PHAS 1511: Foundations of Astronomy

- Lecture notes, problem sheets and answers available at
- `http://zuserver2.star.ucl.ac.uk/~rwesson/PHAS1511`

PHAS 1511: Very broad overview

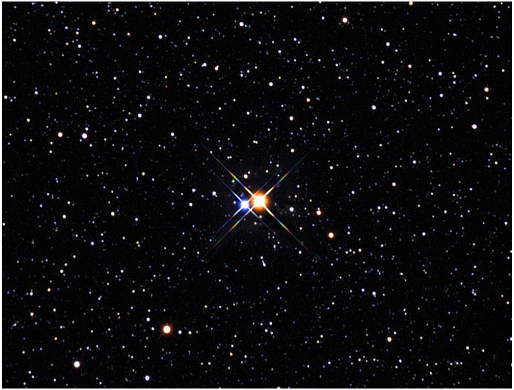
- The celestial sphere - how to find astronomical objects
- The nature of light - what it is, and what we can learn from it
- The structure of matter - atoms and energy levels
- Telescopes - how we observe astronomical objects
- Stars - how they are born, live and die
- Galaxies and the distant universe - how it began and how it might end

Electromagnetic radiation

- Visible light is a kind of *electromagnetic radiation*
- Other kinds of EM radiation are UV, infrared, microwaves and radio waves
- All ‘normal’ matter in the universe emits EM radiation
- Studying EM radiation is our main way of finding out about the universe

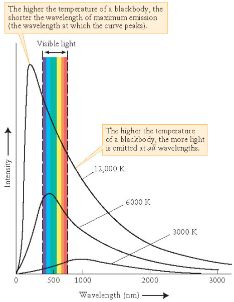
The electromagnetic spectrum and temperature

- A basic observation about stars is that they are not all the same colour. A very good example of this is β Cygni (Albireo).



The electromagnetic spectrum and temperature

- The hotter an object is, the shorter the **wavelength** of light it emits.
- In the idealised case of a **black body** (that is, one that absorbs all the radiation that falls on it), the radiation emitted at a given temperature has a simple form, shown in the figure.
- EM radiation of **all** wavelengths is emitted by any black body.



Black body radiation

- There is a very simple relation between the temperature of a black body, and the wavelength at which its emission will peak:

$$\lambda_{peak} = \frac{0.0029m}{T}$$

- This relationship was discovered by Wilhelm Wien in 1893, and is called Wien's Law.

Black body radiation

- The emission from stars is quite similar to the emission from black bodies. This means that we can estimate their temperatures from the shape of their spectra.
- The Sun's surface is at a temperature of about 5,800K, and black bodies with this temperature emit radiation with a peak wavelength of about 550 nm.

Black body radiation

- β Cygni: the orange star has a temperature of 4000K; the blue one is much hotter at about 30,000K

Black body radiation

- Wien's law tells us the temperature of a black body, if we know the wavelength where its emission peaks.
- Another very useful equation related the total amount of energy emitted to the temperature of a spherical black body, and its area.
- $F = \sigma T^4$
- F is the energy emitted per square metre of surface area. σ is a constant. So, if you doubled the temperature of an object, you would increase the amount of energy it emitted by a factor of 16.
- This equation is called the Stefan-Boltzmann Law, after the two physicists who discovered it.

Wien and Stefan-Boltzmann - example

- Sirius is the brightest star in the sky. Its spectrum peaks at a wavelength of 290nm. So, what is its temperature?

$$\lambda = 0.0029 / T$$

- So,

$$\begin{aligned} T &= 0.0029/\lambda \\ &= 0.0029/290 \times 10^{-9} \\ &= 10,000K \end{aligned}$$

Wien and Stefan-Boltzmann - example

- How much more energy does Sirius emit per square metre of its surface than the Sun does?

$$
\begin{aligned}
\frac{F(Sirius)}{F(Sun)} &= \frac{T(Sirius)^4}{T(Sun)^4} \\
&= (10,000/5,800)^4 \\
&= 8.8
\end{aligned}
$$

Light and motion

- Another thing we can tell from spectroscopy is how fast things are moving, along our line of sight.
- This is possible because of the Doppler effect – familiar to all from the sound of cars going by.
- When a car approaches, the pitch of its engine sounds higher. As it recedes, the pitch of its engine sounds lower.
- The same effect also happens with EM radiation.

