transition is the most common and gives rise to the most prominent line, followed by Hβ which is about 50% the intensity of the Hα. The series continues through the Hγ, Hδ and Hε lines as we progress down into the UV. Further Balmer lines are given numbers, i.e., H8, H9, etc.

Forbidden Lines: Ionization

When an atom absorbs or emits large amounts of energy, the surrounding electrons can be moved through many of the available orbits or even displaced from the atom completely. The atom is then said to be ionized. When more than one electron is removed we can get double and even triple ionization. Due to the enormous amounts of energy required, these transitions have a very low probability of occurring normally and, as they are seldom seen in the laboratory, gave rise to the terminology “Forbidden Lines.” See Fig. 7.4.

In spectroscopy we use square brackets and the uppercase Roman numeral I where the base state is I and subsequent ionization levels are [CaII], [OIII], etc.

The early investigators could not replicate the necessary conditions to see these ionized lines and therefore did not recognize the emission/absorption “signature” of the ionized element. This gave rise to “new” elements being named, such as “Nebulium” for [OIII] and “Coronium” for highly ionized metals.

The forbidden lines of oxygen and hydrogen are generated in most of the emission nebulae we see and are easily recorded by the spectroscope.

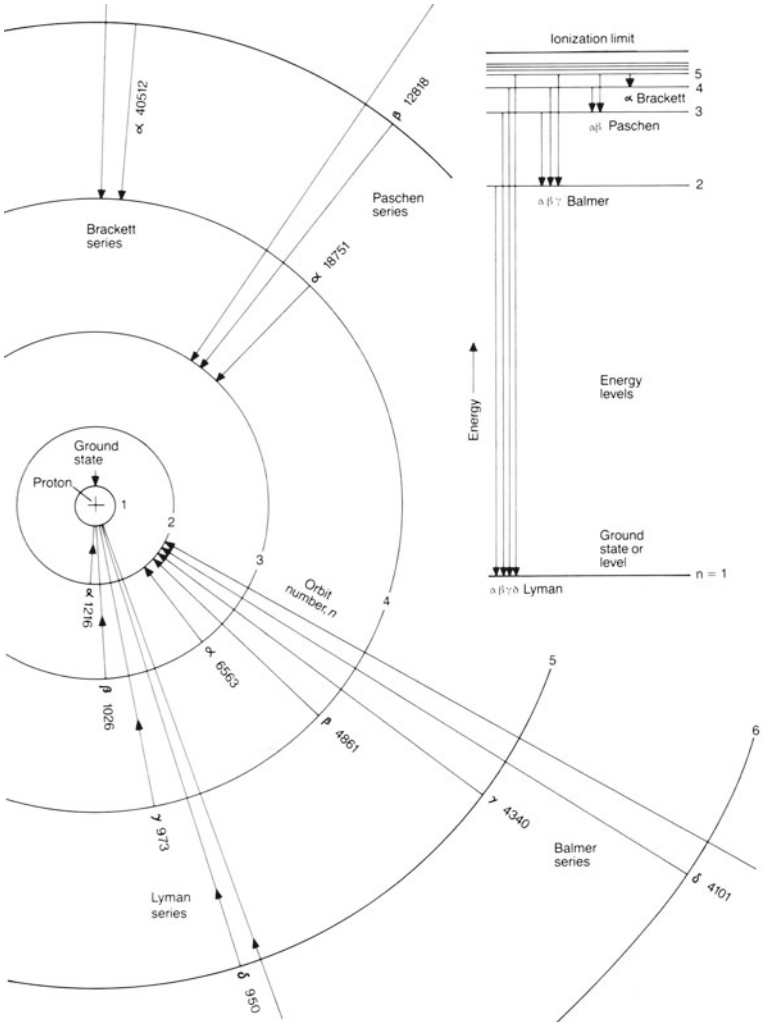

Fig. 7.3 Balmer series (From J. B. Kaler's *Stars and their Spectra,* Cambridge, 1989)

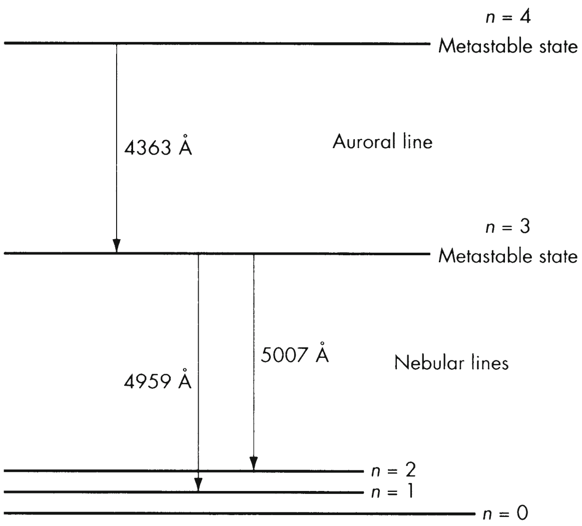

Fig. 7.4 OIII ionization diagram (K. Robinson)

This is only a brief introduction. For more detailed explanation of the various atomic structures and additional line series (Lyman, Paschen, etc.), see the Further Reading section of this book.

Doppler/Redshifts

The Doppler effect is the change in frequency caused by the change in velocity between a source and an observer, easily noticed in everyday life as the rising pitch of the police siren as it approaches you and the sigh of relief when it goes away. Doppler shift is visible in the spectrum when there is relative movement between the observer and the object. As the object recedes the visible wavelengths are moved towards the red. The effect can be seen in the rotation of the Sun and planets as well as binary stars. It allows the measurement of radial velocities, though only towards or away from the observer.

$$\Delta\lambda / \lambda = v / c$$

where $\Delta\lambda$ is the shift in the spectral line, λ its stationary wavelength, v the velocity of recession (or approach) and c the velocity of light (299,800 km/s).

The shift, say, in Hα (6563 Å) for a speed of 500 km/s would be 6563×500/299,800 = 11 Å.

Recording this difference would just be within the capabilities of our gratings, using a suitable range of reference lines for comparison.

In the case of distant galaxies, quasars, etc., the speed of recession (redshift = z) can be significant and give rise to significant movements in the spectral lines.

$$redshift(z) = \left(\lambda_{observed} - \lambda_{emitted}\right) / \lambda_{emitted}$$

It is possible with amateur-sized spectroscopes to measure this shift. Transmission gratings have been successfully used to record the redshift of quasars and other active galaxies by using the zero image and other "stationary" star spectra as reference. See Chap. 3 of this book.

Stellar Classification: What You Need to Know

Stars come in all shapes and sizes. Some are much brighter than others, some more massive than others. With the aid of a spectroscope we have managed to get a better understanding of how the stars were formed, how they live, and, yes, how they will die. The first steps along this path were taken in the late nineteenth century and continue today.

HD Classifications

In the early 1900s the astronomers at Harvard took advantage of the improvements in photography and used the most sensitive photographic plates they could find to record the spectra of stars. Using large objective prisms on their telescopes they produced a large collection of spectra, which resulted in the Henry Draper catalogue (HD) based on the spectra of over 230,000 stars. These spectra were analyzed by a team of dedicated young women, including Annie Jump Canon who, over the next few years, developed a classification system.

The original HD stellar classifications were based on the observed strength of the hydrogen lines, and an alphabetical sequence was used, i.e., A, B, C, etc. This sequence generally followed the temperature of the stars. Classes C, E and H were dropped, and it was left to Cannon to come up with the sequence we are familiar with today:

```
          W       C
          |       |
O    B    A   F   G   K   M
                          |
                          S
```

The R and N stars (carbon rich stars) were combined into the C class of the G branch and S stars (zirconium) of the M branch. The initial classifications of P (planetary nebulae) and Q (nova) are seldom used today.

