



Spectroscopy: Unlocking the Secrets of Star Light

Robert Hollow

CSIRO Australia Telescope National Facility

Robert.Hollow@csiro.au

Introduction

Spectroscopy is a key tool in astronomy. The combination of photography and spectroscopy in the Nineteenth Century led to the birth of astrophysics. In this workshop we will review the basic principles of astronomical spectroscopy and discuss how spectra are obtained. The use of spectra to classify stars is examined in some detail. Recent innovations in multi-object spectroscopy, an area in which Australia is a world-leader, are examined. We will also briefly discuss spectroscopy at other wavebands and for other celestial objects. This workshop will provide you with some simple ideas, demonstrations and analogies that consolidate a conceptual grasp of the theory and skills in option 9.7 *Astrophysics* of the NSW Stage 6 Physics syllabus.

This paper aims to provide teachers with a range of ideas and activities plus some useful data with which to cover the syllabus requirements. It provides an introduction to the theoretical background. Much of the material included in this paper may be found in the Spectroscopy section for the of the Australia Telescope Outreach and Education website; <http://outreach.atnf.csiro.au/education/senior/astrophysics/spectroscopytop.html>. Other material is new or has been incorporated and updated from papers presented at previous Science Teacher Workshops and Science Teacher Association of NSW workshops by the author.

Syllabus Requirements

This paper uses the amended NSW Board of Studies Stage 6 Physics Syllabus of October 2002. The area targeted in this paper is bold points three in option 9.7 *Astrophysics* (page 63 of the printed edition). It is recommended that you read the paper with access to a current copy of the syllabus. It can be obtained online from the Board of Studies at http://www.boardofstudies.nsw.edu.au/syllabus_hsc/.

Historical Background

Spectroscopy is a key tool in astronomy. By obtaining and analysing the spectrum from a distant object astronomers can identify what type of object it is and determine a wealth of characteristics for the object. These include its effective temperature, how fast it is rotating and whether it is moving towards or away from us, how large and dense it is and what it is made of. Within the last decade planets beyond our Solar System have been discovered via their effect on the parent star's spectrum.

Isaac Newton showed that a glass prism could be used to split sunlight into a spectrum in 1666. Further studies by William Wollaston in 1802 revealed some black lines on the component colours of the solar spectrum. More detailed observations by Joseph von Fraunhofer resulted in 574 of these lines being mapped by 1815. These lines were named "Fraunhofer lines" in his honour. The image below shows a solar spectrum with Fraunhofer lines.



Figure 1: Solar spectrum with Fraunhofer lines
Credit: ©Delbouille et al. 1972, 1981 and Paris Observatory BASS2000

Two key questions arise from studying these lines - what do they represent and how are they formed? The solutions to these questions were to take some time. Leon Foucault matched the lines produced by a sodium lamp with some of the dark lines in a solar spectrum in 1849. In 1857 Gustav Kirchhoff and Robert Bunsen identified sodium in a solar spectrum. They found that a luminous solid or highly compressed hot gas could produce a continuous spectrum whilst a diffuse hot gas produced a spectrum with narrow bright lines on a black background.

As spectroscopes were coupled to telescopes additional chemicals were identified in the spectra of stars and nebulae. Sir Norman Lockyer and Jules Janssen independently discovered the element helium in solar spectra before it was isolated

in a laboratory on Earth in 1895. The use of spectroscopy, coupled with the spread of photography for astronomical purposes gave rise to the science of astrophysics from astronomy in the second half of the nineteenth century.

Three general types of spectra were now known, a continuous spectrum, showing all the component colours of the rainbow, and two types of line spectra, the first, dark-line spectra like the solar spectrum and those from stars and the second, bright-line spectra as emitted from gas discharge tubes and some nebulae. The Swiss school teacher, Johann Balmer in 1885 developed an empirical formula that determined the wavelengths of the four visible lines in hydrogen's spectrum. Five years later the Swedish physicist, Johannes Rydberg expanded Balmer's formula to apply to some other elements. The Danish physicist, Niels Bohr, finally provided an explanation as to how spectral lines formed in the 1920s. His work relied on quantum physics and the concept of energy shells or orbits for electrons.

How Are Spectra Produced?

Types of Spectra

Spectra can be simplified to one of three basic types. Simple examples in the visible wavebands are shown below.

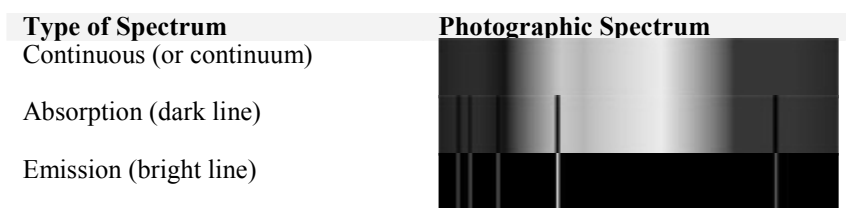


Figure 2: Photographic representations of main spectral types.

One means by which a continuous spectrum can be produced is by thermal emission from a black body. This is particularly relevant in astronomy and is discussed in the next section. Astronomical spectra can be combination of absorption and emission lines on a continuous background spectrum.

Black body Radiation

What gives rise to a continuous spectrum? Imagine heating a solid steel sphere with a blowtorch. When you remove the torch you can feel the heat being re-radiated by the sphere. Applying the torch again puts more energy into the sphere - it gets hotter. Eventually it starts to glow dimly. As you continue heating it the sphere glows first red, then orange, yellow then white hot. If you were able to keep heating it sufficiently it may even glow blue hot. This sphere approximates what physicists call a black body.

A black body radiator is a theoretical object that is totally absorbent to all thermal energy that falls on it, thus it does not reflect any light so appears black. As it absorbs energy it heats up and re-radiates the energy as electromagnetic radiation.

In the real world some objects approximate the behaviour of blackbodies. These must be sources of thermal energy and must be sufficiently opaque that light interacts with the material inside the source. Examples of such objects include the tungsten filaments of incandescent lamps and the cores of stars. The continuous spectrum produced by a black body is distinctive and can be shown as an intensity plot of intensity against emitted wavelength. This plot is called the blackbody curve or the Planck curve, after the German physicist Max Planck who first postulated that electromagnetic radiation was quantised.

The plot below shows Planck curves for an object at four different temperatures from 6,000 K to 4,000 K. Note the wavelength here is expressed in units of Ångstroms. 1 Ångstrom = 0.1 nanometers. If you look closely at the curves you will notice that the object emits some radiation at every wavelength including in the ultraviolet and infrared wavebands. You should also notice that the amount of energy emitted is not the same for all wavelengths and that in this case, the peak wavelength falls within the region of visible light. How do the curves compare? Two key points should be apparent. Firstly, a hotter object emits more energy at every wavelength than a cooler one. Secondly, the hotter the object, the shorter the wavelength of the peak of the curve. The 6,000 K object clearly peaks in the visible part of the spectrum whereas the peak of the 4,000 K object borders the visible and the infrared regions. As already mentioned, stars approximate black body objects and can vary in their effective temperatures from around 2,000 K to about 30,000 K. If you tried to plot the intensity of two stars with these extremes on a plot like the one above it would be extremely difficult to show them on the same linear scale. If we just wanted to compare the peak wavelengths we can plot them using a normalised energy output in which the peak wavelength for each corresponds to an intensity = 1.0.

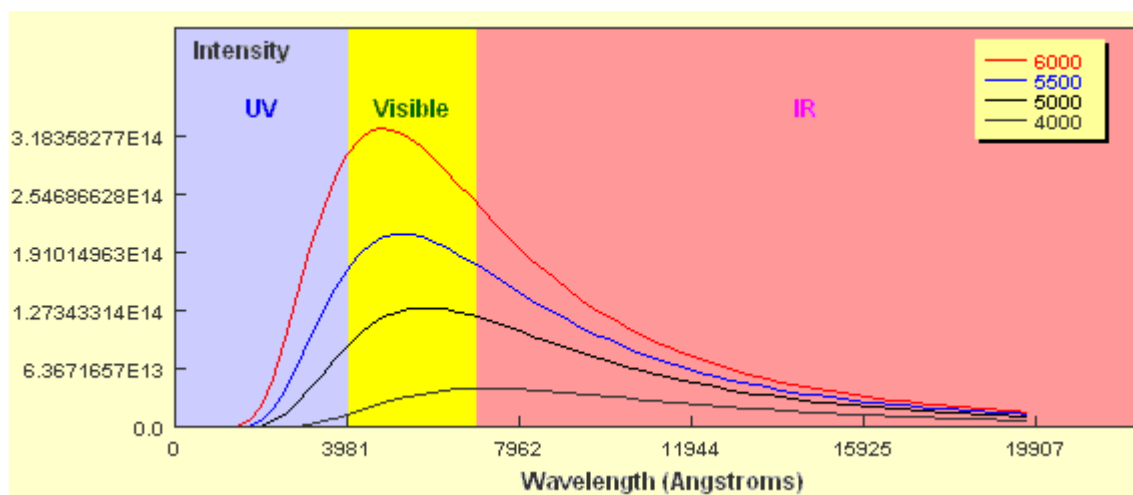


Figure 3: Comparison of Planck curves for 4 different temperatures of blackbody
 Credit: Plot generated from an applet courtesy of Mike Guidry

A 10,000 K star would have its peak wavelength in the ultraviolet part of the em spectrum whilst a 3,000 K star would emit most of its radiation in the infrared part. Not only does the shape of the curve determine the relative intensity of the different components of the continuous spectrum produced by the star, it also determines the colour of the star. A 10,000 K star appears blue-white whilst a 3,000 K star appears red.

Production of Line Spectra

Line spectra appear in two forms, absorption spectra, showing dark lines on a bright background, and emission spectra with bright lines on a dark or black background. These two types are in fact related and arise due to quantum mechanical interactions between electrons orbiting atoms and photons of light. Photons of light each have a specific frequency. The energy of a photon is a function of its frequency and is determined by:

$$E = hf \text{ where } f \text{ is the frequency of the photon, } E \text{ is the energy and } h \text{ is Planck's constant } (= 6.626 \times 10^{-34} \text{J.s})$$

An electron orbits a nucleus in a stable energy level. If a photon of a specific frequency interacts with the electron, it can gain sufficient energy to "jump up" one or more levels. The photon is absorbed by the electron so cannot continue on to be detected by an observer. The electron then "de-excites" and jumps back down to a lower energy orbit, emitting a photon of specific frequency. This photon, however, could be emitted in any direction, not just in the same direction as the original incident photon.

The Balmer series of visible lines for atomic hydrogen are caused by transitions from the $n = 2$ orbit to and from higher orbits. This is shown schematically in the diagram below for the Bohr model of the atom. The Lyman Series involves transitions down to the $n = 1$ orbit and involve higher frequency photons in the UV region whilst the Paschen Series (to $n = 3$) produces IR spectral lines.

