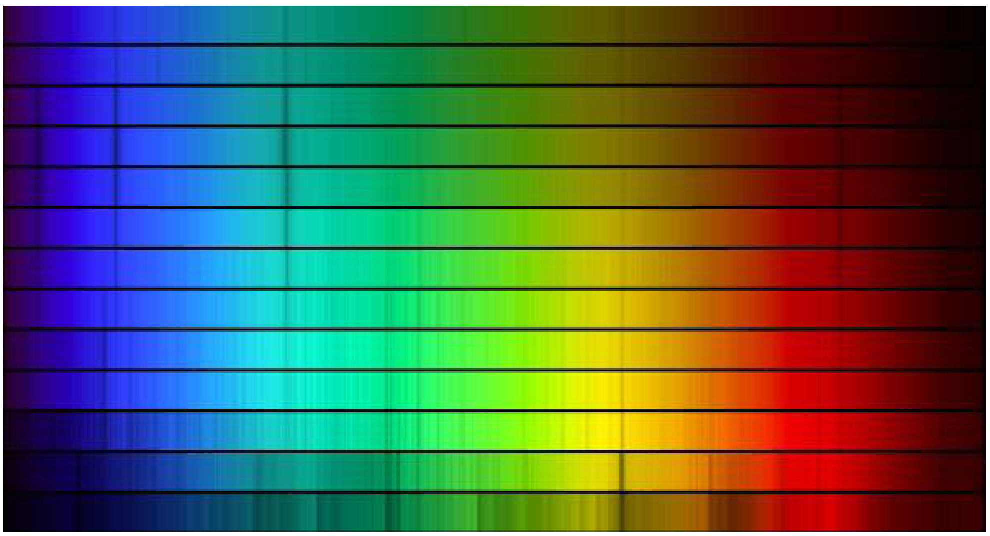
Module 8: From the Universe to the Atom

Part 1: Origins of the Elements



Tammy Humphrey

Contents

Cover photo credit: Stellar Spectral Types: OBAFGKM Credit: KPNO 0.9-m Telescope, AURA, NOAO, NSF

Syllabus content: From the Universe to the Atom

Structure of the Atom

Inquiry question: What evidence is there for the origins of the elements?

Students:

- investigate the processes that led to the transformation of radiation into matter that followed the 'Big Bang'
- investigate the evidence that led to the discovery of the expansion of the Universe by Hubble
- analyse and apply Einstein's description of the equivalence of energy and mass and relate this to the nuclear reactions that occur in stars
- account for the production of emission and absorption spectra and compare these with a continuous black body spectrum
- investigate the key features of stellar spectra and describe how these are used to classify stars
- investigate the Hertzsprung-Russell diagram and how it can be used to determine the following about a star:
  - characteristics and evolutionary stage
  - surface temperature
  - colour
  - luminosity
- investigate the types of nucleosynthesis reactions involved in Main Sequence and Post-Main Sequence stars, including but not limited to:
  - proton-proton chain
  - CNO (carbon-nitrogen-oxygen) cycle

Discovery of the Expansion of the Universe

Background: Einstein, Friedmann and Lemaître

[1]In 1915 Einstein published his field equations of general relativity, which relate the curvature of space-time to the local energy density. In 1922 the Russian theoretician Alexander Friedmann derived solutions to these equations, which were also independently derived in 1927 by Georges Lemaître (who was unaware of Friedmann's earlier work). While Friedmann described a set of abstract solutions (relating to both contracting and expanding universes) Lemaître focused on an expanding universe solution that seemed to align with initial data from Vesto Slipher published in 1923 on the recession of galaxies. He later proposed that the universe was once a "Primeval atom" (an early version of the "Big Bang" theory).

[1] References: Alexander Friedmann and the origins of modern cosmology, Ari Belenkiy, Physics Today 65, 10, 38 (2012); `https://doi.org/10.1063/PT.3.1750`; COSMIC HORIZONS: ASTRONOMY AT THE CUTTING EDGE, edited by Steven Soter and Neil deGrasse Tyson (2000), `https://www.amnh.org/learn-teach/curriculum-collections/cosmic-horizons-book/georges-lemaitre-big-bang`

The significance of Cepheids: Henrietta Leavitt's discovery

Henrietta Swan Leavitt was an American astronomer who discovered the relationship between the luminosity (brightness) and period of a particular class of variable (i.e. varying in brightness) stars called "Cepheid variables", publishing her results for 25 Cepheid stars in the Small Magellanic cloud in 1912.

Ejnar Hertzsprung measured the distance to a number of Cepheids within the Milky Way galaxy in 1913.

Once astronomers could relate the *absolute* luminosity of Cepheids to the period over which the brightness varied, these stars could then be used as "standard candles" - a way in which to determine the absolute distance to other Cepheids that were too far away for the technique of parallax to be used to determine distance.

This marked a huge leap forward in astronomy. In a 1925 paper Hubble used data from 22 Cepheids in M33 (now known as Triangulum galaxy) and 12 Cepheids in M31 (The Andromeda galaxy, see figure 2) to establish that these objects were actually incredibly distant - resolving the "Great Debate" that raged in the 1800s as to the nature of these objects - they were not phenomena in our own galaxy, but isolated galaxies, like our own Milky Way galaxy.

Figure 1: Henrietta Leavitt in 1921. Image credit: Public domain `https://en.wikipedia.org/wiki/Henrietta_Swan_Leavitt#/media/File:Henrietta_Swan_Leavitt_1921.png`

Figure 2: The Andromeda galaxy. Figure credit: By Adam Evans - M31, the Andromeda Galaxy. `https://commons.wikimedia.org/w/index.php?curid=12654493`

Galaxy spectra are redshifted: Vesto Slipher

Vesto Slipher was the first to measure the spectra of galaxies[2], and in 1915 identified that the spectral lines of most galaxies that he measured were redshifted, meaning that they were receding from us.

Redshift refers to a shift in wavelength of the spectral lines of hydrogen and other elements present in the light received from galaxies

Figure 3: Vesto Slipher. Image credit`https://commons.wikimedia.org/wiki/File:V.M._Slipher.gif`

[2] See `https://www.roe.ac.uk/~jap/slipher/` for copies of Slipher's papers

(or other astronomical objects). The light from objects moving away from us is shifted towards red wavelengths due to the Doppler effect for light (analogous to the Doppler effect you studied for sound in year 11), as shown in 4. Light from objects moving towards us is shifted towards blue wavelengths.