Canon herself proposed the mnemonic "Oh be a fine girl kiss me" to remember the classification sequence.

As the O class was at the beginning of the list it became the "early" class and the M series the "later" class. It was subsequently determined that the sequence effectively mapped the temperature of the stars, the hot stars being O class and the cooler stars M class. Early and late descriptions have nothing to do with the evolution of a star. As further investigations continued it was found that the spectra subtly varied with a classification; this was found to be due to the mass of the star.

In the early 1940s the classification sequence was further refined by Morgan, Keenan and Kellman into the MKK system. This resulted in the rationalizing of the subseries (generally 0–9) and the addition of luminosity classes to differentiate between giant, main sequence and dwarf stars and a series of prefixes and suffixes to give further information.

Based on the original objective prism spectra the following criteria were used for classification:

Class O	Ionized helium, silicon, nitrogen, etc.
Class B	Neutral helium, stronger Balmer lines of hydrogen
Class A	Strong Balmer lines, appearance of ionized calcium and neutral metals
Class F	Weaker Balmer lines and ionized metals; strong neutral metal lines
Class G	Balmer lines very weak, strong ionized calcium lines and stronger neutral metal lines.
Class K	Molecular bands (TiO) appear; neutral metal lines
Class M	Dominated by molecular bands (TiO), strong neutral calcium lines

Figure 7.5, below, shows graphically the strength of the various lines used for classification of the stars. It's obvious that the hydrogen lines will be a dominant feature of the A-class star spectra but will get lost in the jungle of metal lines (Fe and Ca) in a Class K star.

The MKK Spectral Sequence

O4–O9.5	
B0–B9.5	(B0.5 added, B4 B6 and B9 omitted)
A0–A7	(Omitting A1, A4 and A6)
F0–F9	(Omitting F1, F4 and F6)
G0–G8	(Omitting G1, G3 G4, G6 and G7)
K0–K5	(Omitting K1)
M0–M9	(Omitting M5 and M6)

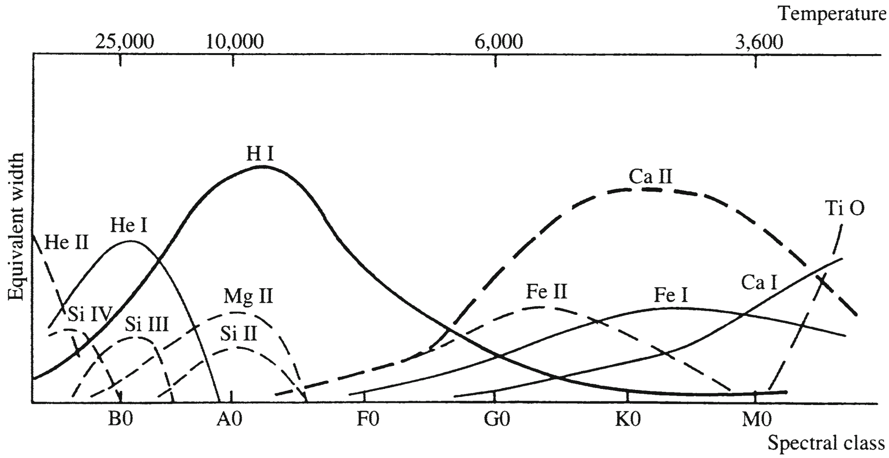

Fig. 7.5 Equivalent line widths (*Elementary Astronomy* p. 259. Struve, O. Cambridge, 1959)

Luminosity Classes

0 –	Extremely bright supergiants
Ia-	Bright supergiants
Ib-	Supergiants
II-	Bright giants
III-	Normal giants
IV-	Subgiants
V-	Main sequence stars
VI, sd-	Subdwarfs
VII, wd-	White dwarfs

Suffixes and Prefixes Used in Spectral Classifications

Prefix

b-	Wide lines
a-	Normal lines
c-	Very narrow lines
d-	Dwarf (main sequence, luminosity class V)
g-	Giant (luminosity class III)
sd-	Subdwarf (luminosity class VI)
wd-	White dwarf (Luminosity class VII)

Suffix

e-	Emission lines
em-	Emission lines (metallic)
er-	Reversed emission lines
ep-	Peculiar emission lines
eq-	P Cygni type emissions
f-	He and N emissions (O-type stars)
n-	Diffuse lines
nn-	Very broad diffuse lines
s-	Narrow or sharp lines
k-	Interstellar lines
v-	Spectrum is variable
pec-	Peculiar spectrum
m-	Strong metallic lines
wk-	Weak lines
!-	Marked characteristics

The spectrum of a star can therefore be classified and recorded as a combination of the above.

Our Sun is a G2V star – a yellow main sequence star in the G2 class with a surface temperature of 5,800°C. Sirius on the other hand is a bright white A1V main sequence star and Arcturus a normal orange Giant K1 III star.

The H-R Diagram

Hertzsprung and Russell took things one stage further when they plotted the spectral classifications against the absolute visual magnitudes (Fig. 7.6). The absolute magnitude of a star is its brightness seen from a fixed distance of 10 pc (a parsec is equal to a distance of 3.26 light years). This magnitude then tells us whether the star is actually a bright (or faint) star and not just close by (or far away). Our Sun has an absolute magnitude of +4.82. (Appendix B in this book gives the absolute magnitudes for some of the brighter stars.)

The graph produced showed a grouping of stars in various regions. This "H-R diagram" clearly showed the differences between giant stars, a group sitting above a larger continuous band of stars (main sequence), and the dwarf stars below.

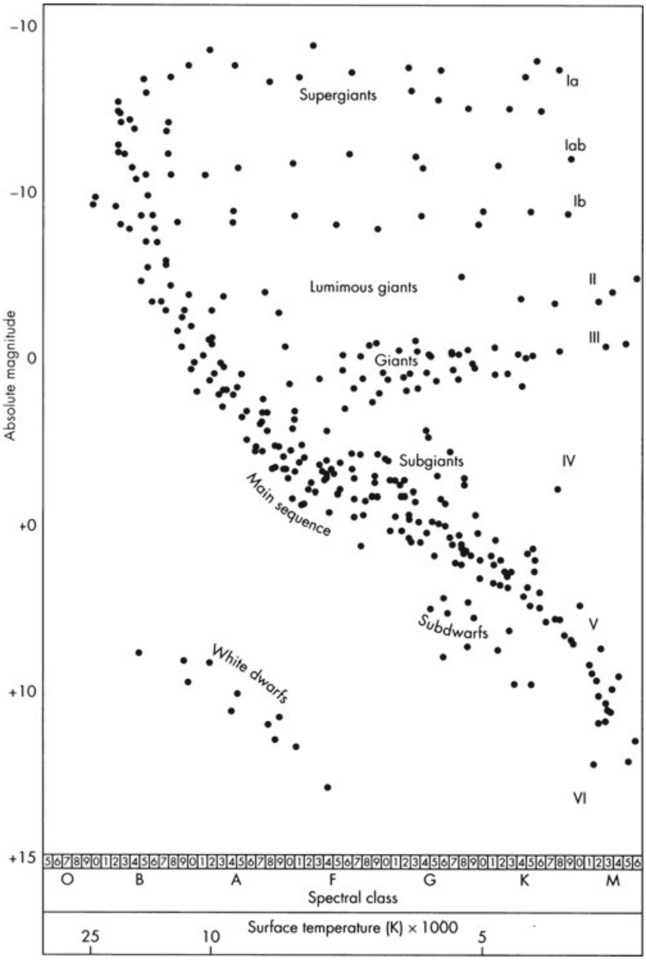

Fig. 7.6 H-R diagram (S. Tonkins)

Standard Spectral Lines and Reference Spectra

Reference Spectra

With the low resolution of the grating many of the discrete emission and absorption lines in the spectrum of stars can get lost. What should be a collection or series of close absorption lines becomes an extended “dip” in the spectrum, making positive identification almost impossible. There are a few resources available that at least can provide some data to assist us.

