Ideas for Effectively Teaching VCE Astronomy & Astrophysics

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Introduction

This workshop will provide you with some simple ideas, demonstrations and analogies that consolidate a conceptual grasp of the theory and skills in the Astronomy and Astrophysics detailed studies in the VCE.

Despite the seeming lack of practical investigative work in these units there are many simple demonstrations and analogies that are effective in engaging and challenging students. They also lend themselves to the use of simulations and other software tools. Fortunately there are several excellent activities and packages freely available that can be used in the classroom and at home.

This paper aims to provide teachers with a range of ideas and activities plus some useful data with which to cover some of the syllabus requirements. It is not intended to provide a detailed theoretical background on all the concepts as this is better covered in the various references but rather it aims to clarify some key teaching points and misconceptions about them. These are generally matched to the relevant syllabus points although some comments and ideas are applicable across several sections of the syllabus.

In addition to the material specifically targeting the Victorian VCE Physics syllabus material from two additional papers has been incorporated into this paper. These were originally written for workshops given to NSW Physics teachers and cover the *Astrophysics* option and the cosmology section of *The Cosmic Engine* core topic.

Two handy papers worth reading by Keith Burrows; *Teaching Unit 2 with Astrophysics in 2004* and *VCE Physics 11 – unit 2: ASTROPHYSICS DS* from the 2004 VCE Physics Conference can both be obtained from http://www.vicphysics.org/teachers/preparingfor2004.html.

Syllabus Requirements for VCE Astronomy and Astrophysics

This paper uses the Physics Victorian Certificate of Education Study Design, Victorian Curriculum and Assessment Authority, 2003. The areas targeted in this paper relate to the Outcome 3.1: *Astronomy* in Unit 1 (pages 14-15) and Outcome 3.1 *Astrophysics* in Unit 2 (pages 20-21). For ease of reference they are included below:

Unit 1 Detailed Study 3.1: Astronomy

- plot the positions of some observed celestial objects as a function of time of day and time of year on a standard grid, for example altitude-azimuth, right ascension-declination;
- describe the diurnal and annual motion of the stars and planets as seen from the Earth;
- describe telescopic observations of changes to celestial objects including planets;
- describe early geocentric models of the Universe and the epicycle orbits of the planets, including the model of Ptolemy;
- describe the Copernican heliocentric model of the solar system and its effect;
- relate Galileo's telescopic observations of the Moon, Sun, Jupiter and Venus to his heliocentric interpretation;
- describe the discovery by telescope of new celestial objects such as planets, asteroids, comets, nebulae, galaxies and black holes;
- assess telescopes, for example commonly available and space-based telescopes, according to their purpose, optical system (reflecting, refracting), mount (altazimuth, equatorial) and data collection system (optical, electronic);

- select appropriate data relevant to aspects of astronomy from a database;
- use information sources to assess risk in the use of astronomical equipment and making celestial observations;
- use safe and responsible practices in the use of astronomical equipment and making celestial observations.

Unit 2 Detailed Study 3.1: Astrophysics

- compare two or more explanations of the nature and origin of the Universe;
- explain the steady state and Big Bang models of the Universe;
- analyse one or more computer simulations of aspects of the nature of the Universe;
- explain the link between the Doppler Effect and Hubble's observations;
- apply a qualitative understanding of methods used for measurements of the distances to stars and galaxies;
- explain the formation of galaxies, stars, and planets;
- describe the properties of stars: luminosity, radius and mass, temperature and spectral type;
- use the Hertzsprung-Russell diagram to describe types of stars, their evolution and death;
- explain fusion as the energy source of a star;
- compare the Milky Way galaxy to other galaxies;
- describe characteristics of the Sun as a typical star, including size, mass, energy output, colour and information obtained from the Sun's radiation spectrum;
- select appropriate data relevant to aspects of astrophysics from a database.

Given the time constraints of a one-hour workshop it is impossible and unwise to attempt to cover all of these dot points in one session. This paper, however, contains additional material that was not presented in the workshop session. It also provides an extensive range of links and resources. Required syllabus points are in red.

Concepts & Ideas for Unit 1 Detailed Study 3.1: *Astronomy*

This section provides some ideas, teaching strategies and material for the dot points in the *Astronomy* study area. It is not intended as a teaching program rather it highlights points to consider in addressing the sections within the detailed study. Many of the comments made are also relevant for the *Astrophysics* detailed study in Unit 2.

- ***plot the positions of some observed celestial objects as a function of time of day and time of year on a standard grid, for example altitude-azimuth, right ascension-declination;***

For this point it is useful to provide example maps of a region of the night sky for a specific time in two versions; one with an altitude-azimuth coordinate system (alt-az), the other using the right ascension-declination system. Students can determine the location of one or more identified stars using the two different coordinate systems. Having done this you could then issue a second pair of charts, this time for an hour later or the same time but at a different location but again showing much the same region of sky. Inspection by the students should lead them to realise that the alt-az coordinates are different but the Right Ascension, declination (RA-dec) ones have remained the same. This can then be used as a starting point for discussing why there are different coordinate systems and the relative advantages and disadvantages of each. You may also mention that other systems such as galactic coordinates also exist.

An easy way to produce these sky charts is to use astronomical planetarium or charting software. There are many excellent packages available. Some commercial packages such as *Starry Night* (http://www.starrynight.com/) come in a variety of levels and prices and even have educational packages with worksheets for classes. Free alternatives that can be downloaded from the web include:

1. *Cartes du Ciel*: http://astrosurf.com/astropc/ (Win PCs)
2. *WinStars*: http://www.winstars.net/english/index2.html
3. *Night Sky* (for Macintosh computers): http://www.kaweah.com/Products/NightSky/

These programs can be used in a variety of ways with students but reward prior use and familiarity. The free packages are almost as versatile and powerful as the commercial ones. Most have add-on data sets if needed.

- ***Describe the diurnal and annual motion of the stars and planets as seen from the Earth;***

Rather than just trying to describe these, students grasp the concept of an Earth rotating on its axis while revolving around the Sun better by using simulations such as those software packages already listed. In addition to these there are some excellent applets and simulations that specifically target this point. They include:

1. *ClassAction Interactive Classroom Materials for Teaching Astronomy* (http://astro.unl.edu/classaction/). These excellent modules were developed by a team at the University of Nebraska and can be run online or downloaded as zipped files to run on your own computer. They come with accompanying detailed teacher manuals. The modules include animations, questions (which you can modify) and background theory all presented in *Flash* windows. There are currently three modules;
    a. *Lunar Cycles*
    b. *Coordinates and Motions*
    c. *Stellar Parameters* (includes sections and activities on photometry,
2. *TKI – Day and Night: Views from the Southern Hemisphere* (http://www.tki.org.nz/r/science/day_night/index_e.php) is an excellent resource produced by Te Kete Ipurangi; The Online Learning Centre in New Zealand. It is a set of *Shockwave* animations that can be downloaded to run on your own computer that develop from basic observations and principles the diurnal motion of the Sun and the phases of the Moon. Apart from its strong pedagogical framework it is particularly useful as it specifically shows how these appear to viewers in the southern hemisphere whereas as much of the other material available online and in publications shows it from a northern hemisphere perspective. The level is aimed below that of VCE students but it is probably worth using as a starting point anyway as most students still have misconceptions about at this stage.

If possible, encourage your students to actually go outside and observe the Sun, Moon and stars. Whilst you may be unable to incorporate a viewing night into your programming (though if you do you may find some useful hints in an article I wrote, available at: http://outreach.atnf.csiro.au/education/teachers/viewing/) they can still make their own observations. Careful questioning can help unearth their prior observations – *does the Sun rise at the same point on their horizon every morning? Can they see the Moon during the day? Where is the Sun when the Moon is a new crescent?* and so on. Students may know more than they think when probed.

- ***Describe telescopic observations of changes to celestial objects including planets;***

Ideally you could have students observe a planet such as Venus or Mars or Saturn over time and note any changes (eg phase and size for Venus, size and ice caps for Mars, size and tilt or rings for Saturn). More realistically you rae unlikely to have time for repeated telescopic observations over an extended period of time. If you do have one observing session and Jupiter is visible try and have your students observe it at the start of the session. See if the Giant Red Spot is visible. Also note the relative positions of the four Galilean moons (not all of them may be visible). View it again after a few hours and see if they can detect any changes, the change in the positions of moons should be obvious. If you have a digital camera you may even try to photograph Jupiter and its moons through the telescope over several hours.

Other objects that may exhibit changes through small telescopes or binoculars over successive nights are comets (if any are visible) and the Moon. With the Moon, concentrate on the terminator, the line between day and night. Some of the brighter variable stars may also be worth observing. The Astronomical Society of South Australia's Variable Star Group has a useful introductory page on observing at http://www.assa.org.au/sig/variables/faq.asp#startup as does the AAVSO at http://aavso.org/newobservers.shtml. If a prominent sunspot group is present on the Sun you could monitor its development and the Sun's rotation via projection through binoculars or a small telescope. **Caution is needed here; do not allow students to directly view the sun!** (see the ASA's recent factsheet on the Transit of Venus for one safe method of projection at http://www.astronomy.org.au/ngn/media/client/factsheet_15.pdf).

If time is short or the weather poor you can always use a series of photos or images of planets or other objects. These are readily available from the web. Ideally try and locate those with time or date information available. The 2003 opposition of Mars generated a wealth of images by amateur astronomers through small telescopes (see http://www.celestron.com/mars/images.htm for examples). Another option is to view movies showing the rotation of a planet such as Jupiter or SOHO real-time movies of the Sun (http://sohowww.nascom.nasa.gov/data/realtime/mpeg/). If you want to show how far technology has developed and impress upon students the dynamic nature of distant stars you can even view time-lapse movies of images from the HST of the expanding ejected jet from the star *XZ Tauri*, at: http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/32/ .

- ***Describe early geocentric models of the Universe and the epicycle orbits of the planets, including the model of Ptolemy; and***
- ***Describe the Copernican heliocentric model of the solar system and its effect;***

These two points are links together here as the ideas and resources are much the same. Rather than try to describe just verbally or through static diagrams let students use simulations. Some of the planetarium-style programs mentioned previously can be used to generate or even view directly the path of a planet relative to the background celestial sphere, thus introducing the concept of planets as "wanderers" and retrograde motion. Numerous applets an simulations exist that allow students to then explore the different models in more details. These include:

1. *Ptolemy's Model*: http://webpages.charter.net/middents/Ptolemy's%20Model.htm which shows the epicycle, equant and deferent centre for the relative motion of a planet around the Earth in a clean simple animation.
2. *Epicycle and deferent demo*: http://www.phy.syr.edu/courses/java/demos/kennett/Epicycle/Epicycle.html is another useful applet with ability to change some parameters and display options.
3. *Webwalk one*: *Greek and Copernican Astronomy*: http://www.d.umn.edu/~aroos/webwalkone.html provides a useful level of detail and some effective animated diagrams.
4. *Alternative Solar System*: http://jove.geol.niu.edu/faculty/stoddard/JAVA/ptolemy.html allows you to compare the models of Ptolemy, Copernicus and Brahe with "Views from Above" and "Views from Earth".
5. *Ptolemaic Model Applet*: http://solarsystem.colorado.edu/applets/Ptolemaic/extra.html also has links to applets of Kepler's laws.

Other useful sites on the early history of astronomy include:

1. *Philosophy of Science – Astronomy and the Scientific Revolution:* http://www.anselm.edu/homepage/dbanach/ph31b.htm which includes useful material and links on Ptolemy, Copernicus, Galileo, Newtonian and others.
2. *Myths about the Copernican Revolution:* http://www.math.nus.edu.sg/aslaksen/teaching/copernicus.html
3. *Starry Messenger:* http://www.hps.cam.ac.uk/starry/ from the Whipple Museum of the History of Science at Cambridge University.

There are many books relevant to this topic and some schools may even possess laboratory material from the old PSSC Physics course from the Dark Ages (well 1960 actually) that featured a strong historical perspective. It had a detailed set of photos showing the retrograde motion of Mars. Go hunting in your store room and you may be surprised! Discussion about the effect of the Copernican model could be wide ranging and provide an opportunity to talk about the birth of modern science, church/state relations and the concept of scientific models.

- ***Relate Galileo's telescopic observations of the Moon, Sun, Jupiter and Venus to his heliocentric interpretation;***

Some of the sites listed in the previous section are obviously useful here. One site however that is essential in dealing with Galileo is *The Galileo Project* (http://galileo.rice.edu/). It is an amazing resource that encompasses many aspects of his life, work and times. Follow the links in the Science section to obtain details about his telescopic observations, including his drawings. A handy exercise is to loan students a small cheap refracting telescope (the sort that can be purchased for under $20 from stores such as *Australian Geographic*) and see if they can obtain their own drawings of these objects and compare them with Galileo's versions.

- ***Describe the discovery by telescope of new celestial objects such as planets, asteroids, comets, nebulae, galaxies and black holes;***

An excellent paper summarising the value of the telescope and other tools in making new astronomical discoveries is *The Growth of Astrophysical Understanding*, in the November 2003 issue of *Physics Today* which fortunately is available online at: http://www.physicstoday.org/vol-56/iss-11/p38.html with diagrams. It is an update of his thought provoking book *Cosmic Discovery: The Search, Scope and Heritage of Astronomy* published in 1984 and regarded as a classic. For more specific detail on the history of the telescope you cannot go past Dr Fred Watson's *Stargazer* published in late 2004 by Allen & Unwin. It is immensely readable and would be a handy purchase for the school library. Fred is well known to listeners of ABC radio and is Astronomer in Charge of the Anglo-Australian Telescope in Siding Spring NSW.