Light and motion

- This means that if you know what wavelength some radiation was emitted at (as you would for, say, a hydrogen Balmer line), then the observed wavelength tells you the velocity of the object along the line of sight.
- The change in wavelength is related to the velocity by a simple equation:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Light and motion

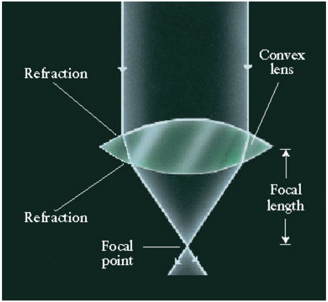
- So, for example, in the spectrum of Sirius, you see the Balmer alpha absorption line at 656.260 instead of 656.277 nm.

$$\begin{aligned} \frac{0.017}{656.277} &= \frac{v}{c} \\ v &= c \times \frac{0.017}{656.277} \\ &= 3 \times 10^8 \times \frac{0.017}{656.277} \end{aligned}$$

- This means that Sirius is moving towards us at 7.7km/s

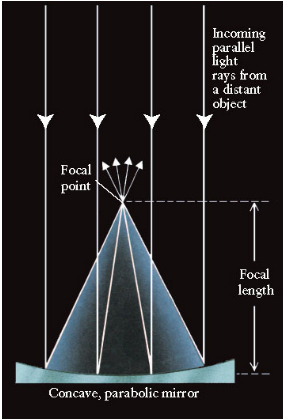
Telescopes - refractors

- EM radiation in a vacuum travels at **c**, the speed of light: 300,000 km/s. But it travels more slowly in a transparent substance like glass. This is called **refraction**.
- With the right shaped piece of glass, you can **focus** the light from a distant object, making it appear larger and brighter.



Reflecting telescopes

- Another way to bring light to a focus is with a curved mirror. This is the principle behind **reflecting telescopes**.



Reflectors - advantages

- Reflecting instead of refracting light has many advantages:
- 1. no chromatic aberration.
- 2. While a refracting lens needs to be of extremely high quality throughout its volume, a reflecting mirror only needs to be of high quality on its surface.
- 3. Unlike a lens which has to sit at the end of a tube, far from the pivot, a mirror can be positioned close to the pivot.
- For these reasons, all the telescopes used today for professional astronomy, and most amateur telescopes as well, are reflectors.

Limits to observations

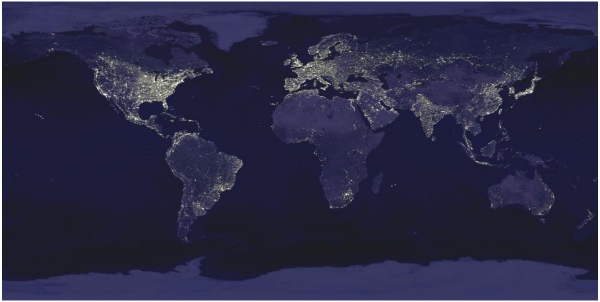
- For a perfectly constructed and polished mirror or lens, the diffraction limit is given by
  $\Theta = 2.5 \times 10^{-4}\ \lambda/D$
- where is the resolution limit, λ is the wavelength in nanometres, and D is the diameter of the mirror or lens.
- So, for visible light (500nm), the human eye's diffraction limit is $2.5 \times 10^{-4} \times 500 / 0.005 = 25$ arcseconds
- For the Hubble Space Telescope, with a 2.4m mirror, the diffraction limit is $2.5 \times 10^{-4} \times 500 / 2.4 = 0.05$ arcseconds
- For the 10m Keck telescope, the limit is $2.5 \times 10^{-4} \times 500 / 10 = 0.0125$ arcseconds

Limits to observations

- In practice, the Hubble Space Telescope can achieve its diffraction-limited resolution, but the Keck could not, originally.
- This is because the Keck is on the surface of the Earth, underneath the atmosphere. The atmosphere is in constant motion, and this 'smears' images out a bit. It is the reason stars 'twinkle'.
- The resolution limit imposed by the atmosphere is called the *seeing*.

Other ground-based problems

- You can overcome seeing limits to a large extent using adaptive optics, but other problems remain.
- Most large telescopes are in remote places, to avoid light pollution. But it is impossible to avoid it completely.

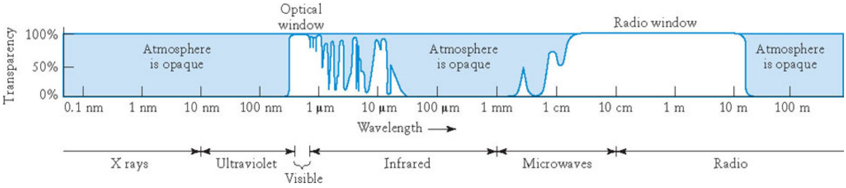


Other ground-based problems

- And even if every light on the planet was switched off at night, there would still be some background light. The atmosphere glows, very very faintly, because of cosmic rays hitting it, ions recombining, and chemical reactions.
- And, when the moon is around, the sky is very bright, because moonlight gets scattered around.
- So, ground-based observations are ultimately limited by the background. Solution – go to space!

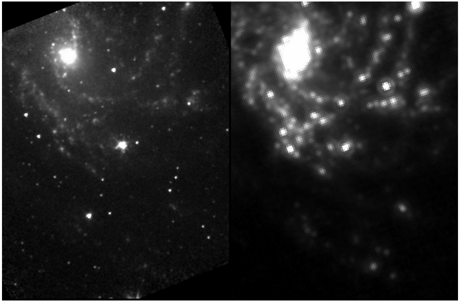
More advantages of space

- Another problem with the atmosphere is that it absorbs very strongly at many wavelengths:
- If you want to observe gamma rays, x-rays, UV or sub-mm radiation, you need a space observatory.