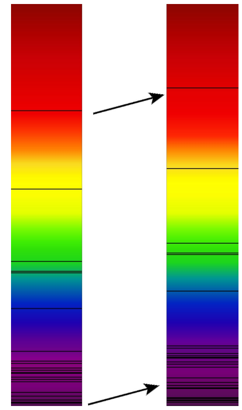


Figure 4: The spectra on the left is shown "redshifted" to longer wavelengths on the right. Image credit: Georg Wiora (Dr. Schorsch) created this image from the original JPG.Derivative work:Kes47 / CC BY-SA `https://creativecommons.org/licenses/by-sa/2.5`)

Edwin Hubble: More distant galaxies are receding faster

[3]In 1929 Edwin Hubble used the 100inch Mount Wilson telescope to measure the spectra of 46 galaxies, as well as using techniques which included the use of Cepheid variables to measure the approximate distance to 24 of them.

Hubble observed that the more distant the galaxy, the more redshifted its spectra. He thus made the extraordinary discovery that we now know as Hubble's law [4]

> Hubble's law:
> The further away a galaxy is, the faster it is receding from us.
>
> $$v = H_0 D$$
>
> where H_0 is known as Hubble's constant.

The implication of this result is that the universe is expanding - with the corollary that at some time in the past all the galaxies in the universe were in the same place.

[3] References for this section: A relation between distance and radial velocity among extra-galactic nebulae, Edwin Hubble, PNAS (1927) `https://www.pnas.org/content/15/3/168`; Modern Theories of the Universe: From Herschel to Hubble, Michael J. Crowe, (1994); "Hubble's Law and the expanding Universe", Neta A. Bahcall, PNAS commentary `https://www.pnas.org/content/112/11/3173`)

[4] recently renamed the "Hubble-Lemaître law" (`https://www.iau.org/news/pressreleases/detail/iau1812/`)

Figure 5: Edwin Hubble, 1931. Public domain.

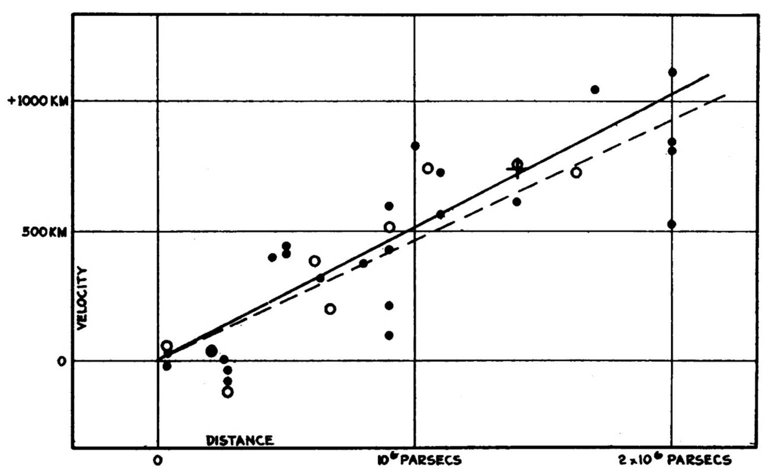


Figure 6: Hubble's graph of velocity (measured in km/s) versus distance (measured in MPc, i.e. millions of Parsecs). The gradient of the graph for Hubble's original measurements is approximately $500 km/s (Mpc)^{-1}$.

Figure from: A relation between distance and radial velocity among extra-galactic nebulae, Edwin Hubble, PNAS (1927) `https://www.pnas.org/content/15/3/168`

The age of the universe: $1/H_0$

The gradient of Hubble's velocity versus distance graph, H_0 has units of $time^{-1}$. The inverse of Hubble's constant $1/H_0$ has units of $time$, and can be understood to be an estimate of the age of the universe.

That is, if we know that a certain galaxy is D parsecs from us (where a parsec is equal to $3.0857 \times 10^{16} m$, which is about 3.3 light years) and is travelling at a speed of v kilometers per second, then the time it has been travelling away from us must be

$$\frac{1}{H_0} = \frac{D}{v} = \frac{1}{500 km/s(Mpc)^{-1}} = \frac{1 \times 10^6 \times 3.0857 \times 10^{16} m}{500 \times 10^3} = 6.2 \times 10^{16} s = 2.0 \times 10^9 \text{years}$$

The problem at the time with Hubble's estimate of the age of the universe as 2 billion years was that it was already well established from geology that the age of the earth was greater than 2 billion years, so it was clear that Hubble's result could not be correct.

The difficulty lay in the fact that the determination of Hubble's constant relied on an understanding of Cepheid variable stars. As scientists understood more about these stars (in particular that there were two types), estimates for H_0 began to decrease (and so estimates of the age of the universe began to increase)[5].

The modern value of H_0 is approximately $75 km/s(Mpc)^{-1}$, giving an estimated age of the universe of 13 billion years. These modern estimates rely upon an understanding of the intrinsic luminosity of type 1a supernovae as well as Cepheid variables as standard candles[6].

[5] see `https://history.aip.org/history/exhibits/cosmology/ideas/hubble-distance-double.htm`

[6] see `https://www.nasa.gov/image-feature/goddard/2016/three-steps-to-measuring-the-hubble-constant/`

Summary: Evidence that led to Hubble's discovery

- Edwin Hubble measured the spectra of a large number of galaxies, determining their recessional velocity from the redshift of the spectral lines (see 4).
- Hubble used the period-luminosity relationship for Cepheid variable stars to estimate the distance to galaxies close enough for these to be identified. For the most distant galaxies he used other techniques such as measuring the apparent luminosity of the galaxies and comparing these to known absolute luminosities of similar galaxies.
- By graphing recessional velocity versus distance, Hubble found evidence for a linear relationship between how far away a galaxy is and how fast it is receding from us (see 6).
- The fact that all (distant) galaxies are receding from us is evidence that galaxies were all in one place at some time in the past - this time (the age of the universe) is given by the inverse gradient of this graph: $1/H_0$, where Ho is now known as Hubble's constant.
- Prior to this work, Hubble had established the (very great) distance to a number of galaxies by using the known Period-Luminosity relationship for Cepheid variables. Vesto Slipher had used spectral redshift to measure the velocity of nearby spiral galaxies, finding some moving towards us (e.g. Andromeda) and many moving away from us.
- Hubble's initial estimate of the age of the universe was smaller than the geologically estimated age of the earth at that time. Eventually, recalibration of the Cepheid period-luminiosity relationship decreased the value for H_0 (increasing the estimated age of the universe). Over time the estimated value of Ho has continued to decrease and is now around 72 km/s/Mpc, giving an estimated age of the universe of 14 billion years.

Evidence for the Big Bang Model

The "Big Bang" is the name given to our current theory describing how the universe evolved from its beginnings to its present state. Video from NASA: `https://www.youtube.com/watch?v=LeUcjqqhNxM` (only 14s long). Hubble's discovery of the recession of galaxies provided substantial experimental support for the idea that the universe is expanding, so is a core piece of evidence in support of the Big Bang model. Other evidence began to accumulate from the 1940s.