- ***Assess telescopes, for example commonly available and space-based telescopes, according to their purpose, optical system (reflecting, refracting), mount (altazimuth, equatorial) and data collection system (optical, electronic);***

This point could develop into an extensive section but regardless of how far you take it there are a few key concepts worth imparting to your students even if they are not explicitly mentioned in the syllabus. More details on some of these points can be found at: http://outreach.atnf.csiro.au/education/senior/astrophysics/observingtop.html.

1. **All telescopes are basically just "light buckets",** that is they collect photons from distant sources. The larger the primary mirror or objective lens of the telescope, the more photons, just as the wider a bucket, the more rain it can collect.
2. **Professional telescopes do not have "eyepieces"** – no one looks through them. All professional astronomy these days relies upon some form of electronic sensor/detector. The rapid uptake of charged-couple devices (CCDs) has even supplanted photography in professional observatories. Kodak, who previously made special emulsions for professional astronomy, has ceased production of them.
3. **Astronomers now utilise the whole of the electromagnetic spectrum**. Different types of telescopes are optimised for different wavebands. As our atmosphere blocks some wavebands (UV, X-Ray, Gamma-ray and

some IR for instance) we need to place telescopes in space to observe at those wavebands. This becomes VERY expensive, the size and lifespan of such instruments is limited and there is little or no chance of fixing faults or installing equipment upgrades (other than with the HST prior to the 2003 grounding of the Shuttle fleet).

4. **Weather**: Even for those wavebands where we can observe from the ground (radio, visible and some IR) the atmosphere can have a degrading effect. Clouds and daylight are obvious factors for optical astronomy. Radio observations can normally be made day and night but at higher frequencies in the mm-wavebands humidity and rain can be factors. IR observations cannot be made through water vapour. In general, optical, IR and mm-wave telescopes are best placed at high altitude.

5. **Light pollution** has reduced the efficiency of some earlier generation professional optical observatories. **Radio frequency interference (RFI)** or radio pollution can affect radio telescopes. This too is an increasing problem with the spread of mobile phones, digital television and so on. Just as there are few optimum sites for optical telescopes, sites suitable for the next generation radio telescopes such as the SKA (Square Kilometre Array) are scarce. Fortunately Australia with its low population density has some ideal sites and is an active bidder for this international project.

6. **Reflector vs refractor**: This battle was resolved over a century ago for professional optical telescopes. The largest refracting telescope made was the 40 inch Yerkes telescope near Chicago. Any refractor larger than this would absorb too many photons passing through its thick lens which would also sag under its own weight. Modern optical and IR telescopes use large primary mirrors. Currently the largest are in the 8 – 10m class either as single mirrors such as the 8.1m Gemini telescopes that Australia has a share in or the segmented hexagonal mirrors such those of the 10m Keck telescopes. A handy reference with details on and links to all the large optical telescopes in the world can be found at: http://nineplanets.org/bigeyes.html. Reflectors are far more efficient than refractors of equivalent size, cheaper to build and require shorter tube lengths for the same focal ratio which means that the dome or enclosure can be smaller.

7. **Telescope mounts – equatorial and alt-azimuth**: Prior to the 1980s most large professional optical telescopes used equatorial mounts to compensate for the Earth's rotation when viewing celestial objects. Whilst easier to work out how to drive such mounts, they normally required large/heavy counterweights and resulted in large domes relative to the size of the telescope. It was only with the advent of more powerful and affordable computers that large telescopes could accurately track objects on alt-azimuth mounts. These mounts can be smaller and lighter than equatorial ones and the domes or enclosures much smaller than otherwise.
   One of the first modern alt-az telescopes was the 2.3m telescope at Siding Spring built by ANU in the early 1980s (http://msowww.anu.edu.au/observing/telescopes/2.3m.php). An interesting point is that the dome of the 3.9m AAT also at Siding Spring which has a horseshoe equatorial mount is about the same size as either of the Gemini domes even though these house 8.1m telescopes on alt-az mounts.
   Computer control has even impacted on amateur telescopes. Computer-controlled telescopes on alt-az mounts such as the Meade ETX125 can be purchased for about $1,500 and smaller models are even less. They are much easier and lighter for the occasional user to set up and use if they want to find and track objects than equatorial mounts, particularly for southern hemisphere users who lack an easily found pole star such as Polaris.

8. **Compensating for atmospheric distortion**: Atmospheric turbulence degrades the actual resolution obtained by ground-based telescopes below their theoretical value. Until recently the best way to minimise this was to locate telescopes where such turbulence was low and average "seeing" of around 1 arc second could be obtained. Improvements in computer and materials technology together with the declassification of military research have spurred the development of **adaptive optics** for large telescopes. Such systems correct the effects of the atmosphere on the image so that a large ground-based telescope can match the resolution of the space-based HST and have greater sensitivity. For more information see http://outreach.atnf.csiro.au/education/senior/astrophysics/adaptive_optics.html.

9. **Large mirrors**: Modern reflector mirrors are much thinner than those on earlier telescopes. The 8.1m Gemini mirrors are only 20cm thick for example. This makes them more thermally efficient so that they can cool quicker. As they are lighter the accompanying mount does not need to be as heavy. One drawback is that they flex and distort under their own weight as they point at different parts of the sky. This is corrected by **active optics**, generally a series of actuators that push back on the mirror through computer feedback to keep it in optimal shape.

10. **Detectors**: Photoelectric detectors have revolutionised both professional and amateur astronomy. A 20cm backyard telescope equipped with a CCD costing a few thousand dollars is able to detect objects that once required long photographic exposures on the 200 inch Hale Telescope on Mt Palomar. Of course this also means that modern large professional telescopes are correspondingly more powerful too. The quantum efficiency of CCDs is much greater than that of the human eye or photographic film. More detailed discussion with illustrations can be found at: http://outreach.atnf.csiro.au/education/senior/astrophysics/photometry_photographicastro.html. Follow the link at the bottom of this page to the next page for details on photoelectric astronomy.
    One way to discuss CCDs with your students is to relate them to digital cameras. Most such cameras currently use CCDs though CMOS chips are becoming increasingly common (eg the entry level Canon digital SLRs).

It is worth pointing out that other types of detectors are used for wavebands such as radio, X-ray and gamma rays.

- ***Select appropriate data relevant to aspects of astronomy from a database;***

One of the great strengths of astronomy as an educational resource for students is that they can readily access professional databases freely over the internet. A major international project at present is the creation of the *Virtual Observatory* which will allow professional researchers and others the ability to access and analyse astronomical data from observatories and instruments around the world. Whilst this is still in the developmental stage useful precursors such as *SkyView* already exist. Another point to emphasise it that is possible for students to make their own discoveries and do their own research investigations using online databases. More likely students will just use a database to access and obtain data which they can then analyse. A common example of this is to obtain a list of stellar properties that can be pulled into a spreadsheet such as *Excel*. Common problems students may then have to solve are to plot the stars on an HR diagram or create a histogram to determine relative numbers of different spectral classes or so on.

There are some exceptional astronomical database resources designed for or at least suitable for educational use. Several are listed below. These are suitable for either the astronomy or the astrophysics design studies.

- *Nearest Stars* (http://www.cosmobrain.com/cosmobrain/res/nearstar.html) is a handy list of the 50 nearest stars with several key properties such as parallax, spectral type and apparent and absolute magnitudes listed in table form. Follow the link to a second table listing the 50 Brightest Stars.
- *NED – NASA/IPAC Extragalactic Database* (http://nedwww.ipac.caltech.edu/) is the main online source of data on objects beyond our galaxy. Fully searchable, provides professional-grade data and references.
- *NStars Database* (http://nstars.arc.nasa.gov/index.cfm)is a NASA with details on 2.600 stars within 25 pc. Fully searchable, provides professional-grade data and references.
- *SkyServer* (http://skyserver.sdss.org/) is the educational home page for the massive Sloan Digital Sky Survey. It has a wealth of material for teachers and students at a variety of levels. There are some excellent tutorials and many projects offered, some of which are open-ended. This educational interface still provides access to the full database but has is easier for students to use.
- SkyView Virtual Observatory is an online facility generating images of any part of the sky at wavelengths in all regimes from Radio to Gamma-Ray.
- ***Use information sources to assess risk in the use of astronomical equipment and making celestial observations;***
- ***Use safe and responsible practices in the use of astronomical equipment and making celestial observations.***

The key problem for the first of these points is locating the information sources. It may be worth starting with a brainstorming session to see which potential safety issues students identify. Believe it or not observational astronomy is not without risks. There have been injuries and fatalities among professional astronomers over the last few decades. Separating the list into amateur and professional observing may be useful. The table below lists some potential risks for each category. It is certainly not an exhaustive list.

Amateur Observing

- Moving around in dark/tripping/hitting object
- Lack of sleep; observing at night then working during the day
- Insect bites at night
- Lifting heavy mounts and equipment
- Observing during cold nights
- Observing the sun using inadequate/unsafe equipment with resultant risk of eye damage

Professional Observing

- Driving too and from observatories, often on steep, windy roads or at odd hours (fatalities have occurred here and overseas)
- Lack of sleep or changes to sleep cycle due to long observing sessions
- Altitude sickness when working & observing at high altitude observatories (Mauna Kea is at 4,200 m for example)
- Working in dark or low-light conditions – moving around observatories in dark (fatalities and severe injuries have resulted from falls and slips)
- Working around high voltage sources or dealing with cryogenics (eg topping up liquid nitrogen dewars for detectors)
- Excessive coffee consumption!

Occupational health and safety has certainly become a significant issue at professional observatories. At the ATNF telescopes for instance, all observers and staff have to complete safety briefings and be trained in emergency procedures. Accreditation is reviewed and updated regularly. The Parkes telescope has a "dead-man" system that must be triggered every 15 minutes or less by the observer to prevent an automatic call out of observatory staff and emergency services. This is of particular importance where a lone observer may be working late at night and minimises the chances or a sick or injured person being left unattended and the telescope itself being damaged.

As regards responsible practices, for professional facilities observing time is generally allocated by a competitive proposal system judged by time allocation committees. Most facilities are over subscribed so observing time is precious and used wisely. Responsible practice for amateur observers may include not using telescopes to view other people's homes. A recent case that may pose problems is that of a man who was allegedly using a green pointer laser to indicate stars to his daughter and "painted" a jet coming in to land nearby.

Concepts & Ideas for Unit 2 Detailed Study 3.1: *Astrophysics*

This section provides brief responses to specific syllabus dot points. Some sections will have expanded discussions in following this part.

- ***Compare two or more explanations of the nature and origin of the Universe***;
- ***Explain the steady state and Big Bang models of the Universe;***

As the second of these points explicitly requires explanation of both the steady state and Big Bang models it is logical to use these for the first dot point too. These two models also have more information readily available than other models. Whilst not stated, most teachers may infer that the two "explanations" may be scientific models of the Universe. An alternative approach could be to compare a scientific model and a mythological tale subject to school sensitivities of course.

In this section you should discuss some of the observational and theoretical evidence that must be taken into account in constructing a cosmological model. Although competing models do exist and are vigorously argued by some in the scientific literature, the vast majority of practising cosmologists/astrophysicists would use a big bang model in one or more of its variations to account for the universe.
Cosmology has rapidly evolved from being a branch of science renowned for low precision and lack of data to being a very high precision field. Any modern model or theory of the Universe must account for observations. Most current models adopt the *cosmological principle*. This asserts that on a sufficiently larger scale the Universe is the same in every place and appears the same no matter what direction you look. More formally such a universe is said to be *homogeneous* (identical everywhere in space) and *isotropic* (appears same in every direction).

As the syllabus uses the above term it may be worth spending time discussing with students what is meant by the term theory in a scientific context. Whilst many practising cosmologists and astronomers may prefer to use the term model a scientific theory is one supported by significant observational or experimental evidence. As a model, the Big Bang has several free parameters, some of which are now fairly well constrained. Whilst the Big Bang model is currently the most widely accepted and successful model it has limitations and some problems yet to be resolved.

The Big Bang Theory

The Big Bang model rests on several key pieces of evidence:

- **The Universe is expanding**. This expansion was first detected by Edwin Hubble in the 1920s by measuring the redshift of galaxies. His results showed that the further a galaxy is from us, the faster it is receding from us. This is not due to the motion of the galaxy itself which may be in any direction relative to us. Instead it is due to the expansion of space itself. The relationship between recession velocity and distance is a linear one and is now known as Hubble's Law. A major goal of astronomers since its discovery has been to accurately measure Hubble's Constant, H_0, the current expansion rate of the Universe. The two best current value for Hubble's Constant, are:
  WMAP: $H_0 = 71 \pm 4$ km s^{-1} (5% margin)
  HST Key Project: $H_0 = 71 \pm 6$ km s^{-1}
  which in turn suggest that the Universe is 13.7 billion years old.
- **Cosmic Microwave Background Radiation (CMBR)**. This is the remnant radiation from the Big Bang. As the Universe has expanded the energy density has dropped so the initial temperature of 10^{19} K at the end of the Inflationary era has cooled to an average background temperature of 2.72 K. This corresponds to a peak wavelength that corresponds to microwave frequencies. The CMBR was first detected in 1963 by Penzias and Wilson for which they were awarded the 1978 Nobel Prize for Physics.

- **The ratio of primordial elements**. The Big Bang model makes predictions about the relative primordial ratios of the light nuclei; hydrogen, deuterium, helium-3, helium-4 and lithium. Observational results fit the model. (see at right) This baryonic matter is ~75% H and ~25% He by mass.