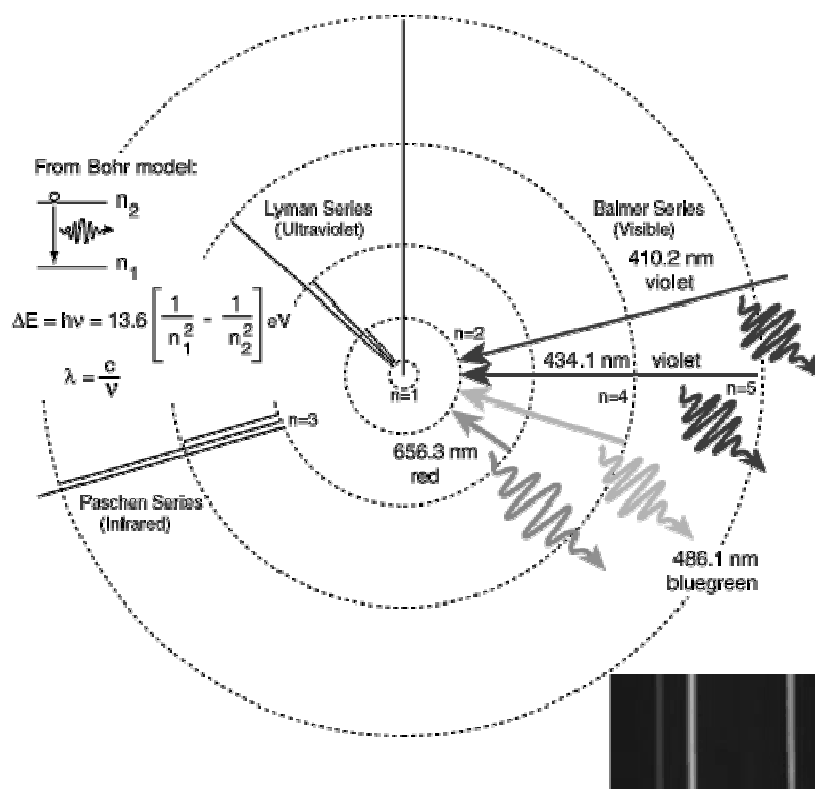


Figure 4: Electron transitions in the Bohr model of the Hydrogen atom. As electrons jump down to the n = 2 orbit, they emit photons of specific frequency (hence colour) that can be seen as emission lines in the visible part of the em spectrum. This visible set of lines is called the Balmer series.
 (Credit: HyperPhysics <http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>)

Balmer line	Wavelength (nm)
H α	656.3
H β	486.1
H γ	434.1
H δ	410.2
H ϵ	397.0

Table : The Balmer Series for Hydrogen

The number of spectral lines that can be produced is vast given the permutations of atoms, molecules and orbital transitions possible.

Obtaining Astronomical Spectra – Spectrographs

How does a Spectrograph Work?

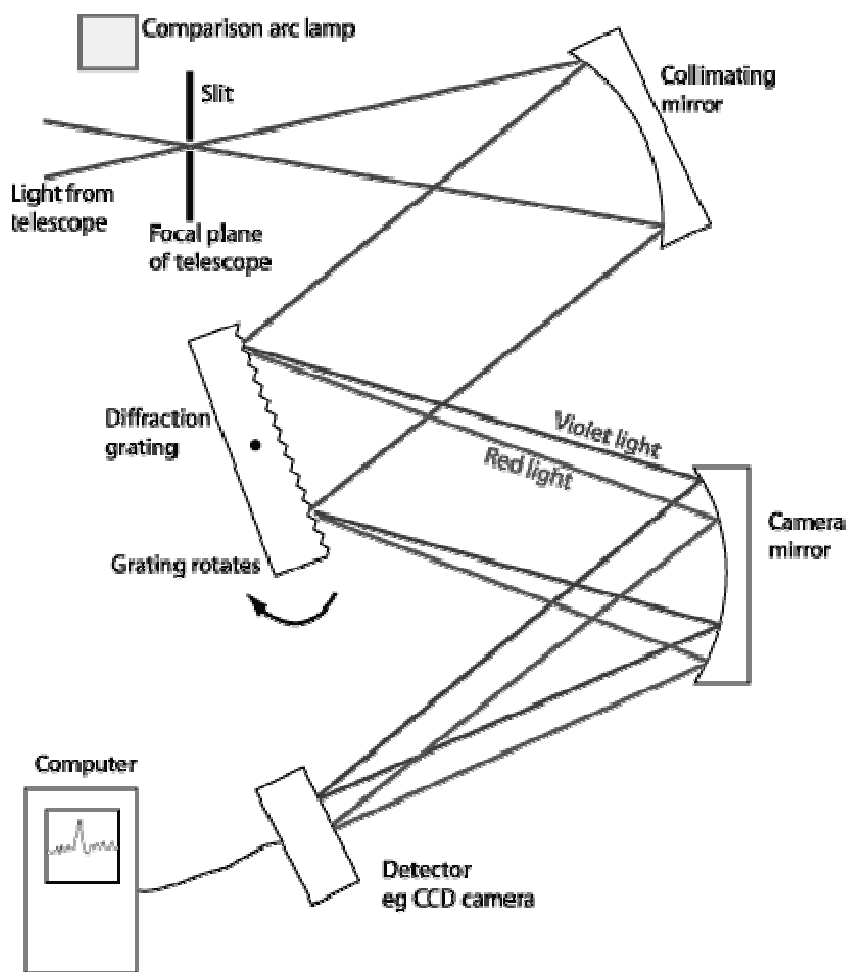
A spectrograph is an instrument used to obtain and record an astronomical spectrum. The spectrograph splits or disperses the light from an object into its component wavelengths so that it can be recorded then analysed.

Dispersing Light

Light entering a spectrograph can be split or dispersed into a spectrum by one of two means, using a prism or a diffraction grating. When Newton split light into a spectrum in the 1660s he used a glass prism. School students often use perspex prisms from ray box kits to disperse or "split" white light from an incandescent bulb into the component colours of the spectrum. This effect arises due to the fact that the different wavelengths of light also have different frequencies. As they pass through a prism, they undergo refraction, a change in velocity due to the change in medium. If the light falls incident to the prism at an angle other than 90° it will also change direction. Red light has a longer wavelength than blue light so its angle of refraction is lower, both at entry to and exit from the prism. This means it gets bent less. The light emerging from the prism is dispersed as shown schematically in the diagram below.

Most astronomical spectrographs use diffraction gratings rather than prisms. Diffraction gratings are more efficient than prisms which can absorb some of the light passing through them. As every photon is precious when trying to take a spectrum from a faint source, astronomers do not like wasting them. A diffraction grating has thousands of narrow lines

ruled onto a glass surface. It reflects rather than refracts light so no photons are "lost". The response from a grating is also linear whereas a prism disperses blue light much more than in the red part of the spectrum. Gratings can also reflect light in the UV wavebands unlike a glass prism which is opaque to UV. A common example of a diffraction grating is a CD where the pits encoding the digital information act as a grating and disperse light into a colourful spectrum.



A Schematic Diagram of a Slit Spectrograph

Figure 5:

Credit: Adapted with permission from a diagram by James B. Kaler, in "Stars and their Spectra," Cambridge University Press, 1989.

The slit on the spectrograph limits the light entering the spectrograph so that it acts as a point source of light from a larger image. This allows an astronomer to take a number of spectra from different regions of an extended source such as a galaxy or of a specific star in the telescope's field of view. Light is then collimated (made parallel) before hitting a diffraction grating. This disperses the light into component wavelengths which can then be focused by a camera mirror into a detector such as a charged-couple device (CCD). By rotating the grating different parts of the dispersed spectrum can be focused on the camera. The comparison lamp is vital in that it provides spectral lines of known wavelength (eg sodium or neon) at rest with respect to the spectrograph, allowing the spectrum of the distant source to be calibrated and any shift of spectral lines to be measured.

Recording the Spectrum

Newton recorded the spectrum of sunlight by drawing it. The rise of spectroscopy for astronomical use was in part due to its linkage with another emerging technology - photography. Astronomical spectra could be recorded by photographing them on glass plates. This was a far superior approach to viewing them with through an eyepiece and trying to draw the image. Photographic records of spectra could be stored for later analysis, copied for distribution or publication and the spectral lines could be measured relative to spectral lines from a stationary lamp producing spectral lines of known wavelength. It was only by observing and photographing the spectra of thousands of stars that astronomers were able to classify them into spectral classes and thus start to understand the characteristics of stars. Photographic spectra were generally recorded on glass plates rather than photographic film as plates would not stretch. The image of the spectrum was normally presented as a negative so that the absorption lines show up as white lines on a dark background. The example in Figure 6 shows the photographic spectrum of a standard reference star, α Lyrae from the 1943 An Atlas of Stellar Spectra.

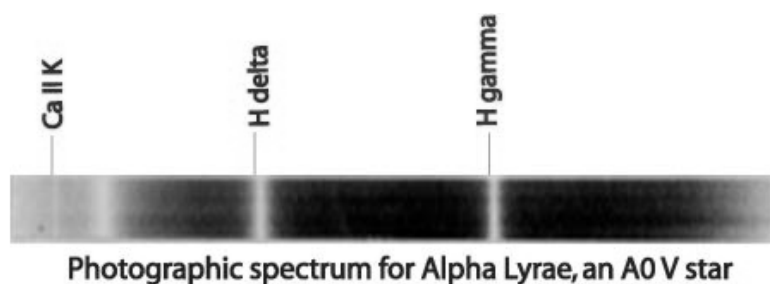


Figure 6:

Credit: Adapted from *An Atlas of Stellar Spectra*, Morgan, Keenan, Kellman

Photoelectric spectroscopy allows spectral information to be recorded electronically and digitally rather than on photographic plates. Modern astronomical charged-couple devices or CCDs can reach a quantum efficiency of about 90% compared with about 1% for photographic emulsions. This means a CCD can convert almost 9 out of 10 incident photons into useful information compared with about 1 in 100 for film. Using a CCD an astronomer can therefore obtain a useful spectrum much quicker than using a photographic plate and can also obtain spectra from much fainter sources. CCDs have a more linear response over time than photographic emulsions which lose sensitivity with increased exposure. A spectra recorded on a CCD can be read directly to a computer disk for storage and analysis. The digital nature of the information allows for rapid processing and correction for atmospheric contributions to the spectrum. Modern spectra are therefore normally displayed as intensity plots of relative intensity versus wavelength as is shown in Figure 10.

Multifibre Spectroscopy

The last decade has seen the growth in multifibre spectroscopy. This involves the use of optical fibres to take light from the focal plane of the telescope to a spectrograph. A key advantage of this technique is that more than one spectrum can be obtained simultaneously, dramatically improving the efficiency of observing time on a telescope. Many of the techniques for multifibre spectroscopy were developed at the Anglo-Australian Observatory for use on the AAT and the UK Schmidt telescopes.

The *2dF* (2 degree field) project revolutionised the emerging field of multifibre spectroscopy by using a computerised robot to precisely position 400 minute prisms onto a metal plate so that each prism could gather light from an object such as a galaxy or quasar. Attached to each prism was an optical fibre that feeds into a spectrograph. The *2dF* instrument sits at the top of the AAT and can take spectra from 400 objects simultaneously over a 2 degree field of view. Whilst observing one field, the robot sets up a second set of prisms on another plate which can then be flipped over in a few minutes to begin observing a new field. This incredibly efficient system allows spectra from thousands of objects to be obtained in a single night's observing run.