Mirrors at other wavelengths

- For a given mirror size, optical performance gets worse at longer wavelengths. (Θ=2.5$\times 10^{-4}\lambda$/D)



Mirrors at other wavelengths

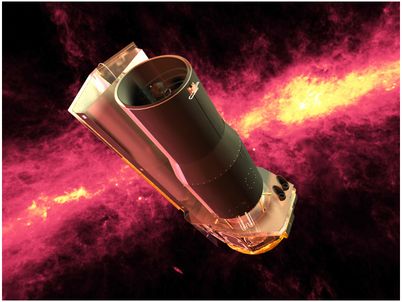
- But, although you need a larger mirror at longer wavelengths, the mirror does not have to be so finely made.
- Surfaces need to be polished to within 1/20th of a wavelength of the required shaped. This is pretty hard for optical (500nm) but much easier for radio (>1cm). Radio telescopes are much easier to make than optical telescopes.

Infrared astronomy

- The atmosphere absorbs strongly at many infrared wavelengths (this is what gives rise to the greenhouse effect). This makes observing infrared radiation from the ground quite difficult.
- Water vapour accounts for about 75% of the absorption, so observing is possible, if you go somewhere dry enough, or high enough (because water vapour is strongly concentrated in the lower parts of the atmosphere).
- Mauna Kea, at 4200m above sea level, is a good place to observe from, as is the Atacama desert in South America, and Antarctica.

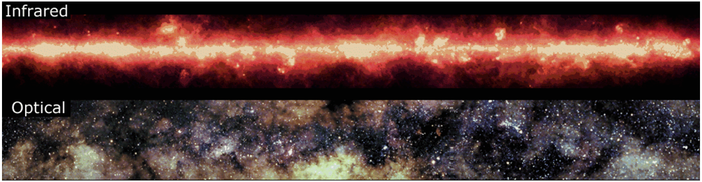
Infrared astronomy

- Observing in Antarctica would also go some way towards solving the other problem with IR astronomy – the equipment itself radiates strongly at IR wavelengths.
- So, telescopes and detectors need to be cooled to reduce their IR emission.



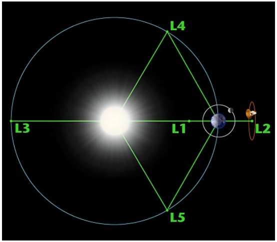
Infrared astronomy

- Why observe in the infrared?
- Cold things emit in the IR - and also things that strongly absorb visible light are transparent to IR.



Infrared space observatories

- Infrared space telescopes have included IRAS in the 1980s, ISO in the 1990s, and Spitzer in the 2000s. All had 60-85cm mirrors.
- Herschel was launched successfully on 14 May 2009. Unlike Hubble it is not orbiting the Earth and cannot be repaired. It is orbiting the sun at a place called L2.

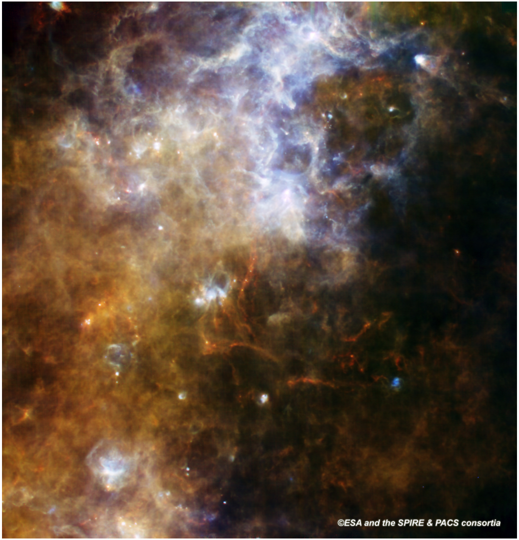


- Herschel has the largest mirror yet put into space - 3.5m across

Herschel

- Like other infrared telescopes, Herschel is cooled to $\sim$4K (-269C) by tanks of liquid helium. The helium evaporating cools down the telescope. This limits the lifetime of the instrument – no more helium = no more IR observations.
- The James Webb Space Telescope, successor to Hubble, will have a large sun shield to allow it to reach very cold temperatures without the need for liquid helium.
- Will be launched in 2014. Or maybe 2020...

Herschel



Stars

- Stars come in a huge range of masses, luminosities and colours:

The luminosity of the Sun

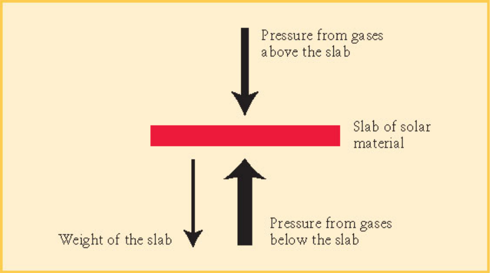
- From its distance, and the Earth's orbit, we can work out the mass of the Sun – it is 2×10^{30} kg. And knowing the distance, we can work out the Sun's luminosity.
- The Sun emits a lot of energy: 3.89×10^{26} J/s. Total amount of energy used by humans since 1980 is 1.2×10^{22}J - enough to keep the Sun going for 0.00003 seconds!