Firstly, remember the equivalent width curves and the OBAFGKMRN sequence given earlier. These provide the starting point for line identification.

Comparing spectra with known references is the next step. There are many spectral libraries available on the Internet as well as the occasional spectrum published in popular magazines such as *Sky & Telescope.* Use these whenever you can.

Richard Walker's *Spectroscopic Atlas* is very comprehensive. The careful annotating of each spectrum provides details of the visibility of the various element lines.

The PICKLES spectral library is included in the VSpec and RSpec database and although not annotated can be compared with the element lines to determine the obvious features. Similarly the ELODIE archives from the Observatory de Haute Provence (a series of high resolution spectra) and the UVES spectra (European Southern Observatory) can be downloaded and imported into VSpec for comparison. (As these are very high resolution spectra it's easier to "dumb them down" and reduce the resolution by applying a spline smoothing filter – similar to the process used on the instrument response curve in Chap. 4 – before comparing them directly with the grating examples.)

Standard Spectral Lines

To accurately calibrate the spectrum we need a series of reference lines that can be used to measure the dispersion of the spectroscope and its resolution. Once we have calibrated our spectrum it is possible to measure the positions of absorption and emission lines to determine the atoms or molecules involved.

The professionals make use of special reference lamps, including thorium/argon, that emit their light in well documented discrete lines. For the average amateur these are very expensive, and alternative methods need to be considered.

The easiest method of spectral calibration is to calibrate the grating setup using known lines in a spectrum of a standard star (such as Vega) and then using this calibration to determine the unknown lines in the target star. The most obvious of these are the Balmer series of hydrogen. See Fig. 7.7.

Balmer Series

Hα	656.3 nm
Hβ	486.1 nm
Hγ	434.0 nm
Hδ	410.2 nm
m = 7, etc.	397.0 nm
m = 8, etc.	388.9 nm
m = 9, etc.	385.5 nm
m = 10, etc.	379.7 nm

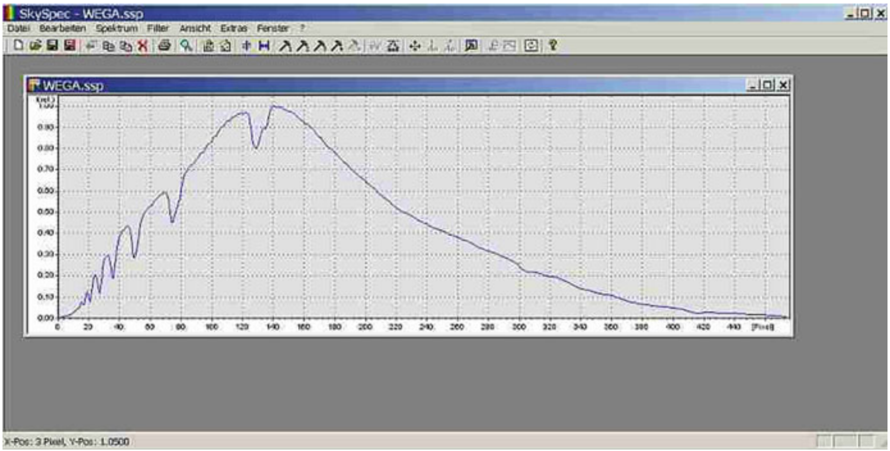

Fig. 7.7 Spectrum of Vega (SkySpec-B. Marquardt)

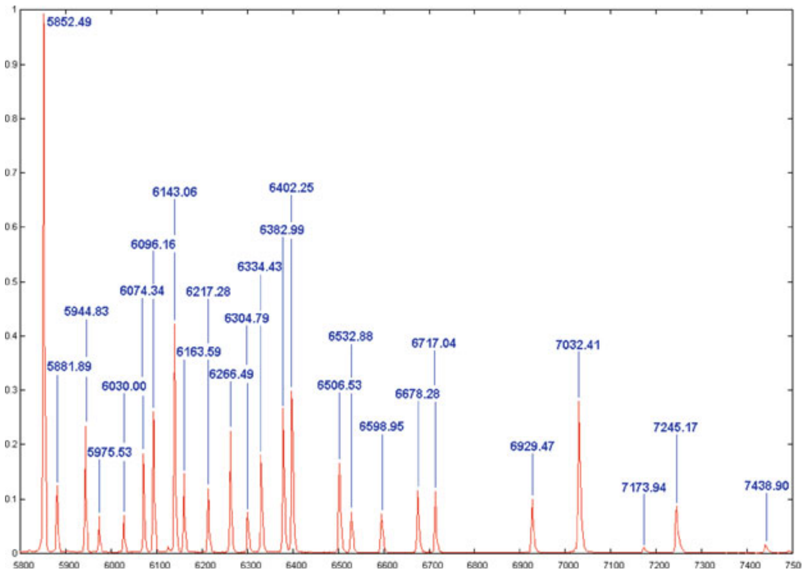

Fig. 7.8 Neon lamp spectrum (C. Buil)

When we use an entrance slit with the grating, a reference lamp can be used to illuminate the slit and provide a series of reference lines. Neon indicator bulbs can be used as a reference light source.

The neon gas gives a series of bright emission lines covering 585.25 nm through to 724.52 nm. See Fig. 7.8.

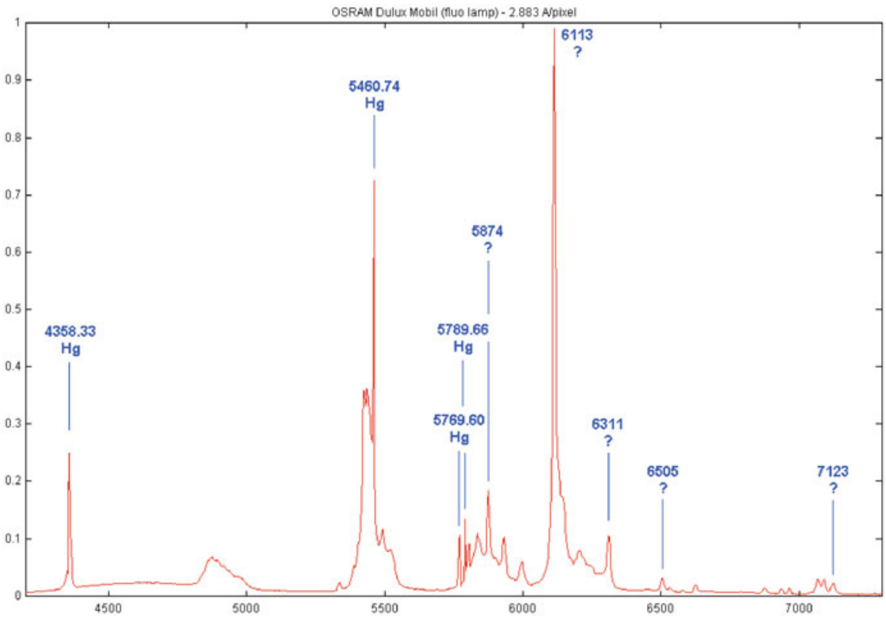

Fig. 7.9 Fluorescent lamp spectrum (C. Buil)

As an alternative to the neon, an energy-saving fluorescent bulb such as the Osram Duluxe Star can be used. These bulbs provide an excellent series of mercury lines from 435.83 to 587.4 nm. There are also some strong emission lines at 611.3 and 631.1 nm as shown in Fig. 7.9.