- **The formation and distribution of large-scale structure in the Universe.** The minute irregularities present in the early Universe have grown due to a slight increase in gravitational attraction over surrounding material. Eventually matter would clump together and continue to grow, forming large gravitationally bound clusters of galaxies. This large-scale structure has been a particularly active field of research over the last decade. Large scale surveys such as the Australian 2dF Galaxy Redshift Survey on the Anglo-Australian Telescope have proved invaluable in helping test and extend our understanding of this field.
- **Observed evolution.** Recent improvements in telescopes and instrumentation now allow us to observe distant (hence normally interpreted as old ∴young) galaxies. They do not look the same as nearby galaxies thus suggesting that they have changed over time. The fact that the Universe has changed over time became evident in the late 1950s and early 1960s via radio surveys of the sky. Bright, extragalactic sources are not randomly distributed
- **Quasars.** These extremely luminous, high-redshift objects are thought to be supermassive black holes in the centre of early galaxies. The absence of any nearby quasars again supports the idea that the Universe has evolved. Recent observations show that quasars with supermassive black holes with a mass of 10^9 solar masses in their cores had formed within a billion years of the Big Bang.

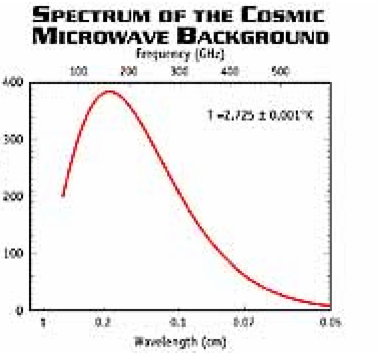


Figure 1: http://map.gsfc.nasa.gov/m_uni/uni_101bbtest3.html

Problems with the Big Bang Model

(summarised from *An Introduction to Galaxies and Cosmology*, Ed Mark H. Jones and Robert J. A. Lambourne, The Open University, Cambridge University Press, 2004.)

1. What is dark matter? (CDM – neutralino best current candidate)
2. What is dark energy? (Candidates include Einstein's cosmological constant, quantum vacuum energy and quintessence).
3. Why is the Universe so uniform? (The horizon problem – why are widely separated parts of the Universe at same temperature and density? Inflation may provide an answer)
4. Why does it have a flat geometry ($k = 0$)? (Inflation may have smoothed the Universe out)
5. Where did the structure come from?
6. Why is there more matter than antimatter? (Grand unified theories allow for 1 in 10^9 parts of matter in excess to antimatter.)
7. What happened at $t = 0$? (This awaits unifying General Relativity with quantum gravity. M-theory may provide clues).
8. Why is the Universe the way it is? (Anthropic principle?)

Inflation

The Inflationary theory was proposed in the early 1980s to address the horizon problem and the flatness of the Universe. It suggests that from 10^{-35} to about 10^{-30} seconds after the big bang the Universe increased enormously in size by a factor of up to 10^{50}. This phase transition was triggered by the breaking of symmetry when the electromagnetic and strong forces separated. Smoothing resulting from this rapid expansion erased primordial irregularities such as magnetic monopoles and domain walls. Quantum fluctuations, however, were boosted in size to become the basis for later structure such as galaxies.

Concepts to Emphasise

In discussing the Big Bang model there are some key points worth stressing.

1. **The Big Bang** was not an explosion. Most books and portrayals of the big bang incorrectly depict it as some form of explosion. This is a mistake. If it was an explosion it must explode from somewhere to somewhere else. This leads to point 2.
2. **The centre of the Universe**. This is always a conceptually challenging idea for students. It is natural to think that the Universe must have a centre. In fact, going back to point 1 above, the centre of the Universe is all around us. Actually the big bang occurred all around us. The Universe does not have a centre in much the same way as the surface of a sphere has no centre. By creating space itself
3. **Galaxies are not moving through space**. To clarify this, what we are really talking about are galaxies moving through space on a cosmological scale. In fact all galaxies show relative motion through space, typically 300 km s^{-1}. Some nearby galaxies are actually moving towards us. Once this is accounted for, the so-called Hubble

expansion is due to the fact that space between galaxies is expanding rather than galaxies all moving through space away from us.

4. The issue of **formation of structure** of galaxies, clusters of galaxies and large-scale structure is one still being resolved. In general "top-down" scenarios have fallen out of favour compared with bottom-up or hierarchical scenarios with cold dark matter (CDM). In these, very high-mass stars form first then form structures equal in mass to globular clusters that then form the protogalaxies. These smaller galaxies, typically of 10^6 $M_\odot$ then produce the larger 10^{11} $M_\odot$ galaxies seen today through collapse and mergers.
   The initial process leading to structure formation comes from gravitational instabilities in the distribution of matter produced in the big bang. By matter we include the baryonic matter such as protons and neutrons and non-baryonic matter that comprises sold dark matter. As yet we still do not know what this CDM is comprised of but currently the *neutralino*, a supersymmetric particle, is the best candidate. *Cold* means that it is slow moving or has non-thermal energies; *dark* means it does not emit or radiate light and *matter* because it interacts gravitationally.

5. **The Big Bang model is currently the most widely accepted and successful model.** There are still several key questions that remain unanswered but work continues on them. It serves as a useful example of science in action. The big bang paradigm has replaced steady state alternatives. There are other models that some researchers discuss (plus a wealth of fringe or crackpot theories, most of which set out to prove Einstein wrong) but they are not widely accepted.

The Steady State Models

The Steady State Model of the Universe, introduced by Hermann Bondi, Fred Hoyle and Thomas Gold in 1948 applied the perfect cosmological principle. The Universe is thus both homogeneous and isotropic and has no beginning or end. As the flat universe is expanding, matter must be continually created to maintain a constant average density of matter. They calculated that the rate of creation of matter must be about 10^{-10} per cubic metre per year. This model arose partly as a philosophical objection to the need for a creation event in the Universe. The model was effectively demolished by the discovery of the cosmic microwave background radiation in the 1960s although modified forms were developed to try and account for this. It also failed to account for the observation that the Universe seems to have evolved. Radio sources such as quasars are not found in the nearby universe, suggesting that they are therefore older. A useful summary of the history and problems of the Steady State theory at an appropriate depth can be found at: http://www.schoolsobservatory.org.uk/study/sci/cosmo/internal/steady.htm as part of the UK Schools Observatory website.

Australian Contributions

Australian scientists have played an active role in recent developments in cosmology. A few of these are outlined below.

1. The **2dF Galaxy Redshift Survey** (http://www.mso.anu.edu.au/2dFGRS/) and **2dF Quasar Redshift Survey** (http://www.2dfquasar.org/) were complementary projects using the **2dF instrument** (http://www.aao.gov.au/2df/)on the 3.9 m Anglo-Australian telescope at Siding Spring. This amazing instrument was designed and built by AAO scientists and engineers and is able to take 400 separate spectra simultaneously whilst a robotic arm places small prisms on another plate so that another 400 can be obtained for a different field with minimal lose of observing time. The 2dF GRS obtained spectra of almost 250,000 galaxies in two wedges in the sky. Analysis of the data has provided a wealth of information to astronomers including a limit on the total neutrino mass, the mass limit and spatial distribution of dark matter and, in combination with CMBR data, precise measurements for the Hubble Constant, and baryon density and evidence for dark energy.

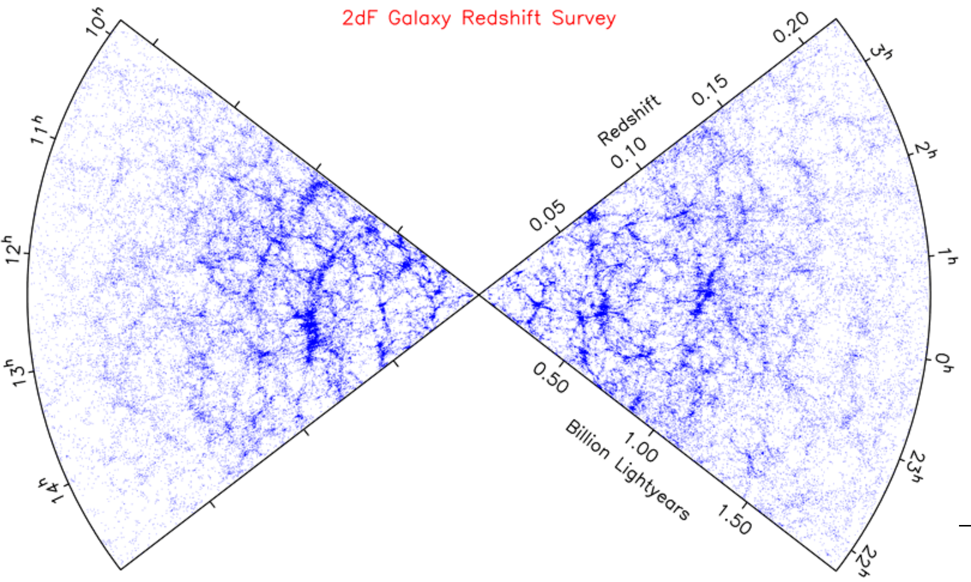


Figure 2

2. The leader of one of the two teams that observed distant Type Ia supernovae to determine the geometry of the Universe was Professor Brian Schmidt from ANU. His **High-Z SN Search** team (http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html) found evidence that the Universe is actually accelerating, a result dubbed by the prestigious journal Science the top research advance of 1998.
3. Australia is at the forefront is planning the next generation radio telescope, the **SKA or Square Kilometre Array** (http://www.askac.org/) that will play a key role in observing the early universe and improve our knowledge about the era of reionisation.
4. Victorian astrophysicists are active in the field of cosmology. Melbourne University has cosmologists working on the era of reionisation and are also planning a new type of radio telescope to probe the high redshift (ie distant) Universe at low frequencies. Swinburne University has the Centre for Astrophysics and Supercomputing (http://astronomy.swin.edu.au/) with staff and post graduate students active in many fields of astrophysics.

Classroom Activities and Ideas for Cosmology

There are many simple activities, analogies and ideas to help convey cosmological concepts in the classroom.

The expanding universe. How best to model or convey the idea that a universe can expand yet not have a centre? Several methods can be employed.

1. **Balloons**. Students can mark a balloon with several dots, each with a number or letter. Blow the balloon up slightly then using string, measure the distance from, eg A to B, A to C and so on and record. Blow the balloon up a bit more and repeat measurements. Do this a third time then study the data. Students should see that the greater the distance initially between two dots, the greater they move apart over time relative to nearby dots. If you use the simple relationship that velocity (speed) = distance/time and take each additional inflation as one time unit they can calculate that more distant dots actually move apart faster than nearby dots. This is the essence of Hubble's Law.
   One problem with the balloon analogy is that the dots students draw (which are supposed to represent clusters of galaxies) actually expand when they blow up the balloon. In reality galaxies do not expand as the Universe ages. It is not the galaxies that are even moving at all, rather it is the space between them that is expanding.
   Balloons can also be used to try and convince students that the concept of the centre of the universe is meaningless. Ask them where is the centre of the surface of the balloon (or of the Earth)? Obviously the balloon's surface is only two-dimensional whereas the universe has extra dimensions but the analogy is sound. To show there are no preferential locations ask them to repeat the initial activity measuring all distances from point B or C. Again, they should see that from B's perspective, all the points move away over time.
   Of course, having balloons in the classroom may also lead to real "big bangs" in cases of over-inflation. Students may also experience deflationary universes! ☺

2. **Balloons 2 – the CMBR**. Draw a transverse wave on a balloon. As you blow the balloon up the wave stretches out to longer wavelengths just as radiation is redshifted in an expanding universe.

3. **Dough & sultana models.** Dough mixed with sultanas and yeast prepared before a class can be left to naturally expand. An advantage of this approach is that the sultanas do not expand though it is harder to perform quantitative measurements.

4. **Overlays of expanding space**. The Astronomical Society of the Pacific's (http://www.astrosociety.org/index.html) *Universe at Your Fingertips* resource manual contains an excellent activity by David Chandler *Visualizing the Expansion of Space.* It uses two seemingly identical images of the Universe where one is photocopied onto a transparency and overlaid on the other. Using both images as transparencies allows you to show it on an OHGP for quite dramatic effect. (Copies of this handed out during the workshop). The manual also contains other relevant activities for classroom use.

5. **Physiotherapy in Space.** Many ageing educators (including me) have a *Theraband* for physiotherapy. These are really useful for demonstrating the expansion of space. Get two students, each holding one end to stand at the front of the room. Other students stand behind the band and each put a large, different coloured peg onto it. The pegs represent galaxy clusters. As the band is stretched, each student can see the distance to the other pegs or students increase but the ones further away move even more than the nearby ones. Another option with a theraband is to lay it flat and draw a transverse wave on it. This represents the background radiation or indeed radiation emitted from a source. As you stretch the band, the wave is also stretched out to a longer wavelength or lower frequency.

6. **Computer simulation of formation of large-scale structure.** There are several sites that allow you to view supercomputer simulations of the formation of galaxies, star clusters and large-scale structure. These are useful in conveying the role of simulation and mathematical modelling in modern cosmology and astrophysics.

7. **Computer-based activities.** Software-based activities such as those provided by *Project CLEA* (see resources at end) provide an interesting and effective way of engaging students and demonstrating some of the principles and technologies involved. The CLEA activities are free and come with detailed manuals as well as pre and post-tests.
8. **The CMBR on TV.** About 1% of the noise or "snow" seen on a TV screen is actually due to the CMBR. Turn on a TV and turn to a channel between normal stations. Part of the noise truly comes from the Big Bang. This is a handy introduction to a lesson.

Online Resources for Cosmology

- *2dF Galaxy Redshift Survey* (http://www.mso.anu.edu.au/2dFGRS/)

- *2dF Quasar Redshift Survey* (http://www.2dfquasar.org/)

- *An Atlas of the Universe* (http://www.anzwers.org/free/universe/index.html) is an excellent site that provides a large set of graphics showing the scale of the Universe zooming out from the Sun.