Nucleosynthesis: The origin of the elements

Ralph Alpher completed his PhD thesis in 1948, under the supervision of George Gamow. He proposed a mechanism by which helium could result from the fusion of protons and neutrons if the universe were much hotter and denser (as it would have been just after the big bang) and that this fusion would cease as the universe expanded and cooled. The ratios of hydrogen to helium (helium is 25% by mass, hydrogen 75%) observed in the universe are consistent with Alpher and Gamow's theory of nucleosynthesis in the big bang, but are not consistent with the ratios that would be produced if the observed helium had been synthesised in stars (which would predict a much lower abundance of helium).

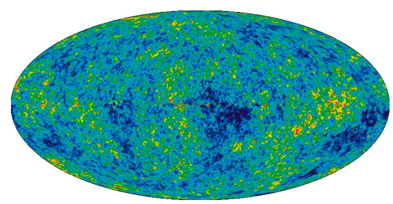


Figure 7: Cosmic Microwave Background radiation over the whole sky, as measured by the Wilkinson Microwave Anisotropy Probe. Public Domain (NASA).

Cosmic Microwave background (CMB) radiation

[7]Immediately after this (still in 1948) Alpher, working together with Gamow and Robert Herman, predicted the existence of the cosmic microwave background radiation (CMBR).

CMBR is remnant (one could say "fossil") blackbody radiation from the moment that the universe cooled sufficiently that neutral atoms were formed and light could begin to travel through the universe without being continually absorbed and emitted by charged nuclei in the hot plasma that existed prior to this moment (about 400000 years after the big bang). As the radiation was in thermal equilibrium with the plasma it has the form of blackbody radiation[8].

At the time that the universe became transparent the characteristic temperature of the blackbody radiation was extremely high (the same as that of the universe when when neutral atoms formed). As the universe expanded the wavelength of this radiation also increased until its temperature was just 2.7K above absolute zero.

The existence of the CMB was experimentally verified in 1965 by Arno Penzias and Robert Wilson. While working at Bell labs on a large microwave receiver, they identified an omnidirectional source of noise and established that it originated from space. This was identi-

[7] References for this section: `https://www.nobelprize.org/prizes/physics/1978/summary/`, `https://wmap.gsfc.nasa.gov/universe/bb_tests_cmb.html`

[8] Short discussion from the perimeter institute for theoretical physics `https://www.youtube.com/watch?v=GzSp8aGKaIg`

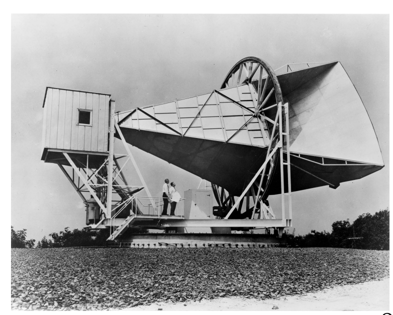


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Figure 8: The microwave horn antenna used by Penzias and Wilson to detect the CMB. Public Domain (NASA).

fied as the cosmic microwave background radiation and they received the 1978 Nobel Prize for Physics for their discovery.

The big bang theory is the only existing theory which can explain the existence of the CMB.

Processes that led to the transformation of radiation into matter after the Big Bang

The current model of the big bang identfies a number of "epochs" in which particular processes dominated, eventually leading to the production of neutral matter and then objects such as galaxies.

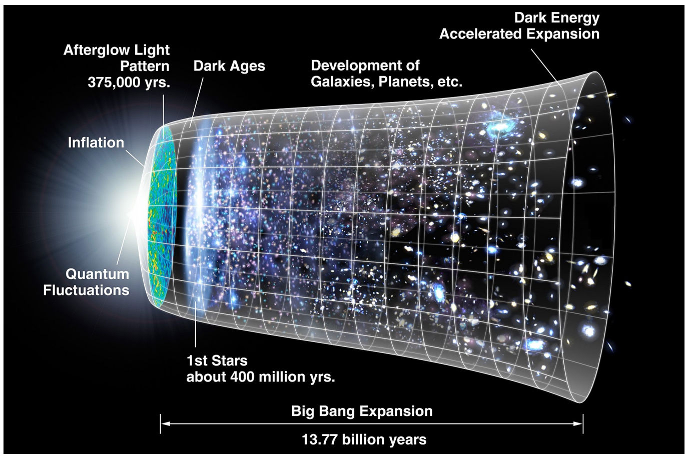


Figure 9: Timeline of epochs in cosmology. Public Domain (NASA).

- The universe was extremely hot and dense immediately following the big bang
- The energy released in the big bang (radiation) produces particle-antiparticle pairs of quarks and leptons
- A very slight imbalance of matter over antimatter provided the building blocks for nuclei and atoms (why this occurred this is still a subject of research)
- By 1µs, the universe had cooled to the point that protons and neutrons formed from quarks
- From 0.01 seconds onwards heavier nuclei (deuterium, He and Li) were formed by fusion of protons and neutrons
- After $\approx$ 400000 years neutral atoms form, decoupling radiation from matter. Light from this moment eventually (as the universe expands) becomes the cosmic microwave background radiation.
- By 700 million years, galaxies begin to form.

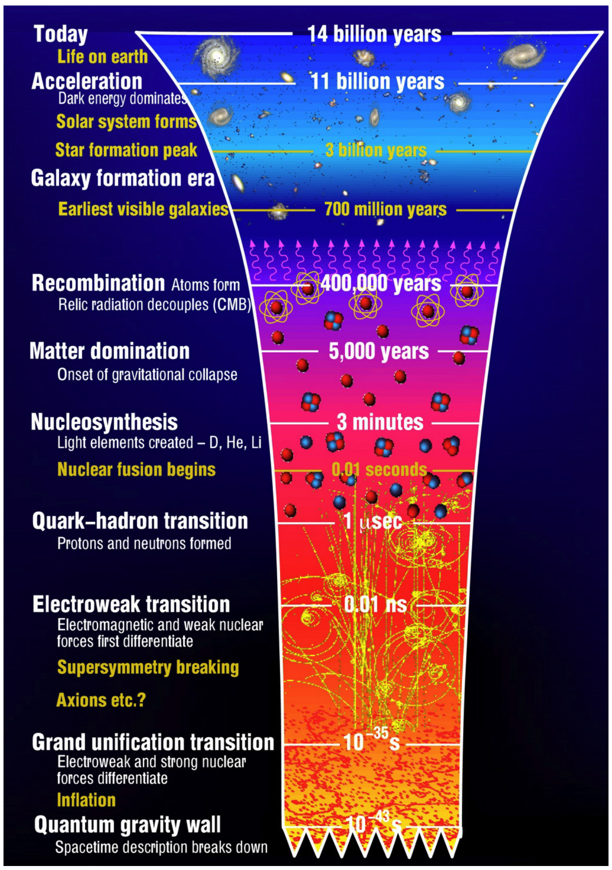


Figure 10: Image credit: The Stephan Hawking center for Theoretical Cosmology `http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php`

Stellar evolution and the origin of the elements

Protostars

[9]Stars begin as a cloud of interstellar gas (primarily hydrogen) collapsing under gravity. As the gas falls inwards, gravitational potential energy is converted to heat.

