



Concepts for *The Cosmic Engine*

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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 module 8.5 *The Cosmic Engine* of the NSW Stage 6 Physics syllabus. Concepts addressed, in varying depths, include historical perspectives, the expansion of space and the Big Bang, colour and temperature of stars, luminosity and the Hertzsprung-Russell diagram.

Despite the seeming lack of practical investigative work in the revised version of the Cosmic Engine unit, there are many simple demonstrations and analogies that are effective in engaging and challenging students.

This paper aims to provide teachers with a range of ideas and activities plus some useful data with which to cover the syllabus requirements. It is not intended to provide a detailed theoretical background on 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. Some of the material included in this paper may be found in The Cosmic Engine section of the Australia Telescope Outreach and Education website; <http://outreach.atnf.csiro.au/education/senior/cosmicengine/>. Other material has been incorporated and updated from papers presented at previous Science Teacher Association of NSW workshops by the author.

Syllabus Requirements

This paper uses the amended NSW Board of Studies Stage 6 Physics Syllabus of October 2002. The three areas targeted in this paper approximately relate to the syllabus outcomes in bold points 1, 2, and 3 in module 8.5 *The Cosmic Engine* (pages 35 – 37 of the printed edition). It is recommended that you read the paper with access to a current copy of the syllabus. It can be obtained online from the Board of Studies at http://www.boardofstudies.nsw.edu.au/syllabus_hsc/.

Historical Models

Astronomy is the oldest of sciences. Numerous ancient sites such as many of the megalithic stone circles of north-western Europe show evidence of astronomical alignment. The growth of agricultural communities required an understanding of seasons and time keeping. Ancient Egyptian and Babylonian records provide evidence of systematic observations of the night sky.



Figure 1: Stonehenge at around Midwinter sunrise © R. Hollow

Five planets, Mercury, Venus, Mars, Jupiter and Saturn plus the Sun and Moon were visible to the unaided eyes of the ancient astronomers. The planets could be distinguished from stars in that through regular observation they were seen to move relative to the stars. The very word *planet* derives from the classical Greek term for *wandering star*. Unlike stars, planets also varied their brightness over time. A final complication in the observed behaviour of planets was that of *retrograde motion*. This is where a planet seemed to back track on its path across the sky through the constellations before reverting to its normal direction. Figure 2 on the next page clearly shows this for the planet Mars in late 2003.

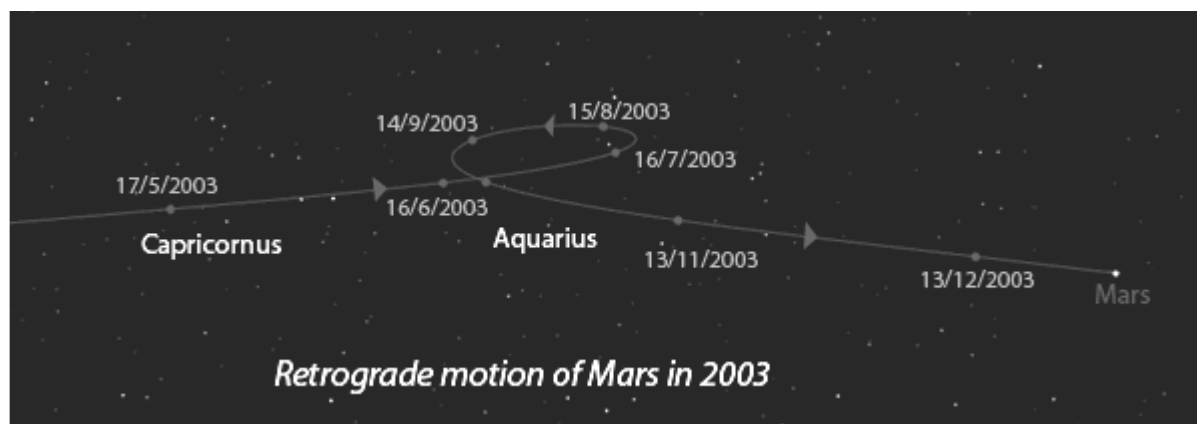


Figure 2. Retrograde motion of Mars (Image was generated using Starry Night Pro software).

The first section of The Cosmic Engine module requires students to **outline** the historical development of models from Aristotle to Newton and to **assess** one of these models and its limitations with respect to the technology available at the time. Given the time constraints for the module it is unrealistic to expect students to study the models in great depth or probe all of the subtle intricacies of, for instance, the Ptolemaic model. There are several useful websites, some listed in the references at the end of this paper, that provide an effective overview and from which students can extract relevant details on a specific model. Rather than just let students choose randomly which model to investigate it may be worthwhile to assign a different model to each student or group and have them report back to the whole class in chronological sequence so as to provide some sense of historical narrative.

Personal Cosmology

Before even starting on an investigation of a specific model, an effective approach is to ask your students to construct their own personal cosmology. An example of a worksheet for this approach is included in McNamara *et al* (1997). In this task ask your student to imagine that their entire Universe is what they can see from their classroom, their world. When prompted to do this many students will be bemused so may need some prompting. They have to describe their “world view” based purely upon what they can observe from their seat. If they have a view out of a window they may be able to see the Sun or they may only be able to see that the outside region can be blue, grey/white (ie cloudy) or dark. Sometimes external objects may seem to move or shake (trees blowing in the wind) or change (deciduous trees in the winter). Ask students as to what they would make of this world if they could not go outside the room and actually examine objects closely? Could they develop a model to account for observations? This, in essence, is what the early astronomers and philosophers had to do and indeed modern astronomers are still largely dependent upon. Forcing students to adopt this approach may make them less critical and more understanding of the problems facing their predecessors. It also illustrates the fact that astronomy is primarily an **observational** rather than an **experimental** science.

If you have the time and capable students you can explore this approach in more depth by using one of the role-playing scenarios developed by Dr Paul Francis from the Australian National University’s Research School of Astronomy and Astrophysics at Mount Stromlo. If you visit his website <http://www.mso.anu.edu.au/~pfrancis/roleplay.html> use the *Understanding the Sky Exercise for 1st Year Astronomy Students* exercise.