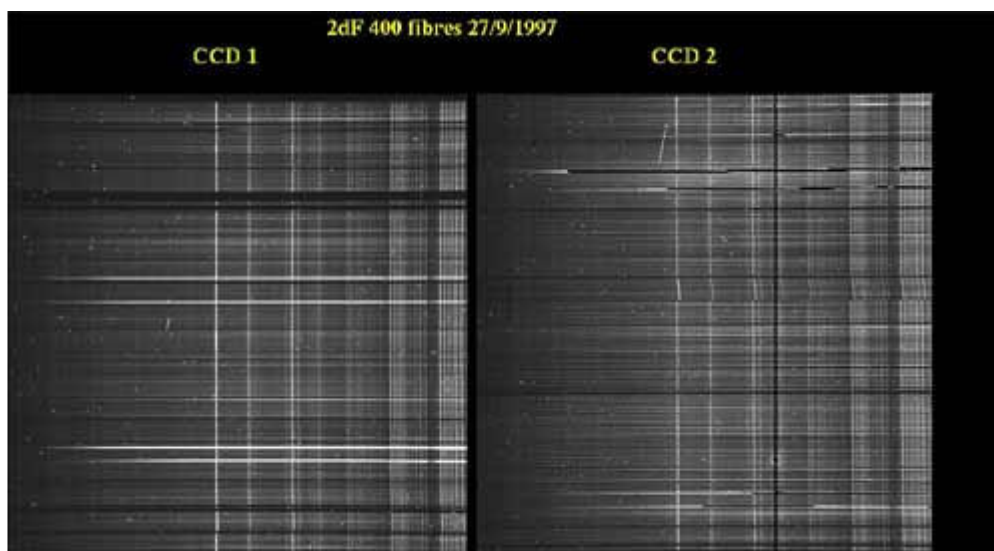


Figure 7: 400 spectra from a 2dF field. There are 2 CCDs each recording 200 spectra that are fed in by fibres coming from the field plate atop the AAT.

Credit: The 2dF Galaxy Redshift Survey

Two key projects, the 2dF Galaxy Redshift Survey and the 2dF QSO Redshift Survey provided the scientific impetus for building this multifibre instrument. These surveys produced accurate data on over 250,000 galaxies and 25,000 quasars that have proved an immense boon for cosmologists studying the formation and large-scale structure of the Universe.

The *6dF* spectroscope operates on the UK Schmidt Telescope on Siding Spring and allows up to 150 spectra to be obtained simultaneously on this wide-field telescope. It uses robotic positioning of the fibres onto the plate. Two key projects utilising 6dF are the 6dF Galaxy Survey http://www.aao.gov.au/AAO/ukst/6dF_survey.html and RAVE (RAAdial Velocity Experiment), <http://www.rave-survey.aip.de/rave/> an international project that is aiming to measure the radial velocity of 1 million stars within our galaxy to within 5 km.s^{-1} . As of mid-2006 about 100,000 stars have been measured.

Australian astronomers and engineers continue to design, develop and build new multifibre devices for the latest generation 8-10 m class telescopes overseas. An Australian consortium from the AAO, ANU and UNSW has just built *OzPoz*, a multifibre spectrograph for ESO's VLT in Chile. It develops the techniques used in 2dF and currently allows 132 spectra to be gathered simultaneously.

In 2006 the AAO commissioned its new instrument, *AAOmega*. It is a general-purpose spectrograph, fed by optical fibres from the 2dF instrument. It replaces the spectrographs of the 2dF system, which had seen ten years of service. The 2dF spectrographs were mounted on the telescope, but improvements in the throughput of optical fibres since 2dF was built has allowed longer runs of fibres to be practical. As a result, the *AAOmega* spectrograph is mounted off the telescope, meaning that it can be made much more stable than the 2dF spectrographs.

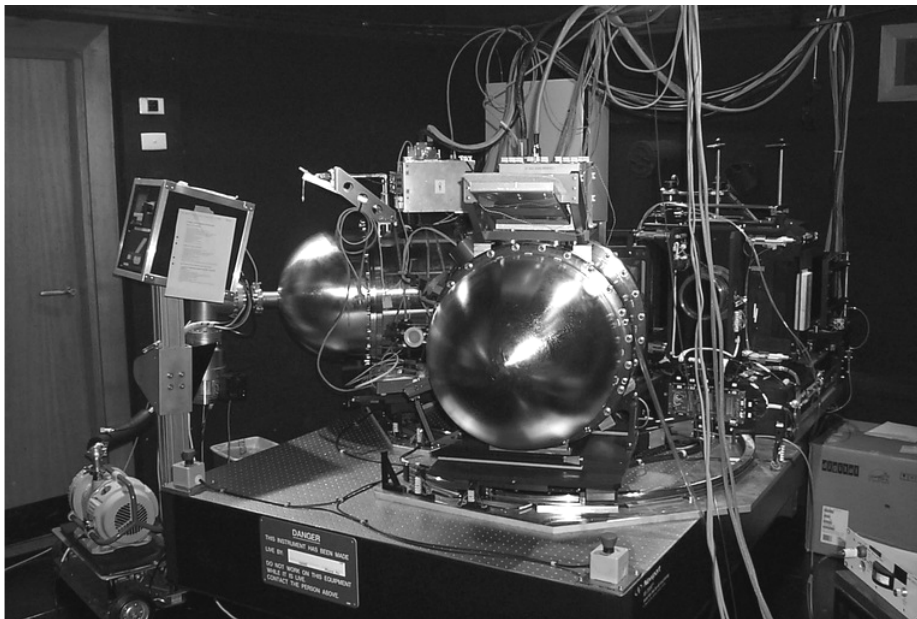


Figure8: AAOmega. Credit Anglo-Australian Observatory.

The 2dF spectrographs were designed primarily to simply measure galaxy redshifts. *AAOmega*, with its higher resolution, throughput and stability, is designed to mass-produce the detailed and accurate spectra needed for astrophysical analysis of both stars or galaxies. The improved throughput and sky-subtraction means it can also routinely observe much fainter objects. *AAOmega* is the world's best wide-field spectroscopic survey facility, and will be surpassed in this regard only when Gemini's proposed WFMOS facility becomes available in about 2012.

Types of Astronomical Spectra

Different celestial objects produce different types of spectra. The spectrum of an object is one means of identifying what type of object it is. How different spectra arise is shown in the schematic diagram below.

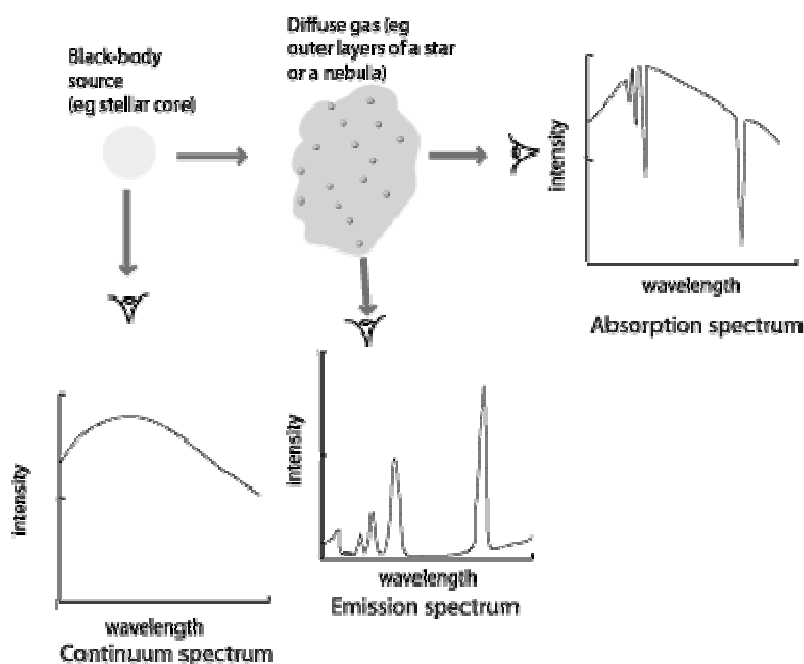


Figure 9: How continuous, emission and absorption spectra can be produced from same source.

Credit: Adapted from a diagram by James B. Kaler, in "Stars and their Spectra," Cambridge University Press, 1989.

Continuum spectrum: In this diagram, a dense hot object such as the core of a star acts like a black body radiator. If we were able to view the light from this source directly without any intervening matter then the resultant spectrum would appear to be a continuum as shown bottom left in the Figure 9 above.

Absorption spectrum: Most stars are surrounded by outer layers of gas that are less dense than the core. The photons emitted from the core cover all frequencies (and energies). Photons of specific frequency can be absorbed by electrons in the diffuse outer layer of gas, causing the electron to change energy levels. Eventually the electron will de-excite and jump down to a lower energy level, emitting a new photon of specific frequency. The direction of this re-emission however is random so the chances of it travelling in the same path as the original incident photon is very small. The net effect of this is that the intensity of light at the wavelength of that photon will be less in the direction of an observer. This means that the resultant spectrum will show dark absorption lines or a decrease in intensity as shown in the dips in the absorption spectrum top right in the diagram above. Stellar spectra typically look like this.

Emission spectrum: A third possibility occurs if an observer is not looking directly at a hot black body source but instead at a diffuse cloud of gas that is not a black body. If this cloud can be excited by a nearby source of energy such as hot, young stars or an active galactic nucleus then the electrons in atoms of the gas cloud can get excited. When they de-excite they emit photons of specific frequency and wavelength. As these photons can be re emitted in any direction an external observer will detect light at these wavelengths. The spectrum formed is an emission or bright line spectrum, as shown by the middle spectrum in Figure 9.

Spectra from Astronomical Objects

Stellar Spectra

The spectrum below is an intensity plot of a star. Note the characteristic absorption line features including strong lines for $H\alpha$, $H\beta$, $H\gamma$ and $H\delta$ - the Balmer Series. The overall shape of the spectrum approximates a black body curve with a peak wavelength. This can be used to determine the effective temperature of the star. Stars of different temperatures, size and metallicities will have different spectra but most exhibit absorption lines even if they do not all show strong Balmer lines as in this star.

The study of many thousands of stellar spectra in the late Nineteenth Century led to the development of our modern classification system for stars. The concept of spectral classes is discussed in more detail on the next page. Careful analysis of a star's spectrum provides astronomers with a wealth of detail including its effective temperature, rotational velocity, translational velocity, its density and its chemical composition and metallicity.

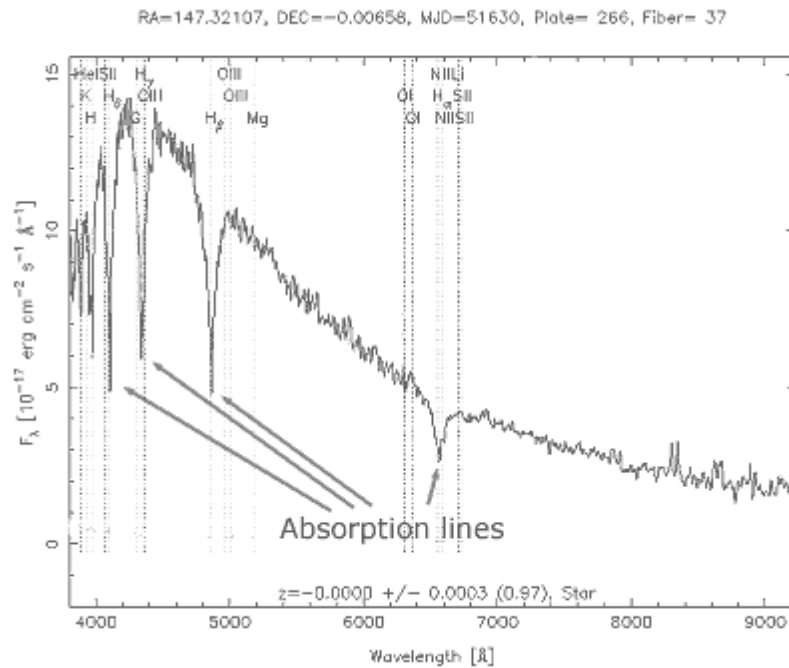


Figure 10: An example of an intensity plot spectrum for a star. Note the absorption lines for the Balmer series. Credit: The Sloan Digital Sky Survey

Most spectra are now obtained photoelectrically, producing 1D intensity plots like that above. Historically most spectra were obtained photographically. Figure 11 below shows a comparison on an intensity plot (or trace) and a photographic plate of the spectrum for the same star.