If the final mass of a protostar is greater than $0.08M_s$ (where M_s represents one solar mass - the mass of our Sun) then the core will become hot enough for fusion of hydrogen into helium to begin. This energy source means the star will reach hydrostatic equilibrium, where the outward pressure due to the release of heat from nuclear reactions in the core is sufficient to balance the inward pressure due to gravity.

Figure 11: The orion nebula - glowing clouds of gas surround protostars. Image credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team

[9] Reference for stellar evolution: `https://chandra.harvard.edu/edu/formal/stellar_ev/story/story.pdf`

Main-sequence stars (nucleosynthesis of helium)

Once a star has begun to fuse hydrogen into helium in its core, it is called a "main-sequence star". There are two different fusion reactions which occur. The "p-p chain" dominates in low mass stars ($< 1.1M_s$) and the "CNO cycle" dominates in high mass stars ($> 1.1M_s$). In stars of mass $1.1M_s$ the two contribute equally.

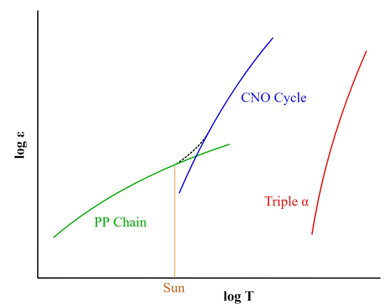


Figure 12: Comparison of the energy output due to the CNO cycle and pp-chain at different stellar core temperatures. It can be seen that more energy is released via the pp-chain dominates at lower temperatures and the energy released via the CNO cycle dominates at higher temperatures.

Image credit: RJHall / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0) `https://commons.wikimedia.org/wiki/File:Nuclear_energy_generation.svg`

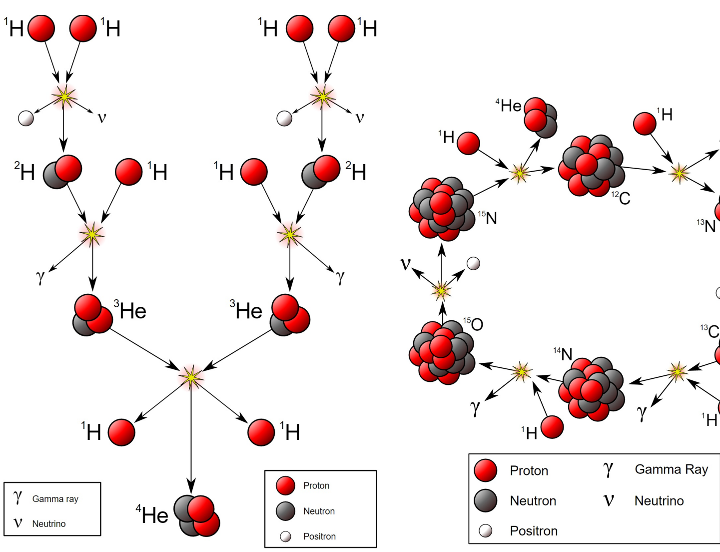


Figure 13: (Left) The proton-proton chain sequence of nuclear reactions that convert hydrogen to helium. Image credit: Sarang/Public domain `https://commons.wikimedia.org/wiki/File:Fusion_in_the_Sun.svg`. (Right) The CNO cycle. Image credit: Borb `https://commons.wikimedia.org/wiki/File:CNO_Cycle.svg`

Post main sequence stars (nucleosynthesis of heavier elements)

The greater the mass of a main-sequence star, the quicker the hydrogen in its core is converted into helium. A star with the mass of our Sun will spend 10 *billion* years as a main-sequence star, but stars with a mass 60 times the mass of our Sun will only spend 3 *million* years in this stage of its life.

When the hydrogen in the core of the star is depleted, the next stage of a star's life depends upon its mass, as shown in figure 23.

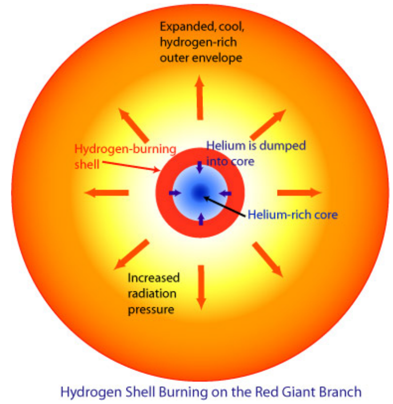


Figure 14: Hydrogen is fusing to helium in the shell of hydrogen surrounding the helium core. Image credit: Robert Hollow, CSIRO `https://www.atnf.csiro.au/outreach/ /education/senior/astrophysics/ stellarevolution_postmain.html`

Low mass stars

In low mass stars, $< 8M_s$, when the fusion of hydrogen into helium in the core ceases, the reduction in outward pressure causes the star to begin to collapse as hydrostatic equilibrium is lost. As mass falls inward the shell around the core heats sufficiently for fusion of hydrogen to helium to occur there. When this occurs, the star expands and its outer layers cool, becoming a red-giant.

Over time the core begins to contract and heat until it reaches the temperature at which helium begins to fuse into carbon via the "triple alpha" process, which is called the "Helium flash". After this the red giant star will fuse helium in its core and hydrogen to helium in a shell around the core.

Once all the helium in the core is converted to carbon, fusion ceases and the star contracts again, heating the shell of helium surrounding the core sufficiently to begin fusing helium to carbon in the shell surrounding the nucleus, and hydrogen to helium in the shell surrounding this. Such a star is known as an "Asymptotic Giant Branch" (AGB) star.

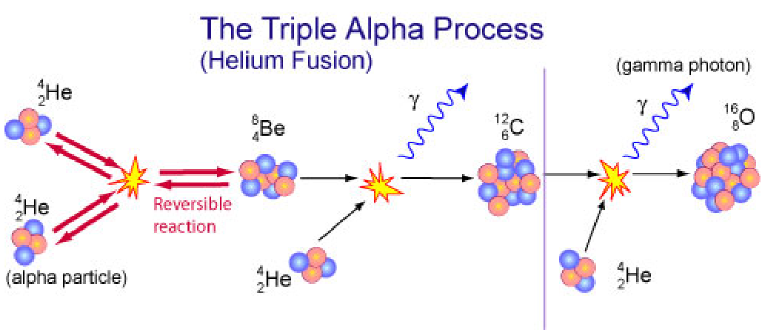


Figure 15: The triple alpha process for conversion of helium into carbon, and then oxygen. Image credit: Image credit: Robert Hollow, CSIRO `https://www.atnf.csiro.au/outreach/ /education/senior/astrophysics/ stellarevolution_postmain.html`

High mass stars

High mass stars ($> 8M_s$) are hot, luminous and have a much shorter lifetime than low mass stars.