- *An Introduction to the Cosmic Microwave Background Radiation* (http://background.uchicago.edu/~whu/beginners/introduction.html) is an excellent guide written by Wayne Hu, a cosmologist from University of Chicago. It provides effective graphics, useful analogies and concise, clear summaries.

- *Bad Cosmology* (http://www.jb.man.ac.uk/~jpl/cosmo/bad.html) has a set of concise answers to key misconceptions. Reasonably technical but worth checking.

- *BBCi - Space -Cosmology Animation* (http://www.bbc.co.uk/science/space/playspace/cosmology/) is an effective Flash movie outlining the history of cosmology up to Galileo.

- *BBCi - Space - Origins* (http://www.bbc.co.uk/science/space/origins/index.shtml) from the BBC provides a concise and clear set of pages on the origin and fate of the Universe

- *The Big Bang Theory - An AskERIC Lesson Plan* (http://www.geminfo.org/Workbench/training/SPA0010.htm) is a class activity that simulates how we investigate the Big Bang, Suitable for grade8-9.

- *Celestia: A 3D Space Simulator* (http://www.shatters.net/celestia/) is an outstanding free software package with a wealth of add-ons. It is a multi-platform package (Windows, Mac OS, Linux, Unix) that allows you to visualise our Solar System and galaxy using real astronomical data. You can "fly" to other stars, visit the planets and even piggybank on any of the current or planned spaceprobes. Excellent educational add-ons and interactive learning documents including one on stellar evolution are available from another site (http://www.fsgregs.org/celestia/).

- *CERES: The Expanding Universe* (http://btc.montana.edu/ceres/html/Universe/uni1.html) is an excellent, detailed set of six classroom activities dealing with the Hubble Law and expansion. Comes complete with Teacher Lesson Plans, student worksheets, evaluation, mapping to US education standards and background science.

- *Computer Simulations of Cosmic Evolution* (http://www.astro.washington.edu/weblinks/Universe/Simulations.html) provides over a dozen animations on galaxies and formation of large-scale structure.

- *Cosmic Mystery Tour* (http://archive.ncsa.uiuc.edu/Cyberia/Cosmos/CosmicMysteryTour.html) is a set of pages that take you through the formation and evolution of the Universe and the formation of galaxies. Its focus is on using animations, images and short video explanations by astronomers to convey concepts. Well worth visiting.

- *Cosmic Survey - What are your ideas about the Universe?* (http://cfa-www.harvard.edu/seuforum/teachers/L3/survey/survey.htm) is an effective set of exercises on scale; size, distance and age of objects in the Universe. Need to convert to SI units.

- *ESA - Education - High School - Big Bang* (http://www.esa.int/export/esaED/SEMTB99YFDD_highschool_0.html) is a brief description of the standard big bang model at an appropriate depth for high school students by the European Space Agency. Has links to related articles.

- *Friedmann* (http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Friedmann.html) is a useful, detailed page on Alexander Friedmann.
- *The Hidden Lives of Galaxies*, (http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/imagine/titlepage.html) a 2.2 MB NASA PowerPoint presentation, lesson plans and teaching guide.
- *High-Z SN Search* (http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html)
- *Hot Big Bang* (http://www.damtp.cam.ac.uk/user/gr/public/bb_home.html) is a cosmology site from Cambridge University that has effective summaries. It discusses the key evidence and some problems with the standard model.
- *HSC The Cosmic Engine* (http://www.phys.unsw.edu.au/hsc/cosmic.html) is a useful set of notes with links and activities by Associate Professor Michael Burton, an astrophysicist at UNSW.
- *LIFE'S BIG QUESTIONS: How did the Universe Begin?* (http://www.pbs.org/safarchive/4_class/45_pguides/pguide_501/4551_universe.html) is a set of activities and a lesson plan for exploring the Big Bang. From PBS in America.
- *Listening to the Big Bang* (http://www.abc.net.au/science/slab/watson/story.htm) is an ABC online article by Dr Fred Watson, Officer in Charge of the Anglo-Australian Telescope at Coonabarabran and well known populariser of astronomy on the radio. This is a short article that clearly describes the Big Bang and addresses several common misconceptions. Useful as an article for in-class reading and comprehension at Stage 5.
- *Ned Wright's Cosmology Tutorial* (http://www.astro.ucla.edu/%7Ewright/cosmolog.htm) has a wealth of information including an excellent set of answers to FAQs in cosmology. The site uses high school mathematics. His site also has a useful discussion of cosmology and religion.
- *Physics: The Cosmic Engine* (http://science.uniserve.edu.au/school/curric/stage6/phys/cosmeng.html) is an excellent set of annotated links by the UniServe Science team at University of Sydney.
- *Powers of 10* is a famous film showing the scale of the Universe by changing the view by a factor of ten every ten seconds. An online zoomable version (http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/) is useful whilst the commercial site with more details and material for purchase is also available (http://www.powersof10.com/#).
- *Project CLEA* (http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html) allows you to download free programs and manuals that allow you to simulate observing, obtaining and analysing data.
- *Recovering Hubble's Original Data* (http://jersey.uoregon.edu/vlab/hubble/Hubble_plugin.html) is a Java applet that simulates Hubble's observations.
- *Science Cartoons Plus – The Cartoons of S. Harris* (http://www.sciencecartoonsplus.com/gallery.htm) has dozens of cartoons by Sidney Harris related to astronomy and physics. They can provide an amusing way to provoke questions and discussion among students.
- *Science, Intelligence and Creativity: Introduction to Cosmology* (http://www.star.qmul.ac.uk/~rmh/cosmology.html) is a concise set of pages that clearly outline the key points in the hot big bang cosmological model. It discusses Inflation as well as current problems with the standard model. Written by a theoretical cosmologist from Queen Mary, University of London.
- *SkyServer* (http://skyserver.sdss.org/) is the educational home page for the massive Sloan Digital Sky Survey. It has a wealth of material for teachers and students at a variety of levels. There are some excellent tutorials and many projects offered, some of which are open-ended.
- *Universe! - EXPLORE: Beyond the Big Bang* (http://cfa-www.harvard.edu/seuforum/explore/bigbang/bigbang.htm) is an excellent site with questions and answers plus sections on current research.
- *Universe in a box: formation of large-scale structure* (http://cosmicweb.uchicago.edu/sims.html) from the Center for Cosmological Physics at the University of Chicago has a set of pages and animations of supercomputer simulations on how large-scale structure forms. It discusses cold dark matter models.

- *WMAP Cosmology 101: Our Universe* (http://map.gsfc.nasa.gov/m_uni/uni_101ouruni.html) provides a clear introduction into modern cosmology. Perhaps too detailed for most students it is however useful for teachers and students who want more detail.

- ***analyse one or more computer simulations of aspects of the nature of the Universe;***

There are a number of excellent free computer simulations that can be used to address this syllabus point. One of the best is

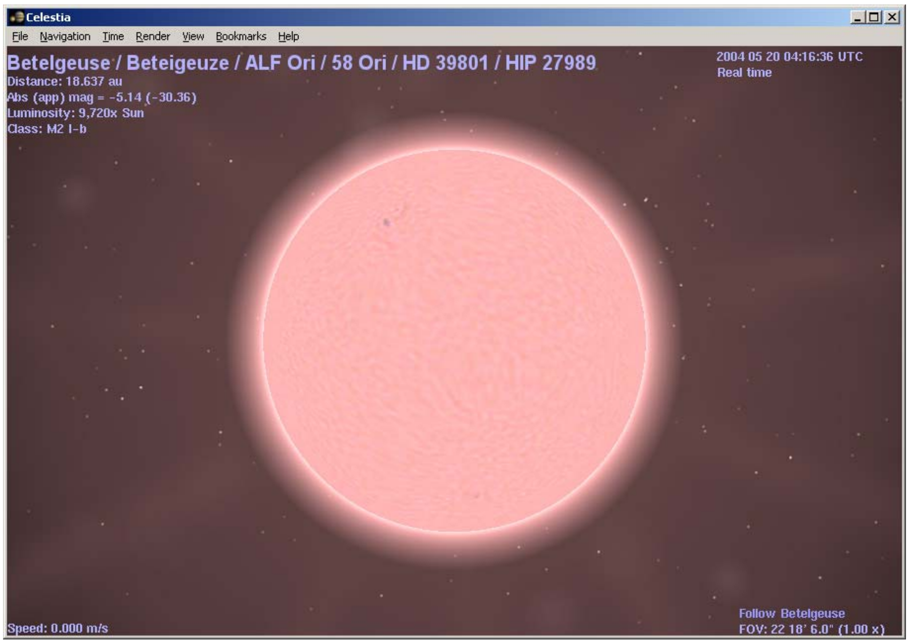
- *Project CLEA* (http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html) allows you to download free programs and manuals that allow you to simulate observing, obtaining and analysing data. *The Hubble Redshift-Distance Relation* and *Large-Scale Structure of the Universe* are particularly relevant for this point whilst others address other aspects of Astrophysics such as spectroscopy and photometry. These are excellent simulations that utilise real data.

- *Recovering Hubble's Original Data* (http://jersey.uoregon.edu/vlab/hubble/Hubble_plugin.html) is a Java applet that simulates Hubble's observations.

There is one other piece of free software that is outstanding and extremely effective in visualising space to students. *Celestia* is freeware that has been developed for a range of platforms including *Windows*, Mac, and Linux. To quote from the Celestia website (http://www.shatters.net/celestia/) from which it can be freely downloaded:

> *Celestia is a free real-time space simulation that lets you experience our universe in three dimensions. Unlike most planetarium software, Celestia doesn't confine you to the surface of the Earth. You can travel throughout the solar system, to any of over 100,000 stars, or even beyond the galaxy. All travel in Celestia is seamless; the exponential zoom feature lets you explore space across a huge range of scales, from galaxy clusters down to spacecraft only a few meters across. A 'point-and-goto' interface makes it simple to navigate through the universe to the object you want to visit.*

What makes the program even more valuable for education use is the large number of add-ons that have been developed by people around the world. These include simulations of a large range of space probes, extra textures for planetary and star surfaces and even spacecraft from movies such as *2001 - A Space Odyssey*. A separate website of educational add-ons at http://www.fsgregs.org/celestia/ includes educator notes, classroom activities and extra modules on a range of topics including "The Life and Death of Stars". You can, therefore take your students on a virtual tour of real objects showing all the stages in stellar evolution. Celestia is also excellent in showing that stars are at different distances from us. As you journey to the Hyades or Pleiades you will see the stars clustered together relative to other stars but then you can "fly-through" the cluster itself. Students can explore systems themselves or you can use it for classroom presentations. This is a highly addictive package with great value for educational use. Figure 3 below shows a screenshot of Betelgeuse from *Celestia*.



Betelgeuse / Beteigeuze / ALF Ori / 58 Ori / HD 39801 / HIP 27989
Distance: 18.637 au
Abs (app) mag = -5.14 (-30.36)
Luminosity: 9,720x Sun
Class: M2 I-b

2004 05 20 04:16:36 UTC
Real time

Speed: 0.000 m/s

Follow Betelgeuse
FOV: 22 18' 6.0" (1.00 x)

Figure 3: Screenshot from *Celestia*

- ***explain the link between the Doppler Effect and Hubble's observations;***

This is potentially a tricky point and one that is commonly applied incorrectly. The Doppler Effect arises due to the relative motion between a source and an observer, resulting in a shift (the Doppler shift) of observed frequency. For an electromagnetic wave with a relative line-of-sight (ie radial) velocity of v, the change in wavelength, $\Delta\lambda$, of the spectral line with a rest-frame wavelength of λ is given by:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$ where c is the speed of light and v is non-relativistic.

By convention, v is positive for receding objects and negative for approaching ones. At cosmological distances all values are positive, ie we see distant galaxies receding from us. For this reason the term *redshift* is commonly used instead of Doppler shift as the spectral lines are shifted towards the longer wavelength, lower frequency, hence red, end of the spectrum.

One key misconception is that the "Doppler Effect" measured by Hubble and now incorporated into the Hubble Law is due to the motion of a galaxy *through* space. Whilst individual galaxies do have proper motions (the great galaxy of Andromeda for instance is moving relatively towards our own Milky Way) the cosmological redshift or *expansion* redshift is due to the expansion of space itself. The galaxies themselves are not expanding nor are they moving through space. Instead we can picture them as being bound objects being carried apart as the space between them expands. Spectral redshift arising due to this effect is more properly termed *expansion redshift* or sometimes *cosmological redshift*.

- ***apply a qualitative understanding of methods used for measurements of the distances to stars and galaxies;***

This point requires students to understand some of the techniques used to measure distance in space. This is the branch of astronomy known as *astrometry*. The following section provides some detail on the history and application of astrometry and concentrates on how parallax is used to measure stellar distances. It concludes with a brief discussion on the extragalactic distance ladder.

Astrometry – measuring distance and position

Astrometry is perhaps the oldest branch of astronomy. Accurate positional measurements of stars was one of the major activities of astronomers in the nineteenth century and the quest to detect the parallax of nearby stars was a key challenge in the first half of that century. Despite many attempts from the invention of the telescope, stellar parallax was not actually detected until 1838 by Friedrich Wilhelm Bessel. He measured the parallax of the 5th magnitude binary star 61 Cygni to be 0.3 arcseconds. The parallaxes for the bright stars Vega and α Cen were soon measured by Wilhelm Struve and Thomas Henderson respectively. Parallax measurements were, however, time consuming and complicated, with the result that by the end of the 19th Century parallaxes had been measured for only about 60 stars.