The luminosity of the Sun

- The Sun, and all stars, shine because of **nuclear fusion**
- In their extremely dense, extremely hot cores, hydrogen atoms collide, forming helium atoms.
- 1×He weighs a tiny bit less than 4×H - matter is annihilated
- $E = mc^2$

The core of the Sun

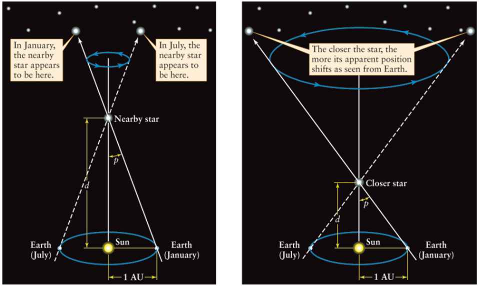
- The Sun is neither contracting nor expanding. It is in a steady state, known as hydrostatic equilbrium.
- What this means is that there is a balance between the forces acting on each part of the Sun:



(a) Material inside the sun is in hydrostatic equilibrium, so forces balance

Stars – parallax

- How can we measure the distances to stars? For the closest stars, we can measure their parallax – the change in their apparent position due to the motion of the Earth around the Sun:



(a) Parallax of a nearby star

(b) Parallax of an even closer star

Stars – parallax

- Remember the definition of a parsec – an object at a distance of one parsec that was one Astronomical Unit across would appear to be one arcsecond across.
- By the same definition, a star at a distance of 1 parsec would have a parallax of one arcsecond. A star at a distance of 2 parsecs would have a parallax of 0.5 arcsecond.
- So, measure the parallax, and you know the distance.
- The closest star, Proxima Centauri, has a parallax of 0.772 arcseconds. So, its distance is 1.3 pc (4.2 light years).

Stars – magnitudes

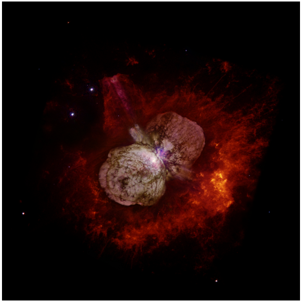
- The brightness of stars is often expressed in *magnitudes*. This is a scale which ultimately comes from ancient Greek astronomy – Hipparchus classified stars roughly so that the brightest were called ’first magnitude’ and the faintest ’sixth magnitude’.
- In the 19th century, the system was refined and updated. Astronomers calculated that first magnitude stars were about 100 times brighter than sixth magnitudes, and set the magnitude scale so that a difference of five magnitudes means a factor of 100 change in brightness.
- 1 magnitude then corresponds to a factor of 2.512 in brightness.
- $2.512 \times 2.152 \times 2.512 \times 2.512 \times 2.512 = 100$

Stars – magnitudes

- In the refined scale, the brightest stars are actually brighter than magnitude 1. Sirius has an apparent magnitude of -1.43.
- The faintest objects that have ever been detected have apparent magnitudes of about 30. $2.512^{31.5}$ = 4 trillion times fainter than Sirius.
- That's about as bright as a cigarette end on the moon would appear to someone on Earth.

Stars – magnitudes

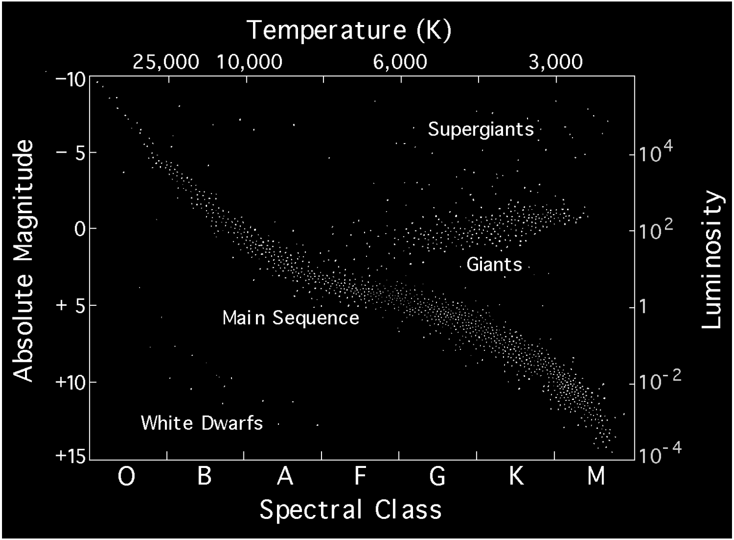
- The **absolute magnitude** of a star is the apparent magnitude it would have, if it was 10 parsecs away from Earth.
- The absolute magnitude of the Sun is about +4.5. Sirius's is 1.42; Canopus is -5.5. Eta Carinae is -10 or less - emits as much energy in 15 seconds as the Sun does in a year.



Stars- the Hertzsprung-Russell diagram

- When you plot a graph of luminosity (or absolute magnitude) against temperature for a large number of stars, you find that they are not just scattered randomly, but concentrated in certain areas.