They follow the same evolutionary path as low mass stars up to the fusion of helium to carbon in the core. However, these stars have sufficient mass that once all the helium in the core is converted to carbon, the core continues to contract and the temperature in-

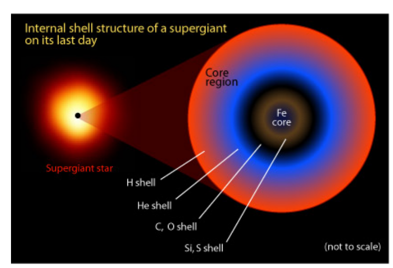


Figure 16: The "onion" like structure of a high mass star at the end of its life. Image credit: Robert Hollow, CSIRO `https://www.atnf.csiro.au/outreach/ /education/senior/astrophysics/ stellarevolution_postmain.html`

creases to the point that the fusion of heavier elements (than helium to carbon) can occur. First carbon and helium to form oxygen, then sodium, neon, magnesium, silicon, sulfur and other elements up to iron. Fusion reactions producing heavier elements release less energy, and once iron is formed no further energy can be released and fusion in the core ceases.

Star death

Low mass stars: Planetary nebula to white dwarf

Asymptotic giant branch stars can through through a number of cycles in which the helium in the helium burning shell becomes insufficient to support fusion and mass falls inwards, heating the hydrogen in surrounding shell sufficiently to produce fusion, creating more helium, which eventually builds up to the level at which fusion to carbon begins again, so that the star expands.

Each cycle of expansion causes gas in outer layers of the star to be ejected at high velocity. Eventually the loss of the outer layers of the star leaves the hot core exposed. UV light from the hot core ionises the outward moving shell of expelled gas, which then glows, in a similar manner to an emission nebula. This expanding shell is known as a **planetary nebula**.

Once fusion ceases, the core of the star gradually cools and the gas continues to expand, eventually dissipating into the interstellar medium. The star then becomes a "white dwarf". All white dwarf stars have a mass less than $1.4M_s$, as any stellar remnant with a mass larger than this will collapse to become a neutron star or black hole (this is known as the "Chandrasekhar limit").

High mass stars: From supernovae to a neutron star or a black hole

For stars with an initial mass greater than $8M_s$, at the extreme temperatures reached in the core just before its death, the protons and electrons combine, forming neutrons. As fusion ceases in the core, there is no longer any outward radiation pressure supporting the outer layers of the star, and these collapse inwards. If the mass remaining in the core is greater than $1.4M_s$ and less than (approximately) $3M_s$ the core cannot compress any further (due to neutron degeneracy pressure) when the inward falling gas hits the rigid core it rebounds causing a shockwave that releases enormous amounts of energy (mostly in the form of neutrinos), outshining a whole galaxy for days or weeks, an explosion that is known as a type II supernovae.

During the final explosion, the enormous release of energy causes elements heavier than iron are synthesised. All atoms heavier than iron in our universe were formed during supernovae explosions.

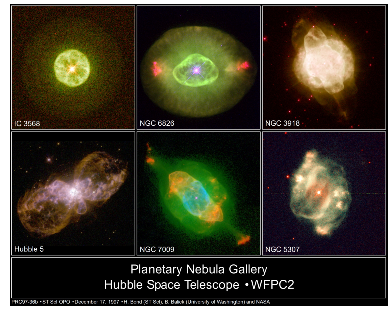


Figure 17: A gallery of images of planetary nebulae photographed by the Hubble Space Telescope. Image credit: NASA and STScI https://hubblesite.org/image/572/category/34-planetary-nebulas

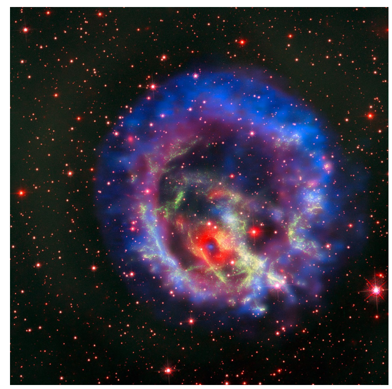


Figure 18: A neutron star and supernova renmant in the Small Magellanic Cloud. Composite imag ESO/NASA, ESA and Hubble. https://www.eso.org/public/images/eso1810a/

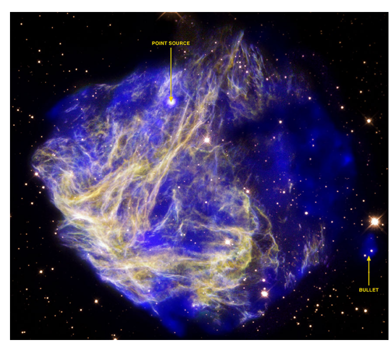


Figure 19: Debris from supernova explosion N49. Composite image from the Chandra X-ray telescope and Hubble. NASA/CXC/Penn State/S.Park et al. NASA/STScI/UIUC/Y.H.Chu R.Williams et al. https://chandra.harvard.edu/photo/2010/n49/ https://www.eso.org/public/images/eso1810a/

Type Ia supernovae occur in binary star systems where a white dwarf accretes sufficient gas from a red giant partner that its mass is pushed over the Chandrasekhar limit. The resulting explosion has a well-characterised luminosity. The extreme brightness of these supernovae mean that they can be used as "standard candles" to determine distances to very distant galaxies (and are thus used in modern estimates of Hubbles's constant).

If the final mass of the core after the explosion is greater than approximately $3M_s$ then neutron degeneracy cannot support the core and it collapses further to form a black hole.

Figure 20: Image of the black hole in the center of the galaxy M87. Credit: Event Horizon Telescope Collaboration `https://eventhorizontelescope.org/`