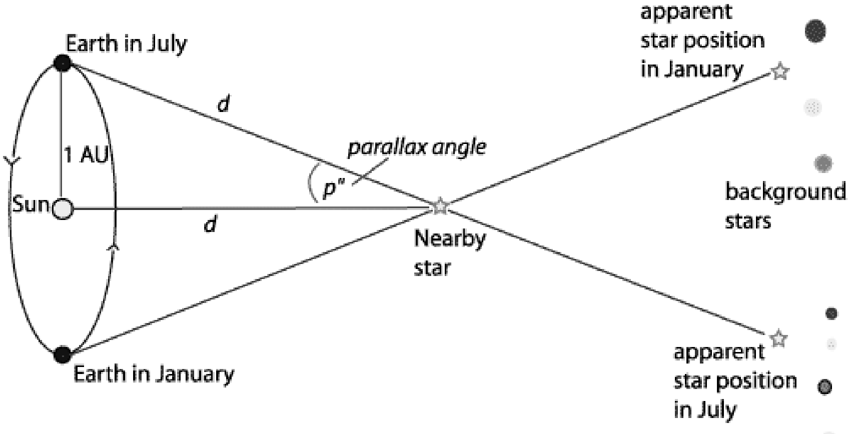
How can we make students appreciate the concepts involved in parallax and distance measurement? The first point to stress is that they are already familiar with parallax – they use it every day. The baseline involved in this is very short – the separation between our eyes, but we use this to gauge the relative distance to objects all the time without consciously thinking about it. The standard method of demonstrating this is to have students hold a finger out at arm's length and look at a reference point between them and, say the board at the front of the classroom. When they look through one eye they should see their finger aligned in one place, closing that eye and opening the other shows the finger to apparently shift. Viewing through the left eye, the finger seems shifted to the right; viewing through the right eye than shifts the finger to the left.

Having started with this simple demonstration you can know challenge them to think what will happen with objects further away, more than an arm length's distance. If you have room go outside so that you have a greater depth of distance over which to examine the variables. If you have a vantage point that provides a view to the far horizon see if you can identify features on the horizon that you can incorporate. Students should quickly realise that the greater the distance between the observer and the object, the less obvious is the observable apparent shift in position between the two eyes. This raises the concept of the limitations of baseline length. A student's eyes are only separated by a few centimetres. We cannot visually detect any apparent shift in the position of stars between our two eyes, as the stars are too distant given the miniscule baseline distance.

Demonstrating Stellar Parallax

Through discussion with students you should be able to hint or suggest (if they have not already offered it) the idea of the need to make observations to a star more than once. Ask them over what time span astronomers would have tried to observe a star to measure its distance? Hopefully once someone has suggested that it may be linked to our motion around the Sun you can extend the simulation to include Earth's relative position to the Sun and star. Students can represent the Earth and star, with a stationary object or point clearly marked as the Sun. The more space you have for this the better. It can work simply by students just eyeballing the relative position of the 'star' against the background from one point in their orbit. As they then walk around the Sun, they should see the star appear to move. When students are on the opposite side of the Sun, they represent the earth six months part from the first observation. They should now see the star in a different relative position. As they now walk back to their original position, the stars now also shifts again back towards its earlier position. Getting students to do a simple walk around should fix the basic concept of parallax with them and can then be used to pose a few more questions:

1. What is the baseline length between the Earth and Sun?
2. What is the maximum baseline length we can obtain from Earth?
3. What would happen if the star were more distant?
4. What times of the day should observations be made to obtain the greatest parallax?
5. Would the parallax be greater for a planet with a larger orbit?



Parallax of nearby star

Figure 4.

There are several possibilities for extending and developing this exercise. You may ask your students how they could measure the apparent shift? This question leads them into an awareness of parallax angle. Parallax is often shown using a diagram similar to Figure 1 above. Whilst such diagrams are schematically useful they can also be misleading for a few reasons. The most obvious trap is that of scale. Most students are either unfamiliar or uncomfortable with small-angle triangle mathematics. The baseline length in the above diagram is 2 Astronomical Units or AU, about 300 million km. The parallax to even the nearest star system, Alpha Centauri, is extremely small and equals 0.74212 arcseconds. This corresponds to a distance of $d = 1/p$, so $d = 1/0.74212 = 1.35$ parsecs. Applying some useful conversion factors;

1 parsec = 3.26 light years
1 parsec = 3.086 x 10^{16}m
1 parsec = 3.086 x 10^{13}km
1 Astronomical Unit = 1.496 x 10^{11}m so
1 parsec = 2.063 x 10^{5} AU

we find that the if we draw a scale triangle with a base of 2cm (1cm = 1AU), then the star would be 1.35x2.063x10^{5} = 277,987cm or nearly 2.8km distant! The minute difference between a line drawn from the Sun to the star and from the Earth to the Sun explains why it is valid to label "d" on both of these lines in the above diagram.

If you wish, an exercise of this type is also a useful way to introduce errors and uncertainties in measurement. Astute students will realise that in effect, you do not directly measure the parallax angle, *p*, directly. Given that measurements are taken six months apart over a baseline of 2AU you end up with a value of 2*p* but even then the angles they actually measure are those between the nearby star and a distant reference star from each observation point. These are then added together then the sum halved to give *p*. By getting students to physically work and walk through a measurement of parallax they are more likely to be able to define the relevant quantities; *parallax* and the *parsec*, explain how trigonometry is used to measure distance and discuss the limitations of the method. The concept of the *light year* can thus also be seen as almost an add-on that is not directly measured by astronomers who typically use multiples of parsecs in their professional work.

Other Considerations in Astrometry

As discussed above, it is often difficult for students to grasp a sense or scale and relative distance in astrometry. The subtle measurements and large relative errors involved in trying to pin down the parallax of even the closest stars was one reason it took so long to detect after the Copernican, heliocentric model became accepted in the 17th Century. What is an angle of 0.74212 or even 1.00 arcseconds? Most students by Year 12 level should be comfortable with the concept of degrees, minutes and seconds and even be able to state that there are 60 minutes in a degree and 60 seconds in each minute of arc (therefore arcminutes) but they will generally have a poor grasp of the reality of this.

A simple way to get them to think about how large an arcsecond is involves them using their hands. Ask them what the angular diameter of the Moon (or indeed the Sun) is. Most students over estimate the size. Rather than them simply guessing they can actually measure it with respect to their hands and fingers, much as people have used body parts for measurement for thousands of years. Fortunately, lunar measurements can be made during the daytime depending ion the phase of the Moon. If it is only up in the night sky then it is a simple task to get them to measure it at home. The Moon actually subtends and angular diameter less than a person's fingertip (about half a fingertip) when the arm is fully outstretched from the body. Students are often surprised to find that their independent measurement agrees with their classmates. There should be little variation between students if they follow the guidelines for using their hands and fingers for measurements as most people are in proportion.

The angular diameter of the Moon is about 30 arcminutes. One-thirtieth of this then is 1 arcminute. If this amount is then divided by 60 you have an angular diameter of 1 arcsecond. This is indeed a very small angle. It may help to put this into an historical perspective. Hipparchus, the Greek astronomer who we credit as the founder of the magnitude system of stellar brightness and cataloguer of stars could measure stellar positions to an accuracy of about 1 degree. This corresponds to the angular height of a human standing 100m away. Check it with your students! Using modern ground-based techniques we can now distinguish the height of a person standing 4,000km away, about the width of Australia. In 1989, the European Space Agency launched the Hipparcos satellite (*HIgh Precision PARallax COllecting Satellite*) to measure the parallax and proper motions of stars. As it orbited the Earth above the effects of the atmosphere, it was able to measure parallaxes to an order of magnitude better precision than previous methods. The resultant Hipparcos catalogue gives positions, distances and proper motions for 118,218 stars to an average accuracy of 1 milliarcsecond (mas). This is equivalent to seeing a person standing on the moon 380,000km away (Brown, 1998)!

Beyond the Nearby Stars

Parallax is only useful for relatively nearby stars. Even most stars within our own galaxy cannot have their distance measured using trigonometric parallax yet. Plans exist for new space-based parallax missions such as GAIA and LISA but these will not be launched till the end of the decade at the earliest. Determining the distance to more distant stars, galaxies and quasars is relies on a variety of methods. Detail as to the methods goes beyond the scope of this paper. Key methods, however include radar measurements (within our solar system), spectroscopic parallax, various period-luminosity relationships for different types of intrinsic variable stars, integrated magnitude for globular clusters then methods based on galaxy brightness, the Tully-Fisher method and the Sunyaev-Zel'dovich effect. A simple web search for the cosmic distance scale or ladder will pull up numerous useful sites. The one below is useful as an activitiy comparing different methods.

- *The Cosmic Distance Scale* http://www.astro.washington.edu/labs/Distance_Ladder.html has a set of three exercises, classical astronomy, stellar parallax and Hubble's Law to show how the known distance of the Universe has grown and been determined.

- ***explain the formation of galaxies, stars, and planets;***

Despite the brief nature of this point it is actually one of the most difficult points in the whole topic. This is due to the fact that there is still lively debate as to which models are best. For planetary formation we are still limited by the sample size of our population; nine (or so) in our solar system and about 120 in other systems though all we really know for these are the masses and orbital parameters. Our understanding of galaxy formation is limited by the observational constraints we currently face though recent HST Deep Field and Ultra-Deep Field images have helped. Star formation is an active field where our understanding has improved significantly over recent years. Improved observational tools at infrared and millimetre radio wavelengths have allowed astronomers to see through the cold dust associated with star birth. This has been matched by better computational simulations. More details and further links can be found at:
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_formation.html.

- ***describe the properties of stars: luminosity, radius and mass, temperature and spectral type;***

The following information related to stellar properties is arranged into three main categories; spectroscopy, photometry and stellar evolution. Each section has some theoretical background but the emphasis is on ideas for classroom use and some conceptual problems students often encounter. More detailed theory can be found

Spectroscopy

Perhaps the most important concept that students should grasp about spectroscopy is that it is the vital tool for most astrophysical observations. A spectrum of an object can normally provide more information than any other single observation. Of course, in reality astronomers will seek to image an object as well but ultimately it is the spectrum that provides the most detail.

Activities for Spectroscopy

Using a Spectroscope

This is a traditional investigation well covered in most textbooks and typically involves examining a variety of spectra produced by discharge tubes, reflected sunlight, or incandescent filaments. 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.

2. **Reflected sunlight** should show the absorption lines, first recorded by Fraunhofer.
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.

There are some interesting alternative ways to demonstrate spectra in the classroom. Holographic film works better than a normal diffraction grating but either will do the job. Place a slide transparency covered in aluminium foil with a small vertical slit (mm or so) in it in a slide projector. When you hold or place the holographic film or diffraction grating in front of it you can project a spectrum on to a wall or screen. Students may already be familiar with the spectral pattern produced from CDs, which act as a diffraction pattern. The value of using these methods is that you can then relate them directly to astronomical spectrographs that use diffraction gratings rather than passing light through a prism as is typically done in junior science classes. You may even ask students why gratings are preferred to prisms and relate this back to issues of sensitivity and resolution. Holographic film may be difficult to track down but is often sold as "Firework" or "Laser" novelty glasses or similar products and can be ordered over the internet.

Using Astronomical Spectra

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 by using optical fibres to feed two spectrographs that have Charged Couple Devices (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.

An excellent activity where students use real data to classify stars can be found online at the SkyServer site at http://cas.sdss.org/dr2/en/proj/advanced/spectraltypes/. 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. Figure 4 below shows one of the stellar spectra from their site.

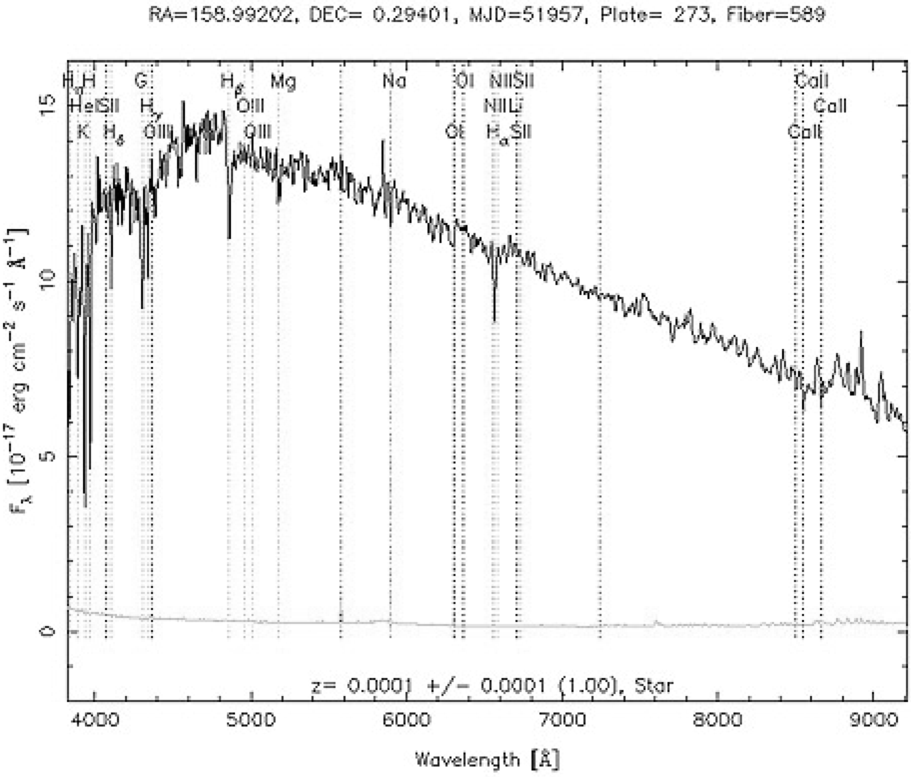


Figure 5. Intensity Plot Stellar Spectrum, (Credit: Sloan Digital Sky Survey, http://cas.sdss.org/dr2/en/)

An excellent 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 de downloaded from the Project CLEA website at: http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html.