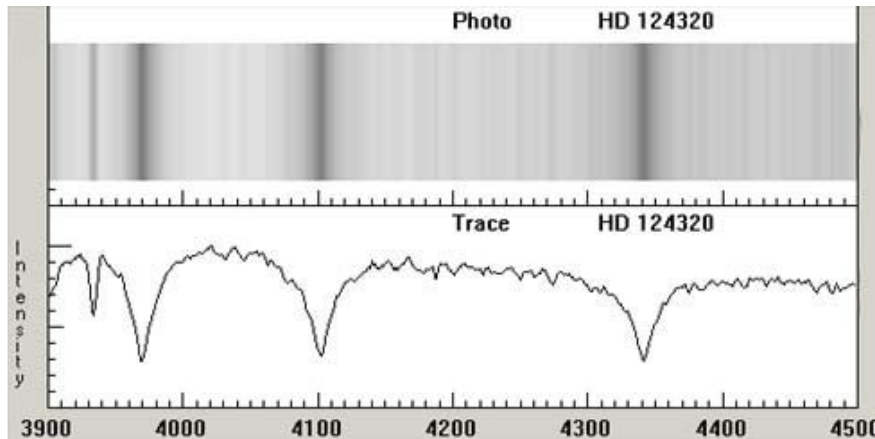


Figure 11: Comparison of photographic and intensity plot spectra for an A3 V star. The units on the horizontal axis are \$\text{\AA}\$ so this is showing part of the visible waveband. Credit: Adapted from data in Project CLEA *The Classification of Stellar Spectra* exercise

Emission Nebulae

Emission spectra can be observed in emission nebulae such as M42, the Great Nebula in Orion and the Eta Carinae nebula. The characteristic pinkish-red colour is called an H II region.

The distinctive colour is due to the spectral line emission when an ionised electron recombines with a proton to form neutral hydrogen. The two spectra below are both of the Eta Carinae H II region. The top one is the original spectra whilst the lower spectrum has been adjusted for sky brightness and the effects of absorption in our atmosphere removed.

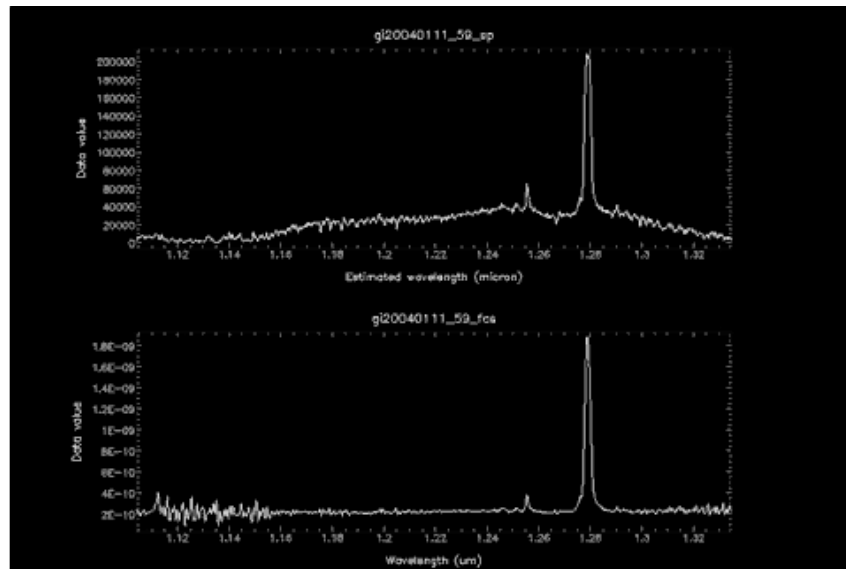


Figure 12:

This spectrum was obtained using IRIS2, an infrared spectrograph on the Anglo-Australian Telescope. Infrared spectrum for Eta Carinae. The top plot shows the raw co-added spectra, and the lower plot is after division by the standard star, flux calibration, and smoothing. The strong line at 1.28 microns is the Pa-beta hydrogen recombination line, while the feature at 1.255 microns is due to [FeII].

Credit: AAO and Nathan Smith, University of Colorado

Planetary nebulae are another type of emission nebulae. Their spectra show strong emission features and analysis of the Doppler shift of the lines can be used to determine how fast the ejected gas is expanding.

Galaxy Spectra

The overall spectrum of a galaxy is simply the combined spectrum of all the stars and other radiating matter in the galaxy. As galaxies vary in structure and relative composition of star type and gas their spectra will vary. The classification scheme for galaxies developed by Edwin Hubble and based on photographic images of the shape of galaxies is now supplemented by comparison of their spectra. Examples of galactic spectra obtained by the 2dF Galaxy Redshift Survey are shown below:

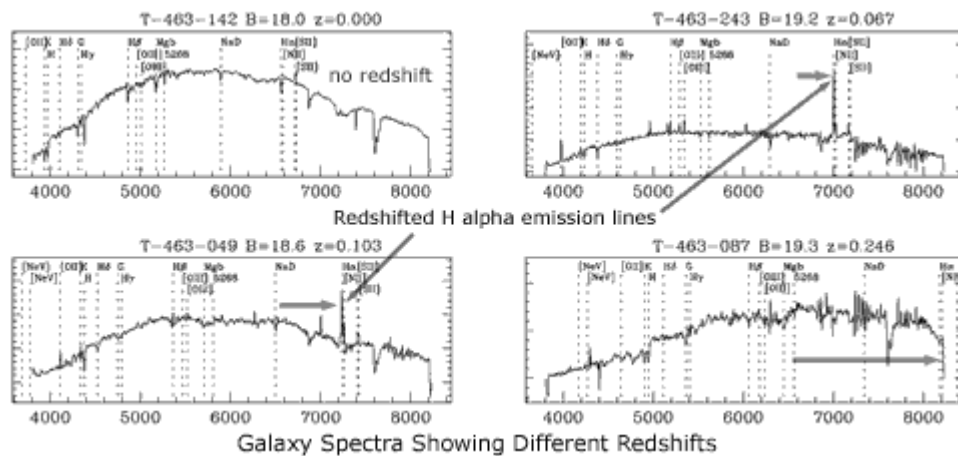


Figure 13:

Four different galactic spectra from the 2dF Galaxy Redshift Survey. Note the differing redshifts of the galaxies.

The top left galaxy is at zero redshift whilst the bottom right one has a redshift of $z = 0.246$. The other two galaxies show prominent H α emission lines suggesting active star formation in them. These H α lines have been redshifted beyond the rest frame value of 6563 Angstroms.

Credit: Adapted from data in The 2dF Galaxy Redshift Survey

Quasar Spectra

Quasars exhibit very bright emission features relative to a low intensity continuum in their spectra. Indeed it was only through careful analysis of the spectra of quasars that astronomers realised they were not just faint stars. The term quasar is actually a contraction of the term quasi-stellar object or QSO.

When the spectrum of the quasar is analysed a few key features are apparent. Firstly, its spectrum shows characteristic strong emission lines rising above a broad continuum. Secondly, the emission lines are not where we would expect to

see them if the object was a nearby star. The Lyman α line on the left of the spectrum is formed by transitions between the $n = 1$ and $n = 2$ energy levels in neutral hydrogen. This normally produces spectral lines with a wavelength of 121.6 nm or 1216 Ångstroms which is in the ultraviolet part of the spectrum. Here, however, the Lyman α line is clearly seen at a wavelength of about 4,100 Ångstroms in the visible part of the spectrum. Why is this? The standard explanation is that the quasar is at a vast distance from us so appears to be receding from us due to the expansion of the Universe. The high recession velocity of the quasar relative to us means that its spectral lines appear shifted to longer wavelengths. They have been redshifted. The quasar shown has a redshift of 2.3251 as measured from the shift in the lines for this spectrum.

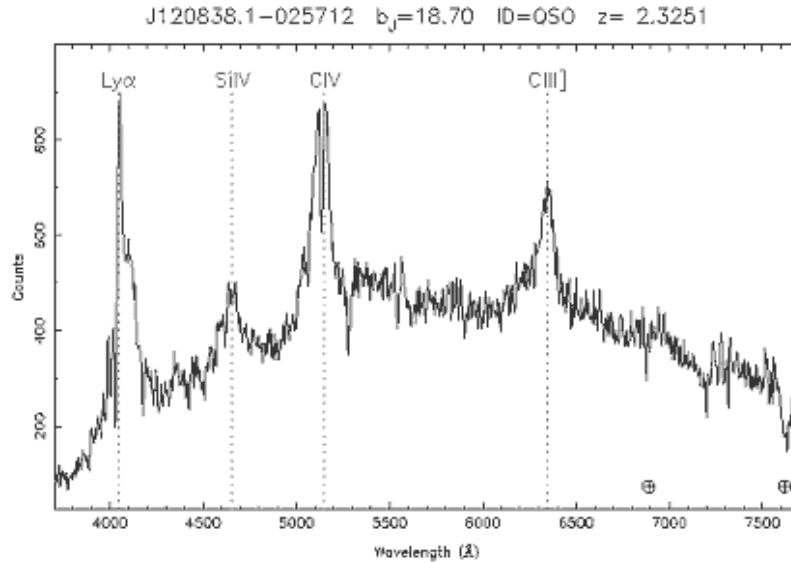


Figure 14: Characteristic QSO spectrum showing distinct, strong, redshifted emission lines.
 Credit: 2dF Quasar Survey

Exotic Star Types

Some exotic types of stars such as Wolf-Rayet stars exhibit strong, wide emission lines of ionised helium, carbon oxygen and nitrogen in their spectra. These rare, hot and extremely luminous stars are losing mass at a great rate. The emission lines result from a shell of expelled gas expanding at speeds of up to 3,000 km.s⁻¹.

Carbon stars can have similar temperatures to G, K, and M-class stars (4,600 - 3,100 K) but have a much higher abundance of carbon than normal stars. Deep red in colour due to the absorption of blue light by their surface-level carbon compounds, they are assigned a type C spectral class. An example of a carbon-rich star's spectrum is shown below.

