Modern Astronomy: Lives of the Stars

Presented by
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School of Physics

Spring 2016

THE UNIVERSITY OF SYDNEY

There is a course web site, at

http://www.physics.usyd.edu.au/~helenj/LivesoftheStars.html

where I will put

- PDF copies of the lectures as I give them
- lecture recordings
- copies of animations
- links to useful sites

Please let me know of any problems!

This course is a deeper look at how stars work.

1. Introduction: A tour of the stars
2. Atoms and quantum mechanics
3. What makes a Star?
4. The Sun – a typical Star
5. Star Birth and Protostars
6. Stellar Evolution
7. Supernovae
8. Stellar Graveyards
9. Binaries
10. Late Breaking News

There will be an evening of star viewing in the Blue Mountains, run by A/Prof John O'Byrne on

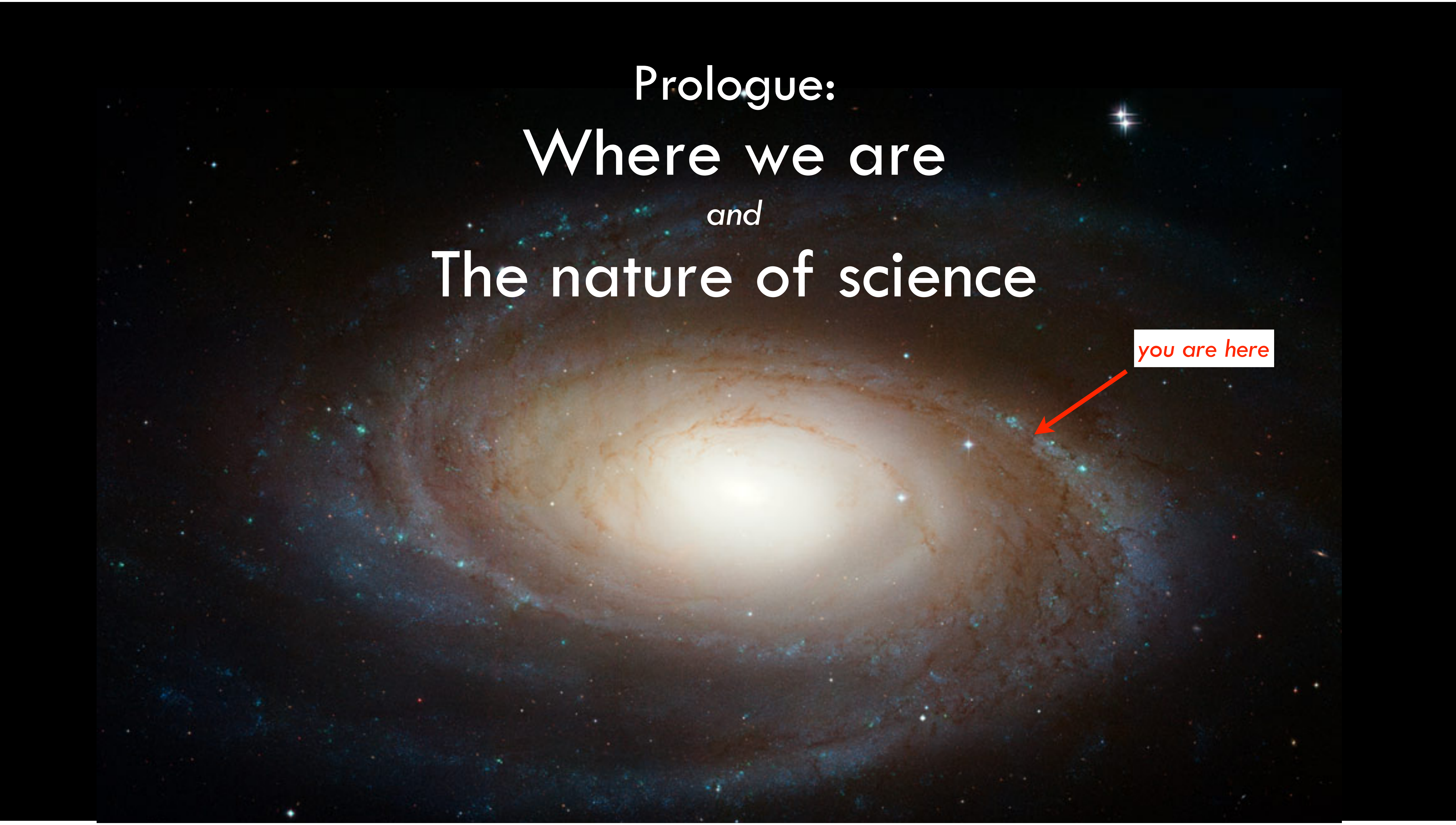
Saturday 29 October

Details of where to go and how to get there are in a separate handout.

John has also offered to show some of the night-sky using our telescope on the roof of this building, during one of the lectures in November (date to be determined).

If the weather is good, I will do a short lecture that evening, and we'll go to the roof around 7:30 pm.

Lecture 1:
Stars: a guided tour


Prologue:
Where we are
and
The nature of science
you are here

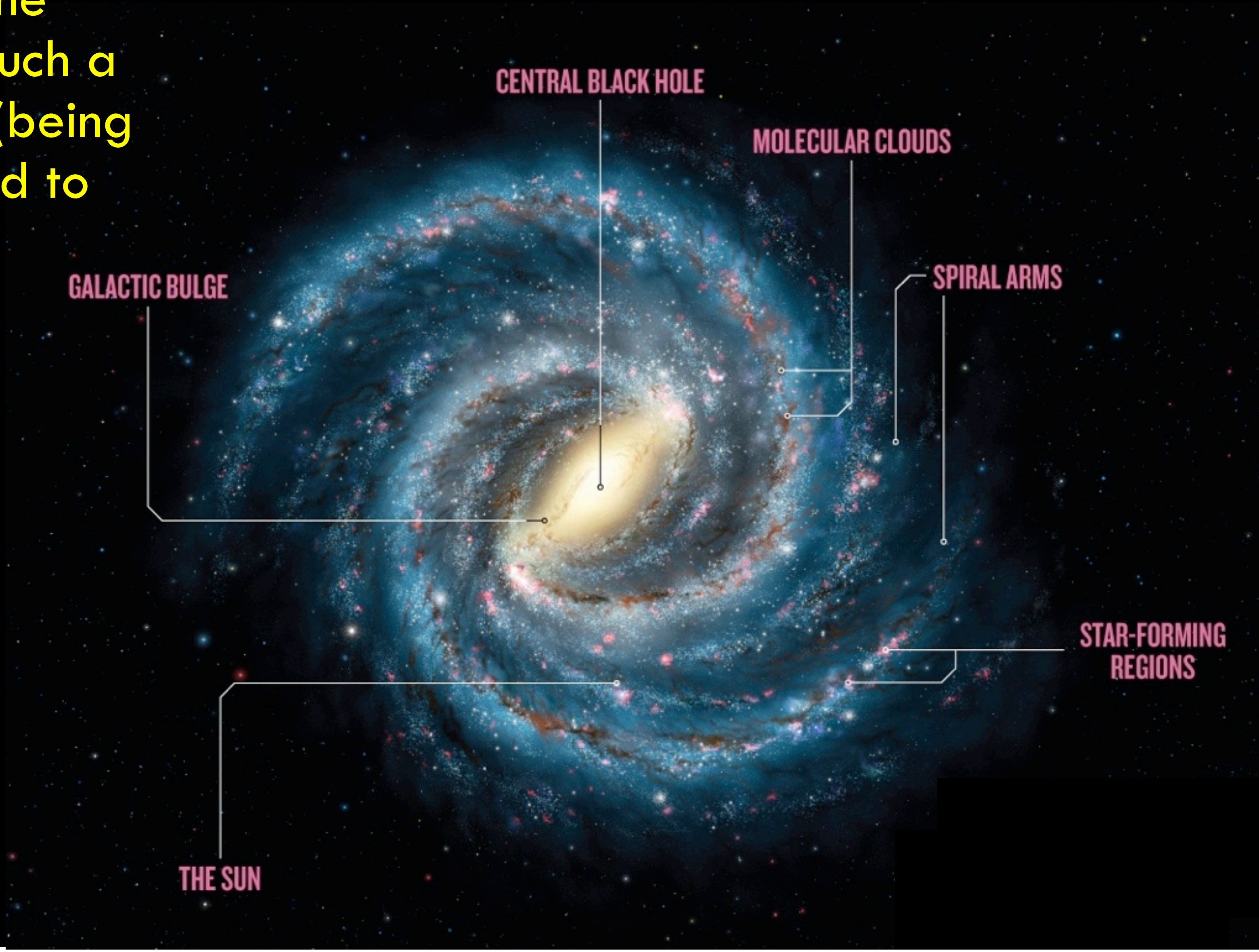

When we look at the night sky, we
see a vista dominated by stars.


If we look with a large telescope, we can see much fainter objects, and most of the faint ones turn out to be entire galaxies.

Each of these galaxies is made up of trillions of stars, together with loose clouds of gas and dust that occupy the space between the stars.

NGC 3982 from Hubble

Our own Galaxy – the Milky Way – is just such a galaxy, except that (being inside it) we have had to deduce its shape.

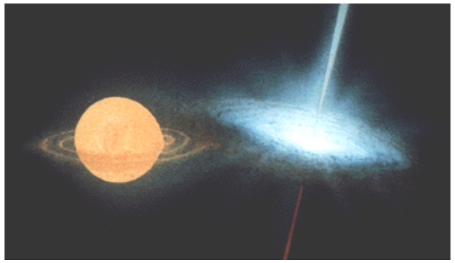



When you look up at the night sky, nearly everything you see is inside the Milky Way.

All these glorious objects are the subject of this course. We will see how our Galaxy is a thriving eco-system, where stars are born, live their lives, and die, and in each stage affecting the environment for other stars.

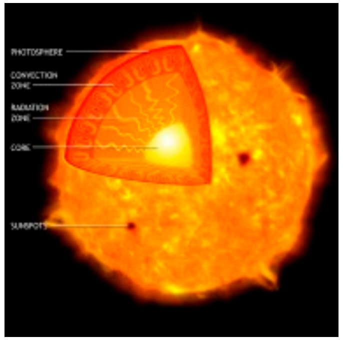
I will not be taking a historical approach, but describing what we know now. But everything I tell you is based on *observations*, often long and painstaking.

long chain of reasoning, informed guesswork → **how jets form**



long chain of reasoning, less confidence → **how supernovae explode**

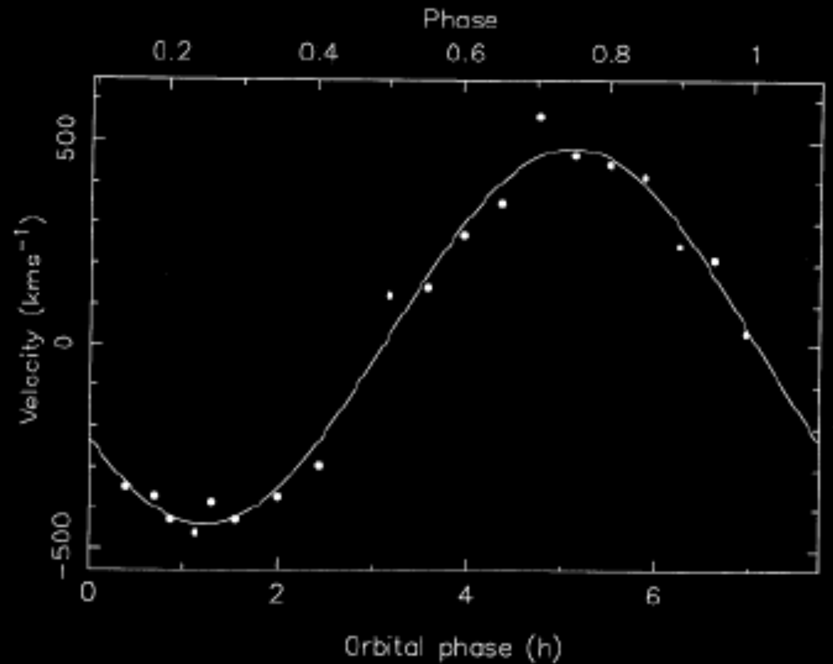
long chain of reasoning, high confidence → **how stars work**



indirect observation, high confidence → **stars evolve**

direct observation → **some stars are in binaries**

Confidence


Phase
0.2
0.4
0.6
0.8
1
Velocity (kms^{-1})
500
0
−500
0
2
4
6
Orbital phase (h)

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

– Donald Rumsfeld, 2002

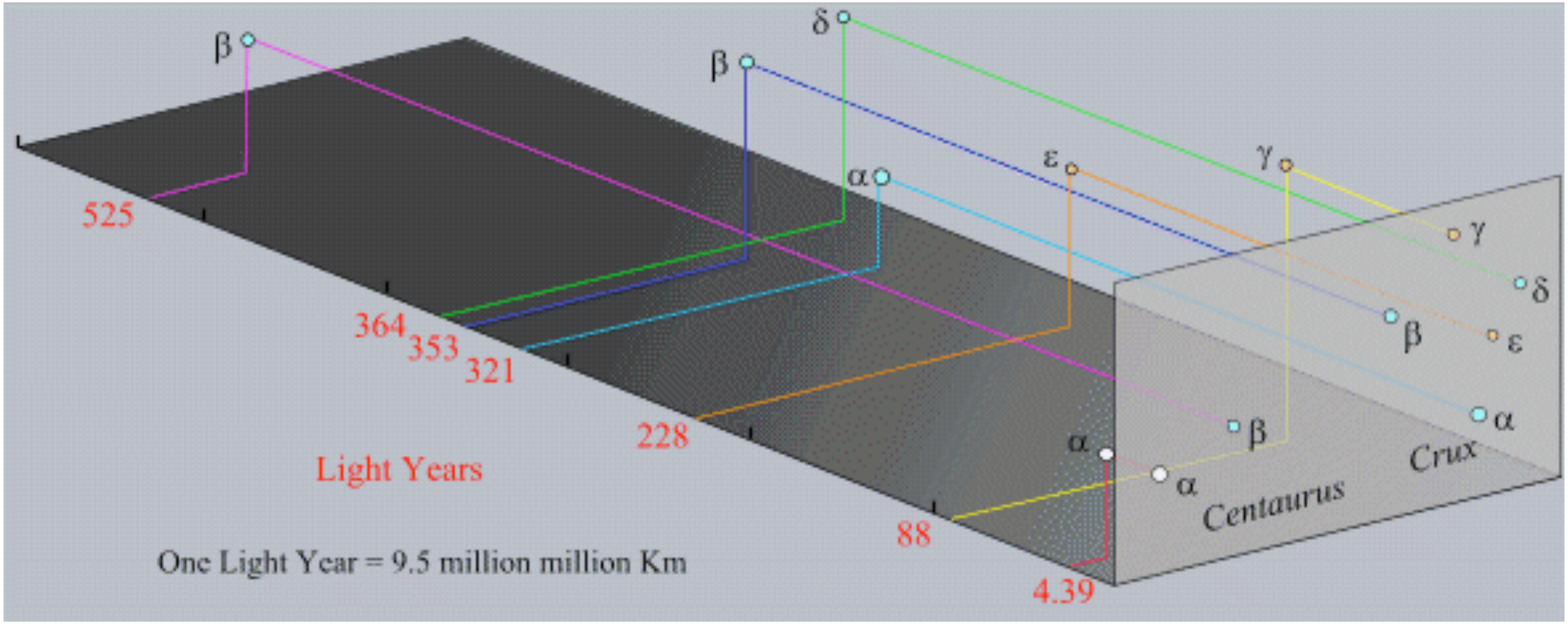

Properties of the stars


When we look at stars, we see brightness and colour.