Kinesthetic and Other Approaches

If you are game you can have the students simulate the processes involved in producing the different types of spectral lines. There are several methods by which this can be done (for a fuller explanation read Chapter 9 of Pompea, 2000 *Great Ideas for Teaching Astronomy* – an extremely useful source of ideas). Indeed a useful challenge could even be for students to design a way to demonstrate the production of an emission or absorption line using several students and various balls.

Mnemonic devices are a traditional way of getting students to learn the spectral sequence *O*, *B*, *A*, *F*, *G*, *K*, *M* (and possibly *R*, *N* & *S*). Rather than just use the standard "Oh, Be A Fine Girl (or Guy), Kiss Me, (Right Now, Slap)" or "Oh Beastly And Fearsome Gorilla Kill My Roommate Next Saturday" ask your students to develop their own. A space-related confectionary item often seems to work as an appropriate incentive for the winner!

Photometry

Photometry is essentially the measurement of the brightness of celestial objects. In practice the brightness of a source is measured within a range of wavelengths of the electromagnetic spectrum, that is a waveband. The concept of photometry can be traced back to Hipparchus of Rhodes (161-126 BC) who used Babylonian records to compile a celestial sphere showing the position and brightness of 850 stars. He developed the concept of **magnitude** as a measure of a star's brightness. His six-point scale classified the brightest stars as being magnitude 1 whilst the dimmest stars were magnitude 6. This scheme has been adapted but in essence continues in use today although it has been extended given the discovery of much fainter stars using telescopes. Pogson adapted the magnitude scale in 1856 and proposed a logarithmic scale. As the human eye's response is nearly logarithmic, Hipparchus' original scheme could be easily adjusted to the new standard.

Student problems with the magnitude scale

The basic concept of the magnitude scale is relatively easy but many students, with good reason, often find it hard to put into practice. There are several reasons for this and points to watch out for when teaching it.

1. **The Reverse nature of the scale.** A very bright star has a lower magnitude number than a dim star. With the now open-ended nature of the system we even have negative magnitudes that sometimes compounds the problem for students. Celestial objects detected thus far range from a magnitude of –26.5 (our Sun) to about +30 using the most sensitive telescopes and detectors.
2. **Standard or reference point.** The mathematical basis of the scale always defines the magnitude of an object relative to another one such as a star. The version of this given in the syllabus is: $\frac{I_A}{I_B} = 100^{(m_B - m_A)/5}$ although it can also be expressed as $m_A - m_B = -2.512\log(I_A/I_B)$ where *m* refers to the (apparent) magnitude of the stars, *A* and *B* and *I* the intensity or energy per unit surface area at the earth's surface. Many students are uncomfortable with ratios and relative measurements – they like absolutes. Astronomers determine the magnitude of a star with respect to one or more "standard" non-variable reference stars.
3. **Dimensionless quantity.** As magnitude is ultimately just a ratio it is simply expressed as a number with no unit. Often, having tried to drum into students the need to express all physical quantities with the relevant SI unit some of them then have problems when presented with one without a unit! Make sure you discuss this point with them and clarify why it has no unit.
4. **Logarithms.** Modern students are less familiar with logarithms than those who grew up using log tables in the pre-calculator days. Most will have had little practice in applying them in a non-theoretical mathematics classroom use. Whilst the nomenclature of **log** implies $\mathbf{log_{10}}$ it is important to emphasise this point as some students will try and use natural logarithms, **ln** when trying to solve equations.
5. **Rewriting formulae**. Even though students are now provided with two forms of magnitude formulae in the Higher School Certificate exam and so do not need to "remember" it some struggle in rewriting it to find a different unknown. Students need to practice taking the original form and reworking it as needed. They will be more successful at this if they are competent at algebra (obviously) but also if they understand the underlying meaning of the formula and how magnitude is determined.
6. **Different types of magnitude** – apparent and absolute. It is important to stress the need for clear writing when calculating or discussing magnitude. Absolute magnitude, ***M*** must be clearly distinguished from apparent magnitude, ***m*** in any equation. In general, try and always prefix the term "magnitude" with "absolute" or "apparent" if appropriate. Students need to be able to explain the difference between the two and why the concept of absolute magnitude is so useful and important.

7. **Colour Index**. Just to complicate matters, once students are comfortable with apparent magnitude they have to extend their understanding to the need for magnitudes at different wavebands. Such measurements are normally made through filters. In fact this is the norm in photometry – astronomers want to know the wavebands they are receiving light at. Stress the great advantage in obtaining a magnitude value for an object at specific wavebands. Although the syllabus only specifically mentions *B* and *V* it is worthwhile to also discuss the other three filters in common use, *U*, *R* and *I*. This would also be a relevant time to discuss the differing spectral responses on most photographic emulsions compared with most CCD chips. If probed, some students will have experience of red lights in dark rooms and suggest that film must be relatively insensitive to red light. CCDs on the other hand are normally more sensitive to red than blue light.

Demonstrations and ideas for showing magnitude

There are many simple ideas you can use in the classroom or elsewhere to reinforce concepts related to magnitude.

1. **Standard candles.** In discussing how to determine stellar and extragalactic distances students should be introduced to the concept of "standard candles". Whilst this often occurs when discussing variable stars and Cepheids in particular it is probably better to introduce it early when discussing magnitude. A number of tea candles at different distances in a room can simulate stars at different distances. In asking students to identify which "star" is furthest away, challenge them to state the assumptions on which their answer is based. Are they assuming that stars have the same "brightness"? Probe them to explain what they mean by "brightness" than try and lead them to linking this with the energy given of by a star or candle then the energy per unit time, that is the power output or **luminosity** of a star. Variations on the candle theme could use low power bulbs or LEDs at different distances. Of course, if using bulbs you can then complicate matters by running them at different voltages to produce "stars" of differing intrinsic luminosities and even colour.
2. **Intrinsic and extrinsic luminosity & brightness.** Once students are comfortable with brightness and luminosity use different size candles or bulbs connected to a variable power pack to produce "stars" with different intrinsic luminosities. The concept of extrinsic luminosity can be shown using sheets of Perspex or stiff transparent plastic. If you have more than one sheet, coat one with soot from a candle flame. It represents a dark nebula, a cold cloud of dust and gas blocking out light from stars behind it.
3. **Star field images and photos.** One of the most versatile resources for teaching is the magnificent poster *The Southern Cross and the "Pointers"* produced by CSIRO Parkes Observatory using a photo by the renowned astrophotographer, Akira Fujii. It shows Crux and the Pointers in colour plus the region around Eta Carina. If possible, have a laminated copy in your classroom when teaching astrophysics. A view similar to the poster is shown in Figure 5 that also has some of the key objects labelled. The unlabelled original of this photo by Professor Mike Bessell can be found online at http://www.mso.anu.edu.au/~bessell/thumbnails/. Ask students to identify the brightest star in the photo then ask them to justify their choice. Challenge them to think why it is brightest. Most should soon see the relationship between the width of the star image and its brightness. Using a laminated copy of the poster students could actually measure the width of various stars and try and determine a relationship between image size and magnitude. If really keen here you can go into the photochemistry of photons interacting with the film material. It is important to point out that all the stars on the image are so far away that they should still be point sources. (The poster is available from Parkes Observatory Visitors Centre, phone 02 6861 1777, or email parkes-vdc@csiro.au).

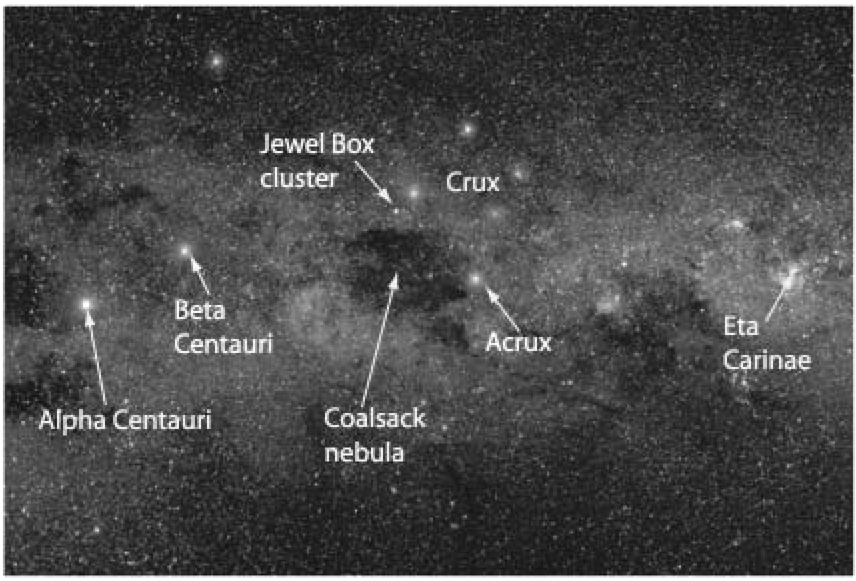


Figure 6: Crux Region with key features labelled (Credit: Adapted from an image by M. Bessell)

4. **Colour and Colour Index.** Using either the online photo or the poster of the Crux region, students are easily able to detect the variations in colours of stars. This provides an effective way of introducing colour, blackbody curves, Wien's Law, and the value of observing through different filters. Provide students with red, yellow and blue cellophane filters. Many ray box kits used to come with colour transparency filters and these are excellent as they are robust and easily held. When students view a coloured star field through different filters they will see that different stars are brighter through different filters; red stars are brighter through red filters and blue stars brighter through blue filters. If you have a Polaroid instant camera or a digital camera and a darkened room you may like to try and photograph different coloured "stars" through different coloured filters. To create the stars simply use a ray box with different coloured transparency slides in the outlet slit or use a fibre optic torch with red, clear, yellow and blue cellophane over different fibres. Use coloured cellophane or ray box transparencies as the filters in front of the camera. Using different filters compare the relative image size of the stars.

5. **Using comparative brightness to calculate distance to stars.** One important application of the concept of magnitude is to use it to determine the distance to a star. A star's apparent magnitude can be readily measured (methods range from naked-eye estimation, measurement of photograph or even CCCD photometry. If you know the spectral and luminosity classes of that star then you can also obtain a value for its absolute magnitude from a Hertzsprung-Russell diagram or tables. Knowing *M* and *m* students then traditionally rework the equation $M = m - 5\log(\frac{d}{10})$ to find d in parsecs. Students must, of course, practise using this formula given any two of the three variables. There is, however, an interesting practical experience that will challenge them and hopefully consolidate their understanding of the principles involved. This activity works best if you are holding a viewing evening and involves students trying to calculate the distance to a bright star of known luminosity such as Alpha Centauri using a torch, some simple mathematics and perhaps a measuring tape (though even the distances can be estimated by pacing).

   Use a reasonably low-powered torch but one where you can determine its power output. If the wattage is not visible students could try and calculate it using Ohm's Law. Cover the front of the torch with foil, making a small hole of known diameter, 1 or 2mm for example. Making some assumptions, students should be able to estimate and calculate the luminosity of the torch through the hole. With one student as the observer, the other student simply walks away, holding the torch up and pointed at the observer until the torch appears as bright as the selected star. Once this spot is located they simply measure the distance between the torch and observer. Using ratios they can know calculate a distance in metres to Alpha Centauri! In practice there is some uncertainty and several assumptions made in this investigation but students are often surprised at how close their value is to the true distance. having a number of pairs perform the investigation allows them to compare results, discuss their assumptions and refine their technique. (This activity is summarised from one presented to me by Dr Case Rijsdijk from the South African Astronomical Observatory and used with thanks. See *Friends with the Universe* at: http://www.saao.ac.za/education/modules.html for this and other modules).

   A classroom variation on this activity is the use of a grease spot photometer. A sheet of brown or white paper with a drop of olive oil is held upright between two bulbs as shown in figure 6 below. In this situation, the power output of an unknown bulb can be determined by moving it until the grease spot "disappears" when it is equally illuminated by a known lamp on the other side. Using ratios, students can easily calculate the luminosity of the unknown bulb. This activity really draws together ratios and the inverse-square relationship of light.

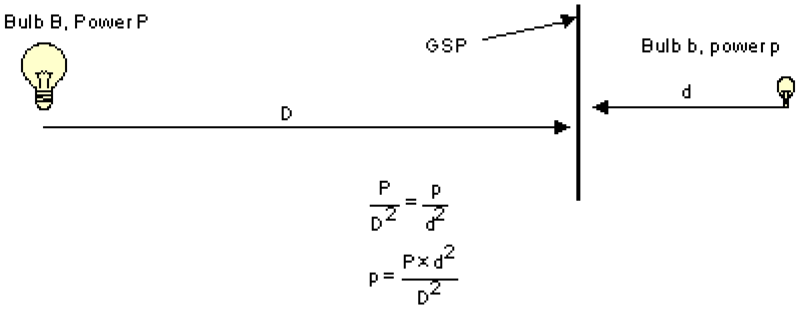


Figure 7: Grease Spot Photometer (Figure from *The Inverse Square law – A workshop module for teachers* by Case Rijsdijk, SAAO)

Stellar Evolution

One point that you may need to emphasise is that astronomers use the word "evolution" in a slightly different sense to biologists. What is really meant by the term is the life cycle of a star. When a star "evolves" it is not being naturally selected rather it is simply changing its physical appearance due to changes in its structure and sources of energy.