Stars- the Hertzsprung-Russell diagram



Stars - the Hertzsprung-Russell diagram

- This diagram is called the Hertzsprung-Russell diagram (HR diagram for short), after the two astronomers who first developed it in the early 20th century.
- Most stars fall in a band running from top left to bottom right. This is called the *main sequence*. The Sun lies on the main sequence. It and all the other stars on it are in a steady state – they are burning hydrogen at their cores, and the energy released supports them against gravitational contraction.
- The position of a star on the main sequence is determined by its mass. Heavier stars are more luminous and hotter, and so they appear further up to the left.

Distances from the Hertzsprung-Russell diagram

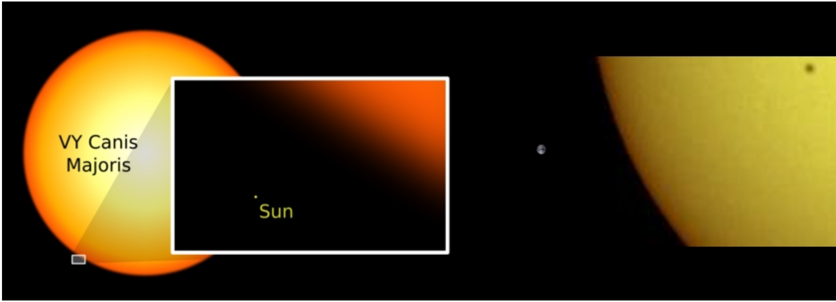
- We can estimate stellar distances using the HR diagram. We can measure the temperature of a star from its spectrum, and if we know (or assume) that it is on the main sequence, then we can find out its luminosity. Then, from its luminosity and apparent brightness, we can calculate its distance.

Stars – sizes

- The **luminosity** of a star is related to its **temperature** and **radius**:
- $L = 4\pi R^2 \sigma T^4$
- So, given that we can find out the temperatures of stars and their luminosities, we can also find out their radii. There turns out to be a very large range. The largest stars are bigger than Earth's orbit, while the smallest are only a few kilometres across.

Stars – sizes

- The largest known star is VY Canis Majoris

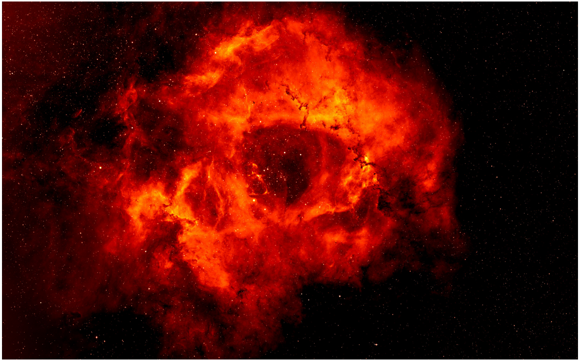


Star formation

- The Sun, and all stars, shine because of nuclear reactions occurring in their cores.
- Stars form out of large clouds of gas and dust. The largest stars have a mass of about 100 $M_\odot$, and the lightest have a mass of 0.08 $M_\odot$.
- More massive stars are hotter and bluer, and use their nuclear fuel much more quickly so their lives are shorter.
- So, the places where stars have recently formed contain many hot blue stars, which illuminate the gas that the stars have been forming from to form an **H II region**.

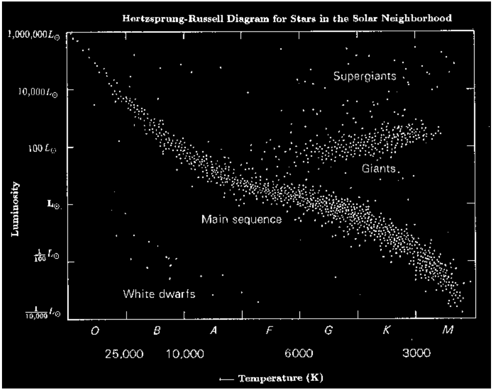
Star formation

- Classic example of H II region is the Orion Nebula. Older H II regions are often 'hollowed out' by the powerful radiation from the hot stars within them – eg the Rosette Nebula:



Star formation

- Once they have begun fusing hydrogen in their cores, stars lie on the **main sequence** in the HR diagram:



Stellar lifetimes

- Stars stay on the main sequence until they run out of hydrogen in their cores. The time this takes depends on the mass – more massive stars burn their fuel much more quickly.
- Stellar lifetimes range from a few million years for very massive stars to hundreds of billions of years for the lightest.

The deaths of stars

- Stars on the main sequence are in *hydrostatic equilibrium* - the energy generated by nuclear fusion stops the star collapsing under gravity.
- When the fuel runs out, the balance between gravity pulling material in and gas pressure pushing it out breaks down. The core begins to contract because energy is no longer being produced.
- As the core contracts, it gets hotter and hotter, as the pressure increases. What happens next depends on the mass of the star.