Impact of Technologies on Historical Models

Many students have a poor understanding or appreciation of historical timelines and associated technologies. It is useful to explicitly refer to sates and intervals for historical periods. A scale timeline or chart in the classroom can be effective as a tool for ready reference. In discussing the development of models solicit a list of possible technologies from students. Whilst most students will identify the telescope many actually neglect the human eye. Few however are likely to identify some of the others in the list below as **technologies**:

- Human eye
- Telescope
- Gnomon or upright stick in the ground. In various forms this is the basis for sundials.
- Astrolabe, quadrant and cross-staff
- Water-clock
- Pendulum (and the pendulum clock)
- Writing and recording, including clay tablets, papyrus, parchment, printing and books
- Mathematics. There are a few branches key to the development of cosmological models including:
 - Numbers systems and notation (including zero)
 - Geometry
 - Irrational numbers
 - Algebra
 - Logarithms
 - Calculus (or *theories of fluxions and inverse fluxions* as Newton originally named it)

Of course technologies are not separate from the cultures and societies that use or develop them so there is a wealth of possible topics for discussion in this section. One or two examples can be used to illustrate the application of these technologies in earlier times. These could include Eratosthenes' measurement of the Earth's circumference using a gnomon, well and camel caravan. Students can link up with another school to perform Eratosthenes' experiment as part of a 2006 competition for National Science Week organised by RMIT, <http://www.rmit.edu.au/scienceweek>. Newton's deduction of the inverse-square law for gravity of Kepler's empirical laws of planetary motion and the use of calculus to determine the gravitational force between the Earth and Moon.

Central to models prior to Kepler was a philosophical reliance on the circle and sphere as the basis for all celestial motions. This mind-set dominated for a few thousand years and influenced models as disparate as Aristotle and Copernicus. Even Kepler spent many years fixated on trying to establish a mathematical model based on regular solids and circular paths to fit observations of the planets. Only through tedious and painstaking calculations did he eventually realise that planetary orbits are elliptical, not circular, with the Sun at one focus (Figure 3).

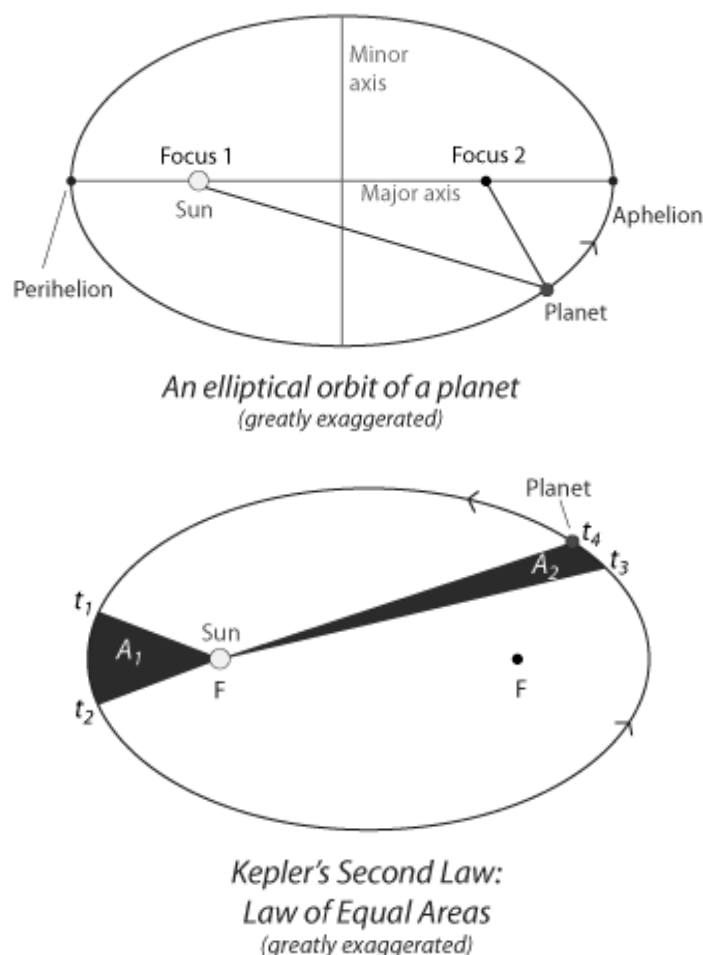


Figure 3: Kepler's First and Second Laws of planetary motion. Credit: R. Hollow, CSIRO

Students can gain an appreciation of the skill of early observers by trying to measure positions of stars or planets using simple inclinometers or cross-staffs. Crude refracting telescopes can be purchased from stores such as *Australian Geographic* and issued to students to see if they can detect the Galilean moons of Jupiter. The science supplier *Cider House*, www.ciderhouse.com.au now imports and distributes the Project STAR material developed by the Science Education Department at the Harvard-Smithsonian Center for Astrophysics. This includes a simple refractor kit and a model celestial sphere that students can construct.

Visualisation tools including planetarium-type programs and online applets allow students to examine and explore different models and view phenomena such as retrograde motion in a timely manner. Examples are provided in the references at the end of the paper, with even more listed on our website.

Cosmology, the Big Bang and the Expansion of Space

The discovery of the expansion of space was a defining step in our understanding of the Universe. The discovery by Edwin Hubble was the culmination of work conducted by many people over a few decades applying the then limits of technology. The story is an interesting one as it illustrates how developments in several fields including theory and technology when linked together can lead to major breakthroughs.

Hubble's work relied upon the use of the world's then largest telescope, the 100 inch Hooker telescope on Mt Wilson, in itself the relatively new technology of a large reflecting telescope as compared with traditional large refractors. He required long photographic exposures on glass plates of faint light from distant galaxies that had been passed through a spectrograph.