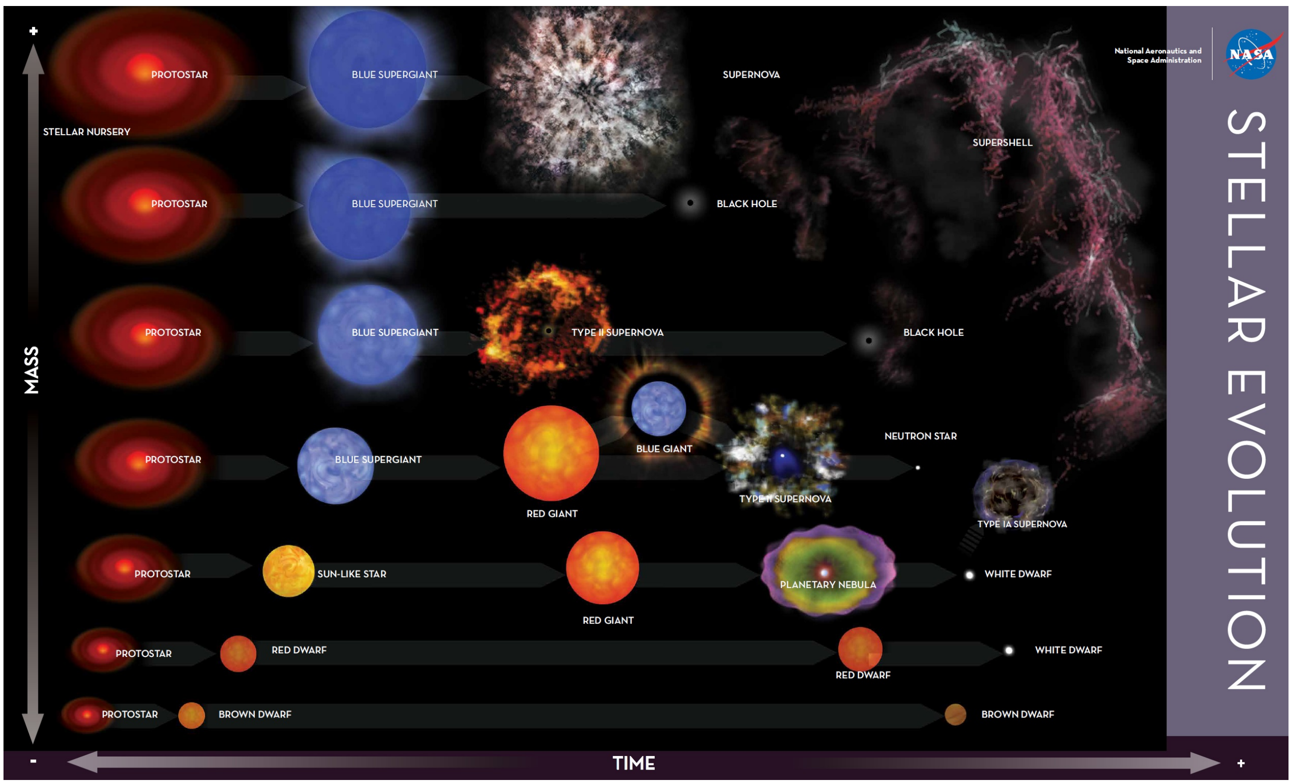


Figure 21: Stellar evolution. Image credit: NASA, The stellar evolution poster by the Chandra X-ray observatory, `https://chandra.harvard.edu/edu/formal/stellar_ev/`

The Hertzsprung-Russell diagram

The Hertzsprung-Russell diagram is a very important tool for understanding the evolution and properties of stars.

In 1911 Ejnar Hertzsprung plotted the absolute magnitude (intrinsic brightness) of stars against their colour (i.e. their temperature). In 1913 Henry Russell independently graphed spectral class (effectively a measure of temperature) against absolute magnitude.

Note the axis of the Hertzsprung-Russell diagram carefully. Brighter (higher luminosity) stars have more *negative* absolute magnitude. Surface temperature *decreases* as you move to the right along the horizontal axis.

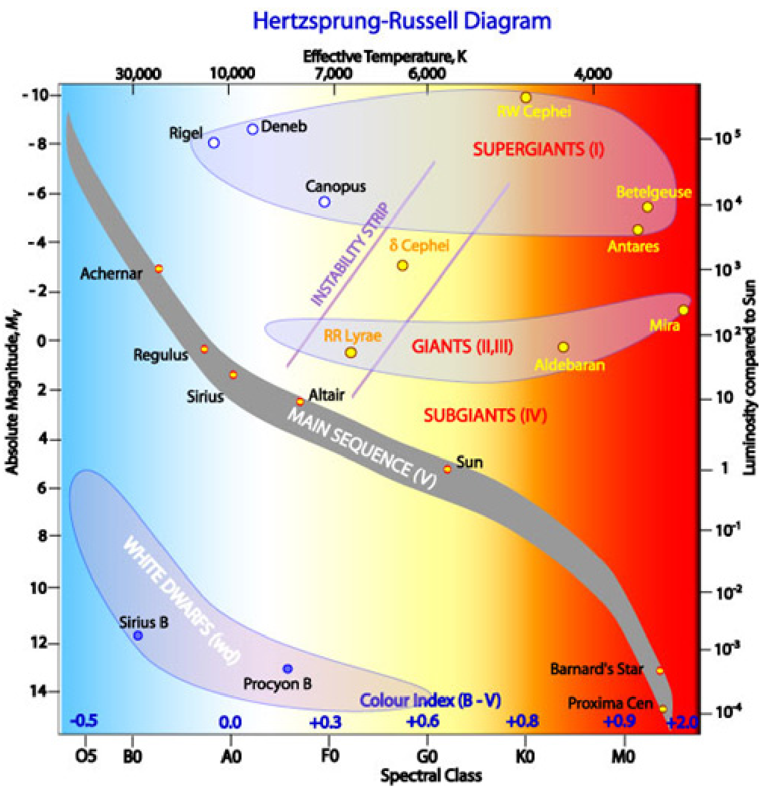


Figure 22: A Hertzsprung-Russell diagram. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach//education/senior/astrophysics/stellarevolution_hrintro.html`

The main sequence

We find that the majority of stars fall on a central band that is called the "main sequence". Stars in this strip share the property that they are all converting hydrogen to helium in their core.

The Stephan-Boltzmann law which expresses the power emitted by a black body in terms of its area A, temperature T (and the Stephan-Boltzmann constant σ):

$$P = \sigma A T^4$$

Stars are (to an excellent approximation) black bodies, in that they absorb all light that falls on them. For this reason the colour of a star is determined by its surface temperature (as we explored in module 7 in the phet `https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html`).

Thus stars that are hotter (and/or have a larger surface area) will be intrinsically brighter than cooler and/or smaller stars.

We can therefore see that massive (bluer) main sequence stars that have high surface temperatures are also intrinsically bright, and low mass (redder) main sequence stars are less luminous.