Other Useful Spectral Reference Lines

Fraunhofer Lines

Label	Wavelength (nm)	Source
A-band	759.4–762.1	Atmospheric O_2
B-band	686.7–688.4	Atmospheric O_2
C	656.3	Hα
a-band	627.6–628.7	
D1	589.6	Na I
D2	589.0	Na I
E	526.9	Fe I
b1	518.4	Mg I
b2	517.3	Mg I

(continued)

(continued)

Label	Wavelength (nm)	Source
c	495.8	Fe I
F	486.1	Hβ
d	466.8	
e	438.3	Fe I
f	434.0	Hγ
G	430.8	Ca/Fe (430.77/430.79)
g	422.7	Ca I
h	410.2	Hδ
H	396.8	Ca II
K	393.3	Ca II

Nebula Emission Lines

NII	658.4 nm
Hα	656.3 nm
OIII	500.7 nm
OIII	495.9 nm
Hβ	486.1 nm
HeII	468.6 nm
Hγ	434.0 nm
NeIII	386.9 nm

O_2 and H_2O Atmospheric Telluric Lines

H_2O	594.45 nm
H_2O	595.86 nm
H_2O	596.83 nm
O_2	627.8 nm
O_2	686.9–694.4 nm
O_2	760.6 nm

Common Light Pollution Lines

Sodium doublet 589.0 nm and 589.6 nm
Mercury (Hg) 404.7/407.8/435.8/502.5/546.1/577.0/579.0/615.2/623.4 nm

Conclusion

Our grating spectroscope has opened our eyes to this new world of quantum physics and allowed us to collect the basic spectral data needed to start down the road of discovery. Our understanding of what the various lines tell us can only grow with more knowledge. More sophisticated spectroscopes using slits and reflection gratings can be used to gain more detailed information – the surface pressure, the amount of each element in the star, observing the interactions of surrounding dust clouds and even if there are planets going around the star. That's the "final frontier" of amateur spectroscopy, and the journey has begun.

There are many good astronomical textbooks available to the amateur. These cover in much more detail all aspects of spectral analysis and stellar evolution. Some are listed in the Further Reading section of this book.

Appendices

Appendix A The Greek Alphabet

Alpha	Α, α
Beta	Β, β
Gamma	Γ, γ
Delta	Δ, δ
Epsilon	Ε, ε
Zeta	Ζ, ζ
Eta	Η, η
Theta	Θ, θ
Iota	Ι, ι
Kappa	Κ, κ
Lambda	Λ, λ
Mu	Μ, μ
Nu	Ν, μ
Xi	Ξ, ξ
Omicron	Ο, ο
Pi	Π, π
Rho	Ρ, ρ
Sigma	Σ, σ, ς
Tau	Τ, τ
Upsilon	Υ, υ
Phi	Φ, ϕ
Chi	Χ, χ
Psi	Ψ, ψ
Omega	Ω, ω

K.M. Harrison, *Grating Spectroscopes and How to Use Them*,
Patrick Moore's Practical Astronomy Series, DOI 10.1007/978-1-4614-1397-4,

Appendix B The Brightest Stars

Bayer name	Common name	RA.	Dec	V	B-V	D(pc)	Mv	Spectrum	Notes
	Sun			−26.74	0.65	–	4.83	G2 V	
α Canis Majoris	Sirius	06:45.2	−16:43	−1.46	0.00	2.65	1.42	A1 V	
α Carinae	Canopus	06:24.0	−52:42	−0.72	0.15	70	−5.00	F0 II	
α centauri	Rigel Kentaurus	14:39.6	−60:50	−0.01	0.71	1.33	4.37	G2 V	Combined, V = −0.29
				1.33	0.88	1.33	5.71	K1 V	
α Bootis	Arcturus	14:15.7	19:11	−0.04	1.23	10.3	−0.10	K1 III	
α Lyrae	Vega	18:36.9	38:47	0.03	0.00	7.5	0.65	A0 V	Standard star
α Aurigae	Capella	05:16.7	46:00	0.08	0.80	12.5	−0.40	G5 III G0 III	Binary
β Orionis	Rigel	05:14.5	−8:12	0.12	−0.03	265	−7.00	B8 Ia	
α Canis Minoris	Procyon	07:39.3	5:14	0.38	0.42	3.4	2.71	F5 IV	
α Eridani	Achernar	01:37.7	−57:14	0.46	−0.16	27	−1.70	B3 V	
α Orionis	Betelgeuse	05:55.2	7:24	0.50	1.85	320	−7.00	M2 Ia	
β Centauri	Hadar	14:03.8	−60:22	0.61	−0.23	95	−4.30	B1 III	
α Aquilae	Altair	19:50.8	8:52	0.77	0.22	5	2.30	A7 V	
α Tauri	Aldebaran	04:35.9	16:31	0.85	1.54	19	−0.49	K5 III	
α Scorpii	Antares	16:29.4	−26:26	0.96	1.83	190	−5.40	M1.5 Ib	Binary
α Viginis	Spica	13:25.2	−11:10	0.98	−0.23	67	−3.20	B2 V	Binary
α Crucis	Acrux	12:26.6	−63:06	1.58 2.09	−0.26	120	−7.10	B0.5 IV B1 V	Binary, Combined, V = 1.05
β Geminorum	Pollux	07:45.3	28:02	1.14	1.00	10.6	1.00	K0 III	
α Piscis Austrinus	Fomalhaut	22:57.6	−29:37	1.16	0.09	6.7	2.02	A3 V	
αCygni	Deneb	20:41.4	45:17	1.25	0.09	500	−7.20	A2 Ia	
β Crucis	Mimosa	12:47.7	−59:41	1.25	−0.23150		−4.60	B0.5 III	
α Leonis	Regulus	10:08.4	11:58	1.35	−0.11	22	−0.38	B7 V	
ε Canis Majoris	Adhara	06:58.6	−28:58	1.50	−0.21	190	−4.90	B2 II	
α Geminorum	Castor	07:34.6	31:53	1.59	0.03	15	0.72	A1 V	Multiple star
γ Crucis	Gacrux	12:31.2	−57:07	1.60	1.60	40	−0.56	M3.5 III	
λ Scorpii	Shaula	17:33.6	−37:06	1.60	−0.20	92	−3.44	B1.5 IV	
γ Orionis	Bellatrix	05:25.1	6:21	1.60	−0.20	40	2.73	B2 III	

V = Visual Magnitude
B-V = Colour Index
D(pc) = Distance in parsecs (1 parsec = 3.26 light years)
Mv = Absolute visual magnitude
Spectrum = Spectral Classification
RA/Dec = Position based on J2000 coordinates