Low-mass stars

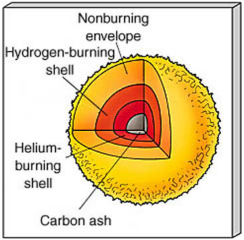
- For stars with less than 0.4 $M_{\odot}$, the temperature does not get hot enough for anything else to happen. The star will end its life as an inert ball of helium, just radiating away its internal heat.
- But the universe is not yet old enough for any stars this light to have burned all their hydrogen.

Medium-mass stars

- For stars heavier than $0.4\,M_\odot$ and lighter than 2 or 3 $M_\odot$, the core contraction and heating makes the outer layers expand and cool greatly. The star becomes cooler but much larger, and thus more luminous. It is a *red giant*.
- The core will eventually heat up to a temperature of 100 million K. Just as hydrogen nuclei can fuse to form helium, releasing some energy, so helium nuclei can fuse to form carbon and oxygen, releasing some energy.
- The temperature and density need to be much higher, and less energy is released per atom.

The deaths of stars

- While helium is burning in the core, hydrogen burning continues in a shell around the centre of the star. What happens when helium runs out in the core?
- Again, the core will contract and heat, the star will expand again. An inert carbon-oxygen core is surrounded by a helium-burning shell and a hydrogen-burning shell.

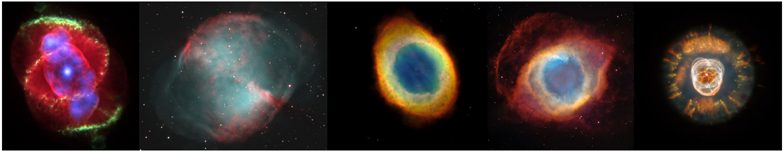


The deaths of stars

- The rate of helium burning is proportional to T^{40}!!
- In a thin shell, a small variation in the pressure causes a small change in the temperature, which causes a large change in the reaction rate. The burning is extremely unstable, and the star begins to shed its outer layers.

The deaths of stars - planetary nebulae

- Instabilities and pulsations drive away the outer layers from stars. Red Giants can lose $10^{-7}\ M_\odot$/year. (The Sun loses about $10^{-14}\ M_\odot$/year)
- If the mass of the star is lower than about 8 solar masses, this mass loss eventually puts an end to its evolution. The reduced pressure stops the nuclear reactions. The atmosphere drifts away, and is lit up by the exposed core. A *planetary nebula* has formed.



The deaths of stars - massive stars

- Stars with masses greater than $\sim 4\,M_{\odot}$ are heavy enough that nuclear reactions can still proceed in the core despite mass loss. The core will eventually get hot enough for carbon to undergo fusion, forming oxygen, neon, sodium and magnesium.
- Stars with $M \geq \sim 8\,M_{\odot}$ will fuse neon, then oxygen, then silicon.

The deaths of stars - massive stars

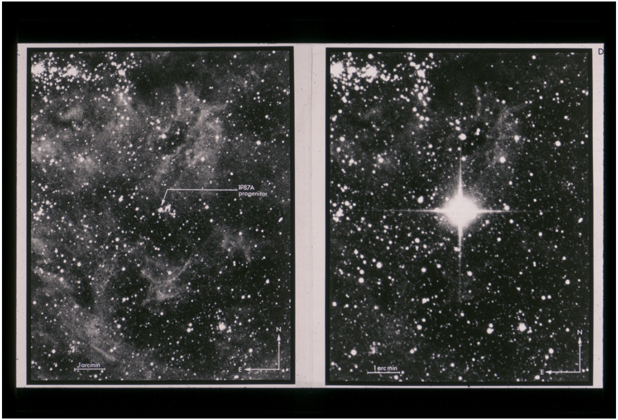
- Each step proceeds more and more quickly:
  - Hydrogen-burning – a few million years
  - Helium burning – a few hundred thousand years
  - Carbon fusion – a few hundred years
  - Neon fusion – a year
  - Oxygen fusion – a few months
  - Silicon fusion – over and done with within a day.
- What next?

The deaths of stars - massive stars

- Nuclear fusion releases energy if the product is more tightly bound than the atoms that went into it. This graphs shows how tightly bound atomic nuclei are:
- The most stable nucleus is iron. Once silicon has fused to form iron, the star has nowhere to go. The core's energy source runs out suddenly.

The deaths of stars - supernovae

- The core collapses. The outer layers are suddenly unsupported, and fall in. They crash into the core, and a huge shock wave rebounds outward, destroying the star in a supernova.



The deaths of stars - supernovae

- Supernovae briefly shine as brightly as a galaxy – and emit as much energy as *hundreds* of galaxies!!
- Most of this energy is carried away in the form of neutrinos. 24 neutrinos from Supernova 1987A were detected on earth – one of the first major successes in neutrino astronomy.
- What is left behind? A supernova remnant – the slowly fading outer layers of the star, moving away into space.
- And at the centre – something exotic - a neutron star or a black hole.

Cosmic distances

- Discussed earlier that the most direct way to measure the distance to a star or other astronomical object is to measure its *parallax* – the small shift in its position over a year caused by the movement of the Earth from one side of its orbit to the other.
- This is only accurate out to a few hundred parsecs at best. So how do we find out the distances to objects further away than that?
- There is an elaborate set of interlinking distance measures which is used to work out the scale of the universe - the *cosmic distance ladder*.