Giants, supergiants and white dwarfs

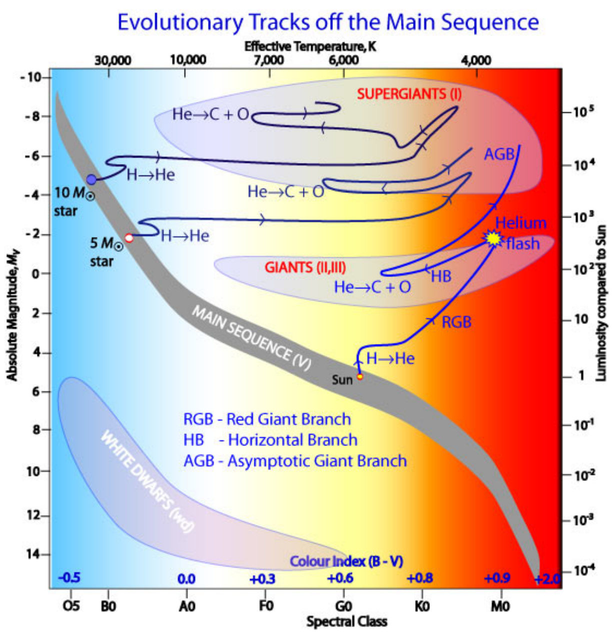


Figure 23: Path on the Hertzprung-Russell diagram followed by 3 different mass stars after they evolve off the main sequence. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach//education/senior/astrophysics/stellarevolution_postmain.html`

In the earlier section on stellar evolution we discussed how stars on the main sequence become red giants after fusion of hydrogen to helium in the core ceases (and is replaced with fusion of hydrogen to helium in the shell surrounding the core and/or fusion of helium to carbon in the core). As the stars expand the surface cools, but the surface area increases dramatically. Thus, by the Stephan-Boltzmann law, the increased surface area results in an increased power output (so increased intrinsic luminosity) even though the surface temperature is lower, so red giants and supergiants are located at the top right of a Hertzsprung-Russell diagram. If the remnants of the core of the star are less then $1.4M_s$ then the core becomes a white dwarf. This is extremely hot but has a very small surface area, so white dwarf stars are located at the bottom left of a Hertzsprung-Russell diagram.

Stellar spectra

Figure 24: (Top) Continuous black-body spectra; (Middle) Absorption spectra; (Bottom) spectra. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach//education/senior/astrophysics/spectroscopyhow.html`

Everything we know about stars, we know only through analysing the electromagnetic radiation that we receive from them (or even from the electromagnetic radiation that is absorbed as light travels to us!)

Emission, absorption and continuous black body spectra

Spectra can be categorised as continuous, absorption or emission spectra. Examples of each of these are shown in figure 24 and the origins of these are shown in figure 25.

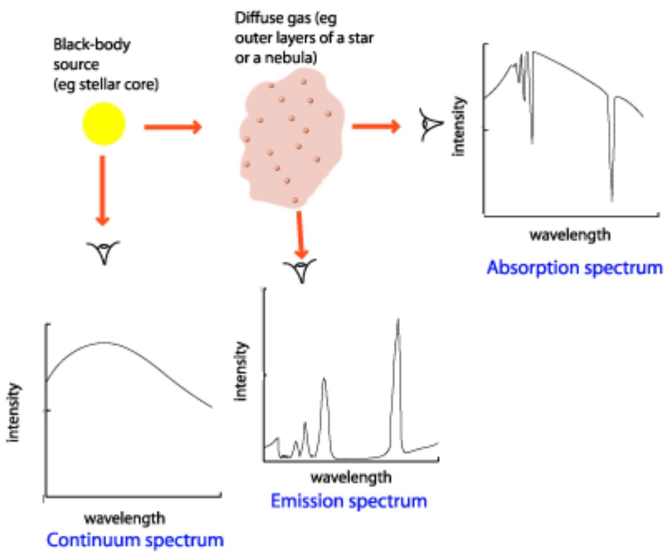


Figure 25: Origin of continuous, emission and absorption spectra. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach//education/senior/astrophysics/spectra_astro_types.html`

Continuous blackbody spectra are emitted from astronomical objects that are sufficiently hot that they exist as a plasma, for example a hot ionised gas, or a stellar core (as shown in fig. 25). In this case the electrons are not bound to atoms but can freely emit and absorb all wavelengths of light, with the emission intensity at each wavelength governed by the temperature of the object.

Emission spectra are emitted from gases that are not completely ionised, so that electrons with excess thermal energy in higher energy levels can fall to lower atomic energy levels, emitting photons with energy equal to the difference in energy levels in the atoms in the gas. Examples include warm interstellar gas or planetary nebulae.

Absorption spectra are observed when a cool (i.e. non-ionised) gas lies between a hot object which emits a blackbody spectrum and the observer. In this case as the blackbody radiation passes through the gas, wavelengths corresponding to the difference in energy levels in the atoms in the gas are absorbed, leaving gaps in the blackbody spectrum at these wavelengths. One example is the spectra of stars, as the outer layers of the star are often not-ionised, and these absorb some wavelengths from the continuous blackbody spectra emitted by the hot core. Another example might be light from distant stars that passes through a cool interstellar gas on its way to us.

Figure 26: Annie Jump Cannon. Image: Harvard-Smithsonian Center for Astrophysics

Classification of stars according to their spectra

Stellar spectra classification was developed in the early 1900's, with much of the most important work done by astronomer Annie Jump Cannon. She developed a scheme where stars were classified according to the strength of their hydrogen spectral lines. The original order of the classification was rearranged to place stars in order of their surface temperature, resulting in an ordering of O, B, A, F, G, K, M, which can be remembered via the mnemonic "**O**h **B**e **A** **F**ine **G**irl/Guy **K**iss **M**e".

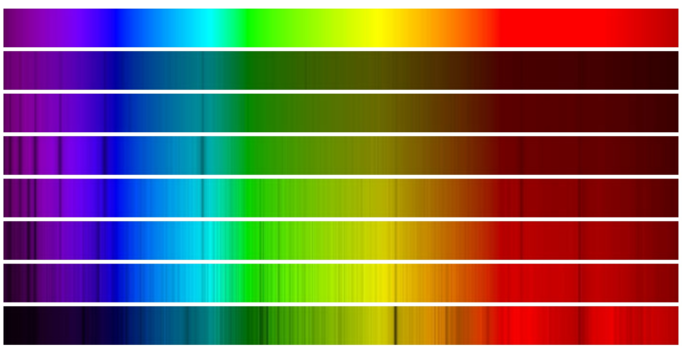


Figure 27: Spectra for main sequence stars classified according to the Havard stellar spectral classification system. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach//education/senior/astrophysics/spectra_astro_types.html`

Class	Effective temperature[1][2]	Vega-relative chromaticity[3][4][a]	Chromaticity (D65)[5][6][3][b]	Main-sequence mass[1][7] (solar masses)	Main-sequence radius[1][7] (solar radii)	Main-sequence luminosity[1][7] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[8]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	light orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	orange red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Figure 28: Features of main stars in different spectral classification categories. Image credit: Wikipedia. `https://en.wikipedia.org/wiki/Stellar_classification`

The spectra of stars is further classified according to mass, via the Yerkes (otherwise known as MKK) luminosity classes, to distinguish stars which have the same surface temperature but different luminosities, as shown in figures 29 and 30.

Main sequence stars have denser outer layers than red giant stars, which results in *pressure broadening* of spectral lines in main-sequence stars due to increased absorption of light at the wavelength of the spectral line as it passes through the outer layers of the star, see figure 31. The width of the spectral lines can therefore be used to assign a luminosity class via the Yerkes system.