Simple Demonstrations related to stellar evolution

Here are a few ideas to help convey some tricky concepts related to stages of stellar evolution.

1. **Difference between main sequence and red giants.** Stars evolve off the main sequence once they run out of hydrogen in their core. In doing so the outer layers of the star expand enormously. The radius of a red giant is typically 100 times that of a main sequence progenitor for stars similar to our Sun. The red giant however is actually slightly less massive than the progenitor star as a small fraction of the mass has been converted into energy via fusion. As the outer layers of a red giant are also held more weakly by gravity the rate of mass loss out from such stars is also greater than that for main sequence stars. Our Sun currently loses about 10^{-17} $M_\odot$ (solar masses) annually whereas as a red giant it will lose about 10^{-7} $M_\odot$ per year. One conceptual problem students may have is that the larger red giant is no more massive than the main sequence star from which it has evolved. How to show this? One simple analogy is that of a bag of microwave popcorn. The flat pack represents a main sequence star. Once it is micro waved it swells up to much greater volume with little or no apparent gain in mass. Even if the bag bursts and popcorn flies out you can put this down to mass loss by out gassing. To extend and perhaps trivialise the analogy further you could relate the expected lifespan of a bag of freshly popped popcorn in a classroom full; of teenagers with the lifespan the bag spent sitting on a supermarket shelf – that is, much shorter!
2. **Pulsars.** These rapidly rotating superdense neutron stars beaming intense beams of radiation off into space can be very hard objects for people to visualise. You can download animations and sound files of pulsars, including the recent binary pulsar from sites such as the ATNF (http://www.atnf.csiro.au/news/press/double_pulsar/) and Jodrell Bank (One effective way of playing the sound files is to use something such as *Windows Media Player* and use the *View* → *Visualizations* → *Bars and Waves* → *Scope* setting to display the waveform similar to that obtainable on an oscilloscope. An example of this is shown in figure 7 below for the Crab pulsar file from Jodrell Bank's website (http://www.jb.man.ac.uk/research/pulsar/).

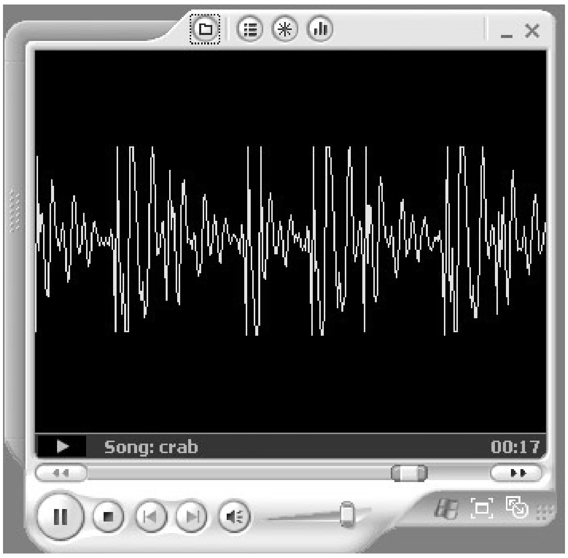


Figure 8: Visualisation of Pulsar Sound File Using *Windows Media Player*

- *use the Hertzsprung-Russell diagram to describe types of stars, their evolution and death;*

The Hertzsprung-Russell Diagram

One of the most useful and powerful plots in astrophysics is the Hertzsprung-Russell diagram (hereafter called the H-R diagram). It originated in 1911 when the Danish astronomer, Ejnar Hertzsprung, plotted the absolute magnitude of stars against their colour (hence effective temperature). Independently in 1913 the American astronomer Henry Norris Russell used spectral class against absolute magnitude. Their resultant plots showed that the relationship between temperature and luminosity of a star was not random but instead appeared to fall into distinct groups. These are seen in the H-R diagram below. It has a few specific stars included in the plot but otherwise just shows the main regions. The key tool to aid students in understanding stellar evolution is the Hertzsprung-Russell (HR) Diagram. If they can understand what it represents they are well on the way to explaining stages in stellar evolution.

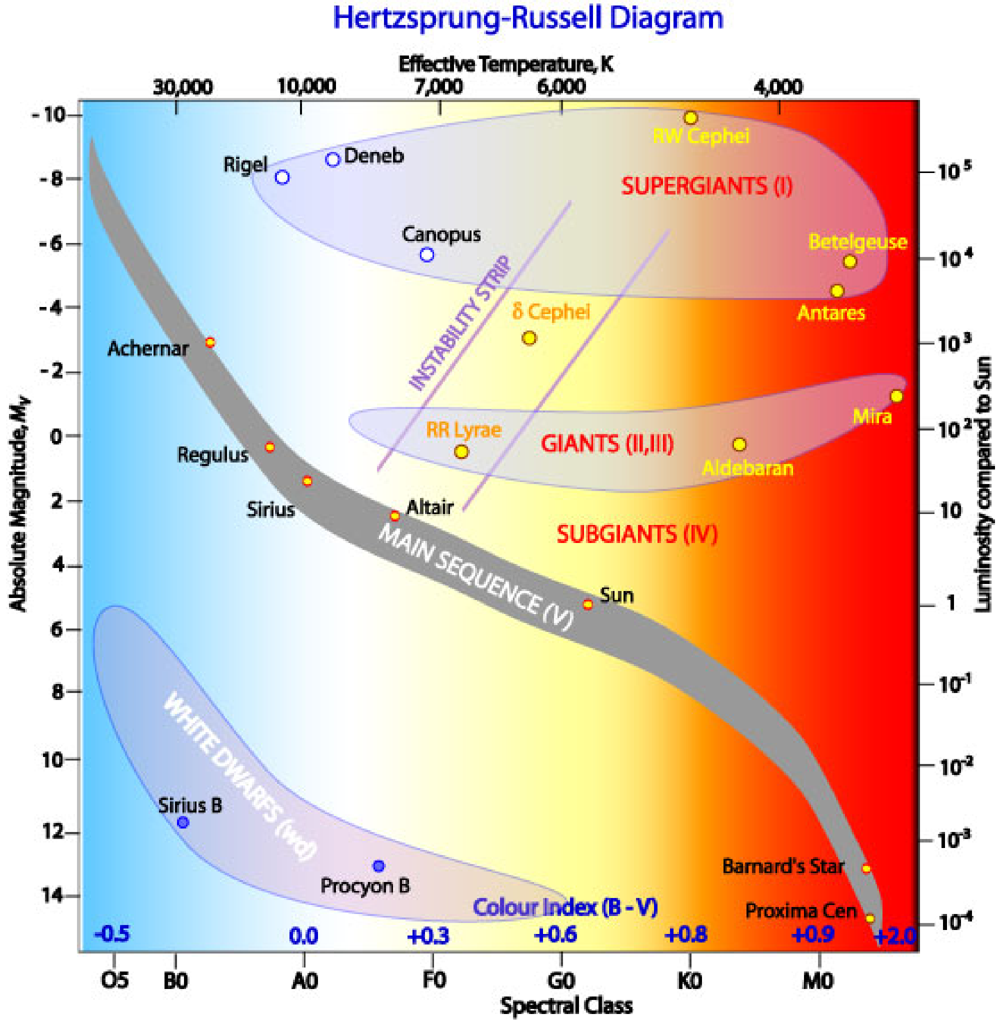


Figure 9.

The **HR Diagram** (Figure 9) poses problems for some students for a few reasons:

1. The **horizontal scale** is reversed from what they normally expect in a graph. The hot stars are placed on the left and the cooler ones on the right hand side. This may not be immediately obvious if you use spectral class to plot the position on the horizontal axis. Colour index can be a better approach, as it will be negative on the left hand side and increasingly positive as you move across to the right. Ultimately students need to be comfortable plotting any of the three types of data, effective (surface) temperature, spectral class and colour index.
2. The **vertical axis** represents the luminosity of a star. This is normally expressed in one of two ways, luminosity compared to the Sun ($L_*/L_\odot$) or absolute magnitude, *M*. Generally plotting values as luminosity poses few problems apart from the large range of values plotted ($10^{4 \text{ or } 5}$ to 10^{-4} times that of the Sun). If plotting absolute magnitude, some students are likely to arrange the scale in ascending order, that is they put the most positive value (and hence the dimmest star) at the top of the axis. If you are not specific with your instructions or worksheets and simply provide them with a table of data it may be worthwhile letting students make this mistake and then discuss it with them.

One way to introduce students to the concept of the HR Diagram is to ask them to plot a set of data such as shoe size versus a person's height, or height versus mass. The advantage of shoe size is that it is a discrete quantity that simulates spectral classes somewhat. An even better introduction is to ask them to estimate rather than directly measure the data before plotting. You can link this to the concept that astronomers have to infer stellar data by observing it from Earth rather than going to the star itself to obtain accurate measurement. When students lot this data they will generally plot it in the normal manner with increasing quantities going to the right and up the respective axes. In asking what type of relationship their plot shows it is worth emphasising the non-random distribution, that is there is a physical relationship between height and shoe size. Once they replot their data with a reversed horizontal scale they have something that approximates a main sequence for stars on an HR diagram. When students come to plot stellar data you can re-emphasise the idea about distribution and relationships so that they start asking why stars cannot be located just anywhere on the diagram.

Graphing or plotting data is an essential tool used by scientists. In attempting to make sense of data and see if two quantities are related we can plot them and seek trends. If we have a look at the two examples below the first shows two quantities, X and Y that an object may have. When they are plotted we can see that there is no discernable relationship between X and Y. In fact in this example there is no relationship, the data is purely random.

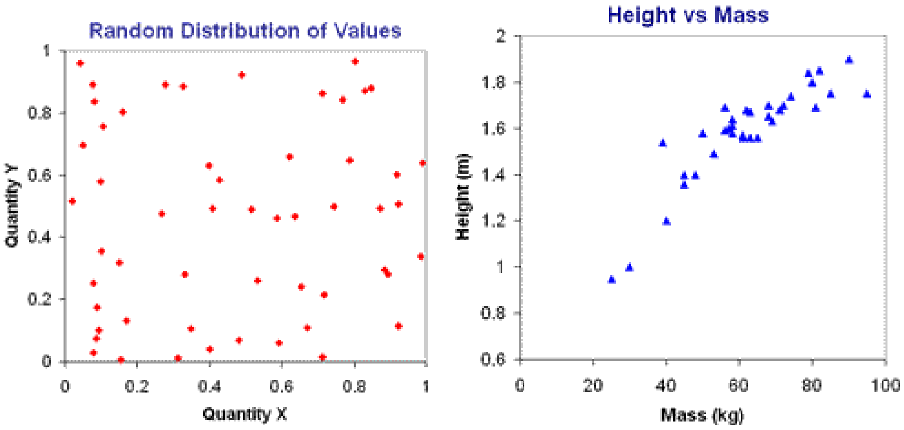


Figure 10.

If we plot data for height versus mass for a small group of people, however, we see a very different pattern as shown above right.

As we might expect, there does appear to be a correlation between the height of a person and their mass. In general, the taller a person is, the greater their mass but as with many other characteristics of humans there is a large variation. Some people are tall and skinny, others shorter but higher mass. There are, however, real physical limitations on both the height and mass of people. We do not expect to find a 3.5 m person with a mass of 10 kg or a 1.0 m person with a mass of 300 kg!

The majority of stars, including our Sun, are found along a region called the Main Sequence. Main Sequence stars vary widely in effective temperature but the hotter they are, the more luminous they are, hence the main sequence tends to follow a band going from the bottom right of the diagram to the top left. These stars are fusing hydrogen to helium in their cores. Stars spend the bulk of their existence as main sequence stars. Other major groups of stars found on the H-R diagram are the giants and supergiants; luminous stars that have evolved off the main sequence, and the white dwarfs. Whilst each of these types is discussed in detail in later pages we can use their positions on the H-R diagram to infer some of their properties.

Using the HR Diagram to Infer Stellar Properties

Let us look at the cool M-class stars as an example. If we look at the H-R diagram below we can see that in fact there are three main groups of these stars.

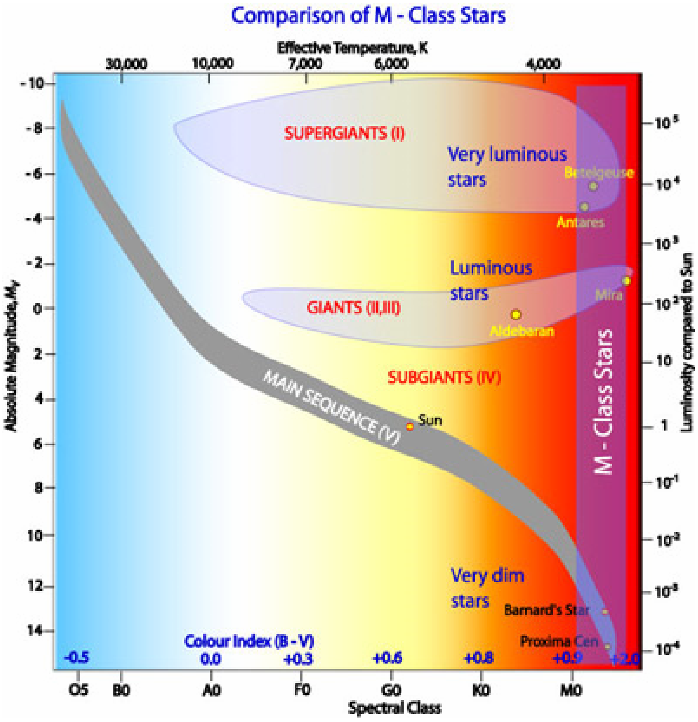


Figure 11.