Relation Between Redshift and Distance for Distant Galaxies

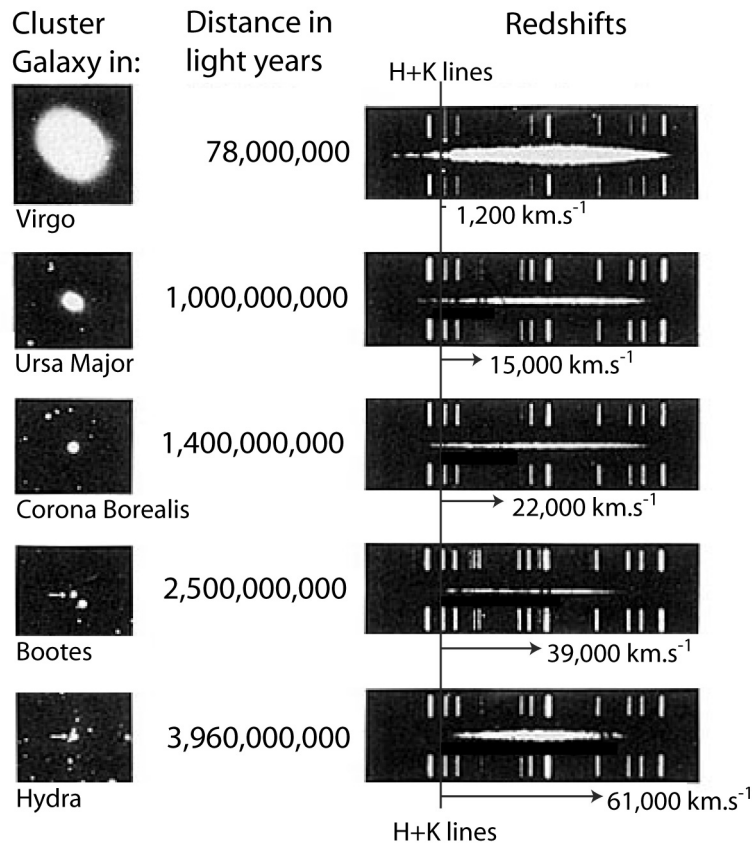


Figure 4:

The conceptual challenges for students came in trying to make sense of Hubble's observations and interpretation. To simplify and paraphrase the findings,

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 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: $H_0 = 71 \pm 4 \text{ km s}^{-1}$ (5% margin)

HST Key Project: $H_0 = 71 \pm 6 \text{ km s}^{-1}$
 which in turn suggest that the Universe is **13.7 ± 0.2 billion years old.**
 Evidence for an expanding Universe now comes from a variety of independent observations.
- Cosmic Microwave Background Radiation (CMBR).** This is the remnant radiation from the Big Bang, and dates to the "decoupling era" 380,000 years after 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 2.725 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. 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 \therefore 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.

Concepts to Emphasise

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 and the remnant of this can be seen in every direction. The Universe does not have a centre in much the same way as the surface of a sphere has no centre.
3. **Not a Doppler shift:** The redshift as measured by Hubble and others since is not actually an example of the Doppler effect arising due to proper motion of galaxies **through** space. It is instead a cosmological redshift due to the expansion of space itself. Actually there are several types of redshift including gravitational redshift and expansion redshift.
4. **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. It is important to emphasise that galaxies themselves do not expand, local gravitational influence is strong enough to overcome any expansion effect.
5. 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 cold 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.
6. **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.

Classroom Activities for Cosmology

There are many simple activities, analogies and ideas to help convey cosmological concepts in the classroom. 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 themselves 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 OHP 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. Of particular use are the CLEA modules *The Hubble Redshift Distance Relation* and *Large Scale Structure of the Universe*.
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.

Luminosity, Colour and Temperature of Stars

The third section of the syllabus for The Cosmic Engine examines the relationship between effective (surface) temperature for a body and the radiation it emits and relates this to the colour of stars. Whilst not explicitly stating that stars can be approximated as black body radiators this is the key to this section. One immediate problem that some students have in linking colour to temperature is that in their everyday experience they normally equate red with hot or warm and blue with cold or icy. Often temperature dials on air conditioners and heaters reinforce this notion. With a black body radiator the opposite is the case, that is *red hot* is cooler than *blue hot*. The simplest analogy to use is to ask students which type of Bunsen flame is hotter – the orange safety flame or the blue heating flame?

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

In the real world some objects approximate the behaviour of blackbodies. These must be sources of thermal energy and must be sufficiently opaque that light interacts with the material inside the source. Examples of such objects include the tungsten filaments of incandescent lamps and the cores of stars. The continuous spectrum produced by a black body is distinctive and can be shown as an intensity plot of intensity against emitted wavelength. This plot is called the blackbody curve or the Planck curve, after the German physicist Max Planck who first postulated that electromagnetic radiation was quantised. The plot below (Figure 5) shows a Planck curve for an object with a 6,000 K effective temperature, the same temperature as the Sun.

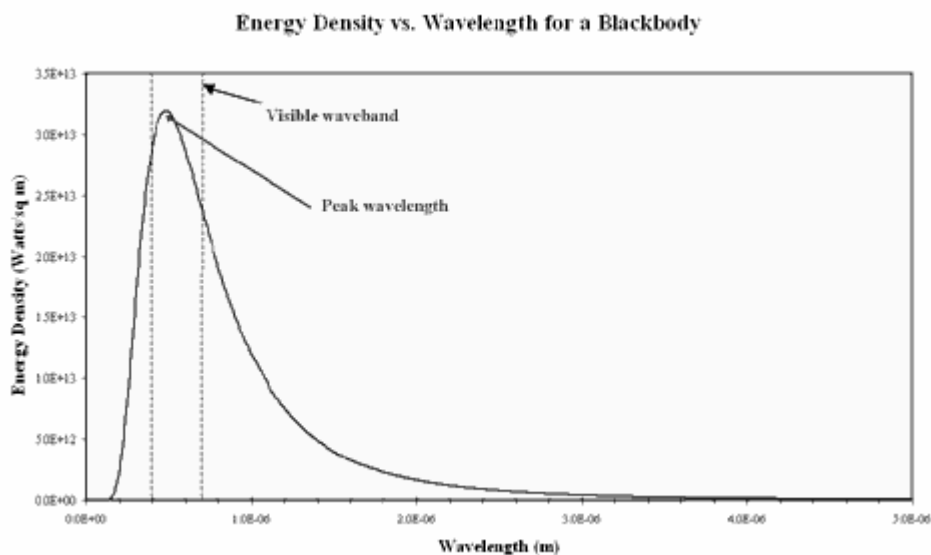


Figure 5: Planck curve for a black body at 6,000 K
Credit: M. Horrell <http://staff.imsa.edu/science/astro/blackbody/>

If you look closely at the curve you will notice that the object emits some radiation at every wavelength including in the ultraviolet and infrared wavebands. You should also notice that the amount of energy emitted is not the same for all wavelengths and that in this case, the peak wavelength falls within the region of visible light. Now what happens if the temperature of the black body source is different? Figure 6 on the next page shows Planck curves for an object at four different temperatures from 6,000 K to 4,000 K. Note the wavelength here is expressed in units of Ångstroms. 1 Ångstrom = 0.1 nanometers.