Appendix C The Brightest Be Stars

Con.	Name	RA.	Dec	V	Spectrum	VSini
Eri	α Eri	1:37:43	−57:14:12	0.50	B6Vpe	235
Cen	η Cen	14:35:30	−42:09:28	2.30	B2Ve	310
Sco	δ Sco	16:00:20	−22:37:18	2.30	B0.2IVe	175
Cas	γ Cas	0:56:43	+60:43:00	2.39	B0IVpe	432
Cas	γ cas	0:01:25	+63:30:15	2.40	B0Ve	
UMa	γ Uma	11:53:50	+53:41:41	2.43	A0Ve	167
Cen	δ Cen	12:08:22	−50:43:21	2.56	B2Vne	260
Oph	ζ Oph	16:37:10	−10:34:02	2.58	O9Ve	348
Col	α Col	5:39:39	−34:04:27	2.60	B9Ve	180
Ara	α Ara	17:31:50	−49:52:34	2.84	B2Vne	290
Tau	Alcyone	3:47:29	+24:06:18	2.87	B7IIIe	140
CMi	β CMi	7:27:09	+08:17:22	2.89	B8Ve	230
Tau	ζ Tau	5:37:39	+21:08:33	3.03	B2IVe	245
Cep	β Cep	21:28:40	+70:33:39	3.22	B2IIIev	20
Car	ω Car	10:13:44	−70:02:16	3.30	B8IIIe	240
Ara	γ Ara	17:25:24	−56:22:40	3.31	B1IIe	302
Cas	ε Cas	1:54:24	+63:40:12	3.34	B3IIIe	30
Car	p Car	10:32:01	−61:41:07	3.36	B4Vne	266
Ori	η Ori	5:24:29	−02:23:50	3.38	B0.5Ve	170
Cen	μ Cen	13:49:37	−42:28:25	3.46	B2Vnpe	124
CMa	κ CMa	6:49:50	−32:30:31	3.52	B1.5Ve	243
Lyr	β Lyr	18:50:05	+33:21:46	3.52	B7Ve	120
UMa	κ UMa	9:03:38	+47:09:23	3.60	A1Vne	201

Appendix D The Brightest Wolf-Rayet (WR) Stars

HD#	WR# (Name)	RA.	Dec	Type	V
68273	11, γ2 Vel	09:31.9	−47:20:12	WC8 + O7.5III-V	1.74
152408	79a	54:58.5	−41:09:03	WN9ha	5.29
113904	48, θ Mus	08:07.2	−65:18:23	WC6(+O9.5/B0Iab)	5.88
92740	22	41:17.5	−59:40:37	WN7h + O9III-V	6.44
93131	24	43:52.3	−60:07:04	WN6ha	6.49
151932	78	52:19.2	−41:51:16	WN7h	6.61
190918	133	05:57.3	+35:47:18	WN5 + O9I	6.70
50896	6, EZ CMa	54:13.0	−23:55:42	WN4	6.94
152270	79	54:19.7	−41:49:11	WC7 + O5-8	6.95
193793	140, V1687 Cyg	20:28.0	+43:51:16	WC7pd + O4-5	7.07
156385	90	19:29.9	−45:38:24	WC7	7.45
192163	136, V1770 Cyg	12:06.5	+38:21:18	WN6(h)	7.65
96548	40, V385 Car	06:17.2	−65:30:35	WN8h	7.85
193077	138	17:00.0	+37:25:24	WN5 + B?	8.10
193576	139, V444 Cyg	19:32.4	+38:43:54	WN5 + O6III-V	8.10
93162	25	44:10.3	−59:43:11	WN6h + O4f	8.14
192641	137, V1679 Cyg	14:31.8	+36:39:39	WC7pd + O9	8.15
165763	111	08:28.5	−21:15:11	WC5	8.23
191765	134, V1769 Cyg	10:14.2	+36:10:35	WN6	8.23
97152	42, V431 Car	10:04.1	−60:58:45	WC7 + O7V	8.25

Appendix E The Brightest Red and Carbon Stars

Con.	Name	RA.	Dec	V	Spectrum
Cet	AE Cet	0:14:36	–18:56:00	4.4	M3
Cet	ο Cet	2:19:18	–02:59:00	2	M6e
Ari	ρ2 Ari	2:55:48	+18:20:00	5.9	M6
Per	ρ Per	3:05:12	+38:50:00	3.4	M4
Hor	TW Hor	3:12:36	–57:19:00	5.7	C5
For	HD 20729	3:19:36	–24:07:00	5.6	M2
Cam	BD Cam	3:42:09	+63:13:00	5.1	S5,3
Eri	DV Eri	4:34:12	–08:14:00	5.1	M3
Dor	R Dor	4:36:48	–62:05:00	5.7	M7
Lep	R Lep	4:59:36	–14:48:00	5.9	N6
Lep	RX Lep	5:11:24	–11:51:00	5.7	M6
Tau	CE Tau	5:33:12	+18:36:00	4.7	M
Ori	α Ori	5:55:12	+07:42:00	0.4	M2
Dor	η2 Dor	6:11:18	–65:35:00	5.1	M2
Gem	η Gem	6:14:54	+22:30:00	3.3	M3
Lyn	UW Lyn	6:17:54	+61:31:00	5	M3
Pup	L2 Pup	7:13:30	–44:38:00	5.1	M5
Pup	KQ Pup	7:33:48	–14:31:00	4.8	M2
Leo	R Leo	9:47:30	+11:26:00	6	M8
Ant	U Ant	10:35:12	–39:34:00	6	N;C5
Hya	U Hya	10:37:36	–13:23:00	4.5	N2
UMa	VY UMa	10:45:06	+67:25:00	6	N0
CVn	2 CVn	12:16:06	+40:40:00	5.7	M1
Com	12 Com	12:22:30	+25:17:00	4.8	G0
Vir	SS Vir	12:25:12	+00:46:00	6	Ne
Cru	γ Cru	12:31:12	–57:07:00	3.6	M4
CVn	Y CVn	12:45:06	+45:26:00	4.8	N3
CVn	TU CVn	12:54:54	+47:12:00	5.8	M5
TrA	X Tra	15:14:18	–70:05:00	5.8	C5
Nor	HD 145384	16:13:12	–53:40:00	5.8	M0
Oph	V2105 Oph	16:27:42	–07:36:00	5.2	M2
Sco	α Sco	16:29:36	–26:26:00	0.9	M1
Her	α Her	17:14:36	+14:23:00	2.7	M5
Pav	V Pav	17:43:18	–57:40:00	5.6	N7
Her	95 Her	18:01:30	+21:36:00	4.3	G8
Lyr	XY Lyr	18:38:06	+39:41:00	6	M5
Lyr	δ2 Lyr	18:54:30	+36:54:00	4.3	M4
Lyr	R Lyr	18:55:18	+43:57:00	4	M5
Vul	HD 183556	19:26:30	+19:53:00	5.8	M0
Cap	υ Cap	20:40:00	–18:08:00	5.2	M2
Cyg	W Cyg	21:36:00	+45:22:00	5.5	M5
Cep	Mu Cep	21:43:30	+58:47:00	4.2	M2
Psc	TX Psc	23:46:24	+03:29:00	5.3	N0;C7

Appendix F Suppliers of Spectroscope Gratings and Accessories

Star Analyser Grating
AVA ASTRO CORP, DBA – Adirondack Video Astronomy
72 Harrison Avenue
Hudson Falls, NY 12839, USA
http://www.astrovid.com/prod_details.php?pid=3490

Field Tested Software
http://www.RSpec-astro.com/sa100

Paton Hawksley Education Ltd
Rockhill Laboratories, Wellsway, Keynsham
Bristol, BS31 1PG, U.K.
http://www.patonhawksley.co.uk/staranalyser.html

Shelyak Instruments
Les Roussets
38420 Revel
France
http://www.shelyak.com/

Rainbow Optics Star Spectroscope
Rainbow Optics
2116 Regent Way
Castro Valley, CA 94546
http://www.staRSpectroscope.com/