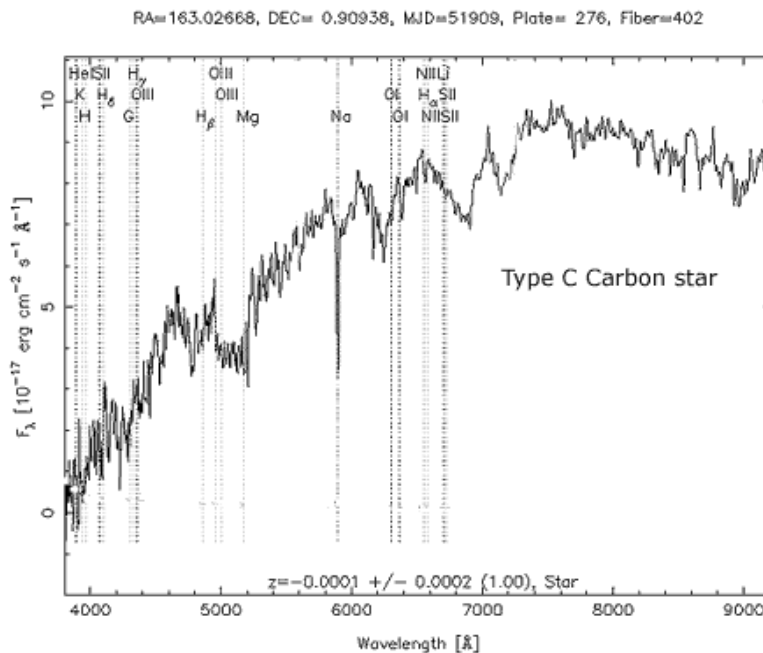


Figure 15: Carbon Star Spectrum
 Credit: The Sloan Digital Sky Survey

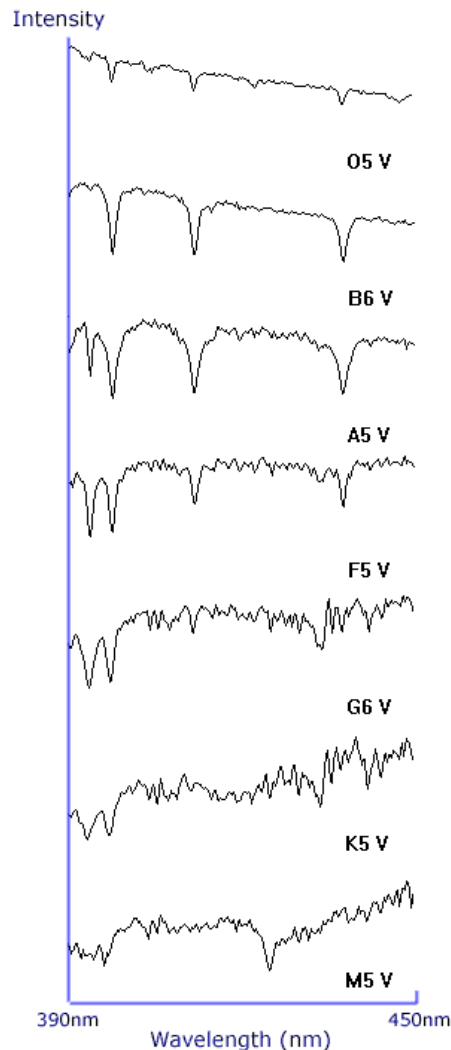
There are other types of exotic stars including Peculiar A stars, Hot Emission-Line stars, and Heavy-Metal-Oxide stars, all of which are classified by their spectra.

Spectral Classification of Stars

The rapid spread of spectroscopy in the late Nineteenth century resulted in a large number of stellar spectra. Astronomers faced the major challenge of trying to make sense of them. This was analogous to the problem faced earlier in the biological sciences and tackled by Linnaeus through his classification system of living organisms. The system now used was adopted in 1910 following detailed and extensive work by Annie Cannon and her team at Harvard Observatory. It has been refined since then but in essence is still the same.

To see how this spectral classification scheme works study the sequence of spectra shown below. The sequence below is for main sequence stars from about the middle of each spectral class. It shows the intensity-plot spectrum for a small region of the visible waveband from 390 - 450 nm. For colour examples of photographic spectra visit:

http://outreach-staging.atnf.csiro.au/education/senior/astrophysics/spectral_class.html



Comparison of 1D intensity spectra for Main Sequence stars

Figure 16: Intensity plot spectra for main sequence stars in region 390 – 450 nm.
 Credit: Adapted from data in Project CLEA *Classification of Stellar Spectra Exercise*.

If we study the spectra across the entire visual waveband we notice some trends. The O-class spectrum has relatively weak lines but lines for ionised He⁺ are present.

O star



The B, A and F stars have a similar pattern of lines that are strongest in the A star. These are the H Balmer series for neutral hydrogen.

A star



F and G stars have lines corresponding to ionised Ca⁺.

G star



The K and M stars have many more lines visible but the Balmer series is very weak. These lines correspond to Fe, other neutral metals and molecules. TiO lines are visible in the spectrum of M stars.

M star



Why do different stars have different lines? This question is the key to helping us classify stars. If we compare an O-class star with an M-class star they have very different lines. The O-class star has weak lines except those for ionised He⁺ and it also has a continuum that is strong in the UV region.

The key factor at work here is temperature. By temperature we really mean the effective temperature of the star (sometimes called the surface temperature). This is the temperature of a black body having the same size and luminosity as the star and is determined by Stefan's Law. The variations in spectral lines for different stars are due primarily to the difference in temperature of the outer layers of gas in the star.

In very hot stars, helium can be ionised so we can expect to see spectral lines due to absorption by helium ions. In most stars the temperature is too cool for helium to ionise so no such lines can form in the spectrum. Even though spectral lines due to helium are not found in cool stars it does not mean that helium is missing from the star. In fact helium is the second most abundant element in the Universe and in stars. The absence of helium lines simply means that the conditions are not right for helium lines to form or be abundant in that star.

Some stars are cool enough that molecules can exist in outer layers without being ripped apart. As the number of possible electron transitions is much greater in molecules than single atoms there are many possible spectral lines that can form hence cool stars typically have many lines.

The standard spectral class classification scheme is thus based on temperature. Most stars fit into one of the following types or spectral classes:

O, B, A, F, G, K, M

These classes go from hot to cool with O the hottest and M, cool. recent discoveries have led to tentative new classifications for even cooler L-class stars. For the moment, however, we will focus on the seven original classes. The letters assigned to each class seem confusing and out of order. This is an historical artefact as classes were assigned to spectra before the underlying physical relationship was known. Rather than reassign letters to different spectra, some classes were merged and the whole sequence arranged in order of decreasing temperature.

How can you remember the sequence?

Many people use a memory device or mnemonic to help them. Here is a common example but feel free to make up your own.

Oh Be A Fine Girl (or Guy), Kiss Me!

The basic system of a letter to denote spectral class is further refined by adding a number from 0 to 9 following it. Each spectral class is thus broken down into ten subdivisions so that, for example, an F2 star is hotter than an F7 star.

The basic characteristics of each spectral class are summarised in the following table. The four columns on the right of the table provide comparison of a star's mass, radius and luminosity (power output) with respect to the Sun and the main sequence lifespan for a star of that spectral class.

Table 2: Spectral Class Summary

Spectral Class	Effective Temperature (K)	Colour	H Balmer Features	Other Features	M/M _{Sun}	R/R _{Sun}	L/L _{Sun}	Main Sequence Lifespan
O	28,000 - 50,000	Blue	Weak	ionised He ⁺ lines, strong UV continuum	20 - 60	9 - 15	90,000 - 800,000	1 - 10 Myr
B	10,000 - 28,000	Blue-white	Medium	neutral He lines	3 - 18	3.0 - 8.4	95 - 52,000	11 - 400 Myr
A	7,500 - 10,000	white	Strong	strong H lines, ionised metal lines	2.0 - 3.0	1.7 - 2.7	8 - 55	400 Myr - 3 Gyr
F	6,000 - 7,500	White-yellow	Medium	weak ionised Ca ⁺	1.1 - 1.6	1.2 - 1.6	2.0 - 6.5	3 - 7 Gyr
G	4,900 - 6,000	Yellow	Weak	ionised Ca ⁺ , metal lines	0.85 - 1.1	0.85 - 1.1	0.66 - 1.5	7 - 15 Gyr
K	3,500 - 4,900	Orange	Very weak	Ca ⁺ , Fe, strong molecules, CH, CN	0.65 - 0.85	0.65 - 0.85	0.10 - 0.42	17 Gyr
M	2,000 - 3,500	red	Very weak	molecular lines, eg TiO, neutral metals	0.08 - 0.05	0.17 - 0.63	0.001 - 0.08	56 Gyr
L	<2,000	Tentative new (2000) classification for very low mass stars.			<0.08	May or may not be fusing H in cores?		

Luminosity Classes

One problem facing early attempts at classifying stellar spectra was the fact that two spectra could have the same lines present, indicating that the stars had the same effective temperature, but the lines in one star's spectrum were broader than in the other. When the star's were plotted on an HR diagram it also became apparent that two stars could have the same effective temperature (hence also colour and spectral class) but vary enormously in luminosity and thus absolute magnitude. To account for this a second classification scheme of Luminosity Class was added to the original concept of Spectral Class. A simplified version of the MK system of luminosity classes is shown in the table below.

Table 3: Luminosity Classes of Stars

Symbol	Class of Star	Example
0	Extreme, luminous supergiants	
Ia	Luminous supergiants	Betelgeuse
Ib	Less luminous supergiants	Antares
II	Bright giants	Canopus
III	Normal giants	Aldebaran
IV	Subgiants	Procyon
V	Main sequence	Sun
sd	Subdwarfs	Kapteyn's Star (HD 33793)
wd or D	White dwarfs	Sirius B

What Information can we obtain from Spectra?

The key point to remember about astronomical spectra is that they provide astronomers with a wealth of detail about the physical characteristics, motion and composition of objects. In this section we will examine what information can be obtained from spectra and how this is done.

Effective Surface Temperature and Wien's Law

As we have already seen, the behaviour of most stars approximates that of black body radiators. This means that they emit some energy at each wavelength but also have a peak wavelength and region in which they emit most of their

energy. In the early 1890s Wilhelm Wien investigated thermodynamics and coined the term black body for an ideal radiator. He discovered that the wavelength of maximum energy emitted from a perfect black body was inversely proportional to the temperature of the body, λ_{\max} is proportional to $1/T$. This relationship is known as Wien's Law in his honour.

$$\text{Wien's Law Formula: } \lambda_{\max} = W/T$$

Equation 1: Wien's Law, where λ_{\max} is the peak wavelength, T is the effective temperature of the black body and W is a constant called Wien's Constant and has a value of 2.898×10^{-3} for λ_{\max} in meters and T in kelvins.
(Note: This equation is not explicitly required for the NSW HSC course)

Wien's Law is a highly significant relationship. He used it to estimate the effective temperature of the Sun at 6,000 K which was much closer than the previous estimate of 10,000 K predicted using the Stefan-Boltzmann law of radiation. The value of Wien's relationship is that if you can measure the wavelength of maximum intensity from a spectrum, you can use it to calculate a value for the effective temperature. Let us see how this works in the example below. Remember, this is an actual stellar spectrum so it approximates a black body and has absorption lines in it rather than being a perfect continuum Planck curve.

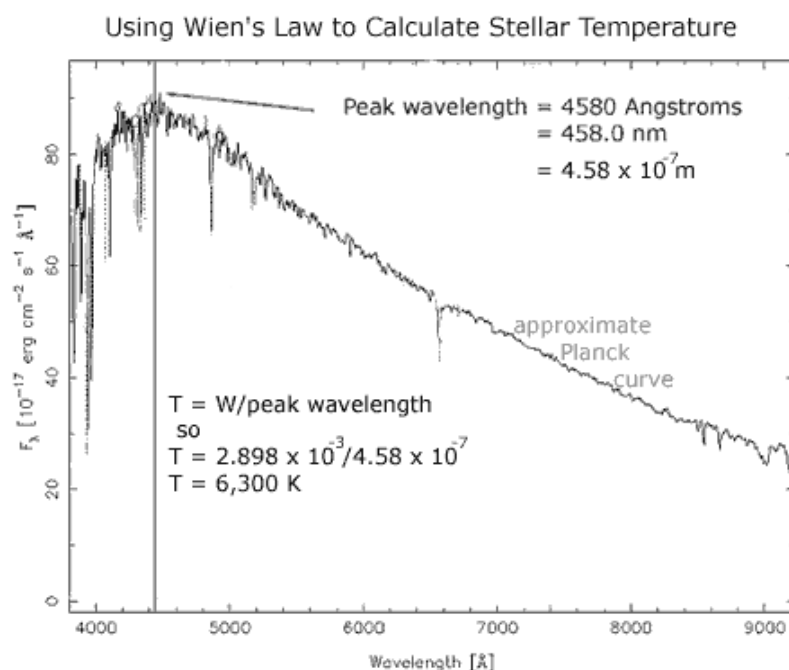


Figure 17:

Credit: CSIRO using data from The Sloan Digital Sky Survey

Astronomers can determine the effective temperature of a star simply by taking its spectrum.