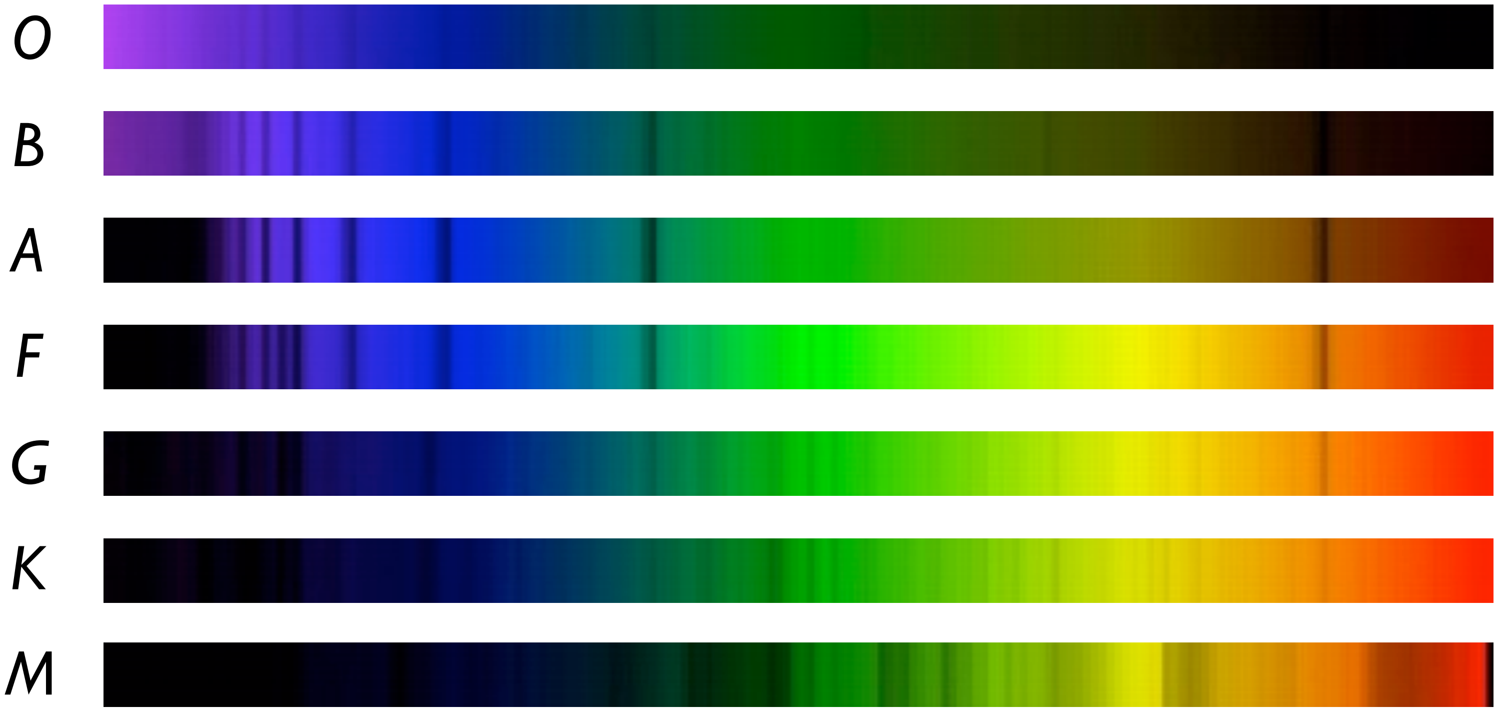
We need to make careful measurements to work out fundamental properties:

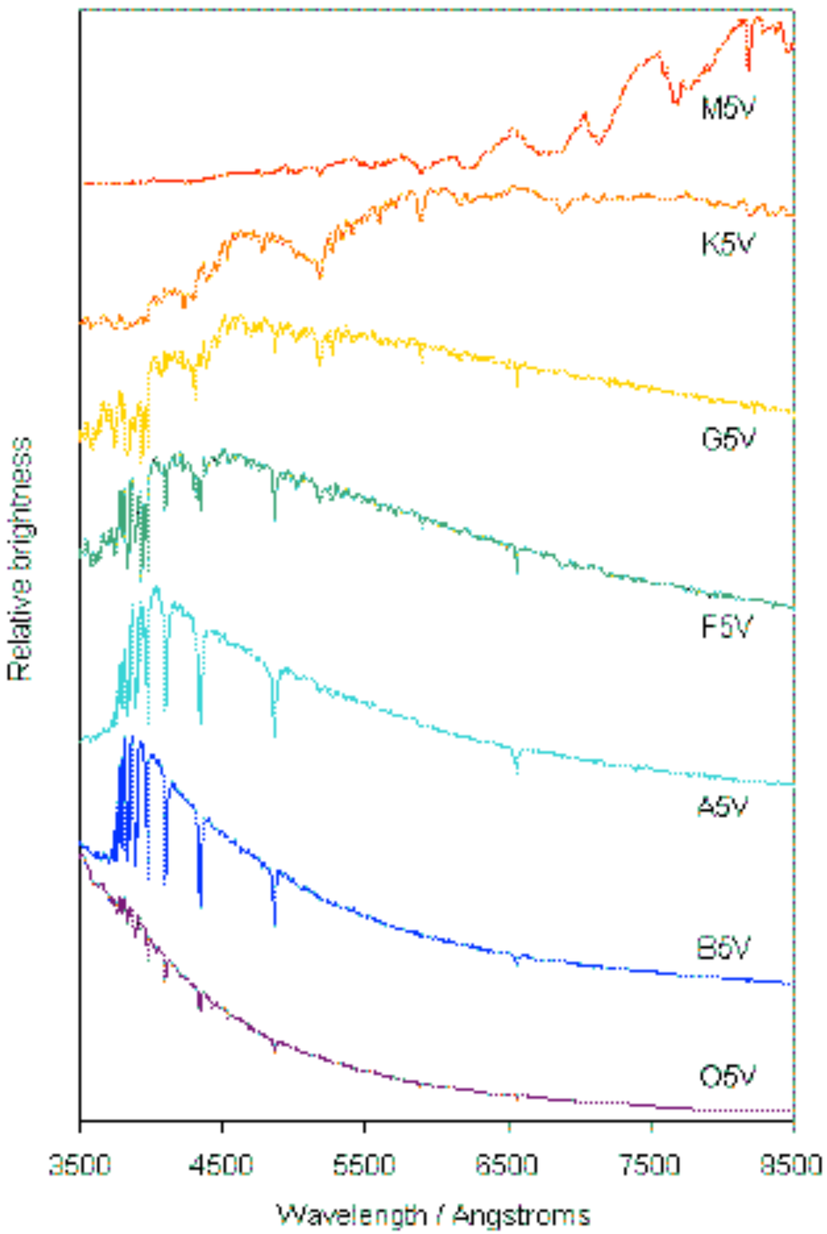
- luminosity (true brightness)
- temperature
- size
- mass

It took astronomy thousands of years to get to this point.


β
δ
β
α
ε
γ
γ
δ
β
ε
α
β
α
α
Crux
Centaurus
525
364
353
321
228
88
4.39
Light Years
One Light Year = 9.5 million million Km

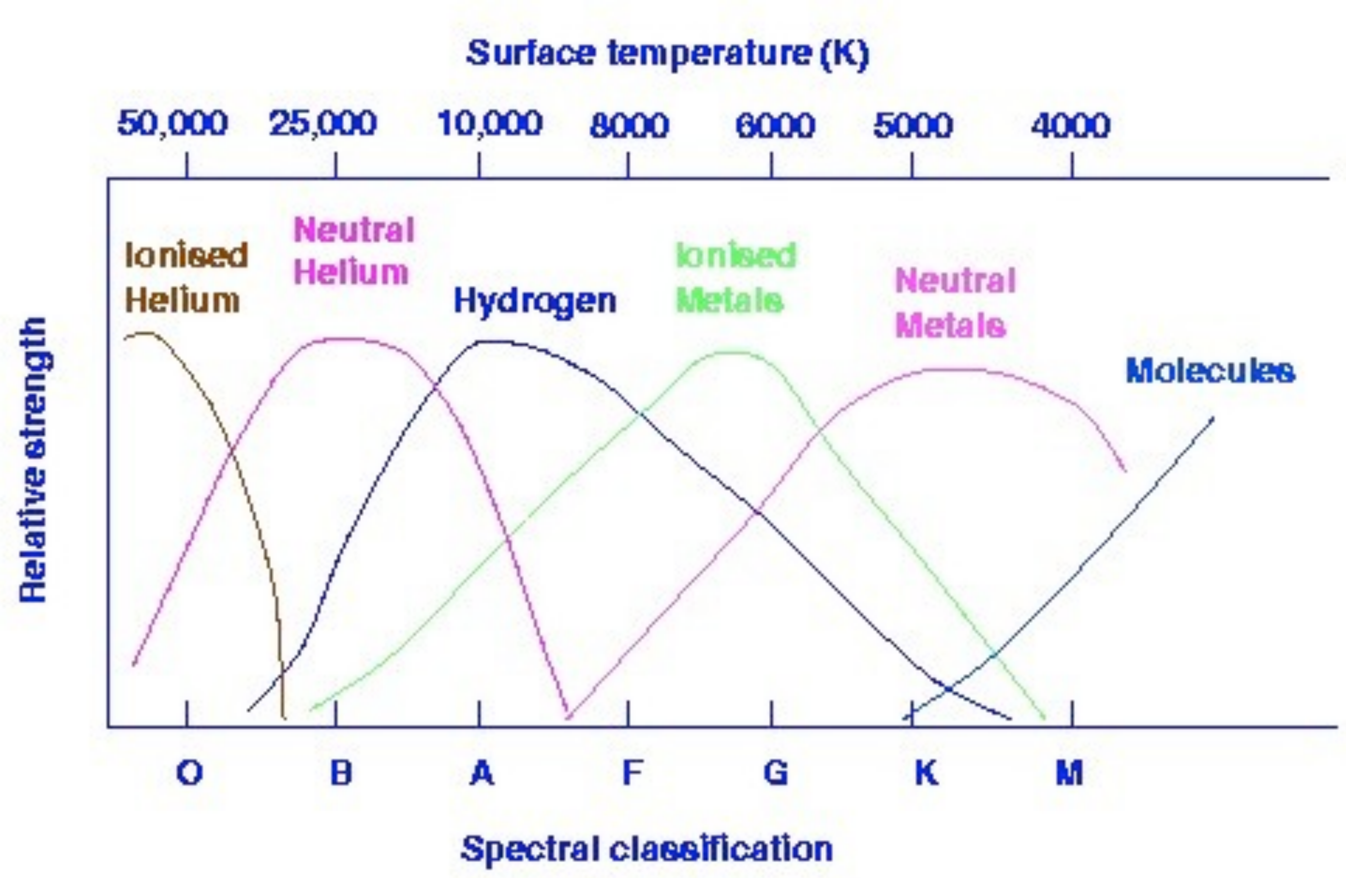
Stars are identified by their *spectral type*, which is a letter-number combination, based on features in their spectra.





Plotting the intensity as a function of wavelength, we can see that not only does the light shift towards bluer wavelength as we go from M stars to O and B stars, but the strength and types of the absorption lines change as well.

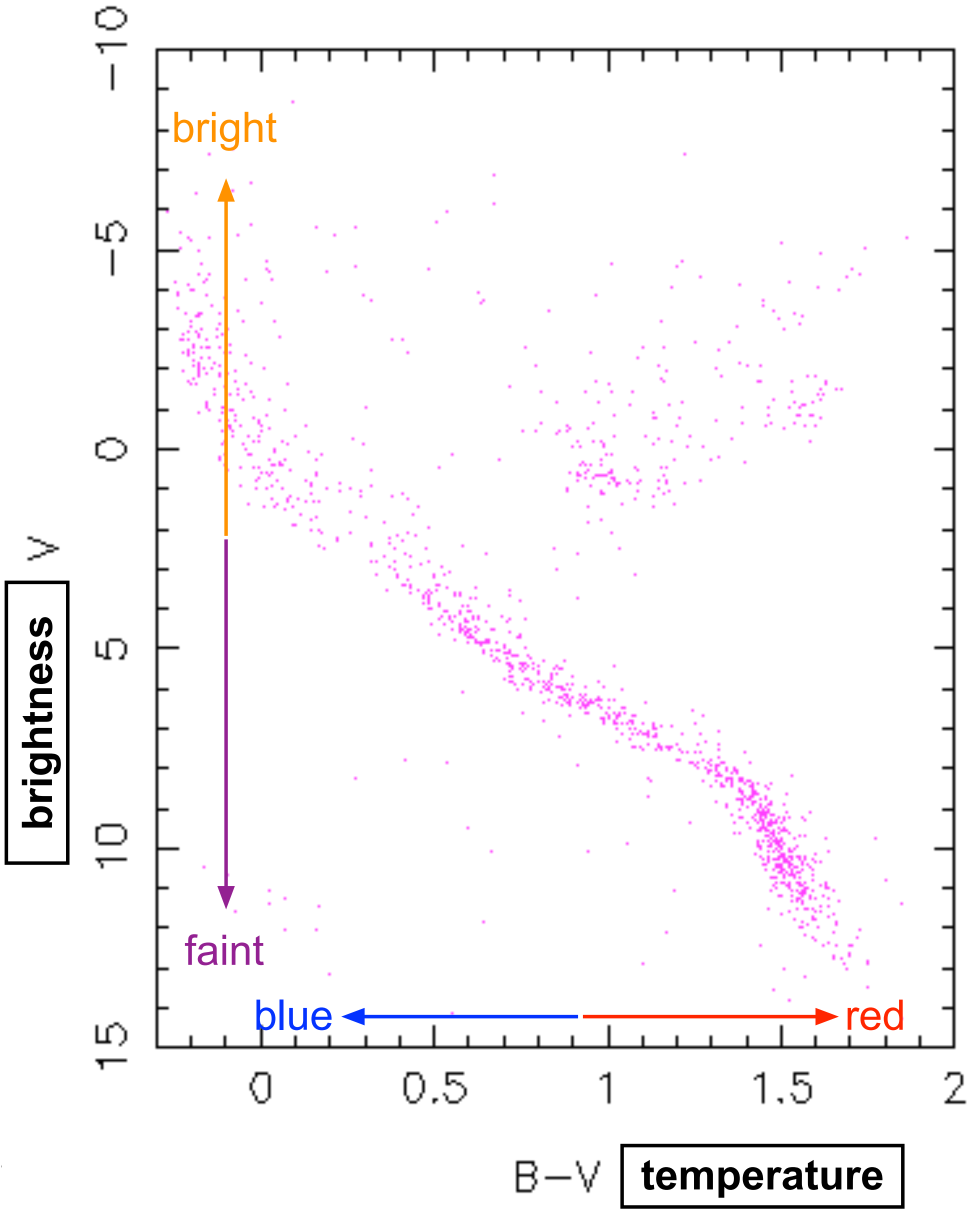
Stars all have very nearly the same composition: the differences in their spectra are almost entirely due to *temperature*.



The Hertzsprung-Russell diagram

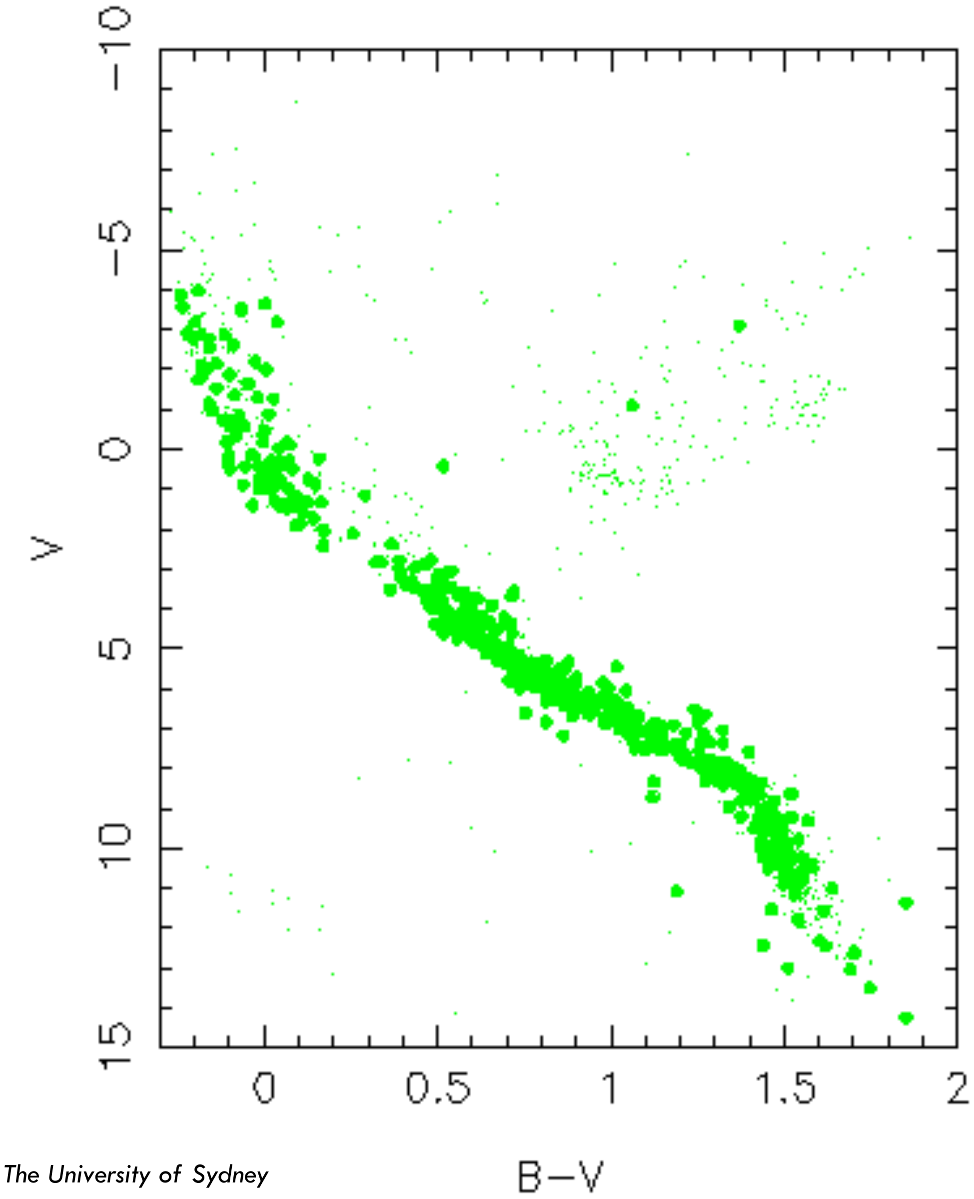
If we examine the intrinsic properties of stars – their brightness, temperature, and mass – we quickly notice that there are patterns in the way stars are made up. Explaining these correlations has been one of the main focuses of 20th century astronomy; we'll be exploring the reasons in the next few weeks.