RS Spectroscope
Rigel Systems
26850 Basswood Avenue
Rancho Palos Verdes
CA 90275, USA
http://www.rigelsys.com/

Diffraction Gratings
Optometrics
8 Nemco Way
Stony Brook Industrial Park
Ayer, MA 01432
http://www.optometrics.com/

Paton Hawksley (See above)

ThorLabs, Inc.
435 Route 206 North
Newton, NJ 07860
http://www.thorlabs.de/

Newport Corp.-(Richardson Gratings)
705 St. Paul St, Rochester, NY 14605
http://www.newport.com/products/overview.aspx?sec=124&lang=1033

Edmund Optics, Inc.
101 East Gloucester Pike
Barrington, NJ 08007-1380
http://www.edmundoptics.com/

Surplus Shed
1050 Maidencreek Road
Fleetwood, PA 19522
http://www.surplusshed.com/

Entrance Slits
Surplus Shed (See above)

Lennox Laser
12530 Manor Road
Glen Arm, MD 21057
http://www.lenoxlaser.com/

Lenses
Surplus Shed (See above)
Edmund Optics (See above)
Thorlabs (See above)

Appendix G Spectroscopy Forums

Forums

http://tech.groups.yahoo.com/group/astronomical_spectroscopy/?yguid=322612425
http://tech.groups.yahoo.com/group/staranalyser/?yguid=322612425
http://tech.groups.yahoo.com/group/amateur_spectroscopy/?yguid=322612425
http://tech.groups.yahoo.com/group/Iris_software/?yguid=322612425
http://spektroskopie.fg-vds.de/
http://www.astrospectroscopy.de/

Other Websites

http://www.threehillsobservatory.co.uk/astro/spectroscopy.htm
http://astrosurf.com/buil/us/book2.htm

Olivier Thizy (Shelyak) has also prepared a "recommended" spectroscopy reading list: http://www.shelyak.com/en/links.html

Yahoo Technical Support Group

A support group dedicated to assisting amateurs in astronomical spectroscopy has been set up by the author.

http://tech.groups.yahoo.com/group/astronomical_spectroscopy/?yguid=322612425

Membership in this group is open to any interested amateur, which is an ideal forum in which to raise questions on any and all aspects of spectroscopy. There are many files available in the "knowledge base" covering spectroscope design and construction as well as the practical aspects of spectral imaging and subsequent analysis. Spectrum images are regularly uploaded to assist the novice, and there are many experienced amateurs who are more than willing to discuss any problem you may have as you move up the learning curve.

The *TransSpec V2 Excel* spreadsheet for calculating grating performance (see Chaps. 2 and 7) is available in the files area of the group.

Berndt Marquandt's *SkySpecV2* – spectral processing software (see Chap. 4) is also available.

Any amendments to this book will be published on the Astronomical Spectroscopy forum. See you there!

For Further Information

Chapter 1. Some Background and Basics

Books

J.B. Kaler, *Stars.* Scientific American Library (1992)
I. Ridpath (ed.), *Norton's Star Atlas and Reference Handbook,* 20th edn. (Penguin Group, Inc., 2004)

Websites

http://astrosurf.com/aras/staranalyser/userguide.htm
http://www.astrosurf.com/buil/staranalyser/obs.htm
http://laserstars.org/spectra/index.html
http://www.staRSpectroscope.com/

Chapter 2. Imaging a Spectrum with the Grating

Books

M.A. Covington, *Astrophotography for the Amateur* (Cambridge University Press, 1985)
M.A. Covington, *Digital SLR Astrophotography* (Cambridge University Press, 2007)
S.F. Tonkin (ed.), *Practical Astronomical Spectroscopy* (Springer, 2002)

Websites

http://tech.dir.groups.yahoo.com/group/ccd-newastro/files/CCDCalc%20Install%20Files/
http://www.stark-labs.com/
http://www.ap-i.net/skychart/start
http://www.stellarium.org/
http://www.licha.de/astro_article_ccd_sortable_compare.php
http://www.eaas.co.uk/news/astrophotography_resources.html

Chapter 3. My First Spectrum: What Else Can I Record?

Books

J. Cox, R. Monkhouse, *Philip's Colour Star Atlas E2000* (Geo Philip Ltd, 1991)
J. Martin, *Spectroscopic Atlas of Bright Stars* (Springer, 2009)
Webb Society Deep Sky Observer's Handbook, Vol 2 – Planetary and Gaseous Nebul*ae* (Enslow, 1979), pp. 18, 45

Websites

http://www.ursusmajor.ch/astrospektroskopie/richard-walkers-page/index.html
http://www.supernovae.net/
http://users.erols.com/njastro/faas/articles/west01.htm
http://www.regulusastro.com/regulus/spectra/index.html
http://www.peripatus.gen.nz/Astronomy/SteCla.html
http://astrosurf.com/jpmasviel/unpeudescience/saf_ohp_spectro_comete.pdf
http://www.peripatus.gen.nz/Astronomy/Index.html
http://www.astrosurf.com/~buil/us/spe6/quasar.htm
http://astrosurf.com/buil/sn2009/spectra.htm
http://www.astrosurf.com/aras/CICyg/CI_Cyg.html
http://www.cfa.harvard.edu/supernova//SNarchive.html
http://www.astronomie-amateur.fr/Projets%20Spectro1.html (in French)
http://basebe.obspm.fr/basebe/Accueil.php?flag_lang=en
http://www.webbdeepsky.com/wperiodical/article117.pdf
http://www.delphes.net/messier/planetar.html
http://www.rochesterastronomy.org/snimages/
http://www.imo.net/
http://members.shaw.ca/epmajden/index.htm
http://www.amsmeteors.org/spectro.html
http://www.pha.jhu.edu/~qzhang/seminar1bfigs/node2.html

Chapter 4. Processing Spectra

Websites

http://www.astronomie.be/registax/
http://deepskystacker.free.fr/english/index.html
http://astrosurf.com/buil/iris/nav_pane/CommandsFrame.html
http://www.astrosurf.com/vdesnoux/
http://www.astrosurf.com/buil/us/iris/iris.htm
http://astrosurf.com/buil/iris/tutorial10/doc27_us.htm
http://www.RSpec-astro.com/
http://www.eso.org/sci/software/esomidas/

Chapter 5. Improving Your Grating Spectroscope

Books

K.M. Harrison, *Astronomical Spectroscopy for Amateurs* (Springer, 2010)

Websites

http://www.threehillsobservatory.co.uk/astro/spectra_33.htm
http://www.regulusastro.com/regulus/papers/grism/index.html
http://www.telescope-service.com/baader/adaptors/adaptors.html#Large
http://www.surplusshed.com/pages/item/m1570d.html
http://astrosurf.com/buil/us/spe1/spectro1.htm
http://bass2000.obspm.fr/solar_spect.php?step=1
http://fermi.jhuapl.edu/liege/s00_0000.html
http://fermi.jhuapl.edu/liege/s00_0000.html
http://www.samirkharusi.net/spectrograph.html
http://e.sarrazin.free.fr/spectro/sepsa.htm (in French)
http://astrosurf.com/buil/filters/curves.htm
http://astrosurf.com/buil/calibration/lamp1.htmhttp://www.sherwoods-photo.com/digiscoping_brackets/digi-scoping_adapters_and_brackets.htm
http://astrosurf.com/buil/
http://www.eso.org/projects/caos/
http://spectroscopy.wordpress.com/documents/
http://www.telescope.com/Astrophotography/Autoguiding-Solutions/pc/4/60.uts

Chapter 6. Some Technical (Nice to Know) Stuff

Books

C.R. Kitchin, *Optical Astronomical Spectroscopy* (Taylor and Francis, 1995)
C. Palmer, *Diffraction Grating Handbook* (Newport Corporation, 2005)
G.D. Roth (ed.), Handbook of Practical Astronomy (Springer-Verlag, 2009), pp. 175–204
J. Schroeder, *Astronomical Optics* (Academic Press, 1999)
R. Scott Ireland, *Photoshop Astronomy* (Willmann Bell, 2005)
R. Wodaski, *The New CCD Astronomy* (New Astronomy Press, 2002)

Websites

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Chapter 7. Spectra Analysis: A Bit of Theory

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Glossary

Absorption lines Dark lines seen in a stellar spectrum. Caused by the change in the energy level of an atom.