The Doppler Effect

The Doppler effect refers to the apparent shift in the wavelength (and frequency) of a wave when there is relative motion between the source or emitter of the wave and an observer. A common example of this effect is the sound made by a passing ambulance. As the ambulance approaches you the sound waves are apparently shifted to a shorter wavelength (hence higher frequency). You perceive this increased frequency as a higher-pitched sound. Once the ambulance passes you it is now receding from you so the sound waves are shifted to a longer wavelength and lower frequency. You hear this as a lower pitched sound.

When discussing electromagnetic waves we use the term Doppler shift to describe this effect. If we obtain a spectrum from an object at rest to us then there is no Doppler shift in the spectrum. The spectral lines for the Balmer series, for instance, would appear at the same wavelengths as those from a hydrogen discharge tube in the laboratory or observatory. No relative motion therefore no apparent shift in lines.

If an object such as a star was moving away from us (or indeed us from it, it is only the relative motion that is important) then the spectral lines would appear to shift towards the longer wavelength or redder part of the spectrum. Such a shift is termed a redshift. The amount of the shift would depend on the relative velocity between source and observer. The greater the recession velocity, the greater the shift in the lines.

In cases where an object is moving towards us, its spectral lines will appear to shift to the shorter wavelength, bluer part of the spectrum. This is called a blueshift. Again, the amount of blueshift will depend upon the relative velocity between source and observer. A basic diagram showing shift for a set of Balmer lines in a stellar spectrum is shown in figure 18.

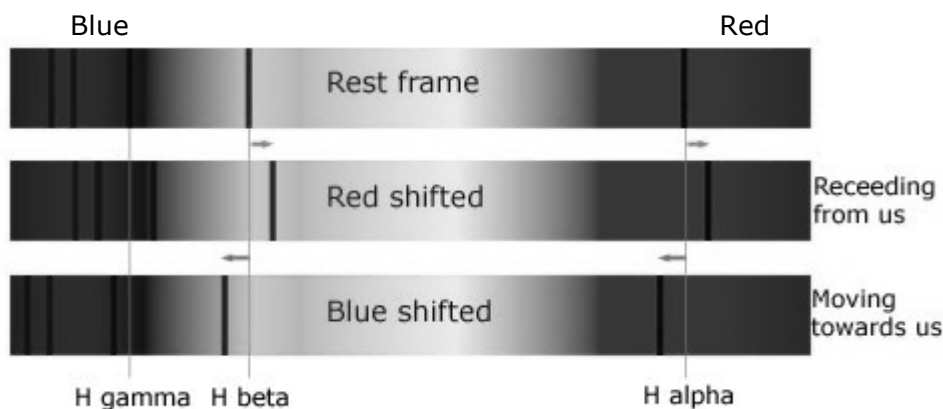


Figure 18:

Diagram showing comparison of position of spectral lines for a source at rest (top), redshift where the source is moving away from the observer (middle) and blueshift where the source is moving towards the observer (bottom). Note that the motion between source and observer is relative.

If a star moves relative to an observer on Earth with a radial velocity v and emits a certain wavelength λ then the Earth-based observer will see a Doppler-shifted wavelength of λ' . These two are related by the following formula:

$$(\lambda' - \lambda)/\lambda = v/c$$

where c = speed of light = $3.0 \times 10^8 \text{ m.s}^{-1}$ and v is non-relativistic in speed. By convention v is positive for receding objects and negative for those approaching. (Note this equation is not explicitly required for NSW HSC Physics candidates).

Translational Motion

If the spectral lines in a star's spectrum are uniformly redshifted this would indicate relative recessional motion between the observer and the star. The amount of redshift would depend on the recession velocity. A complicating factor is the fact that the motion may not be directly away from us. In this case the Doppler shift of lines would depend on the component of velocity away from us, that is the star's radial velocity.

A star moving towards us would, of course, exhibit a blueshift in its spectral lines.

Rotational Motion

Even though we can still only resolve most stars as point sources they are in fact large, roughly spherical balls of hot gas and plasma. Stars rotate, that is they spin on their axis. The Sun's sidereal rotational period is about 26 days on the solar equator and possibly up to 36 days at the poles. The different rates is due to the fact that it is not a solid sphere and the gas and plasma can rotate at different speeds.

If we obtain a spectrum from a distant star that is rotating in the same plane as us then the light gathered is a combination of light from across the disc of the star. As part of the star appears to rotate towards us its light will be blueshifted. The light from the part of the star rotating away from us will be redshifted. The section in the middle of the disc that is moving tangentially to us will not exhibit Doppler-shift.

What effect will this have on the star's spectrum?

The net effect is that the star's spectral lines will appear smeared out. This broadening of lines can be distinguished from the effects of pressure broadening due to stellar pressure discussed in the next section. The beauty of rotational broadening is that it can be used to measure the rotation rate of stars. As with translational velocity the alignment of the plane of rotation of the star with Earth is a factor and must be calculated from the spectrum.

Stellar Density and Pressure Broadening

In attempting to classify stars using their spectral characteristics astronomers faced a problem with some stars. Two stars may appear to have the same lines but one of them shows broader lines than the other in a photographic spectrum. Are they then the same spectral class? This question was resolved when the spectral data was combined with the information about the luminosity some stars that had been obtained separately. A photographic example for A3-class stars is shown below.

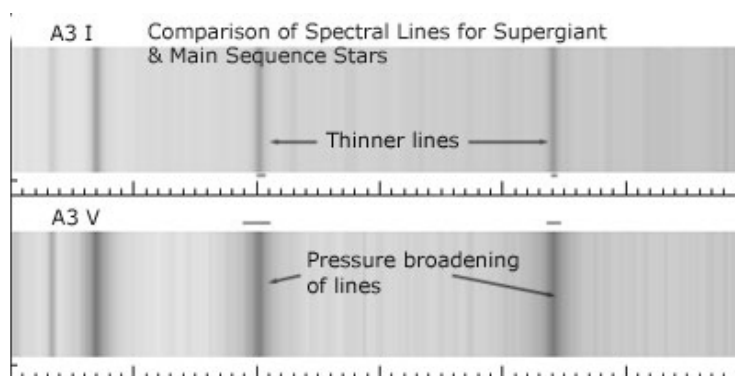


Figure 19:

Comparison of spectral line widths for A3 I and A3 V class stars.

The broader lines for the V luminosity class star arises due to the denser outer layers in the atmosphere of the main sequence star.

For a given temperature, the more luminous the star was, the narrower the spectral lines were. The width of the line (and the depth for an intensity plot) provides information about the outer layers of the star, the region in which the absorption of photons from the core occurs. Large stars have a very low relative density in their outer layers as the volume occupied by a given mass of gas is much greater.

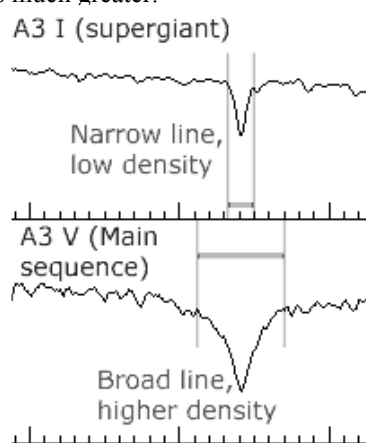


Figure 20:

Pressure-broadening as an intensity plot. The broader lines for the V luminosity class star arises due to the denser outer layers in the atmosphere of the main sequence star.

Chemical Composition and Metallicity

The presence of a spectral line corresponding to a specific energy transition for an ion, element or molecule in the spectrum of a star indicates that the specific ion, atom or molecule is present in that star. This is a fairly obvious statement but one with great importance for astronomers. This was how helium was first discovered in the Sun before it was isolated on Earth. We now know that stars are mostly made up of hydrogen and helium, with small amounts of some other elements. This is only known due to spectroscopy.

A key point to remember, however, is that the absence of a spectral line does not also necessarily mean that that element is not present in that star. It simply means that the conditions in the layers of the star responsible for absorption and emission lines are not conducive to the formation of that specific transition or line.

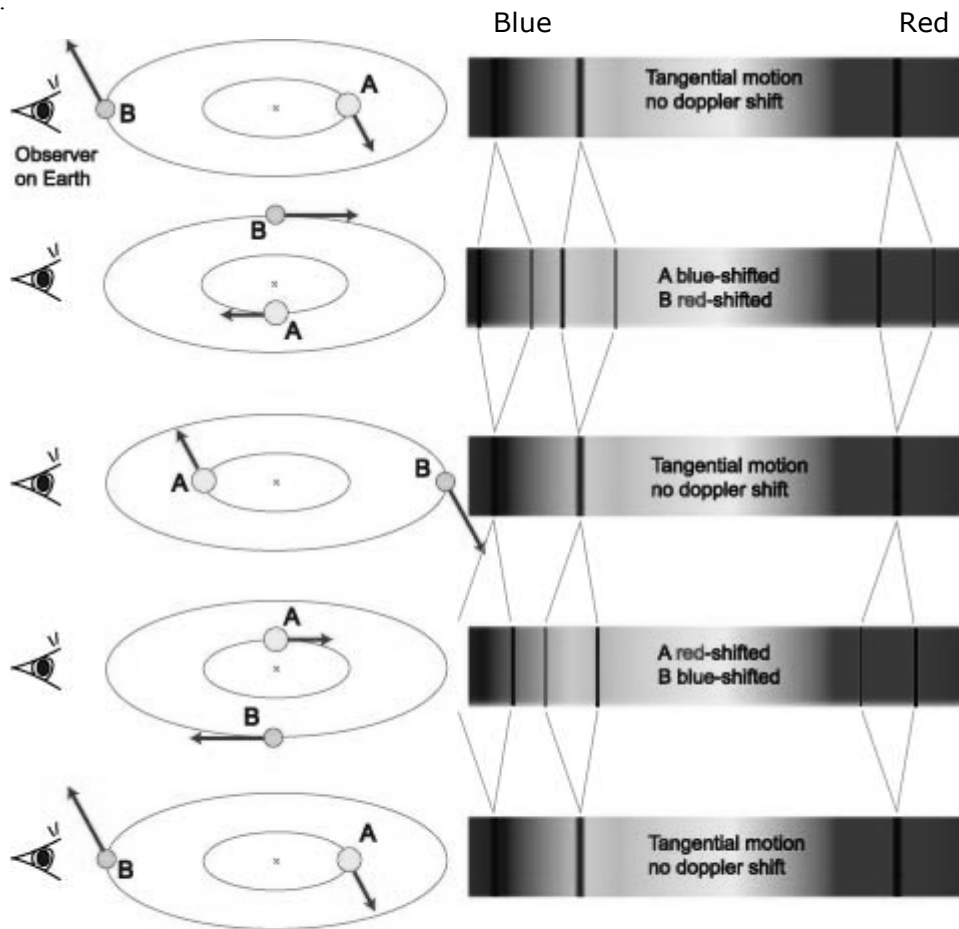
Modern spectroscopy is highly efficient and is often conducted with very high resolution spectrographs that show spectral lines in fine detail. Astronomers can not only detect the presence of a line but they are often able to determine the relative amounts of different elements and molecules present. They can thus determine the metallicity of a star. In astronomy the term metal historically has been applied to any element heavier than helium so that even elements such as carbon and oxygen are called metals. When discussing metallicity then astronomers are actually talking about the relative chemical composition of a star. Stars with a higher proportion of metals are said to have higher metallicities.