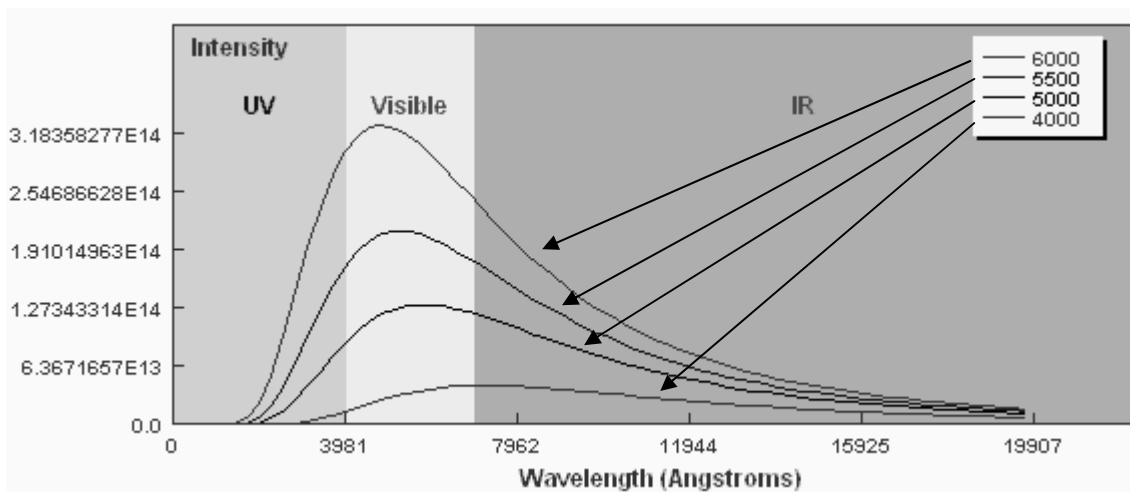


Figure 6: Planck curves for black bodies of different temperatures.
 Plot generated from an applet (<http://csep10.phys.utk.edu/guidry/java/planck/planck.html>)
 courtesy of Mike Guidry

How do the curves compare? Two key points should be apparent. Firstly, a hotter object emits more energy at every wavelength than a cooler one. Secondly, the hotter the object, the shorter the wavelength of the peak of the curve. The 6,000 K object clearly peaks in the visible part of the spectrum whereas the peak of the 4,000 K object borders the visible and the infrared regions. As already mentioned, stars approximate black body objects and can vary in their effective temperatures from around 2,000 K to about 30,000 K. If you tried to plot the intensity of two stars with these extremes on a plot like the one above it would be extremely difficult to show them on the same linear scale.

Demonstrations and ideas for luminosity, brightness and colour

There are many simple ideas you can use in the classroom or elsewhere to reinforce the concepts of luminosity, brightness and colour.

1. **Standard candles.** In discussing how to determine stellar and extragalactic distances students should be introduced to the concept of “standard candles”. 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 off 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.** Differences in the brightness of a star may arise due to internal processes or characteristics of a star (intrinsic) or be due to some external factor such as an intervening cloud or nebula between the star and the observer (extrinsic). 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. Perhaps the best example is the Coalsack Nebula adjacent to Crux, the Southern Cross.

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 3 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).

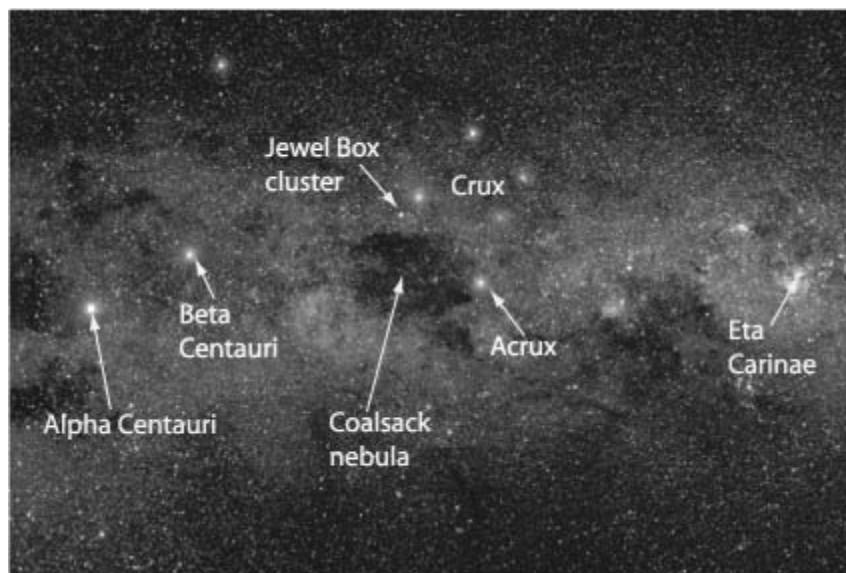


Figure 7: Crux Region with key features labelled (Credit: Adapted from an image by M. Bessell)

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.

A ray box or large 12 V bulb connected to a rheostat is also a quick and effective way to reinforce the relationship between temperature and colour. When low voltage is used, the filament glows dimly and appears red or orange. As the voltage is increased the filament becomes hotter and goes yellowish then white. There is scope to make this a more quantitative demonstration by using light and temperature sensors attached to data loggers.