Achromatic Color correction of a lens, where at least two different wavelengths are brought to a common focus.

ADU Analogue to Digital Unit. The measure of intensity used by CCD cameras. Related to bit depth of the chip.

Angstrom Measure of wavelength. One Å is 10^{-10} m and 10 Å equals a nanometer (nm).

Angular measure In astronomy, full circle = 24 h or 360°, 1° = 60 arc min, 1 arc min = 60 arc sec. One minute of time equals 15 arc min.

APO Apochromatic. Where a lens is color corrected to bring three different wavelengths to a common focus.

Arc sec/min Seconds of arc, etc. See **angular measure**.

Atmospheric lines See **telluric lines**.

Balmer series A series of absorption lines seen in a stellar spectrum. Caused by the various energy levels of the element hydrogen. The strongest line (Hα) is in the red portion of the spectrum.

Bandwidth The measure of a transmission width of a filter, in wavelengths.

Bayer letter A Greek letter used to identify a star within a constellation. The brightest star would be α. For example, Deneb = α Cyg.

Bayer matrix A method of applying filters, normally red, green and blue, to a CCD chip to allow it to record colored images.

Be star A bright B-type star that shows emission spectra.

Beamsplitter A semi-reflective optical plate that can transmit and reflect light.

Bias Sometimes called read noise. The added noise signal applied to an image by the electronics controlling a CCD when the signal is transferred from the chip.

Binary system Two or more stars in close orbit around each other.

Bit depth The maximum intensity recorded by the pixel in a CCD. A bit depth of 16 gives a maximum ADU count of 65,000. (2^{16}).

Blackbody curve The intensity curve of a continuum spectrum that reflects the temperature of the star.

Black hole A region of space where the intense gravity field prevents the emission of any light or radiation. Associated with the death of large stars.

Blazed gratings A diffraction grating that has the shape of the grooves angled to improve the illumination of the first order spectrum.

BMP A bit-mapped image format. Commonly used in Windows applications.

Carpenter prism See **grism**.

Cataclysmic variable A type of variable star. The change in brightness is sudden and irregular. Thought to be surrounded by a shell of material.

CCD Charge coupled device. Used in cameras to record photons and convert them into electrons, which are then used to generate an image.

CfA The Harvard Smithsonian Center for Astrophysics. Location of a large database on supernovae.

Chromatic aberration An optical aberration in a telescope or lens where different colors come to a different focal point. See **achromatic**.

Chromatic coma See **spectral coma**.

Chromosphere The outer atmosphere of a star. Gives rise to absorption lines in the spectrum.

Color index Measure of a star's color. The difference in the star's brightness as recorded by various filters. For example, U-B or B-V color index.

Continuum The continuous underlying spectrum of a star.

Cylindrical lens A lens that only focuses in one axis. Produces a line image from a point source.

Dark An image obtained from a camera in the absence of light. Used to compensate for noise in images.

Deviation angle The angle between the incident light ray and the emerging colored ray from a prism or grating. Varies with the wavelength of light.

Diagonal A prism or mirror used to divert the light in a telescope through 90°.

Dispersion The ability to break white light into various colors. Normally associated with prisms and gratings.

Doppler shift Change in frequency due to the speed of recession or approach. Redshift is a measure of the speed of recession based on the Doppler effect.

Drift enlarging Using the movement of a star in the field of view to increase the height of a spectrum.

DSLR Digital single lens reflex camera. Uses a CCD sensor. The lens can usually be removed from the camera body.

DSO Deep sky object. Astronomical objects other than stars and planets.

Electromagnetic spectrum The range of radiation energy going from the very short wavelengths (X-rays) to the longer wavelengths of radio. The visible spectrum is a small part of this range.

ELODIE A high resolution spectrograph used at the Observatoire de Haute Provence (OHP). Extensive source of spectra used by astronomers.

Emission lines A bright line seen in a spectrum. Caused by the electrons of various atoms dropping energy levels.

Entrance slit A narrow opening (can be adjustable) positioned at the entrance of a spectroscope to improve the resolution.

Equatorial mount A telescope mounting that allows tracking of the stars. Usually having two axes of rotation – a declination axis (Dec), which gives movements north-south and an RA axis that points towards the celestial pole and rotates for tracking.

Exit pupil The image of the objective seen in an eyepiece. Equal to the size of the objective divided by the magnification of the system.

Exoplanet A body orbiting a distant star. Normally evident by slight drops in star brightness as the body moves between the observer and the star.

Eye relief The distance the eye should be positioned behind an eyepiece to see the whole field of view.

Field curvature An optical aberration. The plane of the best focus position varies from the center to the edge.

First order spectrum The brightest and least dispersed spectrum formed by a grating.

FITS Flexible Image Transport System. A digital file structure that allows the maximum information to be recorded. Details of the file contents are encoded into a readable header. Widely used in astronomy.

Flamsteed number A numbering sequence for the stars within a constellation developed by John Flamsteed. The numbers start from the western border of the constellation through to the east. For example, Deneb = α Cyg = 50 Cyg.

Flat An image taken of a uniform illuminated surface. Used in imaging to correct vignetting and dust defects.

Focal length The distance between the objective lens/mirror of a telescope and the point of focus.

Focal ratio The focal length of a lens/mirror divided by the aperture.

Focal reducer A secondary lens that, when placed in a telescope, reduces the effective focal length.

Focus shift Change in focus position required to bring differing wavelengths into focus. Normally associated with field curvature.

Fraunhofer lines Prominent dark lines seen in the solar spectrum. First recorded by Joseph Fraunhofer.

Free spectral range The span of a spectrum that shows no overlap with a subsequent spectral order. Associated with multiple orders from a grating.

FWHM Full Width Half Maximum. A measure of the effective size of a spectral line or star image.

Gain Amplification applied to the signal within a CCD. A gain of ×5 will give an ADU readout five times higher than a gain of ×1.

Grating transmission A series of grooves (lines) embossed on a plastic layer bonded to a glass support plate. Light is dispersed when it travels through the grating.

Grism The name given to a small prism when it is combined with a grating to correct the deviation angle.

HD number A number sequence used to identify a star in the Henry Draper spectroscopic catalog. For example, Deneb = HD 197345.

Imaging software Computer software used to manipulate images. Can also be used to control the camera settings and exposures. Some examples are *AstroArt5, Maxim DL* and *IRIS*.

Instrument response A spectral profile curve that represents the efficiency of an optical system across the spectral range.

IRIS An image processing software package (freeware) developed by Christian Buil.

ISO settings Term used with DSLR cameras to define the gain applied to the signal. An ISO 200 has twice the gain of an ISO 100.

Kelvin Temperature scale based on absolute zero (−273°C).