Other Information

Astronomers can deduce even more about a star from its spectrum. Some of these are:

- **Spectroscopic binaries:** Some stars show a periodic splitting and recombination of spectral lines. This is caused by the fact that what we see as one star is in fact two stars orbiting each other as a close binary pair.

Binary stars discovered by their spectra are termed *spectroscopic binaries*. Most binaries are discovered by this method.



A Spectroscopic Binary System

High-mass star A and lower-mass B orbit around a common centre of mass. The observed combined spectrum shows periodic splitting and shifting of spectral lines. The amount of shift is a function of the alignment of the system relative to us and the orbital speed of the stars.

Figure 21: Credit R. Hollow, CSIRO

- Helioseismology:** The Sun vibrates much like a struck bell. As sections of its atmosphere pulse in and out the spectral lines produced from the emitted light show slight fluctuations. We can now measure variations on the Sun's surface of the order of a few cm.s^{-1} . This information is used to compile harmonic oscillation modes for the Sun which provides details about the solar interior in much the same way as we use seismic waves to probe the Earth's interior. This technique, termed helioseismology is now also used to study other stars. As the sensitivity of instruments improved and the amount of data gathered increases astronomers are able to refine their models of processes that occur inside stars.
- Exoplanets:** The first planet discovered orbiting a sun-like star was in 1995 when two Swiss astronomers detected a Jupiter-mass planet around the star 51 Pegasi. This followed the discovery of a planet orbiting a pulsar the previous year. Since then over 170 planets beyond our Solar System or exoplanets have been found. The bulk of these have been detected using a method known as the Doppler wobble in which the planet's mass causes slight shifts in the spectral lines from the star. As an unseen planet moves away from us when orbiting its parent star, it causes its light to be slightly redshifted. When the planet moves towards us the star's light is blueshifted slightly. Jupiter causes the Sun to wobble with a velocity of about 12 m.s^{-1} . Australian astronomers are actively involved in the search for exoplanets via the Anglo-Australian Planet Search that uses the AAT. It is observing 200 nearby solar-type stars brighter than $V < 7.5$ and relies on the Doppler wobble technique for detection. The precision of the team's method currently stands at about 3 m.s^{-1} .

Spectroscopy at other Wavebands

Spectroscopy is not just the tool of optical astronomers. It can be carried out at all wavebands, each of which provides new insights into the structure and characteristics of celestial objects.

Infrared spectroscopy allows astronomers to study regions of star birth obscured to optical astronomy by cold clouds of dust and gas. Australia is actively involved in infrared astronomy and has built infrared spectrographs such as IRIS 2 for the AAT (see Figure 13) and the ANU's 2.3 m telescope at Siding Spring. The Research School of Astronomy and Astrophysics at Mt Stromlo in Canberra was building the Near IR Integral Field Spectrograph (NIFS) for the 8.1 m Gemini North telescope in Hawaii when fire destroyed most of the facilities on the mountain in early 2003. A replacement NIFS has now been made and was successfully commissioned on the telescope in late 2005. It can operate in conjunction with the ALTAIR adaptive optics system.

NIFS will record spectra in the wavelength range from 1 to 2.5 microns for each 0.1"×0.1" piece of a 3.0"×3.0" region of the sky. By combining the superb image quality of the Gemini telescope and its adaptive optics system with the high spatial and spectral resolution achievable with NIFS, astronomers will be able to study the infrared structure of astronomical objects on scales comparable to those achieved with the Hubble Space Telescope in the optical.
(<http://www.mso.anu.edu.au/nifs/index.shtml>)

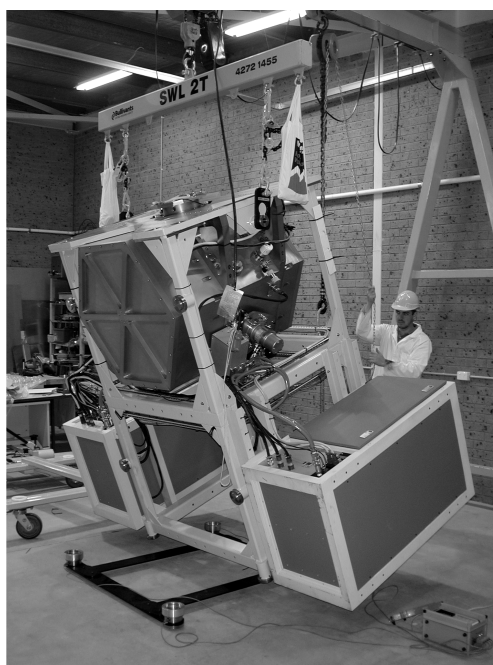


Figure 22:
NIFS – 2 assembled in the Auspace Facility near Canberra prior to shipping to Gemini.
Credit: Courtesy of Australian National University

High-energy spectroscopy in the X-ray and γ -ray regions is more difficult as the instruments have to withstand the rigours of a rocket launch and the harsh environment of space. As high energy photons have much shorter wavelengths traditional optical designs for spectrographs are not suitable or able to be adapted. The resolution of high energy spectrographs cannot match optical ones at present but they allow us to gain greater understanding of violent, energetic objects and events in the Universe.

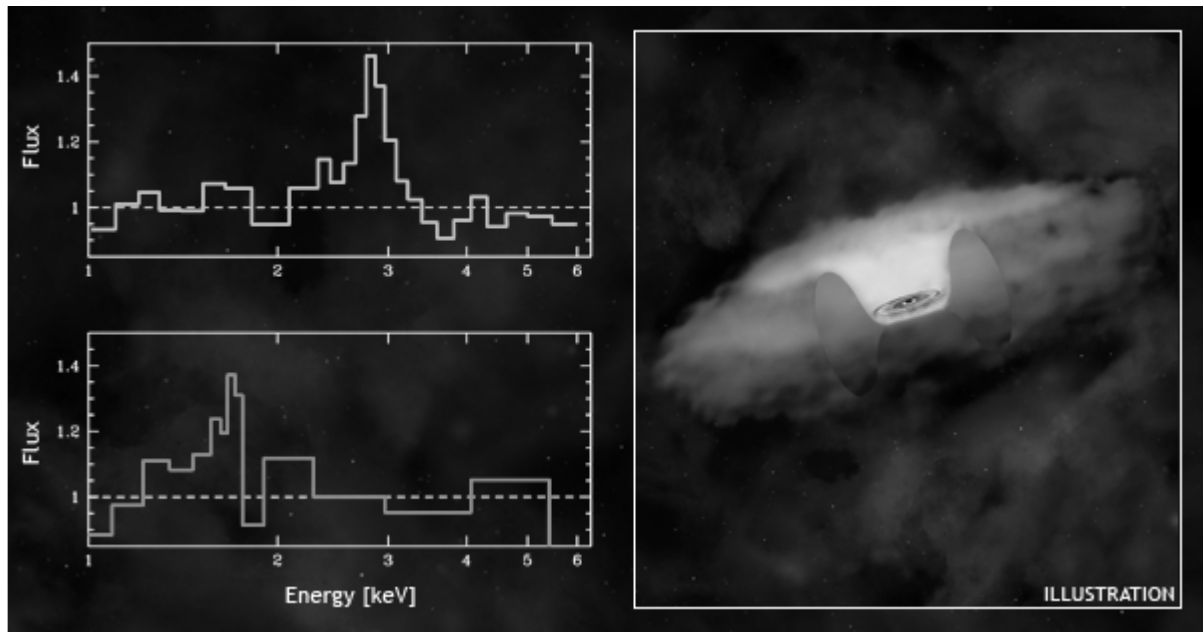


Figure 23:

Iron Spectra from Supermassive Black Holes: X-rays from iron atoms near distant supermassive black holes in the North and South Chandra Deep Fields. These spectra were obtained by the Chandra X-Ray Observatory which is currently orbiting the Earth.

(Credit: X-ray spectra/NASA/CXC/MPI/M.Brusa et al.; Illustration: CXC/M.Weiss)

Radio astronomers also gain spectral information from their observations. Receivers used on radio telescopes can pick up thousands of bands in a given region of the radio band just as you could obtain by moving a radio dial through several stations and measuring the intensity of the received signal. This information effectively provides details about the various transitions emitted by matter. Radio spectral data can give details about frequency and velocity. It can also provide information about the polarisation of the signal, information not normally available in visible spectra.

Improvements in receivers and detectors now allow astronomers to routinely observe at mm-wavelengths where there is a wealth of spectral lines from molecules in space. Molecules such as acetic acid and formaldehyde have been discovered in interstellar clouds and the search continues for the signature of amino acids such as glycine. Information on these will prove vital for astrobiologists and astrochemists.

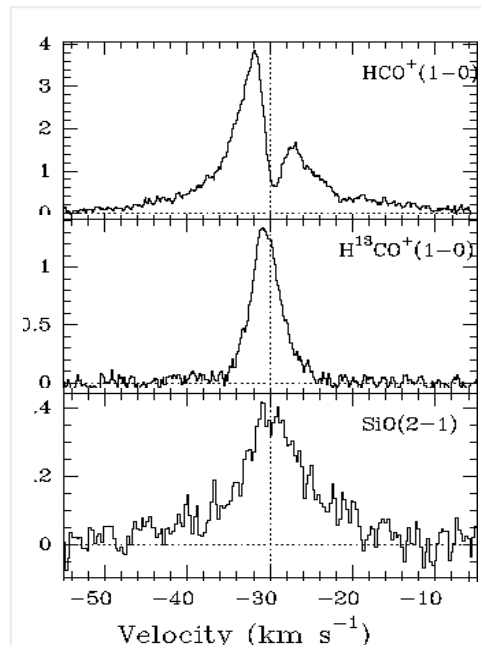


Figure 24:

Spectra of the emission in three molecular lines observed towards the very young massive star IRAS 16547-4247. These spectra were obtained using the SEST radio telescope in Chile. The frequencies of the lines are ~100 GHz. Garay, Brooks et al. 2003, ApJ, 587, 739

Activities for Spectroscopy

Classroom Activities

The first specified activity is that students: *perform a first-hand investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight, or incandescent filaments*. This is a traditional investigation well covered in most textbooks. A few points to note however are relevant in the astrophysics context.

1. **Discharge tubes** produce obvious emission lines but may not be very bright. The tubes are often difficult to align with handheld spectroscopes as students try and cluster around the bench. Care is needed with classroom management. Students should try and measure the prominent lines for the hydrogen discharge tube and compare with stated values for the Balmer series. Also get them to note the colours of emission lines for example, oxygen and hydrogen, so that you can compare this with the colours in images of emission nebulae and SNRs.
2. **Reflected sunlight** should show the absorption lines, first recorded by Fraunhofer. **Students must not point spectroscopes directly at the Sun!**
3. **Incandescent filaments** approximate a continuum emission. Rather than just using a ray box lamp on one setting, by varying the voltage you vary the luminosity and colour of the lamp. This can be seen through a spectroscope as the spectrum gets brighter but also shows more of the blue in the continuum as the bulb is hotter.
4. Although not specified in the syllabus, the spectrum from a **fluorescent lamp** is particularly interesting to observe, as it should show bright emission lines on an already bright continuum. This is a useful analogy for spectra produced by objects such as quasars and Wolf-Rayet stars.

A simple way for students to view a spectra is to use old CDs. The pits on the CD act as a diffraction pattern and produce a very obvious spectrum.

Perhaps the most effective way to produce a spectrum for the whole class to see at once is with a piece of *holographic diffraction grating film*. This material was designed and produced by Learning Technologies in the USA and is now available in Australia from the scientific distributors, *Cider House* www.ciderhouse.com.au. It is available in sheets, a roll or mounted as a slide and comes with information on how it works and suggested activities. Using it conjunction with an OHP or slide projector you can produce a large, bright continuum a few metres in length.