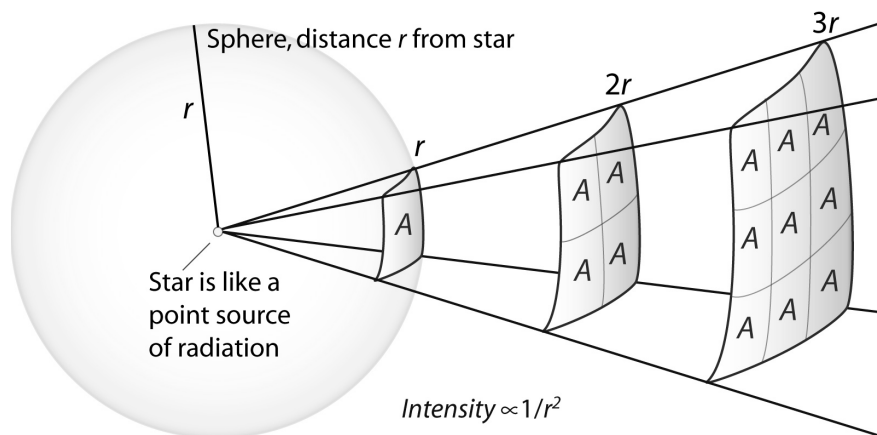
5. **Using comparative brightness to calculate distance to stars.** One important application of the concept of magnitude is to use it to determine the distance to a star. A star's apparent magnitude can be readily measured (methods range from naked-eye estimation, measurement of photograph or even CCD 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 Absolute magnitude, M and apparent magnitude, m

students then traditionally rework the equation $M = m - 5 \log\left(\frac{d}{10}\right)$ to find d in parsecs. Students do not

need to know or apply this formula in *The Cosmic Engine* module and indeed do not actually need to be introduced formally to the concept of magnitude. These concepts and formulae are however explicitly required in option 8.7 *Astrophysics* but it can be handy to introduce it in Year 11 if planning to revisit it in Year 12. Given the use of lower magnitude numbers to denote a brighter star, many students find the terminology confusing. One approach that can help is to think of magnitude 1 as being first-rate, magnitude 2 second-rate and so on.

An interesting practical experience that will challenge students and hopefully consolidate their understanding of the principles 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). This activity obviously works best if you are holding a viewing evening but can be simulated in a darkened lab if necessary. It is an elegant application of the inverse-square law for electromagnetic radiation (Figure 8).

The Inverse-Square Relationship for Light



At a distance $2r$ from the source the radiation is spread over four times the area so is only $1/4$ the intensity that it is a distance r .
 Radiation obeys an *inverse-square* relationship with distance.

Figure 8:
 Credit: R. Hollow, CSIRO

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 now 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 Rijdsijk from the South African Astronomical Observatory as part of their *Friends with the Universe* materials and used with thanks. An updated version of the complete activity was issued to all workshop session participants).

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 9 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.

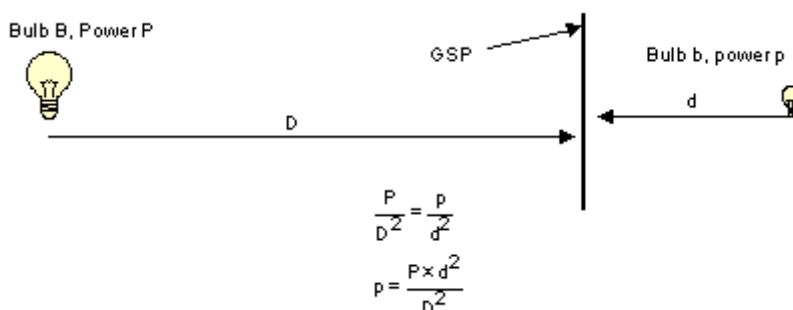


Figure 9: Grease Spot Photometer (Figure from *The Inverse Square Law* by Case Rijdsijk, SAAO)

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. 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.

Conceptual Approaches to the Hertzsprung-Russell Diagram

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 plot 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. The positions on the diagram are constrained by actual physical laws and interactions. By applying these astronomers can infer and determine actual properties of stars.

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 discernible relationship between X and Y. In fact in this example there is no relationship, the data is purely random. If we plot data for height versus mass for a small group of people, however, we see a very different pattern as shown below (Figure 10).

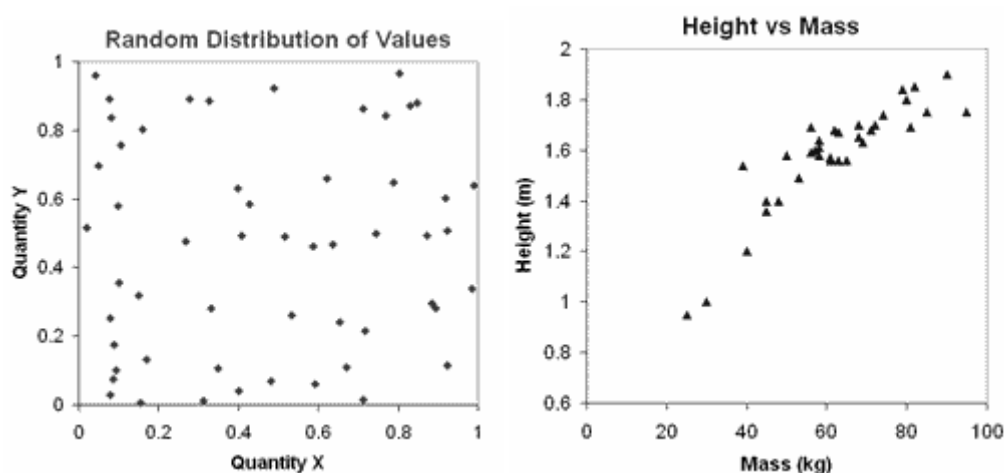


Figure 10: (Credit: R. Hollow, CSIRO)

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 **HR Diagram** poses other 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. Students studying *The Cosmic Engine* module do not need to explicitly learn about colour index or even spectral classes though I would suggest that at least the concept of classifying stars according to spectral characteristics is useful, even if they do not go into great detail. Given the unusual sequence of the spectral classification (O, B, F, G, K, M, N) if you plot stars according to this criteria the temperature trend along the axis may not be immediately obvious. *Colour* is a vague and ill-defined term. Astronomers use the quantitative *colour index* instead of the qualitative colour. Colour index is a better approach, as it will be negative on the left hand side and increasingly positive as you move across to the right but may generally be too complicated or detailed to include at this stage.