Ejnar Hertzsprung and Henry Norris Russell plotted the brightness of stars against their colour, in a diagram which now bears their names.

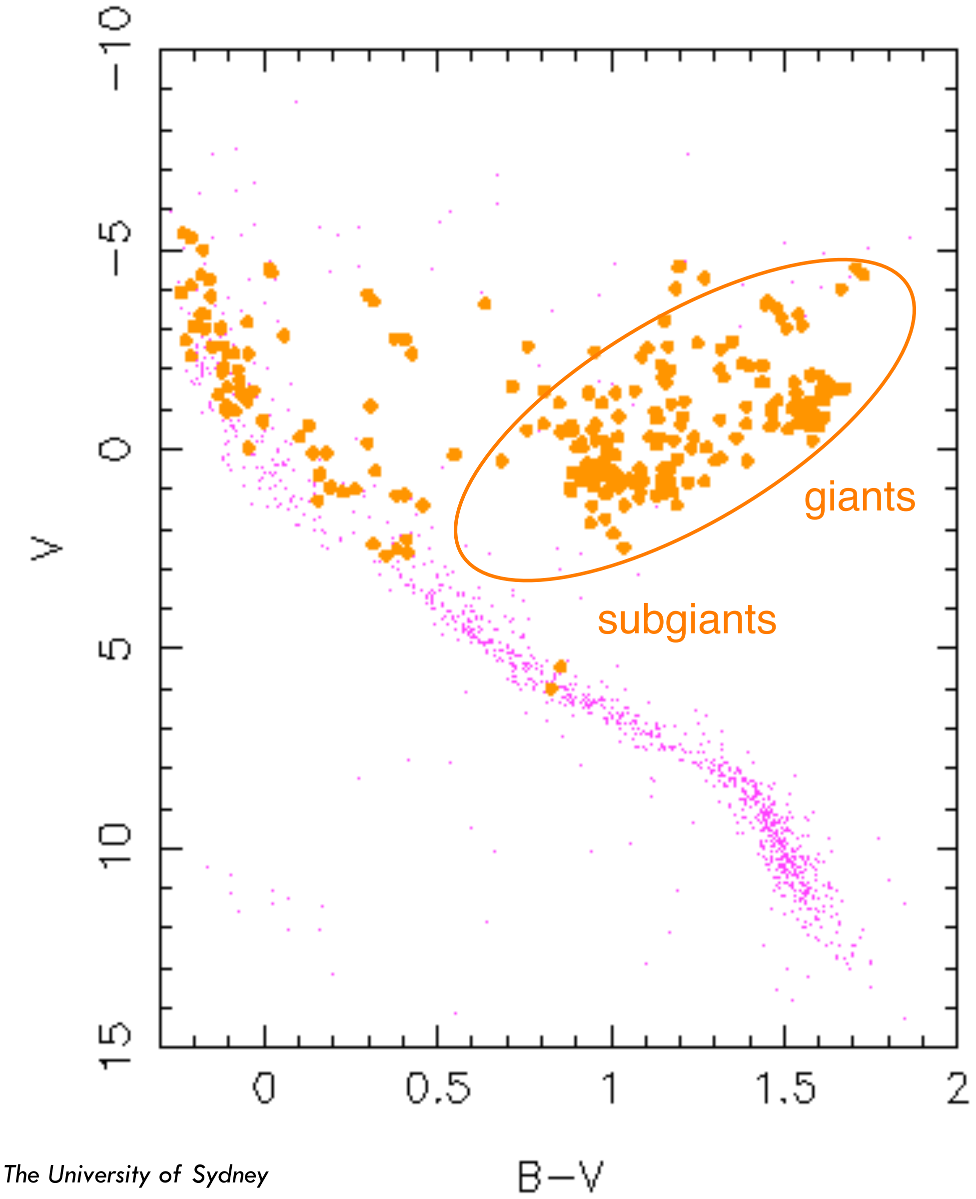


This is an H-R diagram using data from the Hipparcos satellite, which measured distances to over 100,000 stars.

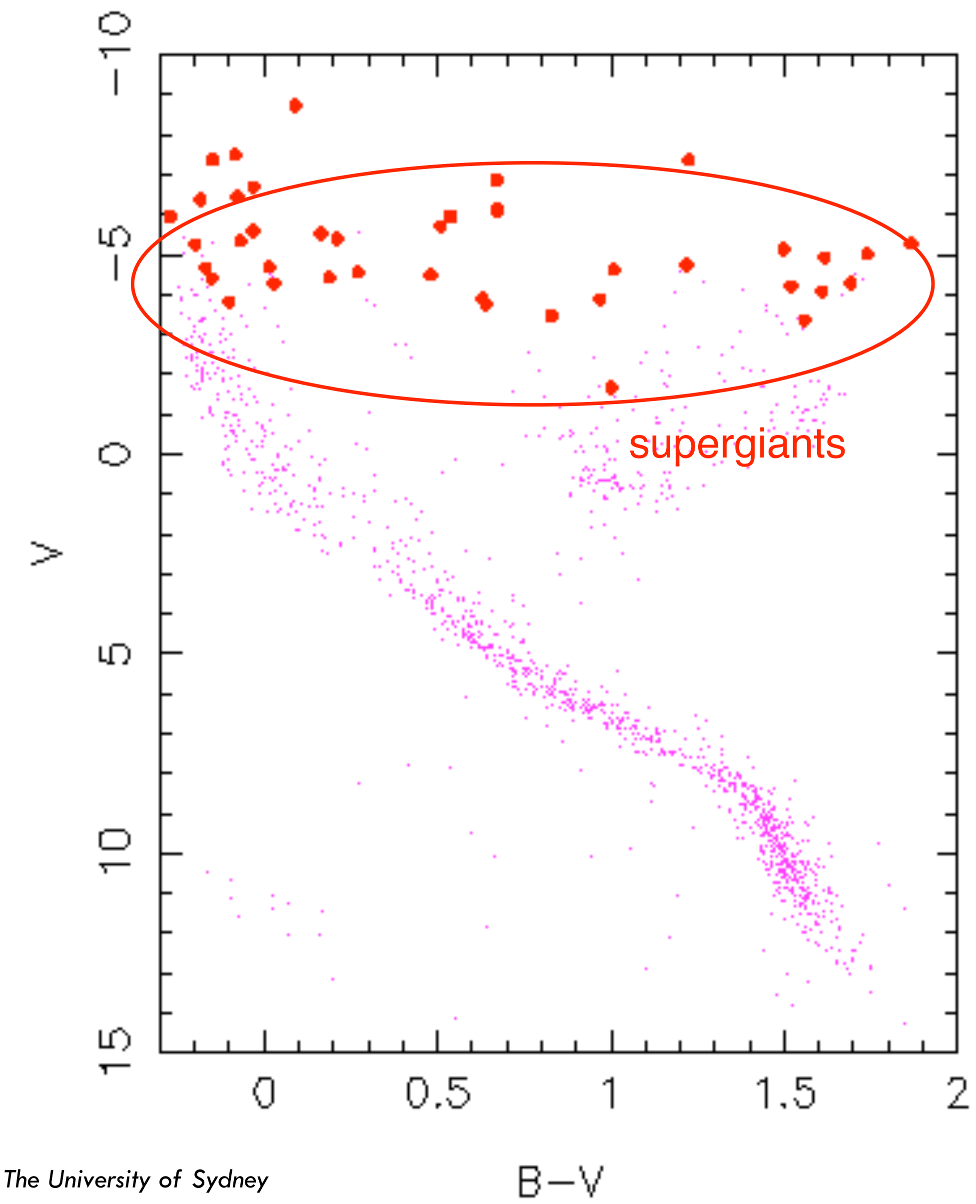
Patterns are immediately apparent in where stars lie.



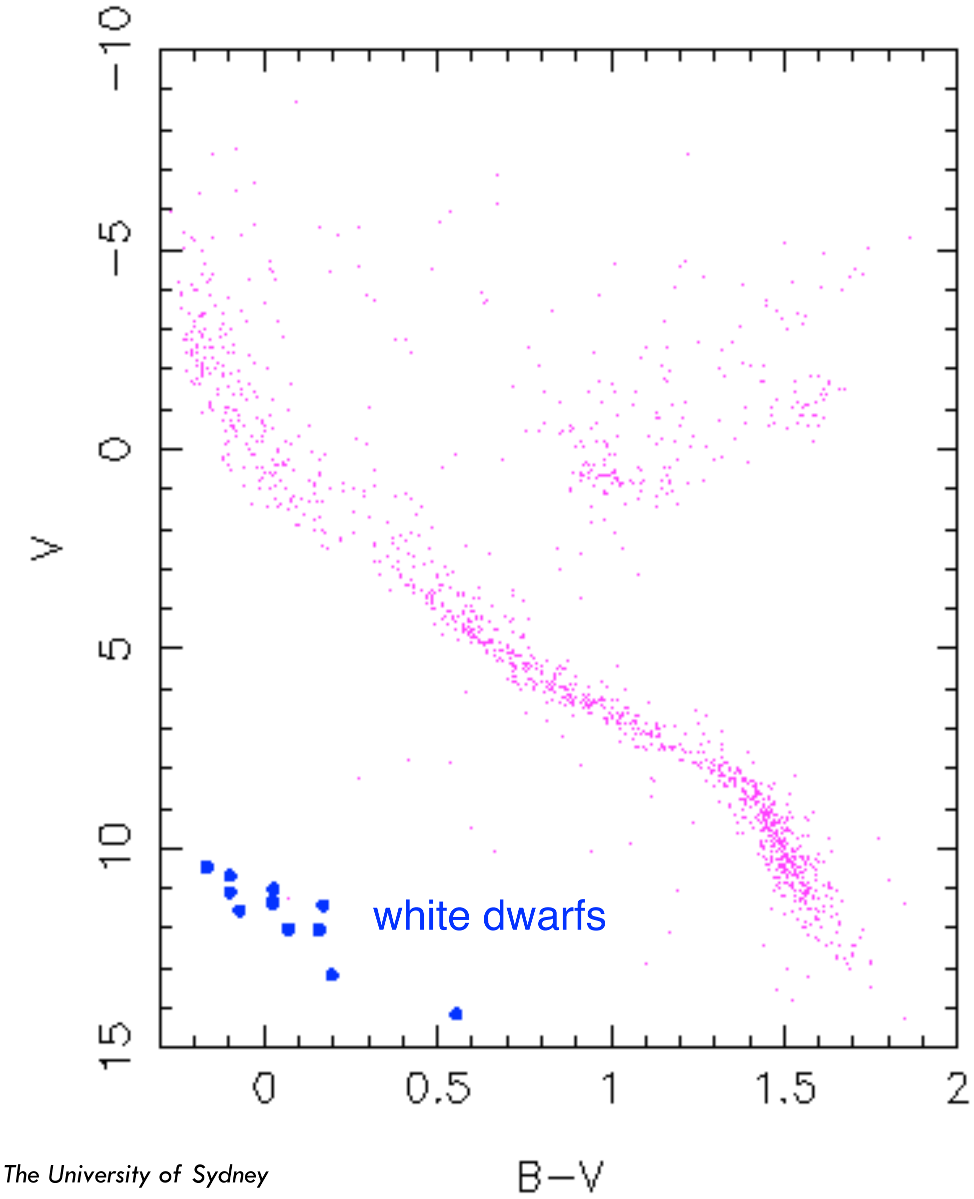
90% of stars fall on the *main sequence*, a narrow strip running from cool and faint to hot and bright.



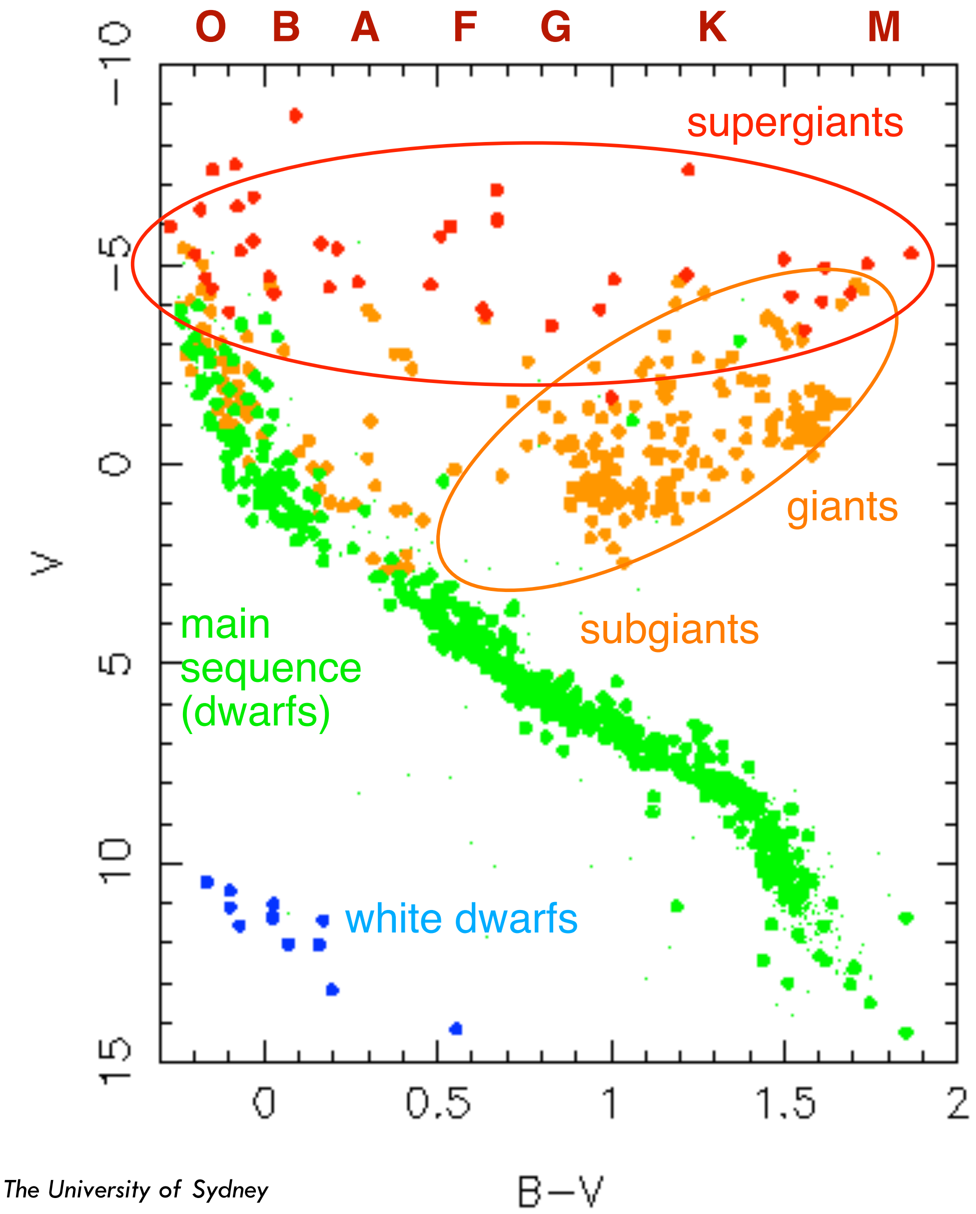
Most of the remaining stars lie in a band from faint(ish) and yellow to extremely bright and red. To be both cool and very bright, these stars must be enormous: the *giants*.



Even brighter than the giants, and hence even larger, are the *supergiants*, which occupy a region across all colours.



Then there are some stars below the main sequence, which are very hot and very faint, which must mean they are very small – the *white dwarfs*.



Here are all those regions together, as well as the spectral classes indicated across the top.

In this lecture, we're going to take a tour around these various types of stars, to see what they are like up close and personal.