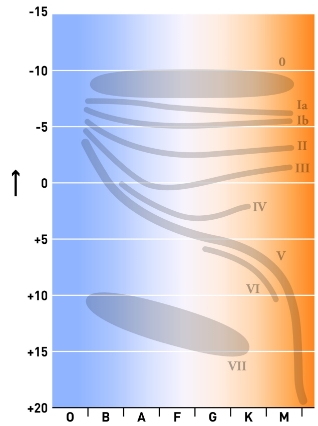


Figure 29: A Hertzsprung-Russell diagram showing the Harvard and Yerkes Classification systems. Image credit: Spacepotato / CC BY-SA (http://creativecommons.org/licenses/by-sa/3.0/), `https://commons.wikimedia.org/wiki/File:HR-diag-no-text-2.svg`

Yerkes luminosity classes

Luminosity class	Description	Examples
0 *or* Ia+	hypergiants or extremely luminous supergiants	Cygnus OB2#12 – B3-4Ia+ [18]
Ia	luminous supergiants	Eta Canis Majoris – B5Ia [19]
Iab	intermediate-size luminous supergiants	Gamma Cygni – F8Iab [20]
Ib	less luminous supergiants	Zeta Persei – B1Ib [21]
II	bright giants	Beta Leporis – G0II [22]
III	normal giants	Arcturus – K0III [23]
IV	subgiants	Gamma Cassiopeiae – B0.5IVpe [24]
V	main-sequence stars (dwarfs)	Achernar – B6Vep [21]
sd (*prefix*) *or* VI	subdwarfs	HD 149382 – sdB5 *or* B5VI [25]
D (*prefix*) *or* VII	white dwarfs [c]	van Maanen 2 – DZ8 [26]

Figure 30: Features of stars in the Yerkes classification system. Image credit: Wikipedia. `https://en.wikipedia.org/wiki/Stellar_classification`

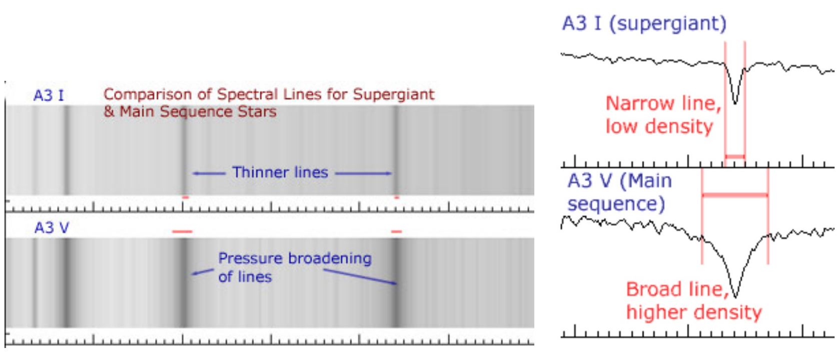


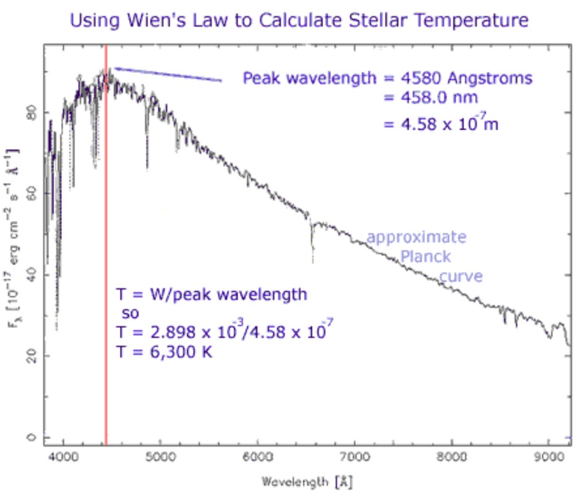
Figure 31: Pressure broadening of spectral lines in a main-sequence star (with dense outer layers) compared to a supergiant (with low pressure outer layers). Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach/education/senior/astrophysics/spectra_info.html`

Key features of stellar spectra

Temperature

[10]The temperature of a star can be determined using Wein's displacement law (studied in module 7) to determine the peak wavelength of the spectrum, and through this, the temperature.

[10] This whole section essentially follows Rob Hollows, CSIRO, `https://www.atnf.csiro.au/outreach/education/senior/astrophysics/spectra_info.html`



Credit: *CSIRO* using data from *The Sloan Digital Sky Survey*

Figure 32: The temperature of a star can be determined from the peak wavelength and Wien's law. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach/education/senior/astrophysics/spectra_info.html`

The Doppler effect: Translational motion and Rotation

Any motion of a star towards or away from us results in a *Dopper shift* of its spectrum towards the red (for receding stars) or to the blue (approaching stars).

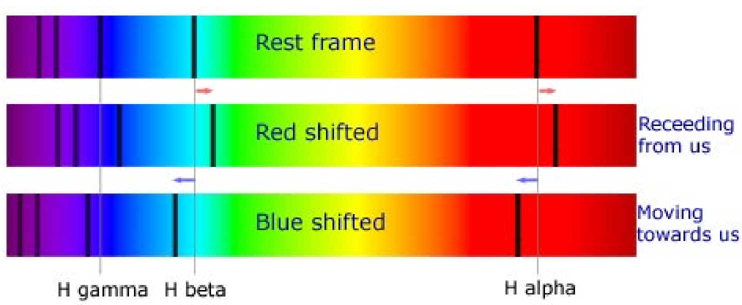


Figure 33: The translational motion of a star can be determined by a Doppler shift in its spectrum. Image credit: Rob Hollow, CSIRO. `https://www.atnf.csiro.au/outreach/education/senior/astrophysics/spectra_info.html`

The rate of rotation of a star can be determined from its spectra by how "smeared out" the spectral lines are. This is due to the fact that some of the light originates from parts of the star moving towards us as the star rotates (and this light is blue shifted slightly) and some of the light originates from parts of the star moving away from us (and this light is red shifted slightly). It is possible to distinguish broadening due to rotation from pressure broadening.

Chemical composition and Metallicity

The presence of spectra corresponding to a particular element or molecule in the spectra of a star indicates the presence of that element or molecule in the outer layers of the star. The *absence* of the spectral lines for an element does not however necessarily mean that this element is not present, but may just be due the temperature being incompatible with the absorption of light by that element or molecule. For example, helium spectral lines are strongest in the hottest stars, as these have sufficient energy to ionise helium, however at lower temperatures there is insufficient energy to ionise helium and its spectral lines are almost absent.

Note that "metallicity" in astronomy refers to the presence of elements heavier than helium.

Spectroscopic binaries and exoplanets

Finally, there are other features of stars and star systems that can be determined through spectra. Firstly, spectroscopic binaries have spectral lines that periodically split (as one of the stars is moving towards and away from us). The presence of exoplanets can sometimes be detected by a periodic "wobble" in the positions of the spectral lines, as the star and (large!) exoplanet orbit around their center of mass.