Use of Real Data

If you want sources of real stellar spectra there are several good websites. One thing to reinforce with astronomical spectra is that most spectra these days are intensity plots obtained by photometric means rather than the more traditional photographic spectra (or their negatives). The Anglo-Australian telescope's 2dF instrument can obtain 400 spectra simultaneously feeding two spectrographs that have CCDs in them to record the spectra. It is worthwhile showing several photographic spectra alongside (even better above or below) the corresponding intensity plot. This allows you to emphasise what astronomers mean by absorption and emission lines and the continuum. Intensity plot spectra are also more effective in conveying the shape of the blackbody curve. Wien's Law can be used if the intensity peak is present on a plot to determine the effective temperature of the star. Two computer-based activities listed below will help students address the other skill requirement in the syllabus that requires students to *analyse information to predict the surface temperature of a star from its intensity/wavelength graph*.

An excellent activity where students use real data to classify stars can be found online at the SkyServer site at <http://skyserver.sdss.org/>. This activity utilises spectra obtained as part of the Sloan Digital Sky Survey in the US. The home site also provides activities for the HR Diagram, color (sic) and image processing as well others related to galaxies and cosmology. Several of the spectra shown earlier in this paper are from this site.

A free simulation whereby students can "drive" a telescope, take, then analyse spectra for a range of stars is the Project CLEA exercise, *Spectral Classification of Stars*. It, along with other useful activities can be downloaded from the Project CLEA website at: <http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html>. This activity works well as an assessment task or class practical activity. There are sufficient stars included in the star field for each student to have a few exclusive stars to classify and also have some common stars to classify for comparison. Work books, guides and pre and post-tests are also available.

Conclusion

Spectroscopy is a vital tool in astrophysics and many other fields of science. This paper provides some background theory, examples and activities to support the teaching of spectroscopy within option 9.7 *Astrophysics* for the NSW HSC course. The ideas and materials presented here may help your students gain a better conceptual grasp of the techniques and underlying theory. If you come up with something that works well with your students and you think may be of use to others please contact me and we may be able to put it in the Teacher Resource section of the *Australia Telescope Outreach and Education* website at ATNF.

References and other useful books

- Andriessen, M., Pentland, P., Gaut, R., and McKay, B., 2001, *Physics 2 HSC Course*, Y. McCallum (consultant), (Jacaranda: Milton), ISBN 0 7016 3466 9 (a revised edition incorporating amendments to the syllabus is now available).
- Board of Studies NSW, 1999 amended 2002, *Physics Stage 6 Syllabus*, (Board of Studies NSW: Sydney), ISBN 0 7313 4358 1.
- Gibbs, K., 1999, *The Resourceful Physics Teacher 600 Ideas for Creative Teaching*, (Institute of Physics Publishing: Bristol), ISBN 0 7503 0581 9.
- Green, S. F., and Jones, M. H., 2004, *An Introduction to the Sun and Stars*, (The Open University and CUP: Cambridge) ISBN 0 521 54622 2.
- Inglis, M., 2003, *Observer's Guide to Stellar Evolution*, (Springer-Verlag: London), ISBN 1852334657.
- Kaler, J. B., 1989, *Stars and Their Spectra*, (CUP: Cambridge), ISBN 0 521 30494 6 (updated edition now available).
- McNamara, B. J., Burnham, C. C., Bridges, C. W., French, M. G., 1997, *Investigating Astronomy: Model Building & Critical Thinking* (Mosby: St Louis), ISBN 0-8151-4337-0
- Pompea, S. M.(ed), 2000, *Great Ideas for Teaching Astronomy Third Edition*, (Brooks/Cole, Thomson Learning: Pacific Grove), CA, ISBN 0-534-37301-1.
- Smith, R. C., 1995, *Observational Astrophysics*, (CUP: Cambridge), ISBN 0 521 27834 1.
- Zeilik, M., 2002, *Active Learning Astronomy for "Astronomy: The Evolving Universe"*, (CUP, Cambridge), ISBN 0-521-52901-8

Useful Web Sites

There is a wealth of information available on the web and far too many to list separately here. Sites provide information at a range of depths. Some are more suited as general introductions whilst others provide detailed technical information. The Australia Telescope Outreach and Education website <http://outreach.atnf.csiro.au> contains comprehensive online course material for both the *Astrophysics* option and *The Cosmic Engine* module. Each section has numerous pages that directly address each syllabus point and beyond. The material incorporates up-to-date observations and emphasises Australian facilities and research. There are hundreds of links to other sites, too many to list them all here. Questions with solutions are provided, as are some activities that can be downloaded and printed out for class use. For the *Astrophysics* section visit: <http://outreach.atnf.csiro.au/education/senior/astrophysics/>. Additional support material for teacher may be found in the Resource Section: <http://outreach.atnf.csiro.au/education/teachers/resources/>.

Another valuable starting point is the *UniServe Science* resource page for the *Astrophysics* option for the NSW HSC Physics course at: <http://science.uniserve.edu.au/school/curric/stage6/phys/astrophys.html>.

Spectra applets and activities

- *Absorption Spectroscopy* <http://phys.educ.ksu.edu/vqm/html/absorption.html> uses *Macromedia Shockwave* in a web browser to simulate spectra from discharge tubes of different elements. You can produce different absorption lines and try and identify an unknown lamp.
- *Applet: Spectrum* <http://lectureonline.cl.msu.edu/~mmp/applist/Spectrum/s.htm> is a simple but effective Java applet that shows the frequency, wavelength and energy of any region of the em spectrum as you drag a mouse across it. It also shows sources of the different wavebands, how we detect them and some uses of each.
- *Blackbody* <http://www.colorado.edu/physics/phet/simulations/blackbody/blackbody.swf> is a *Shockwave* applet that opens in your browser. By altering the temperature of the object you see the change in the shape and peak intensity of its Planck curve, the colour of the object and more. You can run this applet or online or download it to run on your own computer.
- *BlackBody Physlet* http://webphysics.davidson.edu/Applets/java11_Archive.html is an effective *Java* applet that allows you to see the Planck curve and colour for stars of different temperatures.
- *black body Radiation Exercises: Planck Law Radiation Distributions* <http://csep10.phys.utk.edu/guidry/java/planck/planck.html> is a Java applet that allows you to plot up to 10 Planck curves for temperatures from 3,000 to 30,000 K and compare them. It was used to produce some of the images used in this site. It also has links to applets for *Wien's Law* and *black body: The Game* where you have to try and determine the temperature of an unknown object to match a given Planck curve.

- *Color and Stellar Temperature* <http://zebu.uoregon.edu/nsf/planck.html> is an effective applet that allows you to compare the black body curves for two stars of different temperatures and determine their colours. You can add waveband filters and explore the infrared and ultraviolet parts of the spectrum as well as the visible.
- *Diffraction Grating – The Study of Color & Light* <http://www.rainbowsymphony.com/teacher-lesson.htm> is a lesson plan using diffraction gratings, lights and diffraction glasses to study colour and spectra.
- *Hydrogen Energy Levels* <http://www.spectroscopynow.com/Spy/tools/HELApplet.html> is a simple applet demonstrating the use of the Bohr equation to calculate the energy levels of a hydrogen atom. It shows an energy level diagram vertically from infinity to the ground state.
- *HyperPhysics hydrogen energies and spectrum* <http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html#c4> has a handy applet that calculates the wavelength for different transitions in hydrogen. The page also has useful energy level diagrams.
- *IMSA Astrophysics: Stellar Spectra and Planck black body Radiation* <http://staff.imsa.edu/science/astro/blackbody/> is an excellent resource with detailed theory, clear diagrams and an Excel spreadsheet where you can model Planck curves and analyse data.
- *Mini Spectroscopy* <http://mo-www.harvard.edu/Java/MiniSpectroscopy.html> "is a simplified version of the Harvard-Smithsonian Center for Astrophysics full-featured spectroscopy software called Virtual Spectroscope." The Java applet allows you produce a spectrum from a fluorescent lamp, the Sun, a red LED, Hydrogen and three galaxies. They appear as photographic and intensity plots against a reference spectrum.
- *Project CLEA The Classification of Stellar Spectra* <http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html> is an excellent free simulation for Win PCs. You can download the software, a User's Guide, pre and post tests and a comprehensive Student Manual free from the CLEA site. The simulation allows you to control a telescope and spectrograph to take spectra of a large number of stars. You can then attempt to identify them by comparing with spectral standard reference stars. It includes stars of different luminosity classes. Spectra can be examined as photographic or intensity plots. This is worth spending time with. The student manual is comprehensive and a handy resource. You can use this for classroom activities or even as a practical assessment task with some prior exposure.
- *Properties of Stars* <http://www.unm.edu/%7Eastro1/101lab/lab8/lab8.html> allows to examine the properties of several stars using a virtual observatory then explore some of the evolutionary stages. An excellent activity with high quality graphics and pedagogy from University of New Mexico.
- *SkyServer SDSS* <http://skyserver.sdss.org/> has an excellent activity/project leading you through the classification of stellar spectra, *Spectral Types* using actual Sloan Digital Sky Survey data. It is accompanied by detailed instructions and relevant theory. Highly recommended. Other activities and projects can also be found by following the links from the home page.
- *Stellar Parameters* <http://astro.unl.edu/classaction/> is an excellent tool, part of the *ClassAction Interactive Materials for Introductory Astronomy* <http://astro.unl.edu/classaction/> at the University of Nebraska. Click on the link to the Stellar Parameters page to run the module from the web or download a zipped version to run on your own computer. The module uses Flash simulations to investigate the distance modulus, stellar velocity, parallax, spectroscopic parallax, luminosity, flux and the HR Diagram. It also contains a quiz, images, tables and an outline of each concept. You can also download an Instructors manual. An excellent resource.
- *Thermal Radiation Curves Applet* <http://cas.sdss.org/dr2/en/proj/basic/color/physlet/blackbody.asp?textBox=5750> allows you to specify a temperature or a peak wavelength for a star and view the corresponding Planck curve with a simulated visible spectrum superimposed on it.

Catalogs and Sources of Spectra

- *A library of stellar spectra* http://adsabs.harvard.edu/cgi-bin/bib_query?1984ApJS...56..257J is an online version of the 1984 paper from Astrophysical Journal Supplement Series of 161 O-M stars. This is a professional 25-page paper with numerous references, data tables and plots of the spectra.
- *An Atlas of Stellar Spectra* http://nedwww.ipac.caltech.edu/level5/ASS_Atlas/frames.html is a very detailed site with archived photographic plates of the spectral standard stars.
- *BASS2000 Solar Spectrum* http://mesola.obspm.fr/solar_spect.php is a queryable database on the solar spectrum and related solar studies from the Paris Observatory. It also has links to live solar webcams in different wavebands.
- *SkyServer SDSS* <http://skyserver.sdss.org/> is the public and education site for the Sloan Digital Sky Survey. It has provides spectra of stars, galaxies and quasars together with a range of educational projects and informative articles. Data on over 88 million objects can be accessed online.
- *The 2dF Galaxy Redshift Survey* <http://magnum.anu.edu.au/~TDFgg/> provides access to over 250,000 galaxy spectra obtained in this survey. The site also has a lot of useful images of the 2dF instrument and other material. It is aimed at professional astronomers.
- *The 2dF QSO Redshift Survey* <http://www.2dfquasar.org/> provides spectra, field images and other information on 25,000 QSOs gathered using the 2dF instrument on the AAT. The "Non-astronomer's guide to redshift surveys" is an effective introduction to the role of redshift surveys in modern cosmology.