Expansion parallax

- Compare plane-of-sky expansion with line-of-sight (Doppler) velocity: the Crab Nebula is at a distance of 2000+-500 parsecs.

Expansion parallax

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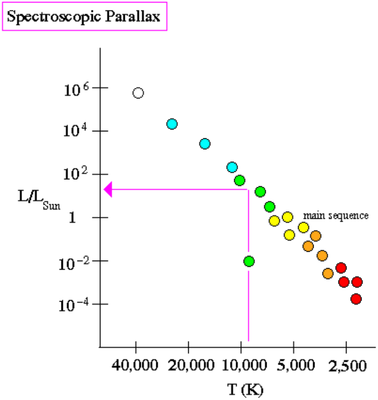
Spectroscopic parallax

- If we can work out the position of a star on the Hertzsprung-Russell diagram, we know its absolute magnitude, and therefore its distance.
- Temperature is easily determined, and therefore its luminosity can simply be read off from the diagram.
- This is known as *spectroscopic parallax*. It's not particularly accurate. And it's also not anything to do with parallax!

Spectroscopic parallax



the true brightness of a star can be found if the color is known by matching the star to the main sequence. Knowledge of the observed brightness plus the true brightness derives the distance to the star.

Main sequence fitting

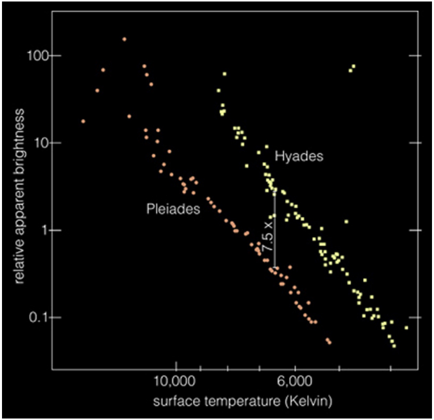
- More useful than the spectroscopic ‘parallax’ is *main sequence fitting*. If we observe a cluster of stars, and plot an HR diagram using apparent magnitude and temperature, we will see the main sequence.
- The distance to the cluster is then easily determined from the difference between the apparent magnitude of its main sequence, compared to the absolute magnitude of the standard main sequence.

Main sequence fitting

- Example: Pleiades and Hyades - two nearby well-known star clusters.
- On an HR diagram, we see that the main sequence of the Hyades is about 7.5$\times$ brighter than the main sequence of the Pleiades.

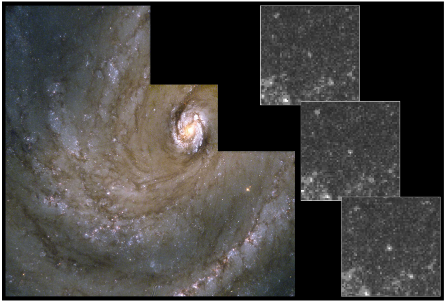
Main sequence fitting

- From the inverse square law, this means that the distance to the Pleiades is $\sqrt{7.5} = 2.7$ times the distance to the Hyades.



Standard candles

- As discussed earlier, many evolved stars go through phases where their brightness is variable. A very useful type of variable star is called a *cepheid variable*, named after δ Cephei, the first known example. The Pole Star is also a cepheid



Standard candles

- Cepheids brighten and fade extremely regularly over periods ranging from a few hours to a few weeks.
- They are are extremely useful because it turns out that their luminosity and period are tightly related – the longer the period, the brighter the Cepheid.
- The brightest cepheids are many thousands of times brighter than the Sun. This means they can be seen out to large distances – as far away as 60 million light years.

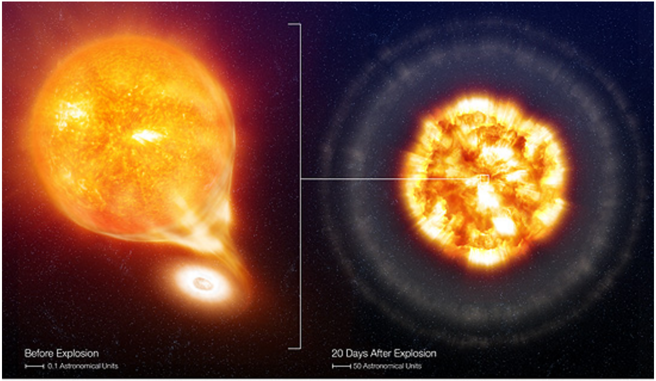
Cepheid variables

- Cepheids answered some major questions in astronomy: Shapley observed them in our galaxy and determined its size.
- Edwin Hubble observed cepheids in the Andromeda Galaxy, and thus showed that it was outside our own galaxy.
- One of the main aims of the Hubble Space Telescope was to observe cepheid variables in distant galaxies, to refine the cosmic distance scale.

Standard candles

- Cepheids are one of the most important of the *standard candles* – objects whose absolute magnitude is known and so whose distance can easily be found.
- Other examples of standard candles are:
  - RR Lyrae stars (similar to Cepheids but less luminous)
  - planetary nebulae
  - Type Ia supernovae
- Type ıa supernovae result from binary system in which matter is flowing from a red giant onto a white dwarf.