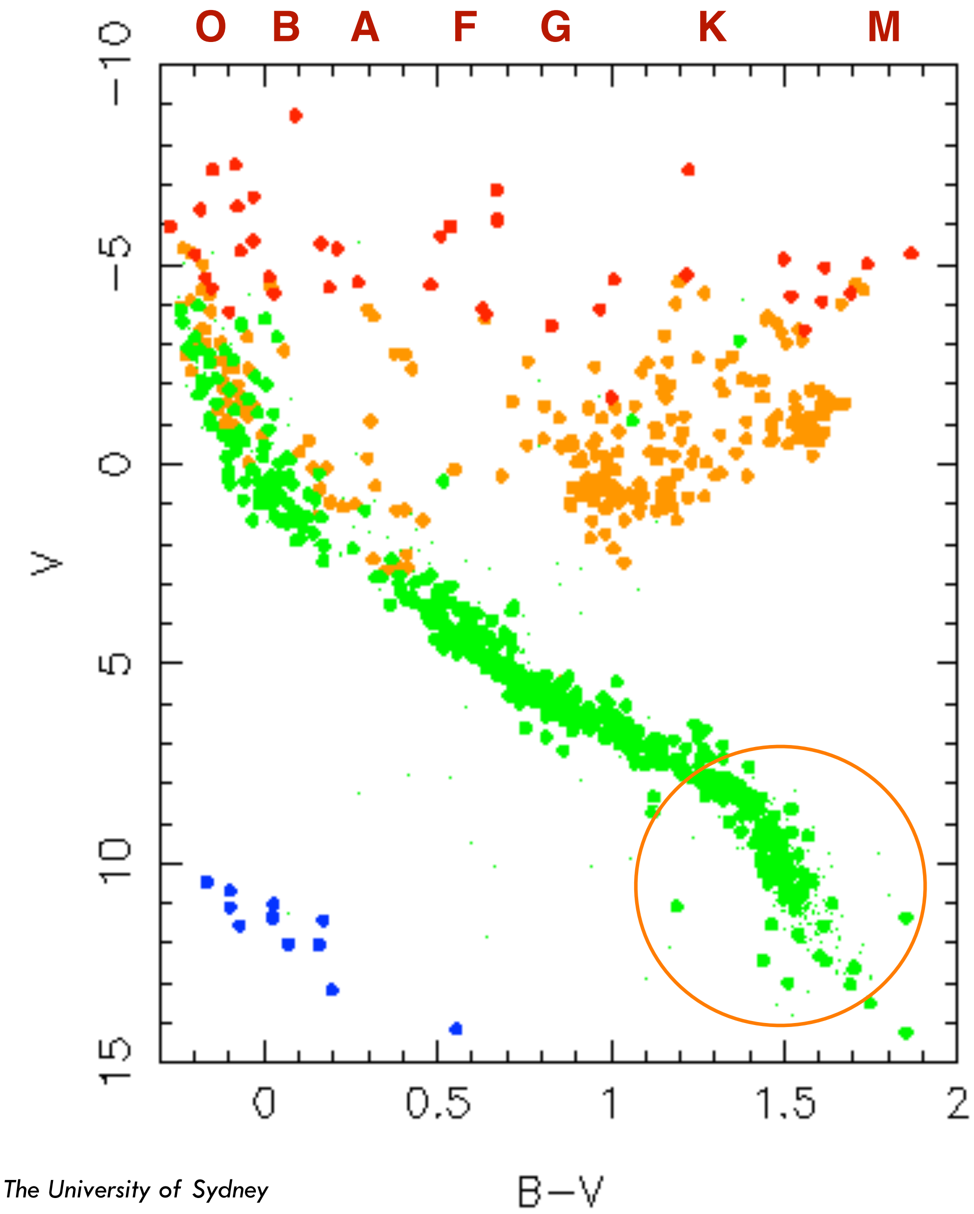
The main sequence

Let's start with the *main sequence*, which makes up the bulk of stars. This is a band of stars running across the diagram. This means that the temperature of the star is correlated with its brightness – as stars get hotter, they also get brighter.

It is hard to contemplate just how much the brightness of stars varies from one end of the main sequence to the other. The brightest star is more than 50,000 times brighter than the Sun, while the faintest is a million times fainter.

To light the day with a faint M star, we would have to orbit at a distance of 150,000 km – half the distance to the Moon.

Around a bright O star, we would need to orbit at a distance of 200 AU – five times the distance to Pluto – to receive the same amount of light we get from our Sun.



M and K stars: the coolest stars

Let’s start our tour with the coolest stars, in the bottom right-hand corner: the M and K dwarf stars.

M stars are extremely common, so that even though their masses are small (a few tenths of a solar mass), they make up about half of the mass of stars in the Galaxy. For every A star like Sirius, there are 100 M stars; for every O star, there are 1.7 million M stars.

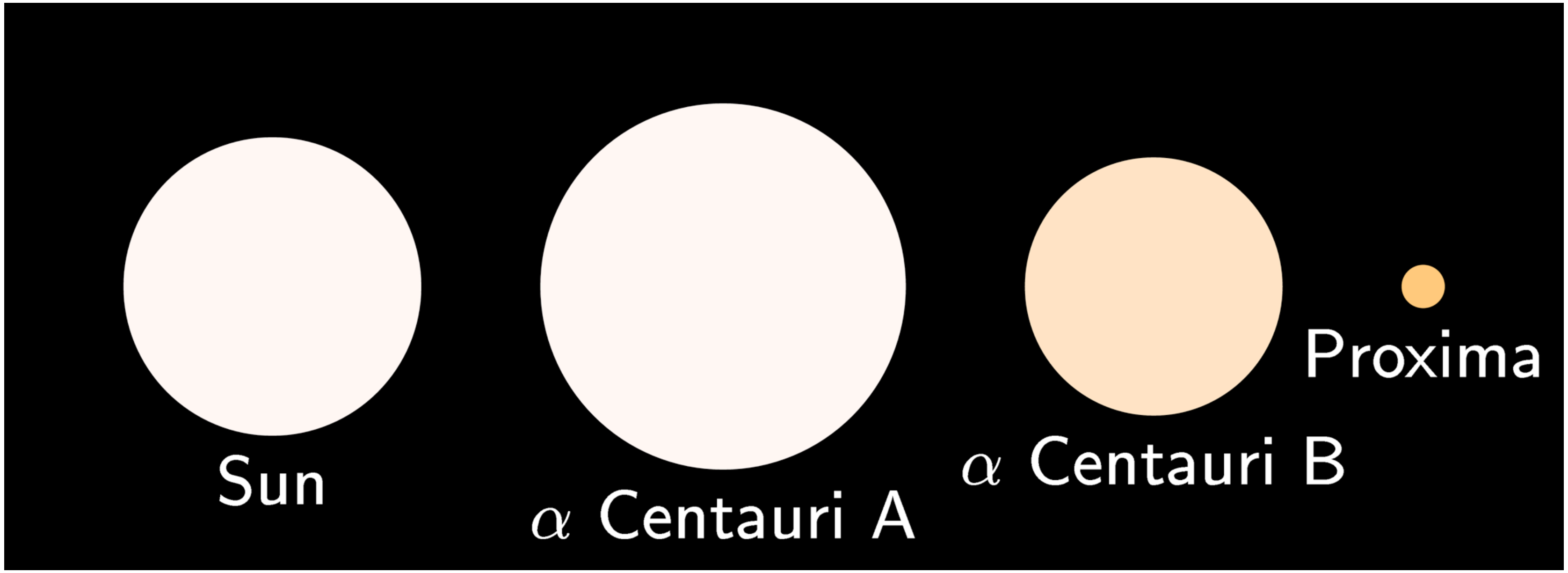
It is surprising, then, to learn that there is not a *single* M star visible to the naked eye.

K stars have masses between roughly 0.5 and 0.7 times the Sun's mass, and there are about 1/6 as many of them as there are M stars.

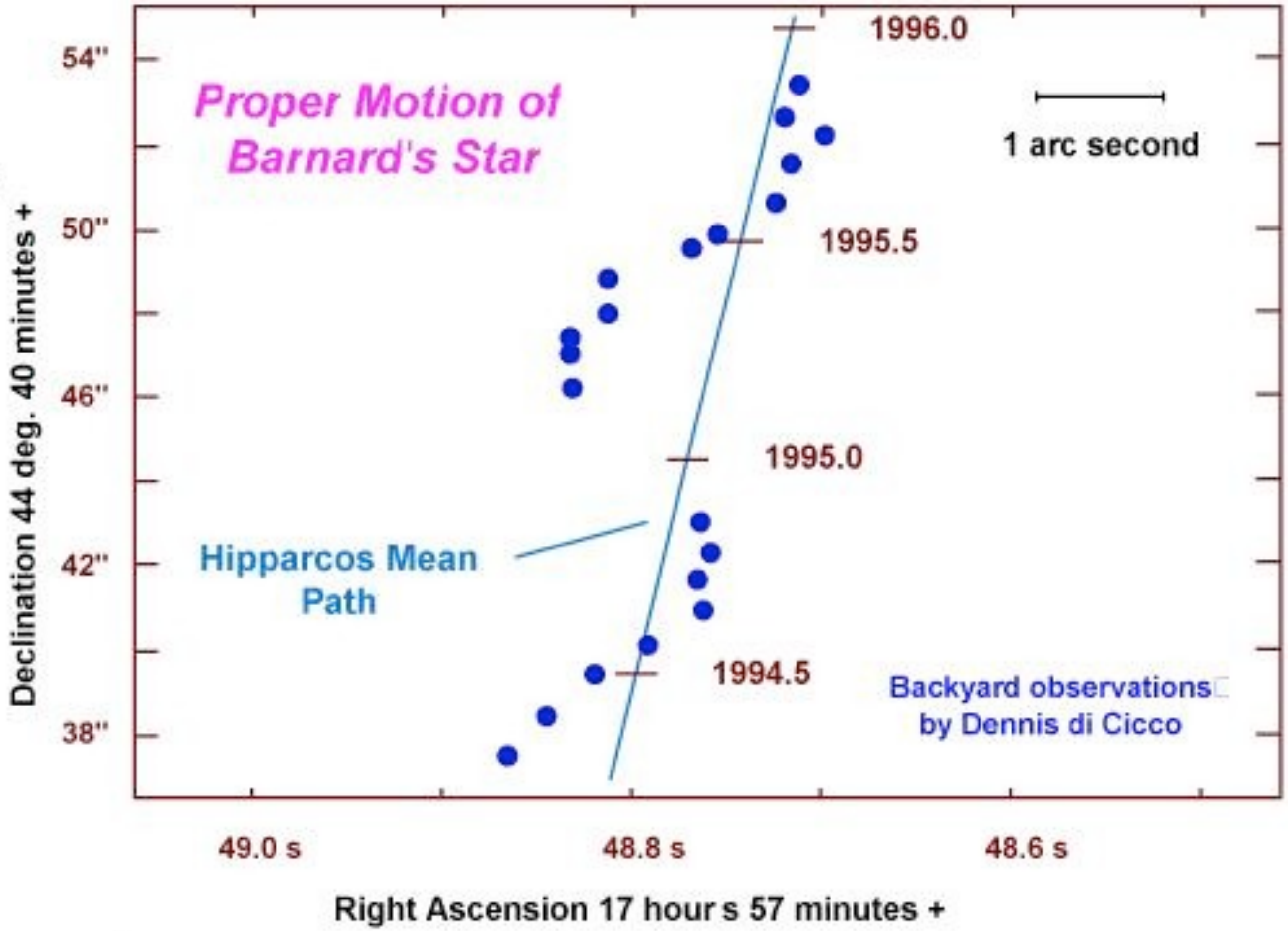
The nearest star to the Sun, Proxima Centauri (which may be in orbit around the binary α Centauri) is an M5 star. Despite being at the same distance, it is 11 magnitudes fainter than the brightest star, α Cen A, which is almost a twin to our own Sun. α Cen B, the fainter member of the α Centauri binary, is a K1 dwarf.

α Cen A and B are both hidden in the glare; Proxima is arrowed at the lower right.

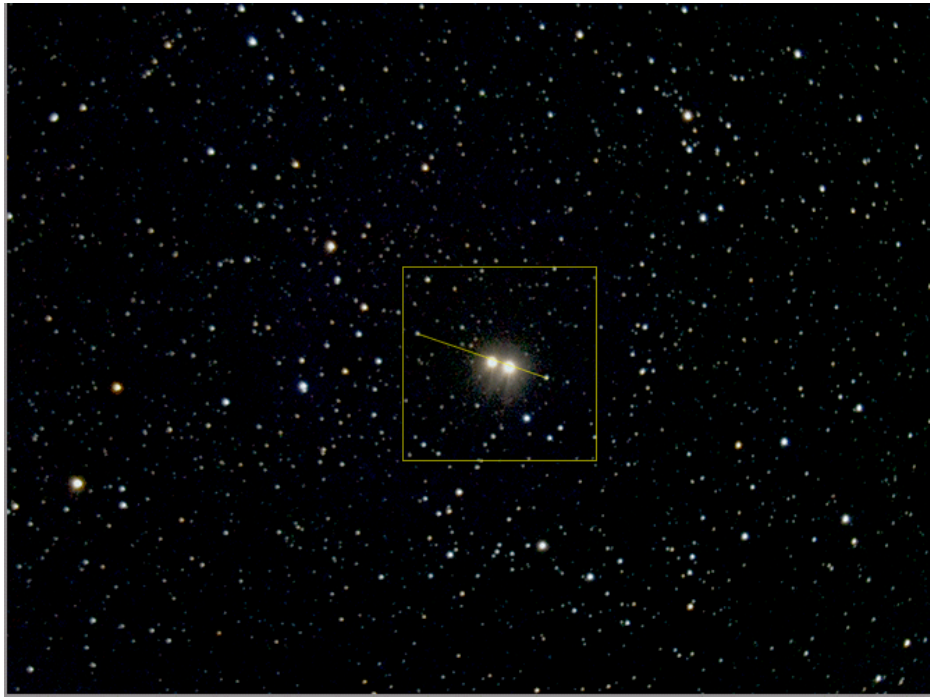
The diameter of Proxima Cen is 1/7th that of the Sun, or just 1.5 times Jupiter. Its distance from α Cen is 15,000 AU (0.21 ly), and it is probably bound, with an orbital period of about 500,000 years.



The star with the highest known proper motion, Barnard's Star, which is zipping along at an astounding 10.4 arc seconds per year, is also an M5 star.



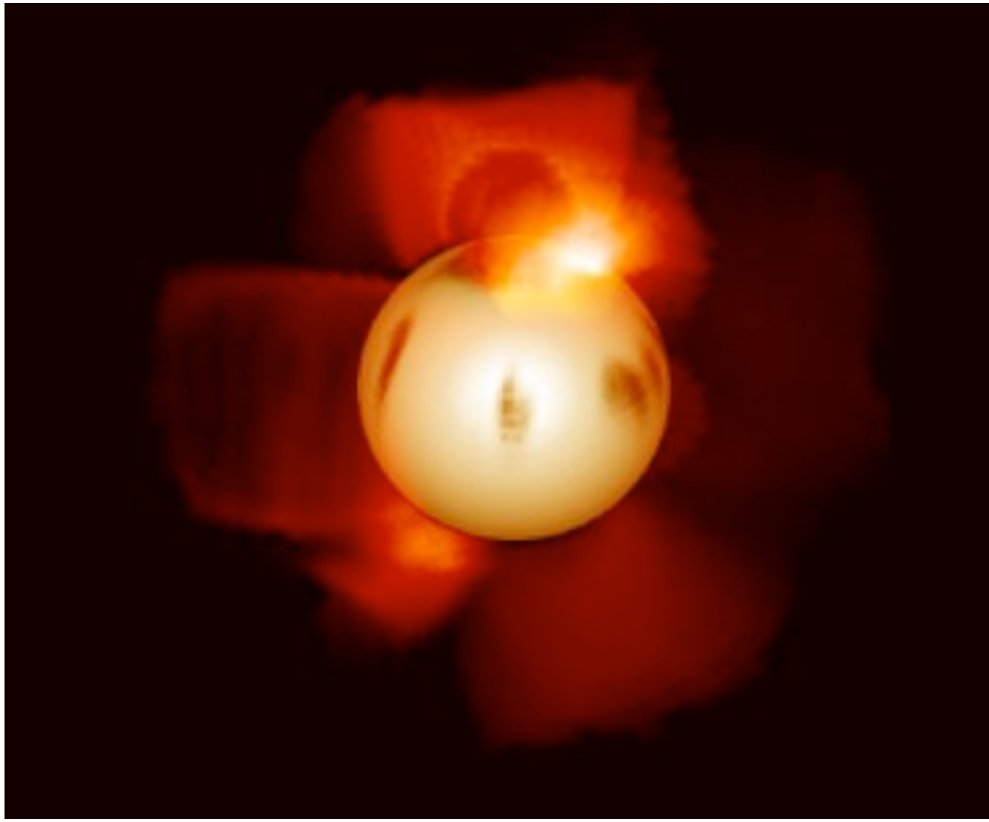
Amongst other notable K dwarf stars: 61 Cygni, the first “star” to have its parallax measured, is actually a pair of K dwarfs, K5–K7.



The faint star Gliese 710 is a 9th magnitude K7 or M1 star, which is currently 19 pc away. It is approaching the Sun, and will come within nearly 1 light-year of the Sun, about 1.5 million years from now. At its closest, it will reach 0.6 magnitude.