- The **vertical axis** represents the luminosity of a star. This is normally expressed in one of two ways, luminosity compared to the Sun or absolute magnitude (the magnitude a star would have it at a fixed distance of 10 parsecs, about 33 light years, from us). The more intrinsically luminous the star, the higher up the axis it is plotted. Generally plotting values as luminosity poses few problems apart from the large range of values plotted (10^4 or 5 to 10^{-4} times that of the Sun). The concept of Absolute magnitude is not essential at Year 11 level but if used 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.

Once students have plotted a number of stars onto an HR diagram or are even supplied with a completed diagram with a range of stars they have to be able to identify key star types. At this level it is required that they identify the following:

- Main sequence stars
- Red giants
- White dwarfs

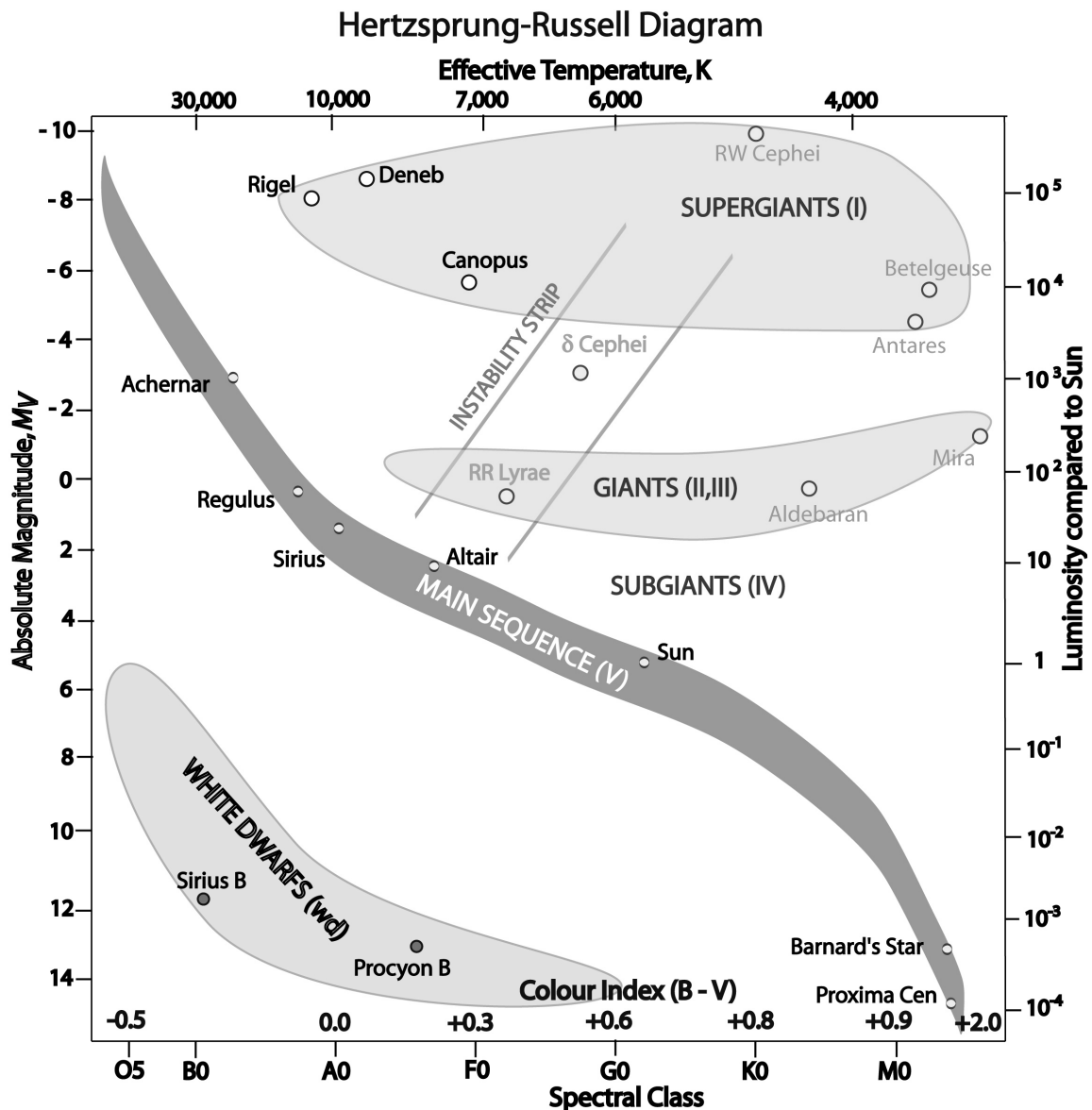


Figure 11: (Credit: R. Hollow, CSIRO)

In order to differentiate between two stars plotted on the diagram, students need to be able to determine two properties; one from each axis. What makes the HR diagram conceptually more challenging than most graphical representations that they may have previously encountered is that there is not just one relationship shown. At first glance it may seem sensible to suggest that the hotter a star is the brighter or more luminous it is. Conversely the cooler a star, the dimmer it should be. Indeed when we plot a large number of stars on the plot we see this trend. It is called the Main Sequence and

goes from the bottom-right to the top-left of the diagram. Most stars, including our Sun, are main sequence stars. They share a common source of energy – hydrogen fusion within their cores (sometimes confusingly termed *hydrogen burning* even though it is a nuclear, not a combustion process). The more massive the star, the higher up and along the main sequence it is placed. Interestingly, and to some students counter-intuitively, the more massive a main sequence star is, the shorter its lifespan on the main sequence. The stronger gravitational force inwards results in higher core temperature and an increased rate of consumption of core hydrogen hence shorter main sequence lifespan.

In studying stars on the HR diagram, ask students to identify cool (ie *red*) stars (Figure 12 below). There are normally three groups represented; red main sequence stars (also referred to as *red dwarfs*), red giants and red supergiants. Rather than apply these terms initially then ask students to locate them see if they can discern the groupings simply by looking at the distributions. Once the groups are identified, and perhaps labelled with terms such as *group A, B & C*, see if your students can account for the differences and infer what we can learn about the properties of the different groups. Hopefully they may suggest a link between the luminosity of a star and its size assuming that they have correctly realised that all these stars have the same effective temperature. For two stars of the same temperature, the more luminous star must be larger (have a greater surface area).