Standard candles



SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)

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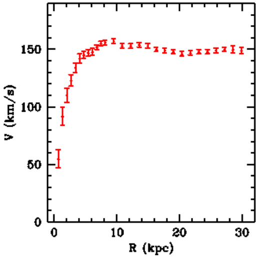
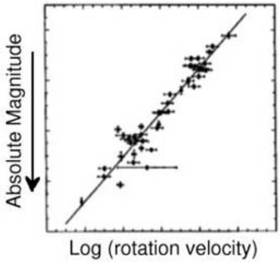
Standard candles

- As it gets heavier, the temperature in the white dwarf rises. When the white dwarf reaches a critical mass, the temperature is high enough to trigger sudden explosive nuclear fusion, and the star explodes violently.

Greater distances

- Using all these distance measuring techniques, the distances to many relatively nearby galaxies have been found.
- It has been found that the *faster* the stars in a galaxy are orbiting the centre, the *brighter* the galaxy is. The relationship between rotation and luminosity is called the Tully-Fisher Relation

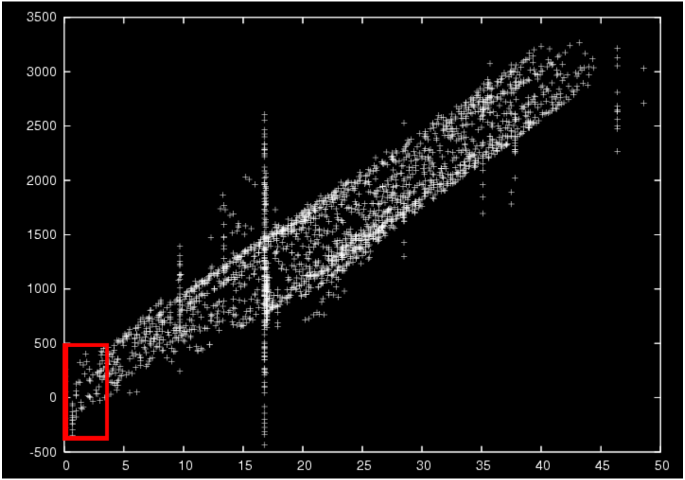




Hubble flow

- Edwin Hubble was the first to find (using cepheids) that all external galaxies (except the ones in the Local Group) are receding, and that the velocity of recession is proportional to the distance.
- $v = H_0 D$
- Ho is a constant, with units of km/s/Mpc, called the Hubble Constant. It is one of the most important numbers in astronomy.

Hubble flow



3500
3000
2500
2000
1500
1000
500
0
-500
0
5
10
15
20
25
30
35
40
45
50

Hubble flow

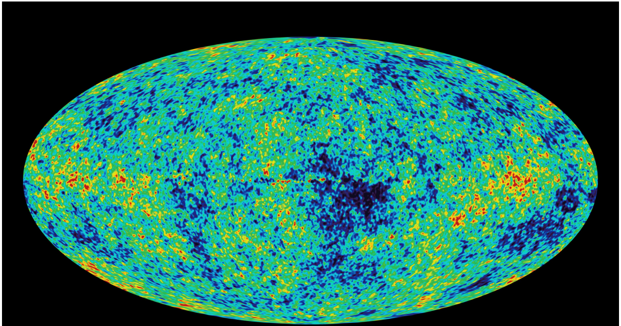
- Using all the distance indicators discussed eventually allows us to estimate the Hubble Constant. The generally accepted value is about 70 km/s/Mpc.
- Once it is known, then for very distant galaxies, measuring the redshift gives us an idea of the distance.

The Big Bang

- Tracing the expansion back implies that the universe had a beginning, and that beginning was about 15 billion years ago.
- Fred Hoyle - strong proponent of ‘steady state theory’ - derisively referred to the notion as the ‘Big Bang theory’.
- The name stuck.

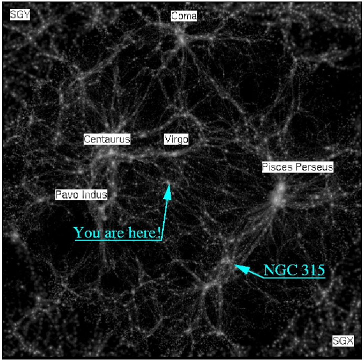
The Big Bang

- In 1964, Penzias and Wilson detected microwave emission that was coming from all parts of the sky with highly uniform intensity.
- It was characteristic of a black body with a temperature of 2.7K
- This Cosmic Microwave Background Radiation was exactly what the Big Bang theory had predicted



The Big Bang

- Further evidence comes from the amounts of Helium and Lithium in the universe, which are well predicted by Big Bang theory, and also the large-scale structure of the universe.



The Big Bang

- Large simulations of how a universe would evolve if it started with a Big Bang give results that look very much like what is observed.
- Finally, some types of object are seen in the distant universe but not nearby, ruling out any kind of ‘steady state’ universe
- eg quasars