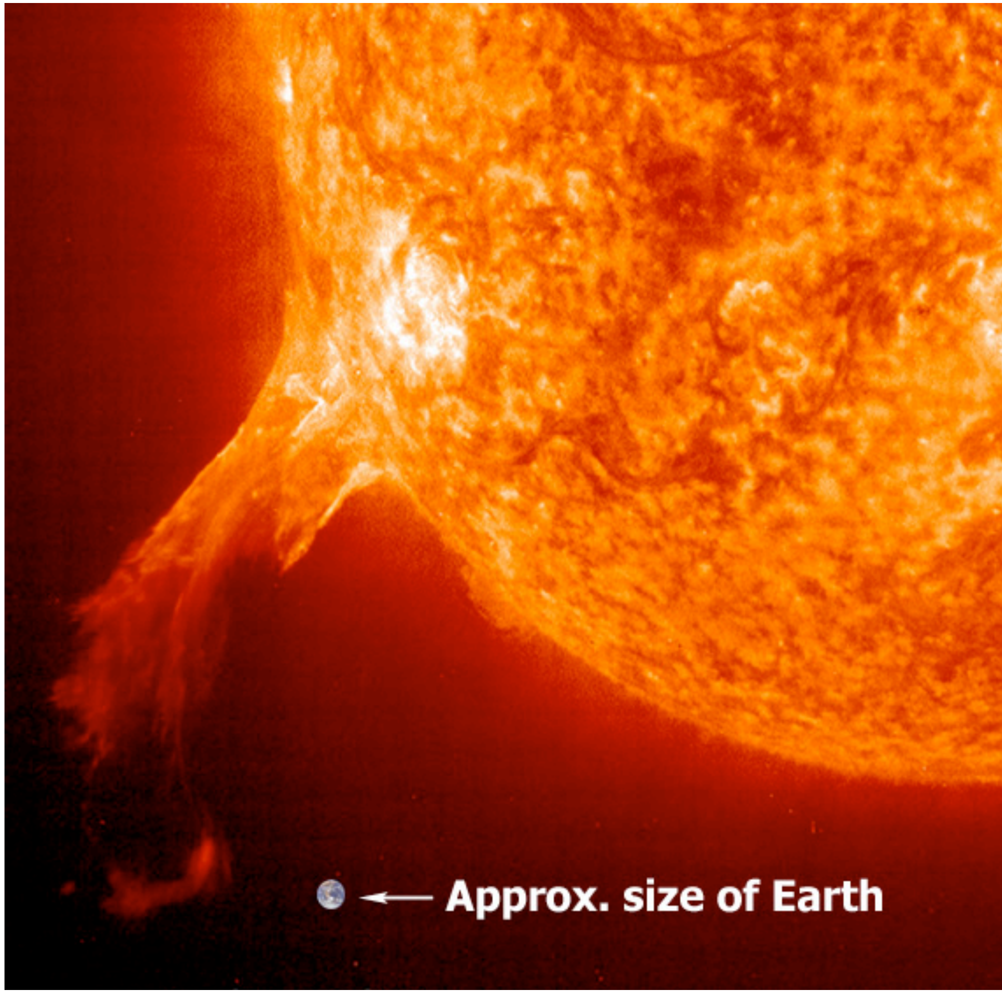
The temperatures of M stars are about 2000–4000 K. This is cool enough to allow molecules to form in their atmospheres; in hotter stars the atoms have enough energy to break molecular bonds, so K stars don't show as many molecular lines in their spectra.

M and K stars show evidence of magnetic activity, including star-spots.

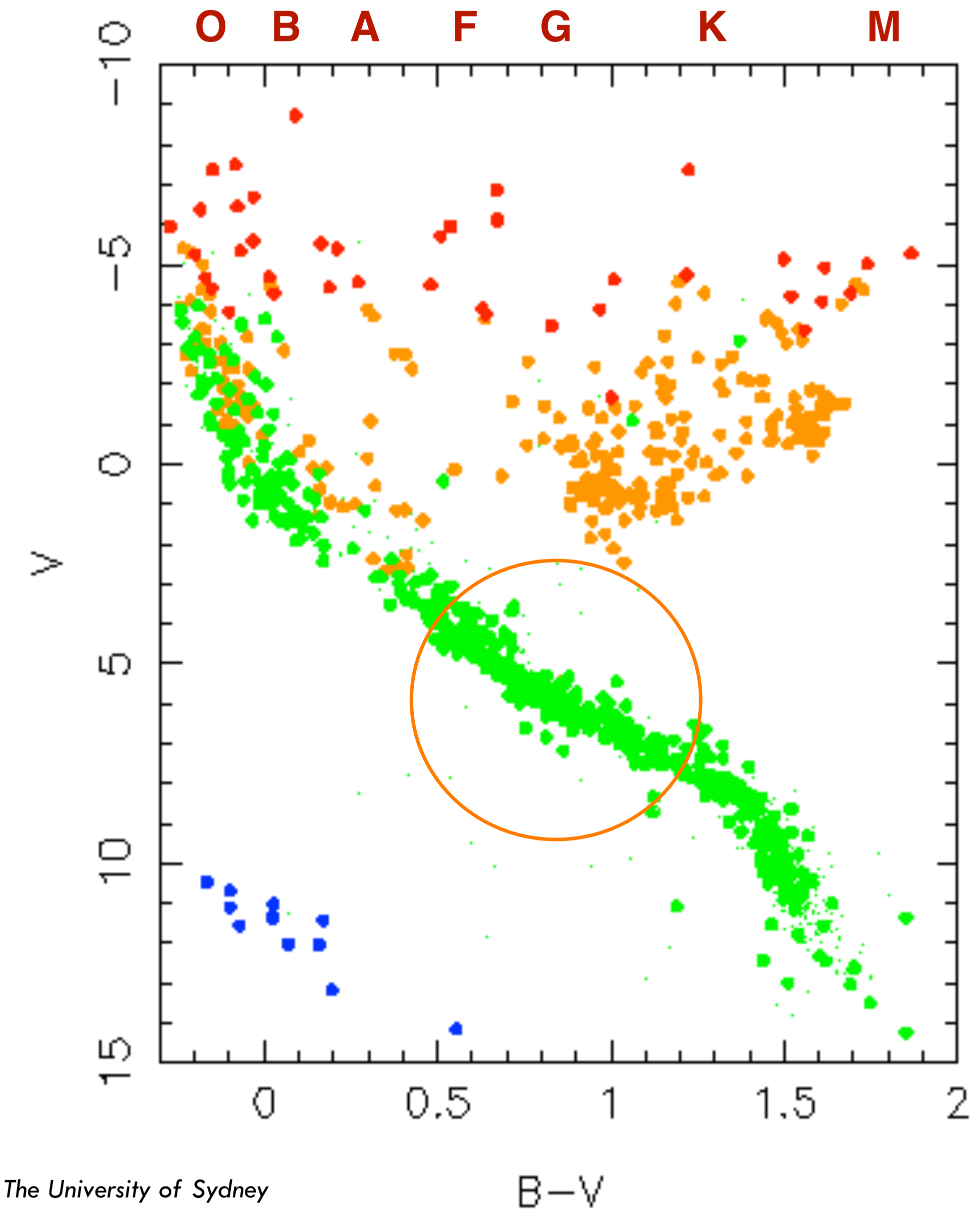


Computer model of starspots on the K0 dwarf star AB Doradus, which rotates 50 times faster than the Sun, measured using Doppler tomography.

M dwarfs are very often *flare stars*: they suddenly change in brightness by a magnitude or more, then settle back over minutes or hours. These outbursts seem to be rather like solar flares, only they involve the whole star instead of just a sunspot, and the star can increase in brightness by a factor of 10.

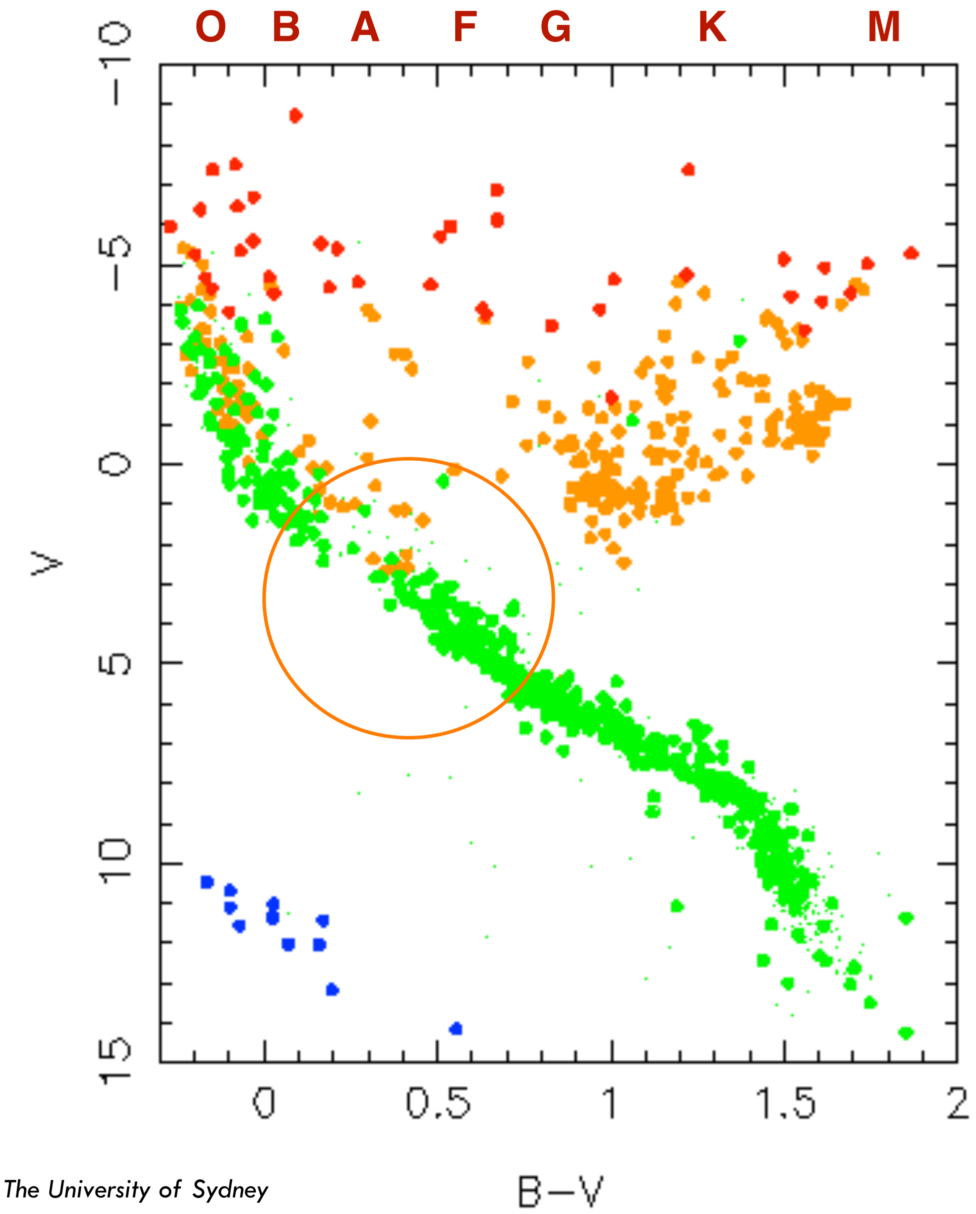


Flare with coronal mass ejection observed by SOHO on our Sun.



Cousins to the Sun:
G stars

Our Sun is a G2 star. α Cen A is a near twin with the same spectral type. Its mass is 10% higher than the Sun, its radius is 25% larger, and it is 60% brighter, indicating it may be approaching the end of its hydrogen fuel.

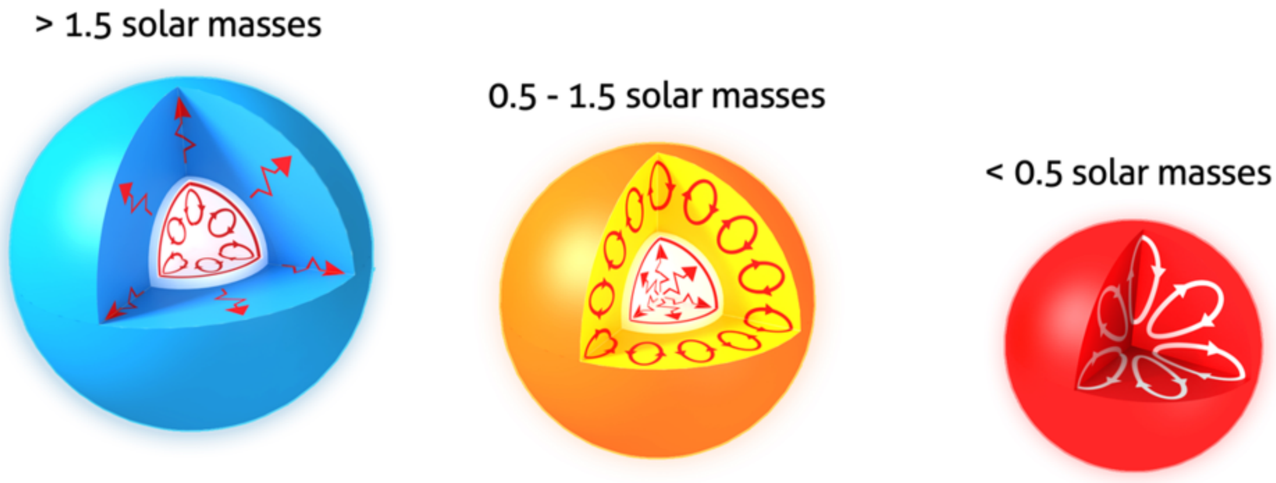


F and A stars

F stars mark the boundary between "low-mass" and "high-mass" stars; in many ways, they are transitional stars.

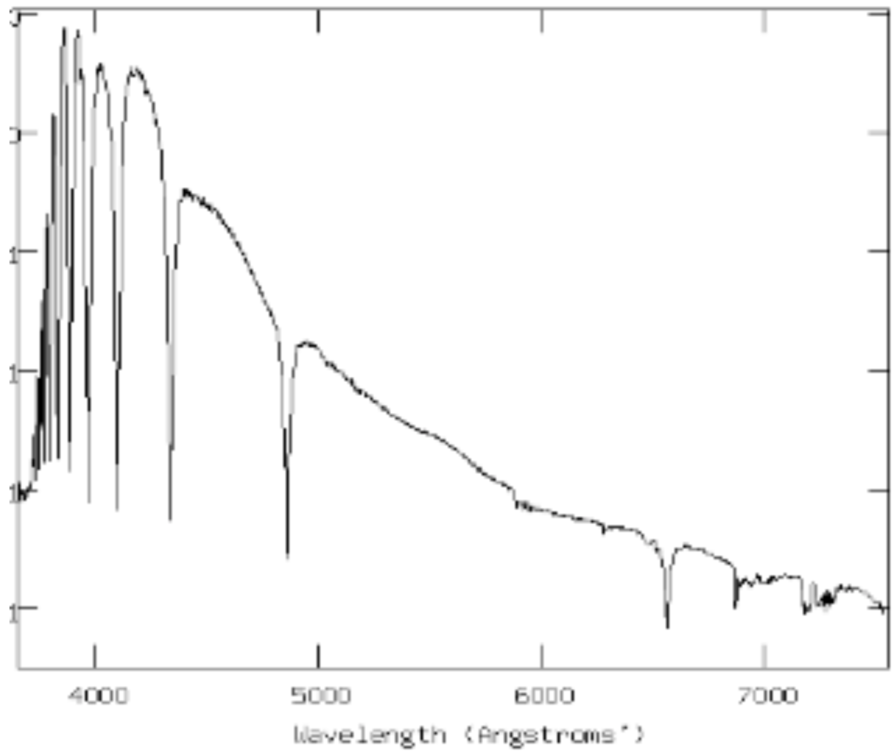
F stars spin much more rapidly than lower-mass stars; 30 km/s or more, compared to 5 km/s for G stars and even slower for K and M stars. This is believed to be because the magnetic fields of the fainter stars act as brakes, slowing them down gradually. F stars have much smaller magnetic fields, so are still rotating as fast as they were when they were born.