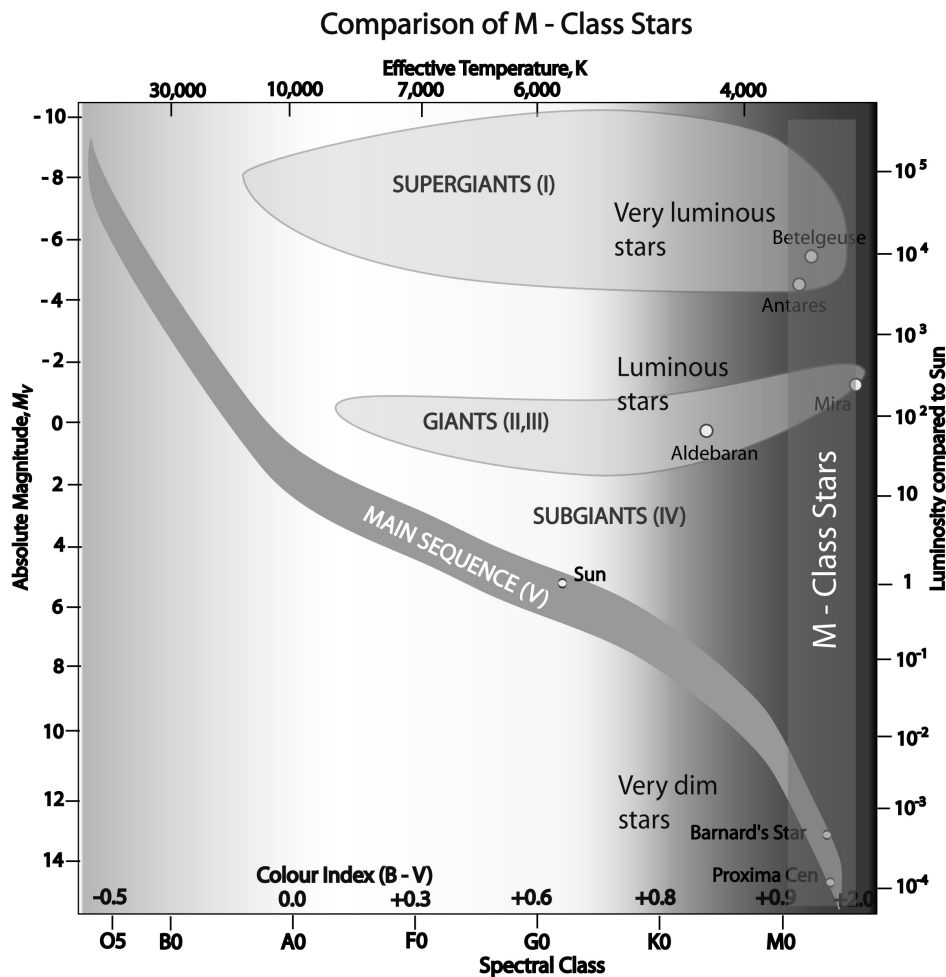


Figure 12: Comparison of cool (M-class) stars.
Credit: R. Hollow, CSIRO

A similar approach can be used in comparing white dwarf stars with hot main sequence stars. One of the key points to emphasise with students here is that by taking a few observations such as a distant star's colour index or spectral class and its brightness we can start to infer other properties such as size that we cannot directly measure.

Conclusion

This paper provides some ideas to help you try and relate some of the necessary concepts covered in *The Cosmic Engine* to students in a manner which may challenge them but also hopefully make them think and gain a better understanding. It has not covered every possible aspect of the syllabus nor addressed even all the dot points within the chosen sections. 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 in the Teacher Resource section of the *Australia Telescope 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 the CSIRO 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 online material for senior Physics including *The Cosmic Engine* module: <http://outreach.atnf.csiro.au/education/senior/cosmicengine/>

It 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.

Another valuable starting point is the *UniServe Science* resource page for *The Cosmic Engine* module for the NSW HSC Physics course at: <http://science.uniserve.edu.au/school/curric/stage6/phys/cosmeng.html>. It has a wealth of annotated links.

Historical Models

- *Gravitational Orbits* <http://www.physics.nwu.edu/ugrad/vpl/mechanics/planets.html> explores Kepler's laws via a two-body system that allows you to change parameters and displays.
- *Kepler's Second Law* <http://www.walter-fendt.de/ph11e/keplerlaw2.htm> is a useful applet that allows you to model the orbit of the various planets and Halley's Comet or set your own parameters.
- *Imagine the Universe! Theatre: Kepler's Laws, I, II and III* <http://imagine.gsfc.nasa.gov/docs/features/movies/kepler.html> is a NASA site that allows you to view AVI or Quicktime© movies of each of Kepler's Laws and view descriptions.
- *Ptolemy's Model* <http://webpages.charter.net/middents/Ptolemy%27s%20Model.htm> is an effective applet that demonstrates equants, deferant centre and epicycles for a planet orbiting the Earth.
- *RMIT Eratosthenes Project* <http://www.rmit.edu.au/scienceweek> This competition is open to students across Australia and will run in August 2006. Teacher and student guides may be downloaded from the site.
- *Role-Playing and Problem-Based Exercises for Teaching Undergraduate Astronomy* <http://www.mso.anu.edu.au/~pfrancis/roleplay.html>

Cosmology

- *Bad Cosmology* <http://www.jb.man.ac.uk/~jpl/cosmo/bad.html> from Jodrell Bank Observatory highlights common misconceptions in cosmology.
- *CERES: The Expanding Universe* <http://btc.montana.edu/ceres/html/Universe/uni1.html> is a set of learning activities that use a balloon to model the expanding Universe and Hubble's Law. It contains Teacher Lesson Plans, worksheets and scientific background. An excellent resource.
- *Frequently Asked Questions in Cosmology* http://www.astro.ucla.edu/~wright/cosmology_faq.html, part of the excellent *Ned Wright's Cosmology Tutorial* from UCLA is a very handy reference for answering student questions.
- *Hubble Law Lab, the Short Version* <http://www.astro.washington.edu/labs/clearinghouse/labs/HubbleLawShort/lab.html> is a clearly explained lab where students can examine images and spectra from nearly 30 galaxies to produce a plot to determine Hubble's constant and the expansion age. You can download and print out student worksheets and graph paper.
- *Project CLEA* <http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html> has two excellent cosmology-related simulations that can be downloaded and run on a PC.
The Hubble Redshift-Distance Relation
The Large Scale Structure of the Universe
They can be downloaded from the Project CLEA website together with user manuals, student workbooks and pre and post-tests.
- *Recovering Hubble's Original Data* http://jersey.uoregon.edu/vlab/hubble/Hubble_plugin.html is an applet that allows you to simulate obtaining spectra from the galaxies that Hubble observed then analysing them to plot the Hubble relationship.
- *The Hubble Law Java Applet* <http://zebu.uoregon.edu/2002/ph123/hub.html> has instructions and background information. It allows you to measure the redshift on intensity spectra to determine redshift and then plot Hubble's relationship.