At the bottom-right of the diagram we can see two named stars, Proxima Centauri and Barnard's Star. These are both cool (approximately 2,500 K) and dim (absolute magnitudes of about -13, only about 1/10,000 the luminosity of our Sun). Following the broad band straight up we come across Mira, also cool but much more luminous. Travelling further up we come across Antares and Betelgeuse. Again these stars are cool but they are extremely luminous, almost 10,000× as luminous as the Sun. *Why do these three groups differ so much in luminosity?*

The answer to this question depends upon the Stefan-Boltzmann relationship. The energy emitted per unit surface area per second is simply a function of the fourth power of temperature, that is:

$$l \approx \sigma T^4$$

where σ is a constant

If two stars have the same effective temperature they each have the same power output per square metre of surface area. As the H-R diagram however shows that one is much more luminous than the other it must have a greater total power output therefore must have a much greater surface area - the more luminous star is bigger. We can see this from the full expression for luminosity in the equation:

$$L = 4\pi R^2 \sigma T^4$$

The difference between the three groups of M-class stars is thus a difference in size. This is acknowledged by the names given to each of the groups. The most luminous ones are called *supergiants* (luminosity classes I and II), the luminous ones are called *giants* (luminosity class III) and the dim ones are part of the main sequence (luminosity class V) though historically the term *dwarf* stars was applied to this group.

If we look at the vertical band on the H-R diagram for hotter stars around type A spectral class we see a similar pattern:

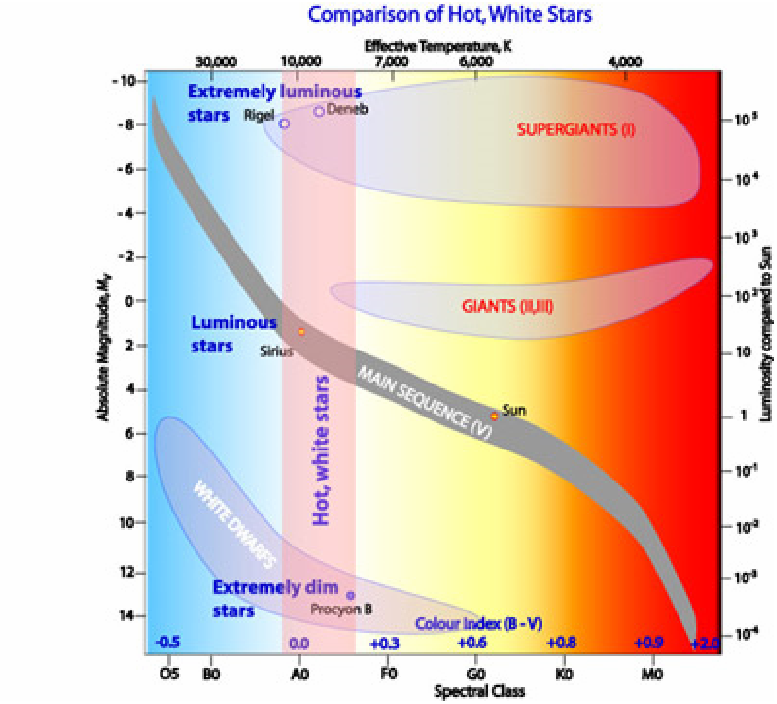


Figure 12.

In this case the supergiants Rigel and Deneb have the same effective temperature as Sirius but have extremely high luminosities. They have large radii than Sirius hence greater surface areas and higher luminosities. Sirius is a main sequence star but because it is hotter than the red main sequence Barnard's Star it is much more luminous than it. If you follow the pink band for hot stars down to the bottom of the H-R diagram you will notice that it intersects another group of stars that includes Procyon B. These are the white dwarfs. They are very hot (about 10,000 K or hotter) therefore emit a lot of energy per second for each square metre of their surface. The fact that they are so dim however, means that they must be extremely small and have a very low surface area. The terminology of white dwarf must not be confused with the old-fashioned term of dwarf stars that was applied to main sequence stars. White dwarfs are very different objects to main sequence stars as we shall see in a later page. Technically they have a luminosity class of *wd*. Simple calculations provide a size for white dwarfs roughly that of our Earth, less than 1/100 that of the Sun.

If we compare the dimmest stars on the H-R diagram we can also make some inferences. The following diagram shows the lower region of the H-R diagram.

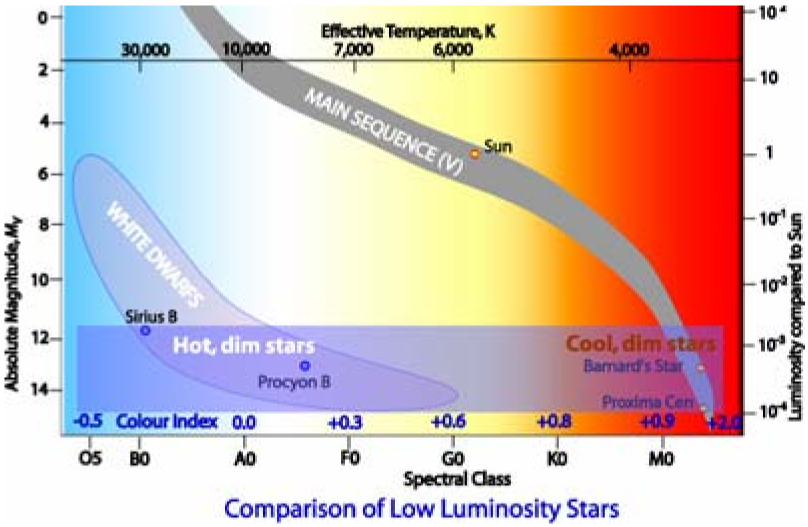


Figure 13.

Procyon B and Barnard's Star share the same low luminosity with an absolute magnitude of about +13. Procyon B however is much hotter than Barnard's Star thus emits much more energy per second per unit surface area. Given that they have the same total power output Procyon B must therefore have less surface area than Barnard's Star, that is its radius is smaller.

- *explain fusion as the energy source of a star;*

It is probably worth comparing fusion (as an energy source in stars) with fission (as used in reactors) as one way to introduce this. Another approach is to tackle the idea of the energy source in the Sun from a historical perspective. This covers initial ideas of a perfect, unchanging Sun in Classical Greek times to an awareness that it must give energy. Initial suggestions of combustion as a source much like burning coal or wood on Earth could fit in with a biblical age for the Sun but became untenable in the 18th/19th centuries with geological evidence on Earth pointing to it being much older than hitherto thought. To explain how the Sun could continue to produce energy for millions of years as then thought necessary, the idea of gravitational contraction was proposed by Kelvin. The current model invoking nuclear fusion was not well developed until the mid-20th Century. This story is an interesting example of how an understanding of and breakthroughs in fundamental physics provides answers to key problems. Nuclear fusion provides a solution to the problem of the Sun being billions rather than millions of years old.

A key point to convey is that nuclear fusion within stars including the Sun not only releases energy but is responsible for elements heavier than helium. The carbon, oxygen and iron atoms in our bodies were initially formed within stars. This process is called *nucleosynthesis*.

Nuclear fusion in stars is probably best broken into two sections, main sequence and post-main sequence phases. Detailed explanations with useful diagrams can be found at:
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_mainsequence.html and subsequent pages. Hydrogen to helium is main energy source in main sequence stars, either as the proton-proton chain for most stars or via the CNO-cycle for more massive stars of second generation and later.

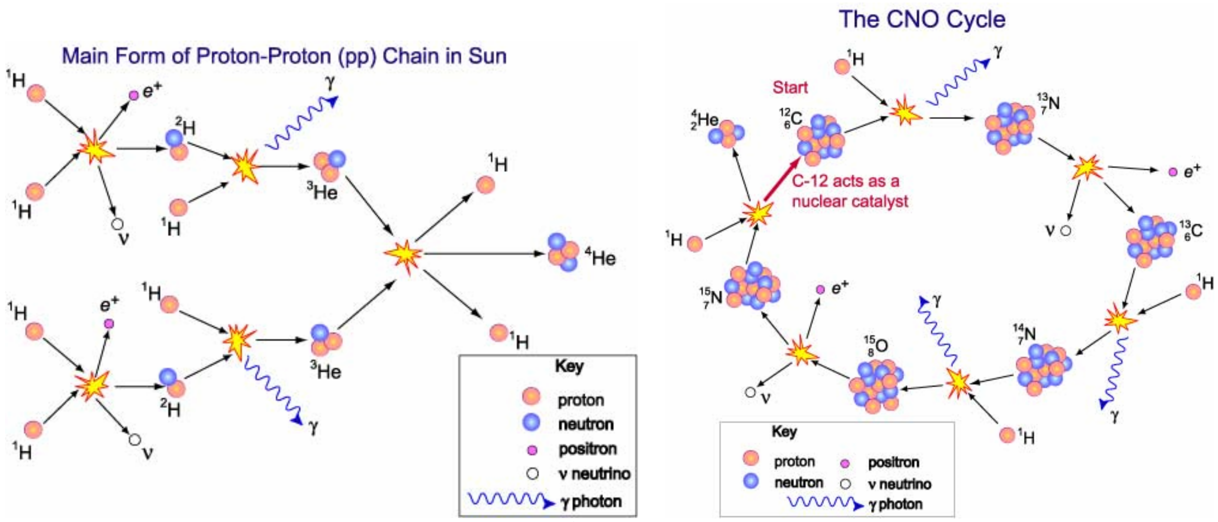


Figure 14.

Helium fusion within post-main sequence stars initially produces carbon. For stars such as our Sun this is initiated as a *helium flash*.

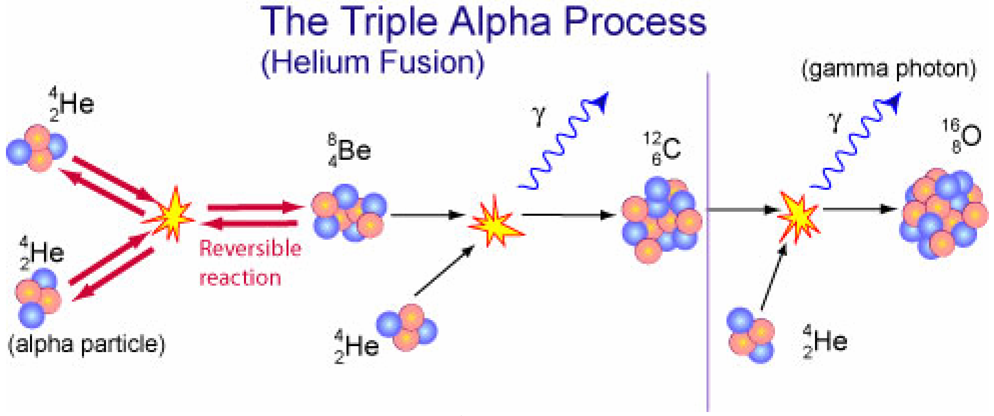


Figure 15.

More massive stars can synthesise even heavier elements via a series of *shell burning* layers within the star. Fusion can ultimately produce elements as heavy as iron. Beyond iron, neutron capture and decay is responsible for the heaviest elements. Some of these are only produced in the last second or so of a massive star's life before it explodes as a supernova. More details about post-main sequence nucleosynthesis can be found at:
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_postmain.html.

A final point to note about fusion within stars is that many texts refer to *hydrogen burning* or *helium burning*. It is essential to emphasise that it is not really a form of combustion. It is a nuclear, not a chemical reaction. The "burning" term is another example of an historical artefact in the language of physics and astronomy.

- ***compare the Milky Way galaxy to other galaxies;***

Our galaxy, the Milky Way, is a relatively average spiral galaxy that has recently been found to have a central bar. It is not the largest in our Local Group, M31, the Andromeda galaxy is larger but it provides a useful comparison as to what our own galaxy would look like from a distance. Spiral galaxies are larger than the dwarf galaxies and most spirals seem to have smaller neighbouring dwarf galaxies associated with them.

- ***describe characteristics of the Sun as a typical star, including size, mass, energy output, colour and information obtained from the Sun's radiation spectrum;***

The Sun is actually a relatively normal star though above average mass. It is a single star rather than most that are found in binary systems. As the nearest and hence best studied star, astronomers use it as a reference to compare the properties of other stars against. Many of the points outlined in previous sections such as those on photometry and spectroscopy are equally relevant to the Sun as to other stars.

- ***select appropriate data relevant to aspects of astrophysics from a database.***

Refer to the equivalent syllabus point for the *Astronomy* design study for some useful online databases and data sources.

Conclusion

This paper provides some ideas to help you try and relate some of the necessary concepts for astronomy and astrophysics to students in a manner which may challenge them but also hopefully make them think and gain a better understanding. Try some of these ideas out and see if you can develop some of your own. If you come up with something that works and you think may be of use to others please contact me and we may be able to put it on Outreach and Education website at ATNF.

References and other useful books

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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.

Australia Telescope Outreach and Education http://outreach.atnf.csiro.au/ is the outreach and education website of CSIRO's Australia Telescope National Facility. It has a range of material available and is continually being added to.

A major part of the site is the new online material for senior Physics. The first part of this is a complete online module for the *Astrophysics* option in the NSW Physics syllabus that also covers much of the material in the Victorian VCE syllabus. This can be reached directly at: http://outreach.atnf.csiro.au/education/senior/astrophysics and contains 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. It is likely that this section will be adapted directly for the VCE syllabus soon but regardless of this is still relevant and useful.

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/astrphys.html. It has a wealth of annotated links.

Australian Astronomy (http://www.astronomy.org.au/) is the official portal for all aspects of astronomy in Australia. Has sections for professionals, amateurs, education and the public.