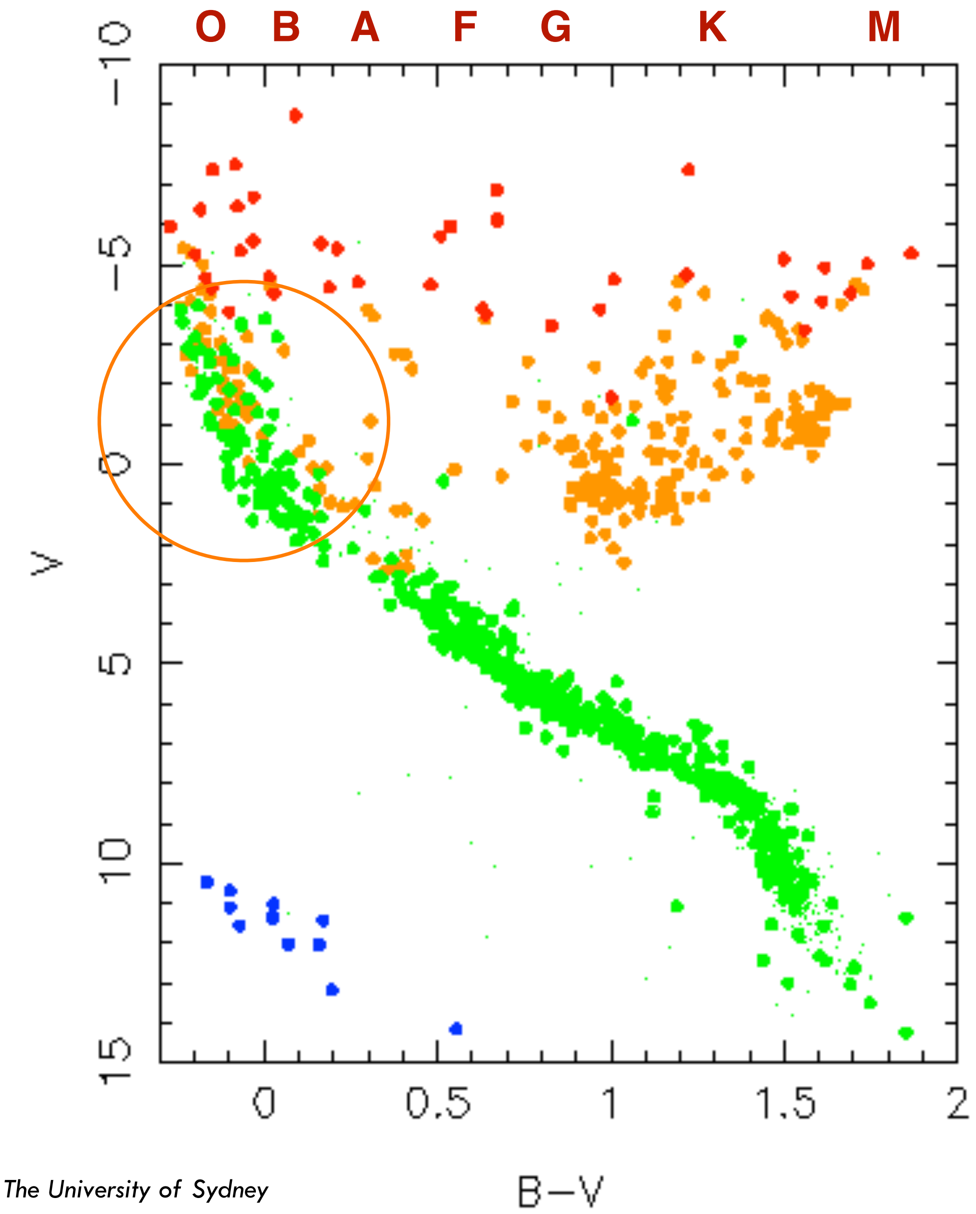
The smaller magnetic fields are related to the fact that the *convection zone* in F stars is getting much smaller, disappearing entirely in A stars.



A stars are common among the brightest stars in the sky, although there is only one for every 100 M dwarfs. The brightest star, Sirius, is an A star, as are Vega and Altair.

A stars have spectra which, at first sight, show almost nothing but hydrogen lines. This is not because they contain no other elements, but because the temperature and pressure of the atmosphere are such that only hydrogen lines are produced in abundance.

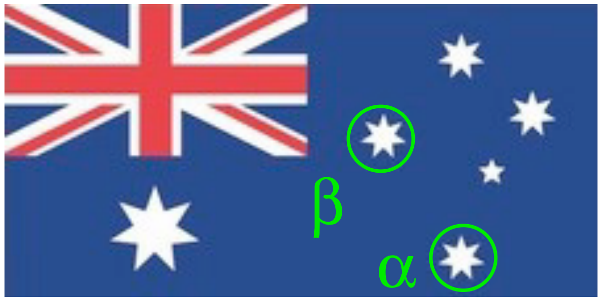


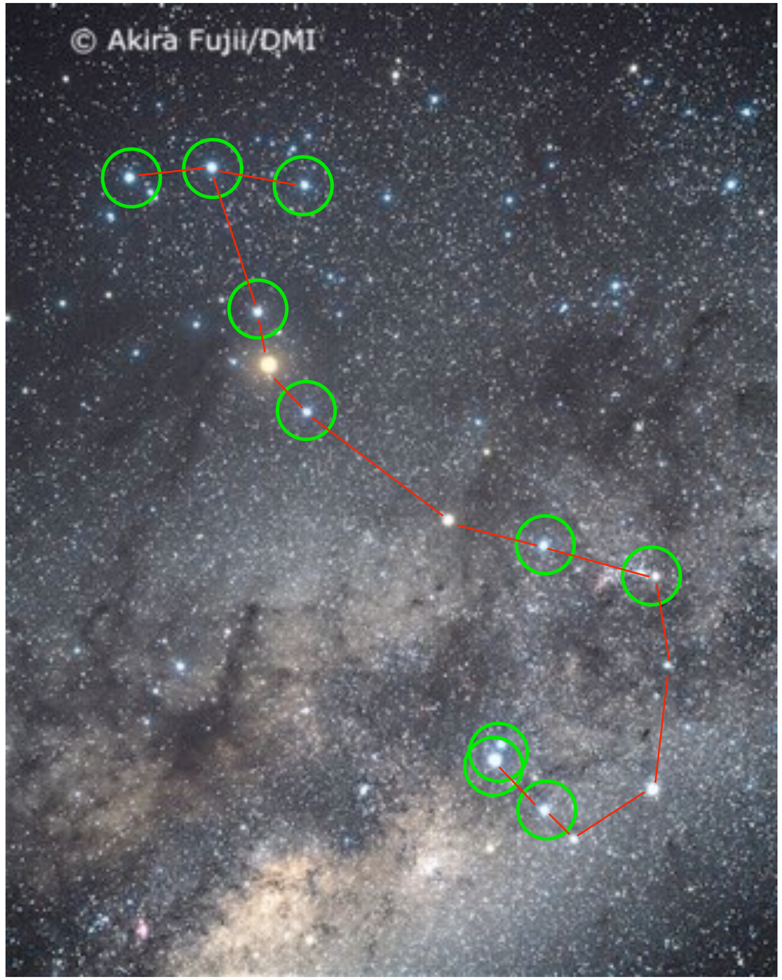


The hottest stars: B and O stars

Nearly at the head of the main sequence, we reach the B stars, which are extremely common when we look at the night sky. More than a third of the hundred brightest stars are B stars.

Some of the bright B stars in the sky include α and β Crux, the two brightest stars in the Southern Cross, most of Scorpio, and four of the seven stars in Orion.

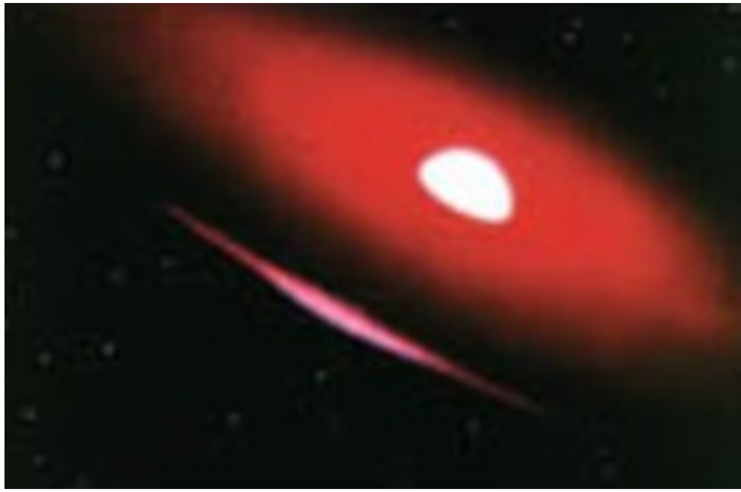




But B stars are not common: there is only one B star for every 500 M dwarfs. We see so many because they are so bright that we see them over large distances. B stars (and their cousins, the O stars) tend to clump together in OB associations, like Orion, or young clusters, like the Pleiades. Faint blue wisps around the stars are light-reflecting dust left-over from the birth of the stars; these are known as *reflection nebulae*.

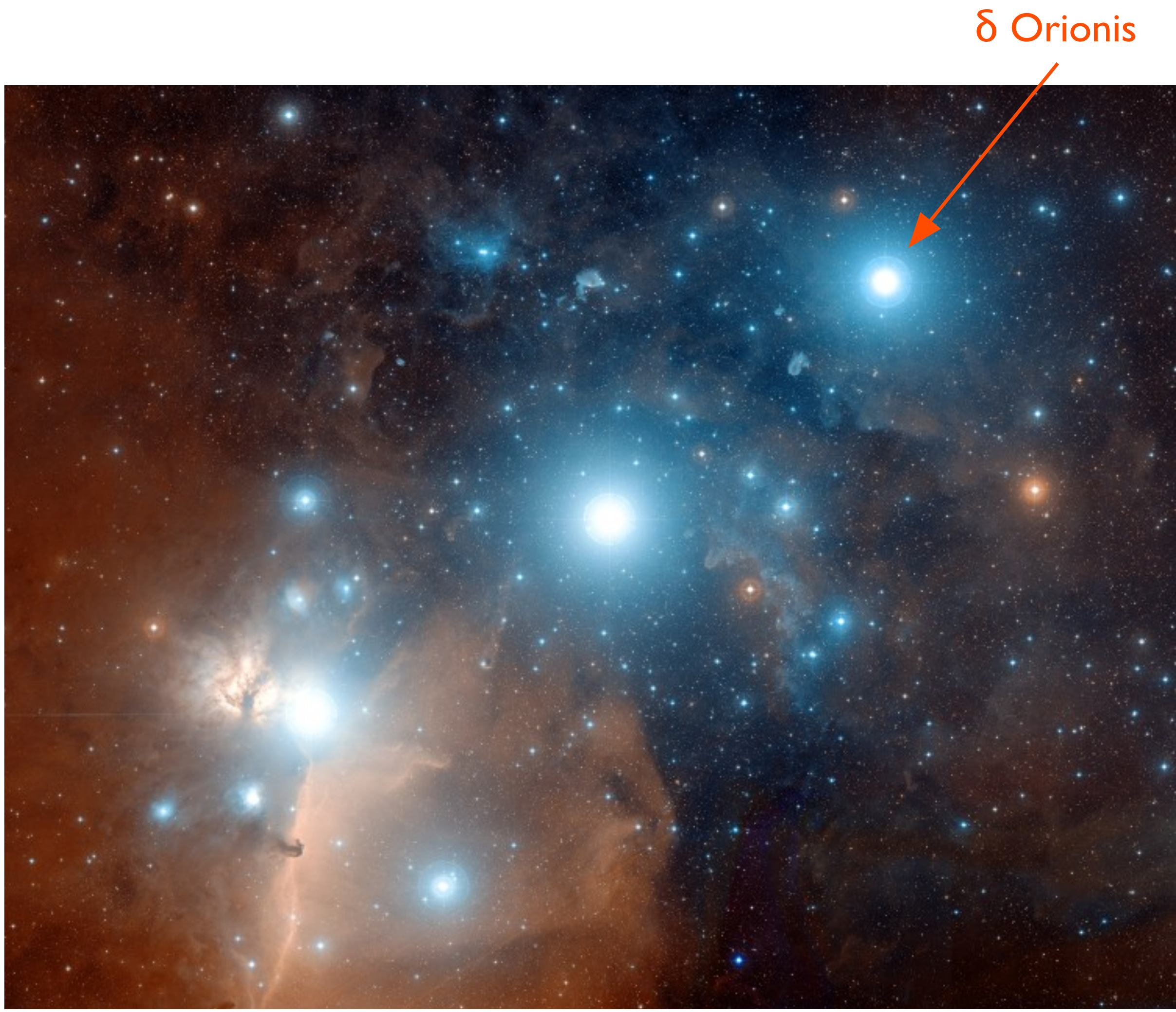
B stars span an enormous range of mass (from 3 to 20 times the mass of the Sun) and temperature (from 10,000 K to 30,000 K). Their spectra show hydrogen beginning to fade, while helium, which holds on to its inner electron more strongly than any other element, begins to be visible.

About 20% of B stars show strong emission lines. These stars, called *Be stars*, rotate so rapidly – over 200 km/s – that material spins off the surface and forms an equatorial ring around the star, which radiates emission lines.



O stars are the rarest of all stars: there are 1.7 million M stars for every O star in the Galaxy.

Because of their rarity, there are no O stars close to us. The eastern-most star in Orion's belt, δ Orionis, is an O9 main sequence star (its neighbour, ζ Orionis, is an O supergiant).

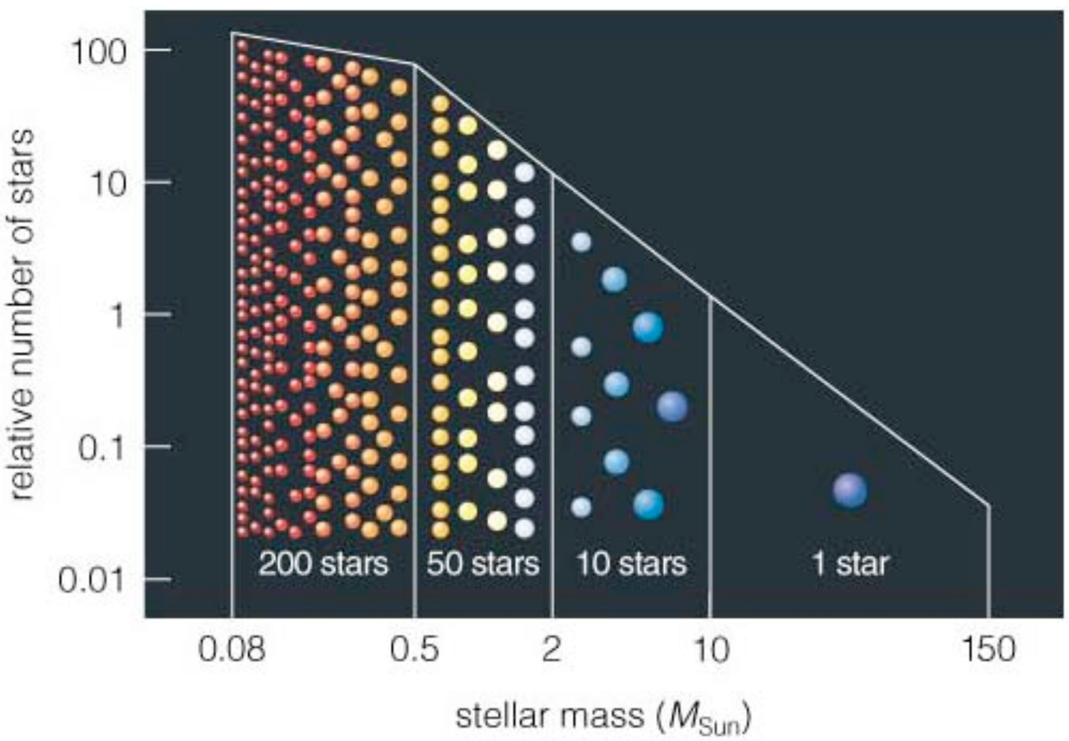


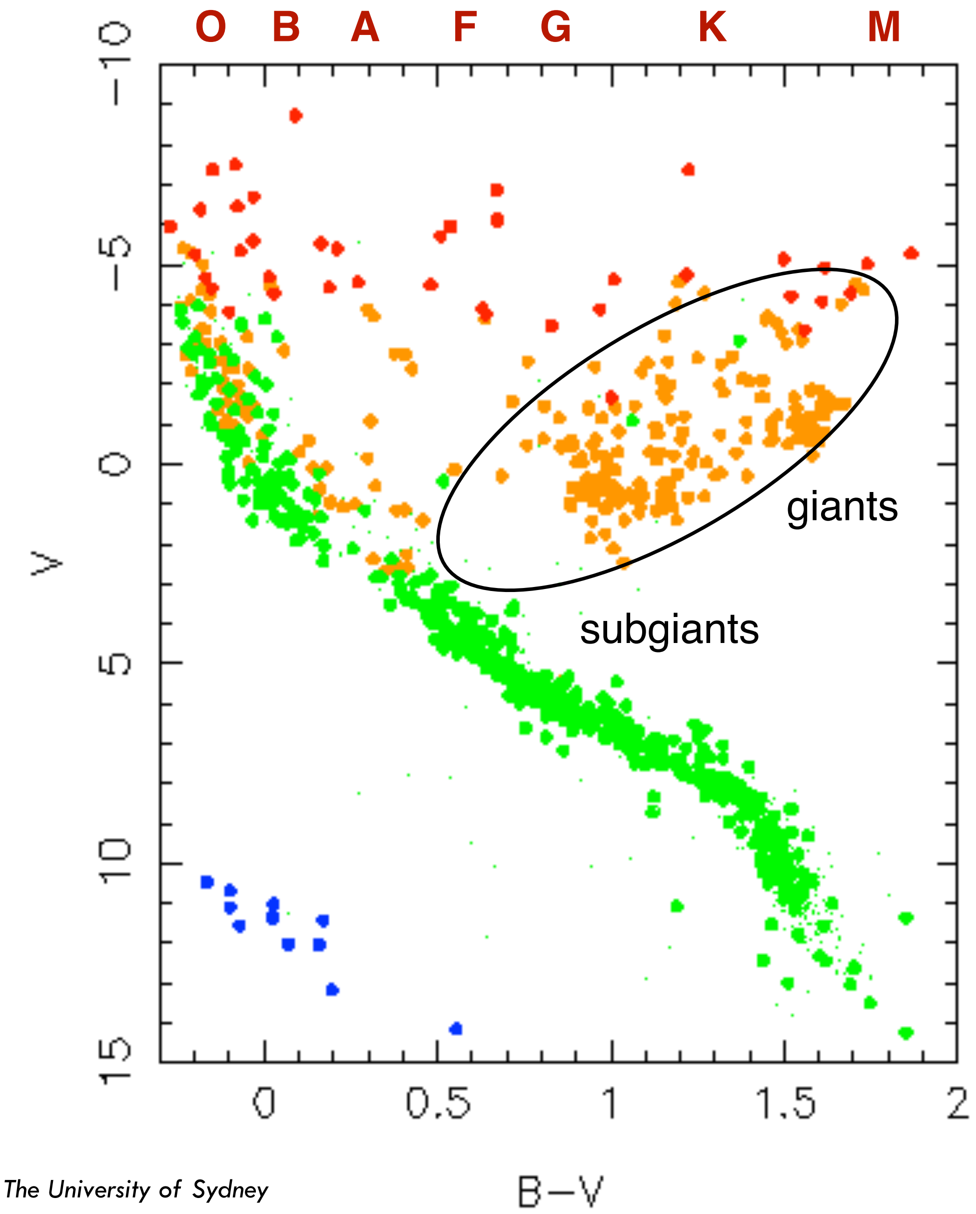
Most dramatically, O stars produce *emission nebulae*, or *OII regions*, which are some of the most beautiful objects in the sky. O stars produce enough photons below 912 Å, which is the energy needed to ionise hydrogen, that they ionise all the hydrogen gas around them, surrounding themselves with a bubble of hydrogen plasma, which glows as the re-combining electrons emit Hα photons.