Kirchhoff's laws Three laws developed to explain the spectral continuum and absorption and emission lines.

Light year An astronomical unit of measure. 0.9461×10^{16} m. The distance traveled by light in one year.

Linear dispersion See **plate scale**.

Line broadening The increase in width of a spectra line due to pressure or temperature.

Micron 10^{-6} μm. A common measure for CCD pixel sizes and other small dimensions.

Mono CCD A CCD where each pixel is responsive to all wavelengths.

Nanometer Measure of wavelength. 1 nm = 10^{-9} m = 10 Å.

Neutron star Extremely massive star with low luminosity. The possible remnant of a supernova explosion.

Non-uniform spectra Normally associated with prisms. The spectrum produced is non-linear in scale. The red section is less spread out than the blue section.

Nova A star that shows an extreme increase in brightness due to an explosion that destroys the star.

Nyquist sampling Information transfer theory developed by Harry Nyquist. As applied to spectroscopy, it can be used to evaluate the accuracy of the spectrum image. Normally a minimum of two pixels are required to determine resolution. Less than two is called "under sampling."

Objective The main (front) lens (or mirror) of a telescope or camera lens. The size of the objective determines the amount of light collected. Larger objectives allow fainter objects to be seen or recorded.

Objective grating When a transmission grating is placed in front of the objective of a camera lens.

Optical aberrations Image distortions caused by the optical system. These can be chromatic aberrations, coma and field curvature, etc.

Optical axis The virtual line through the center of all the optical components such as in a telescope/lens, etc. Optical aberrations are usually at a minimum on the optical axis such as the coma.

OSC One shot color. Applied to a CCD fitted with a Bayer filter to record images in color.

parsec An astronomical unit of measure. 3.0857×10^{16} m, or 3.26 light years.

P Cygni profile A profile of a spectral line that shows both absorption and emission features. Associated with gaseous shells surrounding a star.

Periodic Table A tabulated listing of all known elements, grouped by similar properties.

Pixel size An important measure for CCD chips. Measured in microns, for example, 6.4×6.4 μm pixels. Larger pixels are usually more sensitive to incoming light. The size of the pixel can affect the final resolution of the image.

Planck constant Symbol $h = 6.6256 \times 10^{-34}$ Js (Joule second). Used in the energy equation, $\Delta E = h\nu$ that relates the energy change (ΔE) of an electron to the frequency (ν) of the emitted/absorbed wavelength of light.

Planck curves A series of stellar spectrum intensity curves that show the peak wavelength position changes with temperature.

Planetary nebula Gaseous shell formed by the collapse of a star or as the result of a nova.

Plate scale Also called linear dispersion. The scale, in Å/mm or Å/pixels of a spectrum. The higher the plate scale, the smaller the size of the spectrum and the lower the final resolution.

Prism Shaped piece of glass that produces a spectrum due to dispersion. Can be used with a grating to compensate for the deviation angle (grism).

Quantum theory A branch of physics that deals with small particles. Uses both wave and particle analogies to resolve interactions at a subatomic level.

Quasar Quasi-stellar object. An object in a distant galaxy that shows significant redshift in its spectrum.

RAW A proprietary image format used by manufacturers of DSLR cameras. It contains additional information on each color channel and provides the maximum amount of image data.

R value A measure of the resolving power of a spectroscope. Equal to the wavelength (λ) of a pair of lines, just separated, divided by the distance between them ($\Delta\lambda$). For example, $R = \lambda/\Delta\lambda$. $R = 100$ is a low resolution spectroscope. $R = 40{,}000$ is a very high resolution instrument.

Redshift Symbol, z A measure of large Doppler shifts in the spectrum due to the expansion of the universe. $z = (\lambda_o - \lambda)/\lambda$.

Reflecting telescope A telescope, such as a Newtonian, that uses mirrors to form the image. Does not suffer from chromatic aberration, as all wavelengths of light come to a common focus.

Refractive index Symbol n, a measure of the dispersing power of a prism. The refractive index varies with the wavelength of light. Glass has a typical index of $n = 1.5$.

Resolution The ability to see two close lines as separate lines. Measured by the smallest distance between them, normally in Å.

RGB Red, green, blue. The sequence of color filters used in the Bayer matrix.

RSpec Commercial software package for the processing of spectral images.

SCT Schmidt Cassegrain telescope, such as Meade/Celestron. A corrector lens is used with a spherical mirror to provide an optically corrected image. Usual focal ratio of f10.

Seeing The size of a star's disk as seen through a telescope. The size varies with atmospheric conditions. Usually measured in arc seconds.

SEPSA Slit Eyepiece Projection for Star Analyzer. A method of using an entrance slit with a filter grating.

Sidereal tracking An astronomical mount fitted with a drive motor. This rotates the polar axis in RA at a rate of 360° per sidereal day (23 h 56 min 4 s), thereby keeping track of the celestial movement of the sky.

Slitless In spectroscopy, where the entrance slit is much wider than the star image.

SNR Signal to noise ratio. A measure of the unwanted interference (noise) found in images and spectra. An SNR > 50 is normally required in results for professional acceptance.

Spectral coma An optical aberration where the edge of the field of view shows distorted images that vary in size and color.

Spectral lines Bright or dark lines seen in a spectrum. Caused by the absorption (or emission) of energy by atoms.

Spectroscope Instrument containing a dispersion element (prism or grating) to form an image of the spectrum.

Star bloat Enlarged star image usually caused by chromatic aberrations.

Star classification A sequence of star spectra based on absorption features. Originally based on the visibility and clarity of hydrogen absorption lines. The classification sequence is OBAFGKM.

Supergiant Large luminous star with an absolute magnitude greater than −4.6. The majority of supergiants are K- and M-type stars. They are identified in the star classification system with the suffixes Ia and IIa, for example, M5 Ia.

Supernova An exploding star where the magnitude change is more than 10 mag. Usually old massive stars go supernova at the end of their stellar evolution cycle.

Swan bands Dark absorption bands in the spectrum caused by molecules. The original swan bands were identified with carbon compounds.

Telluric lines Absorption lines in the spectrum caused by oxygen and water vapor in Earth's atmosphere.

TIFF Tagged image file format. Uncompressed high quality image format.

T thread An M42 × 0.75 mm pitch thread, commonly used on camera adaptors.

UVES A high resolution spectrograph used by the European Southern Observatory (ESO). Extensive source of spectra used by astronomers.

Vignetting Light loss in an optical system caused by interference to the light path. Usually seen as darker edges in an image.

Visible spectrum The part of the electromagnetic spectrum visible to the human eye. Usually from 4000 to 8000 Å. Also called the optical spectrum.

Visual magnitude Apparent brightness of a star. Sometimes called apparent magnitude. The brightest star is seen at a magnitude −1.46 (Sirius), and the faintest naked eye star is about +6.0 mag.

VSpec Freeware software by Valerie Desnoux for processing spectra.

Wavelength A characteristic of electromagnetic energy. Short wavelengths give gamma rays, X-rays, etc., and long wavelengths infrared and radio. A small portion of the electromagnetic energies with wavelengths between 4000 and 8000 Å are visible (optical or visual spectrum).

White dwarf Low luminosity star, usually a B- to F-type star with an absolute magnitude <10.0. Identified with the suffix D.

Wolf-Rayet star A star that shows emission lines in the spectrum. Caused by high rates of mass loss.

Zero order image The undeviated image of the target star seen with a grating. The zero order image lies on the optical axis and represents a zero wavelength position. For example, for calibration purposes, zero order wavelength, $\lambda o = 0000$ Å.

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