Stars

- *Blackbody* <http://www.colorado.edu/physics/phet/simulations/blackbody/blackbody.swf> is a *Shockwave* applet that opens in your browser. By altering the temperature of the object you see the change in the shape and peak

intensity of its Planck curve, the colour of the object and more. You can run this applet or online or download it to run on your own computer.

- *BlackBody Physlet* http://webphysics.davidson.edu/Applets/java11_Archive.html is an effective *Java* applet that allows you to see the Planck curve and colour for stars of different temperatures.
- *Black body Radiation Exercises: Planck Law Radiation Distributions* <http://csep10.phys.utk.edu/guidry/java/planck/planck.html> is a *Java* applet that allows you to plot up to 10 Planck curves for temperatures from 3,000 to 30,000 K and compare them. It was used to produce some of the images used in this site. It also has links to applets for Wien's Law and black body: The Game where you have to try and determine the temperature of an unknown object to match a given Planck curve.
- *Color and Stellar Temperature* <http://zebu.uoregon.edu/nsf/planck.html> is an effective applet that allows you to compare the black body curves for two stars of different temperatures and determine their colours. You can add waveband filters and explore the infrared and ultraviolet parts of the spectrum as well as the visible.
- *Cluster Color-Magnitude Diagrams and the Age of Stars* <http://www.astro.washington.edu/labs/clearinghouse/labs/Clusterhr/cluster.html> provides colour indices and magnitude data for the Pleiades and 47 Tuc, a globular cluster so that you can plot colour-magnitude diagrams and determine cluster ages.
- *HR Applet* (© McGraw Hill) <http://www.mhhe.com/physsci/astronomy/applets/Hr/frame.html> is an online applet showing stellar evolution on the HR diagram. You can specify a star's parameters and watch it evolve. An evolutionary track is plotted. The site has accompanying explanations and background information.
- *HR Diagram* <http://www.astro.washington.edu/labs/clearinghouse/homeworks/hrdiagram.html> is an exercise that you can print out. It provides background theory and tables of bright and nearby stars for you to plot on the accompanying HR plot and frequency plot.
- *HR Diagram Simulator* <http://www.astro.ubc.ca/%7Eescharein/a311/Sim/hr/HRdiagram.html> allows you to place 1, 10 or 100 stars on the main sequence then compare their evolution off the main sequence either in steps or as a movie. Useful for demonstrating the concept of ZAMS.
- *IMSA Astrophysics: Stellar Spectra and Planck black body Radiation* <http://staff.imsa.edu/science/astro/blackbody/> is an excellent resource with detailed theory, clear diagrams and an Excel spreadsheet where you can model Planck curves and analyse data.
- *Jewels of the Night* <http://www.noao.edu/education/jewels/home.html> is an excellent and effective activity that you can download and printout. Students have to classify stars in this open cluster according to colour and magnitude. Has full instructions, worksheets, teacher
- *Properties of Stars* <http://www.unm.edu/%7Eastro1/101lab/lab8/lab8.html> allows to examine the properties of several stars using a virtual observatory then explore some of the evolutionary stages. An excellent activity with high quality graphics and pedagogy from University of New Mexico.
- *Star Brightness Worksheet and Info* <http://www.telescope.org/nuffield/galaxy/galaxy9b.html> is a simple page that can be printed out with a set of questions and data for students.
- *Star Clusters* http://www.unm.edu/%7Eastro1/101lab/lab10/lab10_C.html is another detailed activity from University of New Mexico where you find the distance to star clusters then use them to explore stellar evolution and the ages of stars. Excellent graphics and development of concepts. Useful for understanding the concept of ZAMS and spectroscopic parallax.
- *Stellar Evolution Simulation* <http://instruct1.cit.cornell.edu/courses/astro101/java/evolve/evolve.htm> from Cornell allows you to alter the mass of a star and see how this affects its evolutionary track from the main sequence onwards. The results are plotted on a luminosity/temperature HR diagram in time steps with representations of star size. It comes with a useful set of instructions. Highly recommended.
- *Stellar Magnitudes Applet* http://www.ioncmaste.ca/homepage/resources/web_resources/CSA_Astro9/files/multimedia/unit2/magnitudes/magnitudes.html is a simple applet designed for secondary students that relates the brightness of different stars to a varying number of light bulbs. It provides a link to a clear set of pages discussing properties of stars.
- *Stellar Parameters* <http://astro.unl.edu/classaction/> is an excellent tool, part of the *ClassAction Interactive Materials for Introductory Astronomy* <http://astro.unl.edu/classaction/> at the University of Nebraska. Click on the link to the Stellar Parameters page to run the module from the web or download a zipped version to run on your own computer. The module uses Flash simulations to investigate the distance modulus, stellar velocity, parallax, spectroscopic parallax, luminosity, flux and the HR Diagram. It also contains a quiz, images, tables and an outline of each concept. You can also download an Instructors manual. An excellent resource.
- *The Inverse Square Law* <http://zebu.uoregon.edu/nsf/inverse.html> is a *Java* applet that simulates photometer readings at varying distances from light bulbs and stars. You can produce flux vs distance plots for each situation.
- *Thermal Radiation Curves Applet* <http://cas.sdss.org/dr2/en/proj/basic/color/physlet/blackbody.asp?textBox=5750> allows you to specify a temperature or a peak wavelength for a star and view the corresponding Planck curve with a simulated visible spectrum superimposed on it.