We have reached the end of the main sequence. Here is a summary of useful numbers for the various classes.

class	% of stars	mass (solar masses)	temperature (K)	size (solar radii)
O	0.00004	20–100	28,000–50,000	12–25
B	0.1	4–20	10,000–28,000	4–12
A	1	2–4	7500–10,000	1.5–4
F	4	1.05–2	6000–7500	1.1–1.5
G	9	0.8–1.05	4900–6000	0.85–1.1
K	14	0.5–0.8	3500–4900	0.6–0.85
M	72	0.08–0.5	2000–3500	0.1–0.6

The number of stars of each mass (at birth) is called the initial mass function. As shown in the table, it is an extremely steep function of mass: as the mass of the star increases by a factor of 10, the number of stars goes down by nearly 250. However, at the low end the curve can't keep going up forever, and finding at what mass the mass function peaks is an active research question.



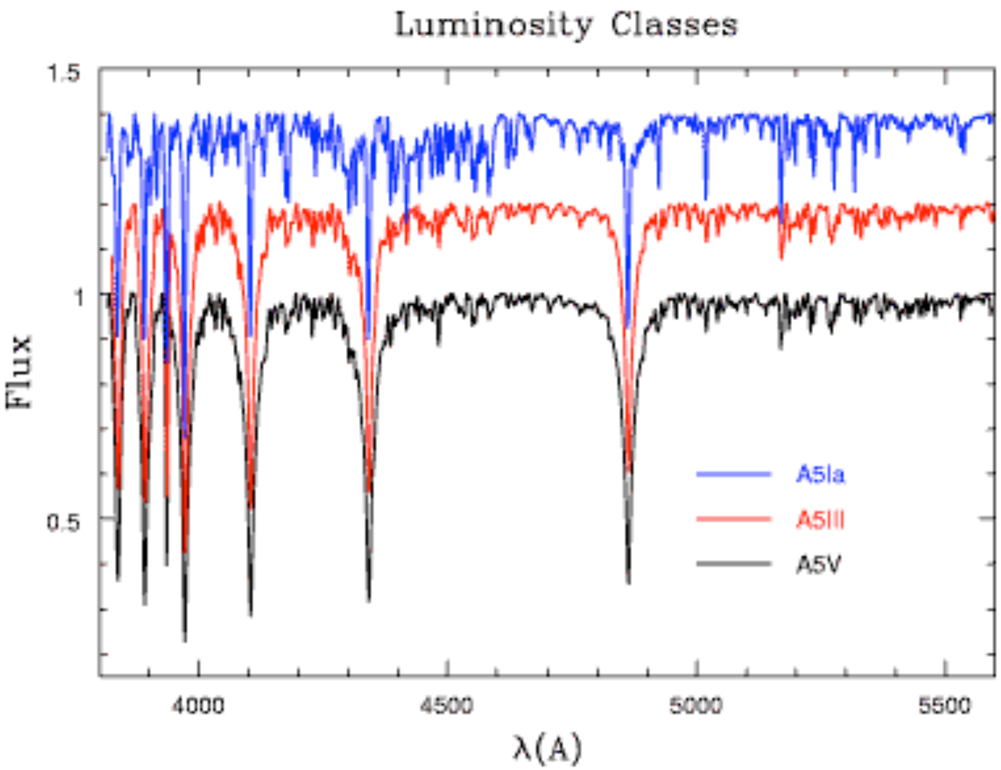


Giants

The *giant* stars form a group to the right and above the main sequence. Stars between giants and the main sequence are called *subgiants*.

Although giants are cool, they are much brighter than stars like the Sun because they are large – 10 to 100 times the size of the Sun.

Red giants form the most distinct group. They have spectral types M through G, but are several magnitudes brighter than their main counterparts. They can be distinguished because the spectral lines are much narrower than in dwarfs, implying lower surface gravity.

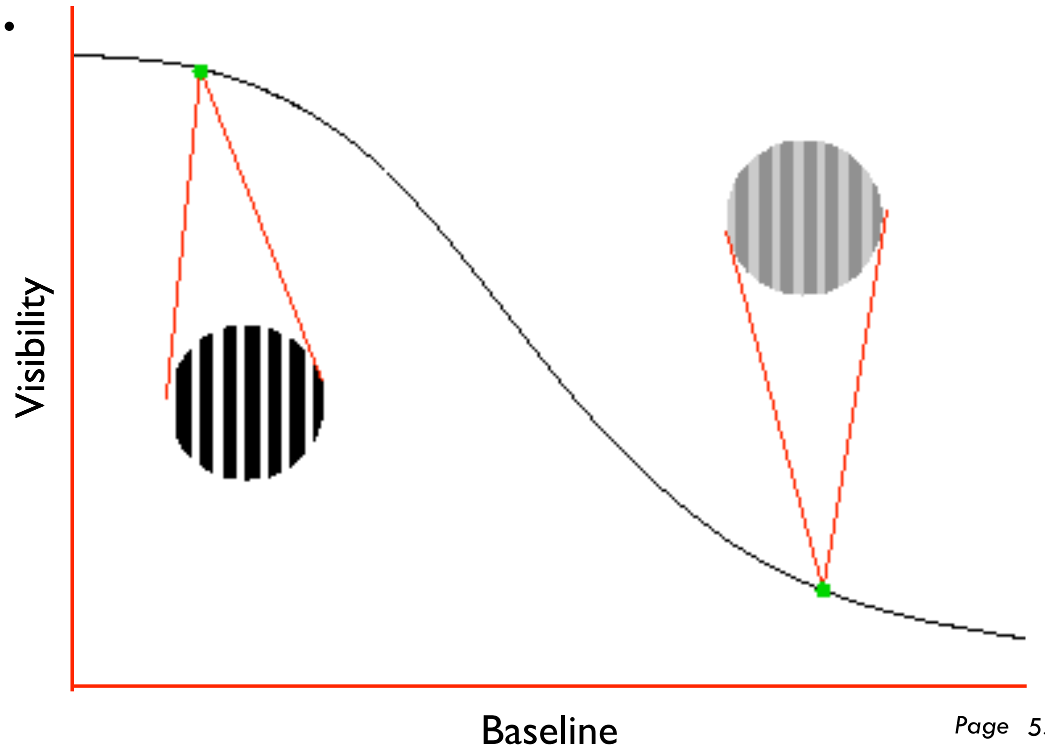


Giants are large enough that their sizes can be measured directly.

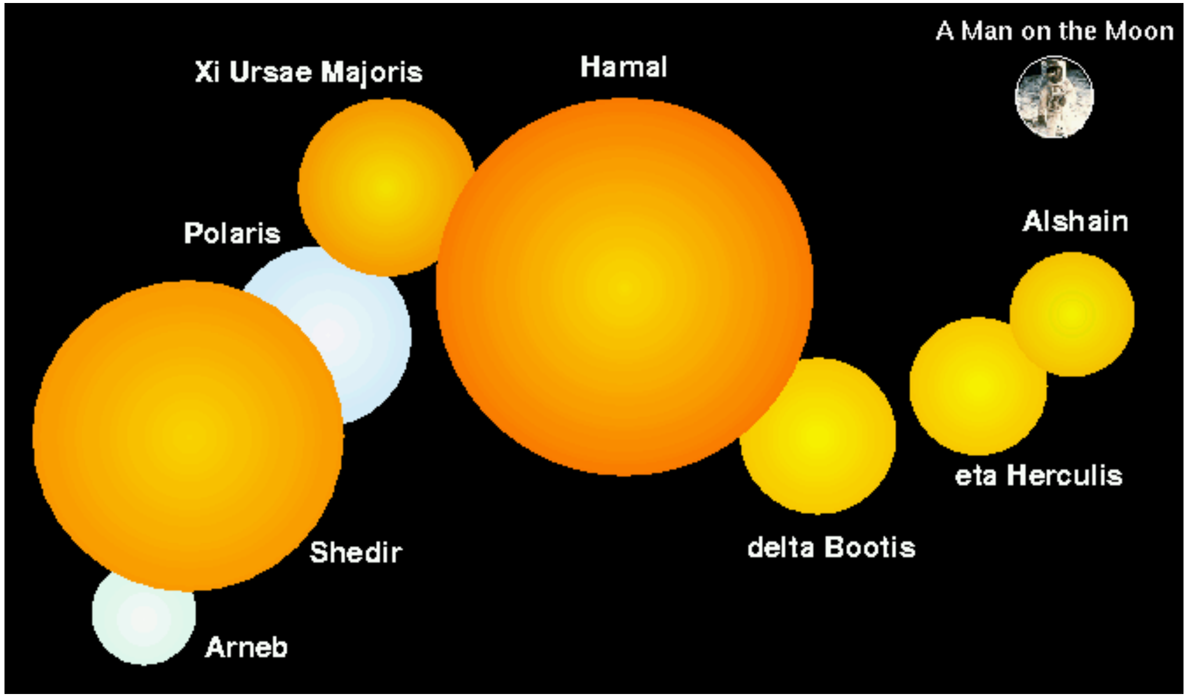
This is done using *interferometers*, which overcome the blurring effect of the Earth's atmosphere by combining the light from two separate beams, yielding the same resolution as a telescope the size of the baseline of the interferometer.

SUSI, the Sydney University Stellar Interferometer at Narrabri, NSW.

An interferometer does not form an image; instead, the two beams *interfere* with each other, producing light and dark strips called *fringes*. The contrast between the light and dark fringes (the *visibility*) changes depending on the size of the star and the spacing between the elements. By measuring how the visibility changes with baseline, the size of the star can be deduced.



Several hundred stars have now had their diameters measured in this way.

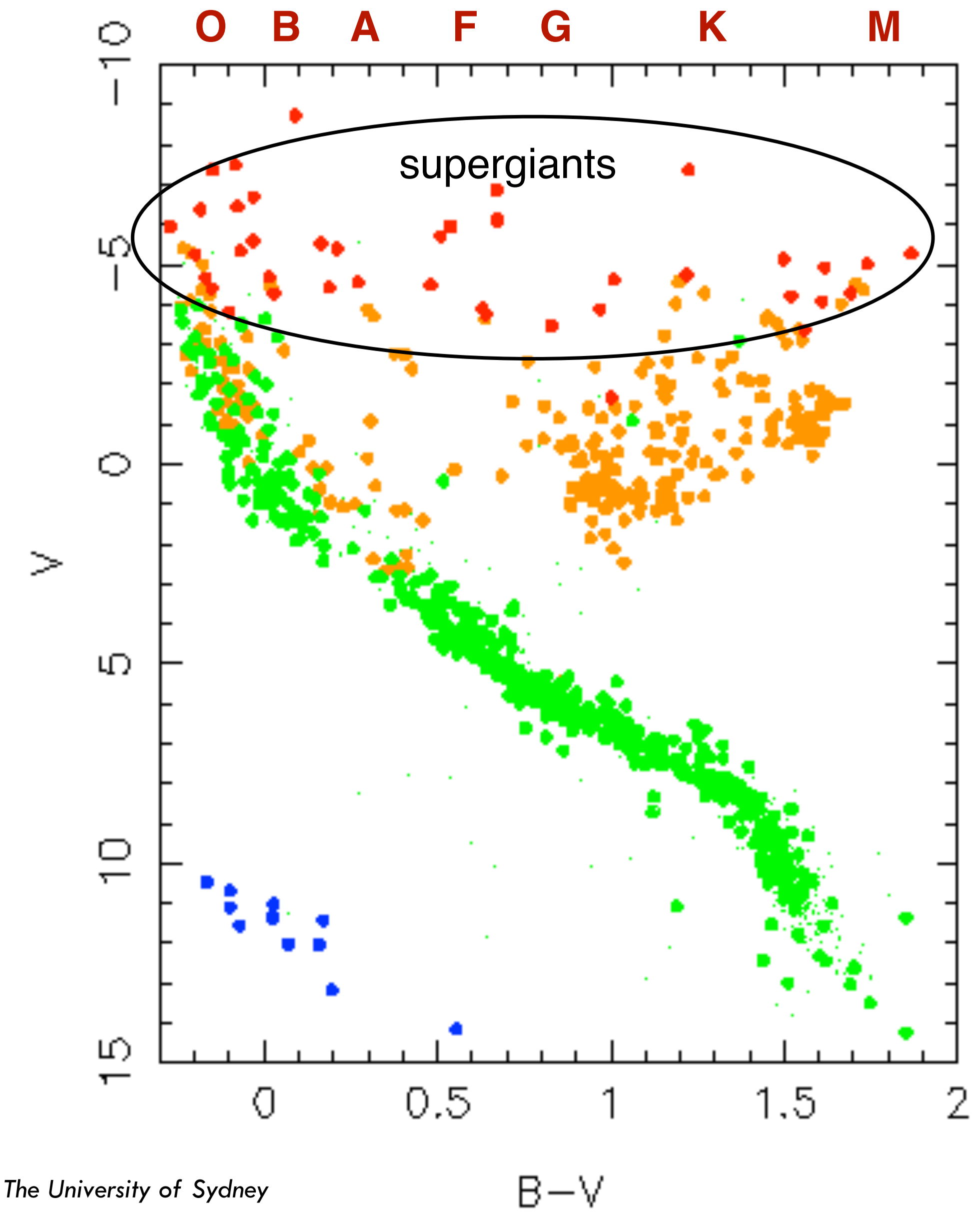


Relative sizes of eight stars with diameters measured using interferometry. The largest star, Hamal, is a K2 giant, and has a diameter of 6.9 milliarcseconds. The man on the moon has a size of 1 milliarcsecond.

The same techniques can also be used to measure the orbits of binary stars, the pulsations of Cepheid variables, and the sizes of structures like dust shells around stars.

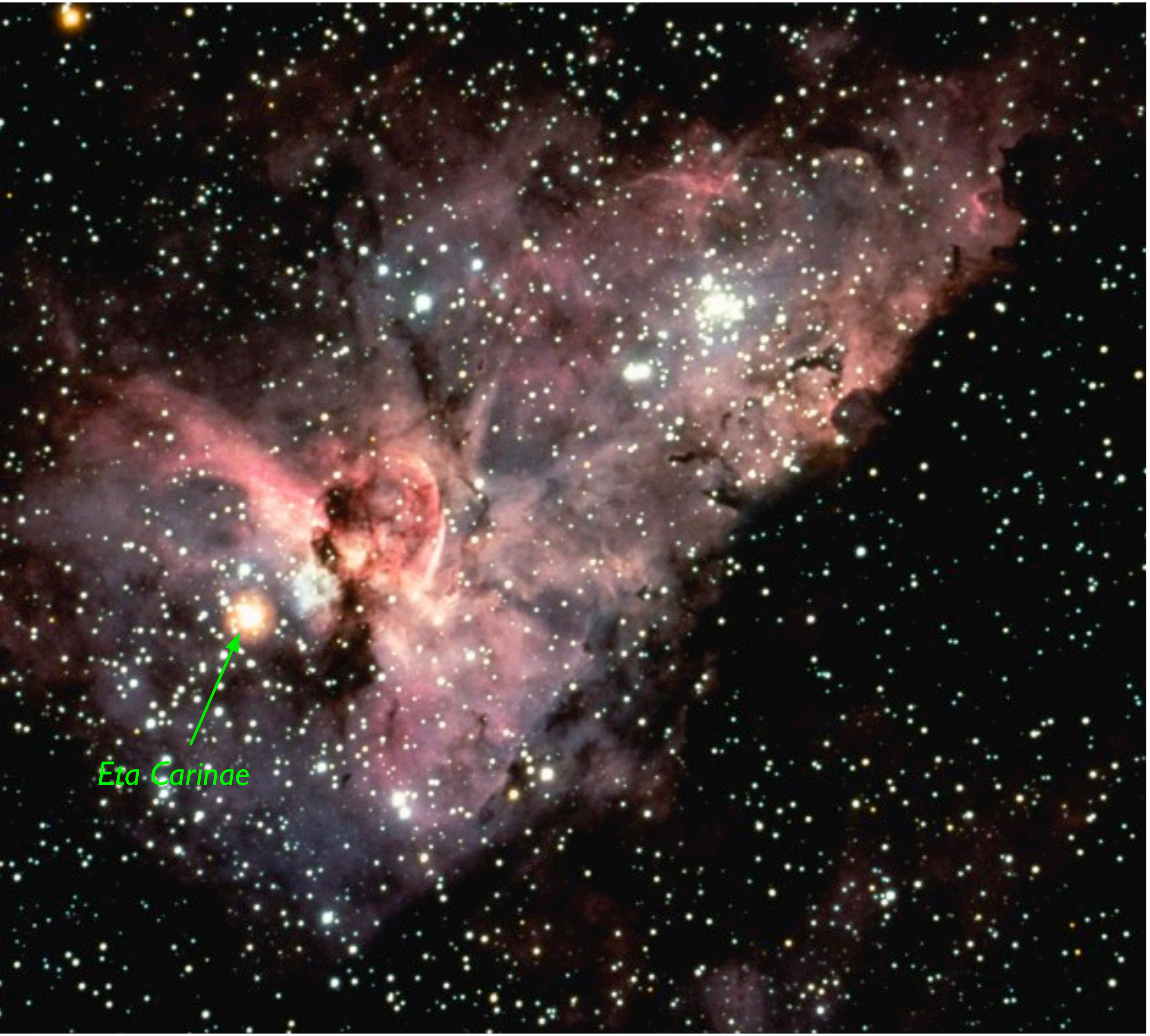
A subset of red giant stars have much more carbon than oxygen in their spectra: the *carbon stars*. They tend to be noticeable because of their strong red colour. These stars appear to be dredging carbon from their cores to the outside through convection. We are seeing evidence that stars actually change their composition as they age.

Infrared image of the carbon star IRAS 06088+1909



Supergiants

The *supergiants* span the whole colour range from blue to red. They have roughly comparable brightness across the whole range, so the sizes of the cooler stars must be enormously larger.

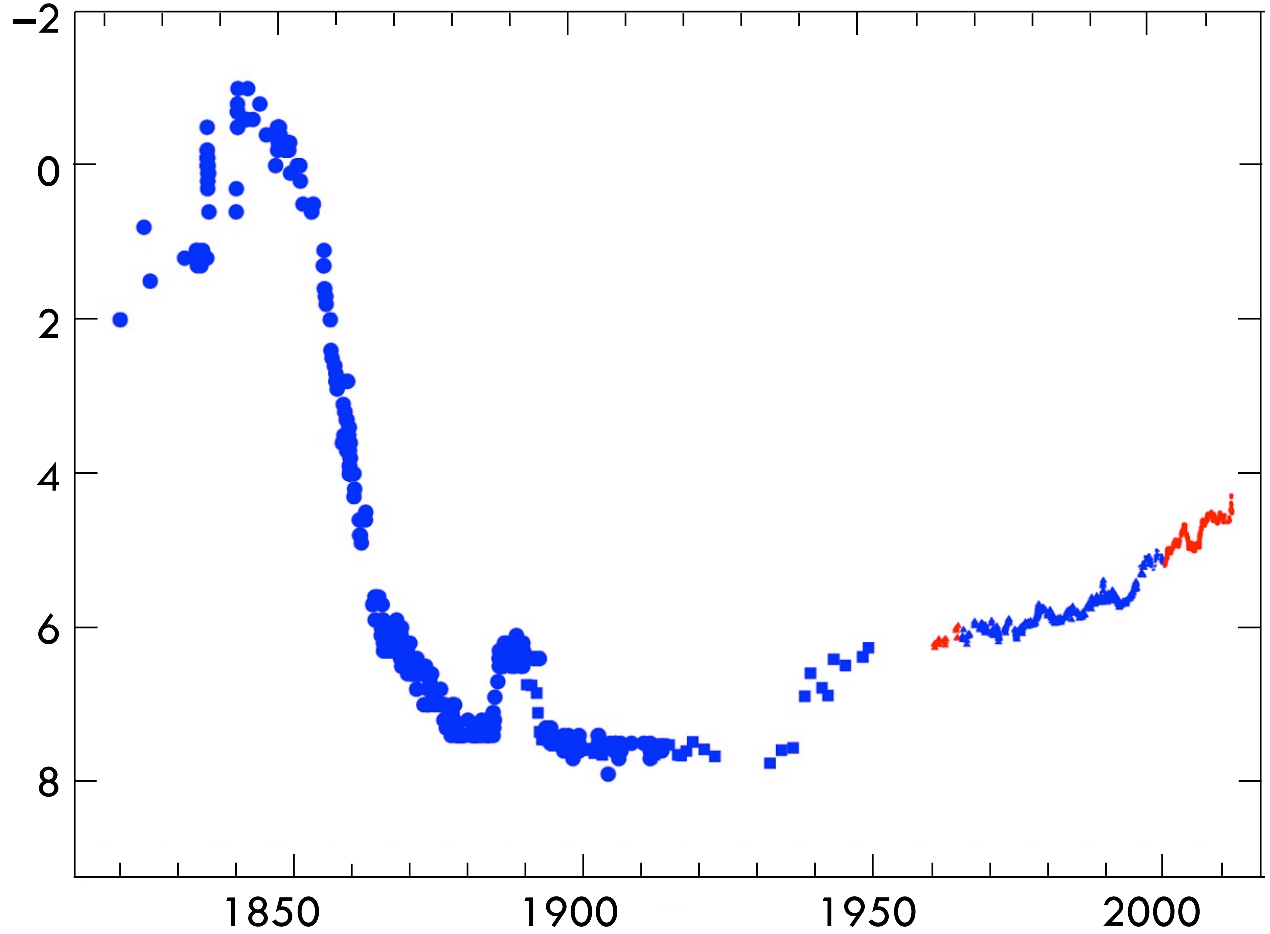


The blue supergiants are the brightest stars in the Galaxy. The brightest star in the Galaxy, allowing for the radiation in the ultraviolet, is an O3 supergiant called HD 93129A.

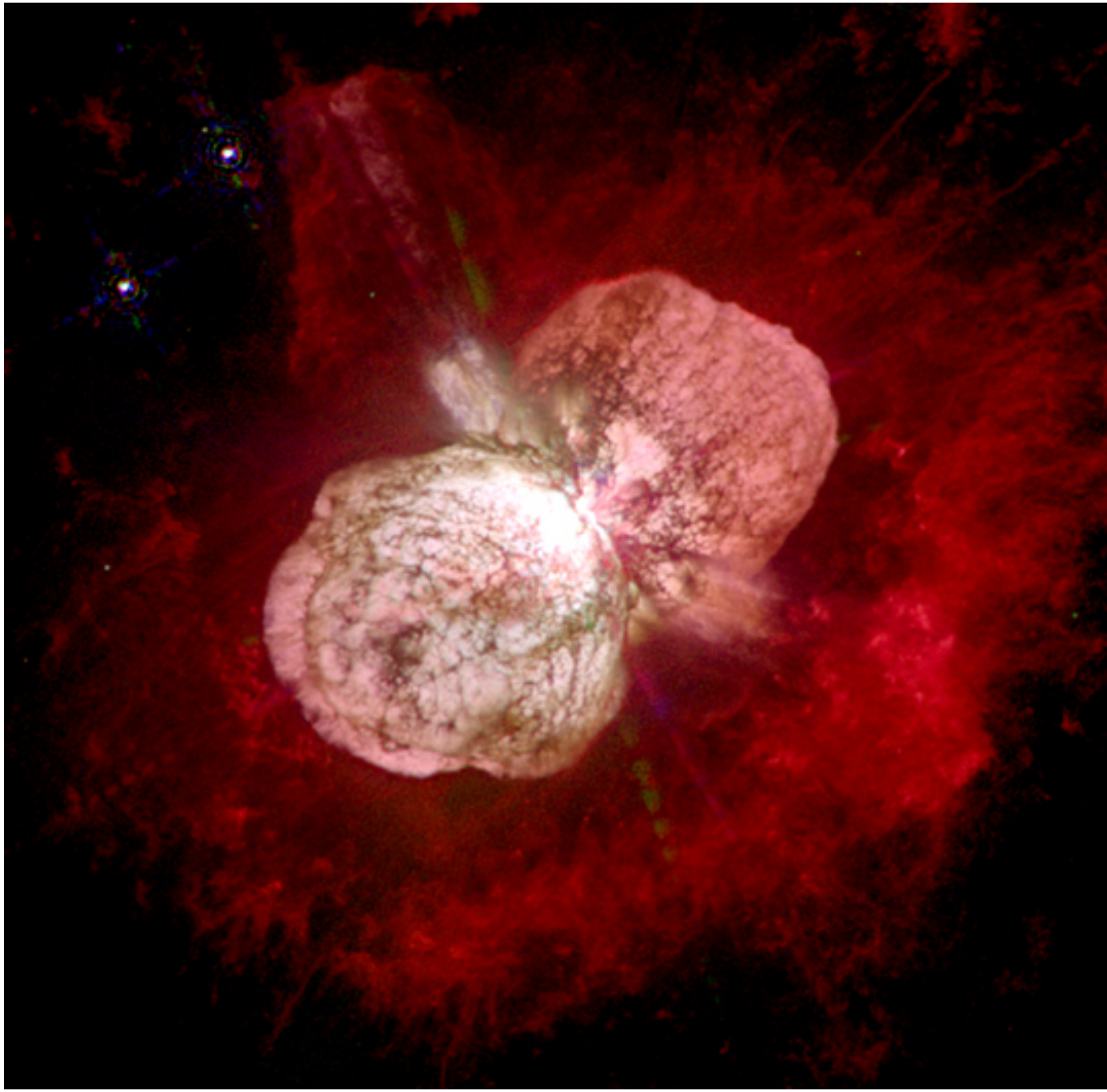
The center of the Eta Carinae Nebula. HD 93129A is the brightest star in the cluster at the upper right.

A close-up of the Keyhole Nebula and Eta Carinae.

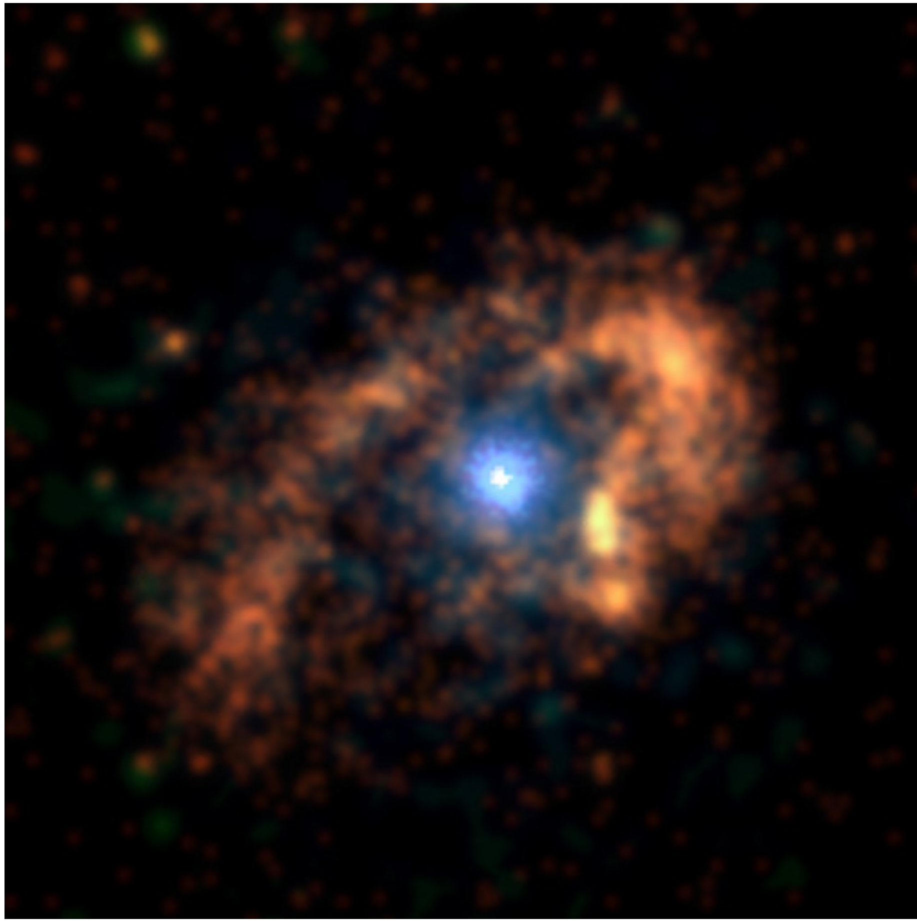
Only marginally fainter is Eta Carinae, a blue "hypergiant" in the centre of the vast Carina nebula. Eta Carinae is a *luminous blue variable* star. Before 1840, it shone with apparent magnitude 3, then it started to brighten, until by 1848 it shone at −1, one of the brightest stars in the sky. It then dropped to 8th magnitude, then began to brighten again, and is now at magnitude 4.5.



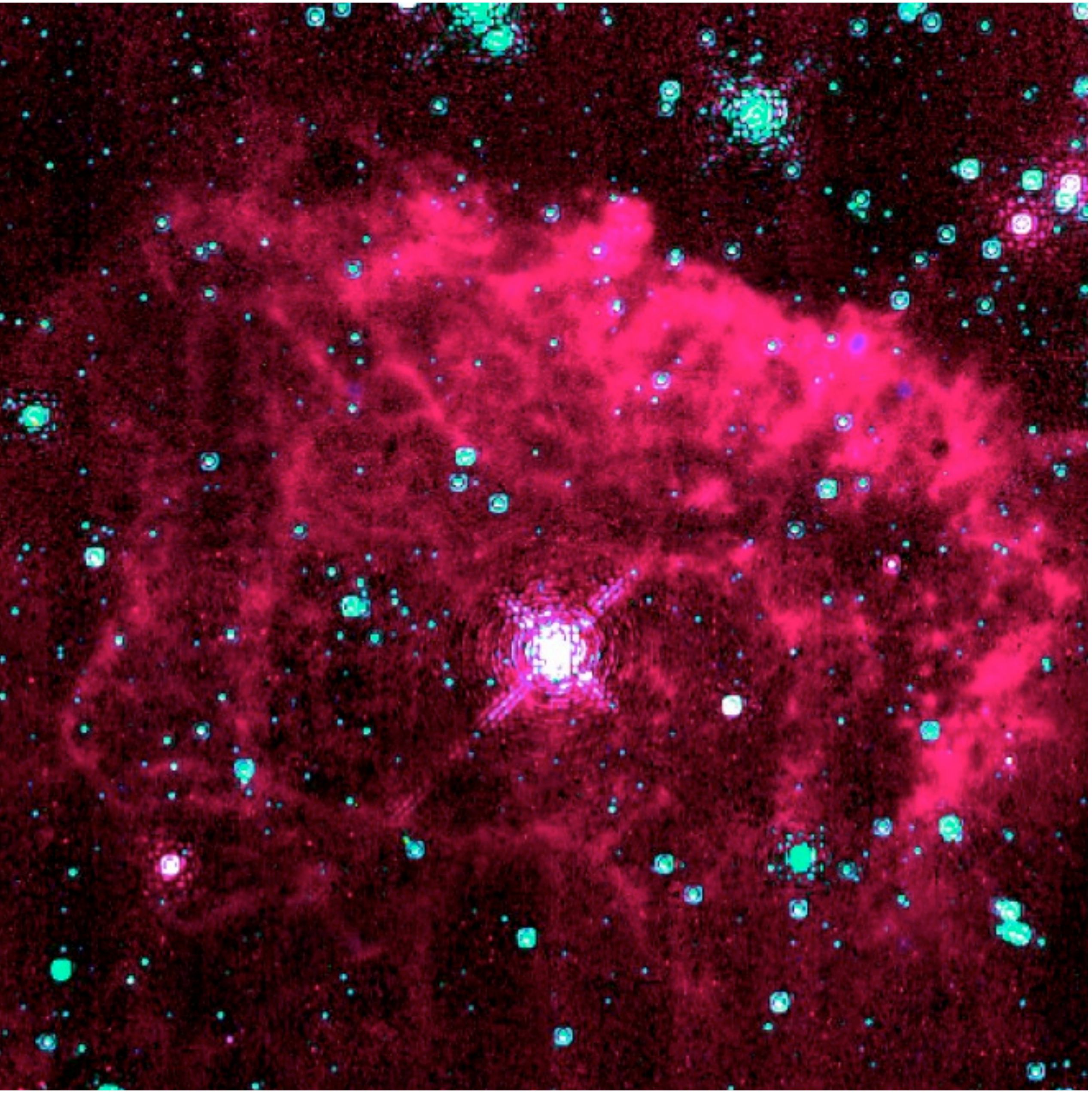
Hubble images show the star is surrounded by two enormous bubbles of gas, threaded by black dust lanes. These pictures suggest that 150 years ago the star erupted in a huge wind, during which it lost a solar mass of material; the cooling cloud of gas now hides the star, dimming its light.



X-ray images from Chandra show a hot central source (the superstar), a hot inner core about 3 light months in diameter, and an outer ring about two light years in diameter. This must be the remnant of another large explosion more than a thousand years ago.



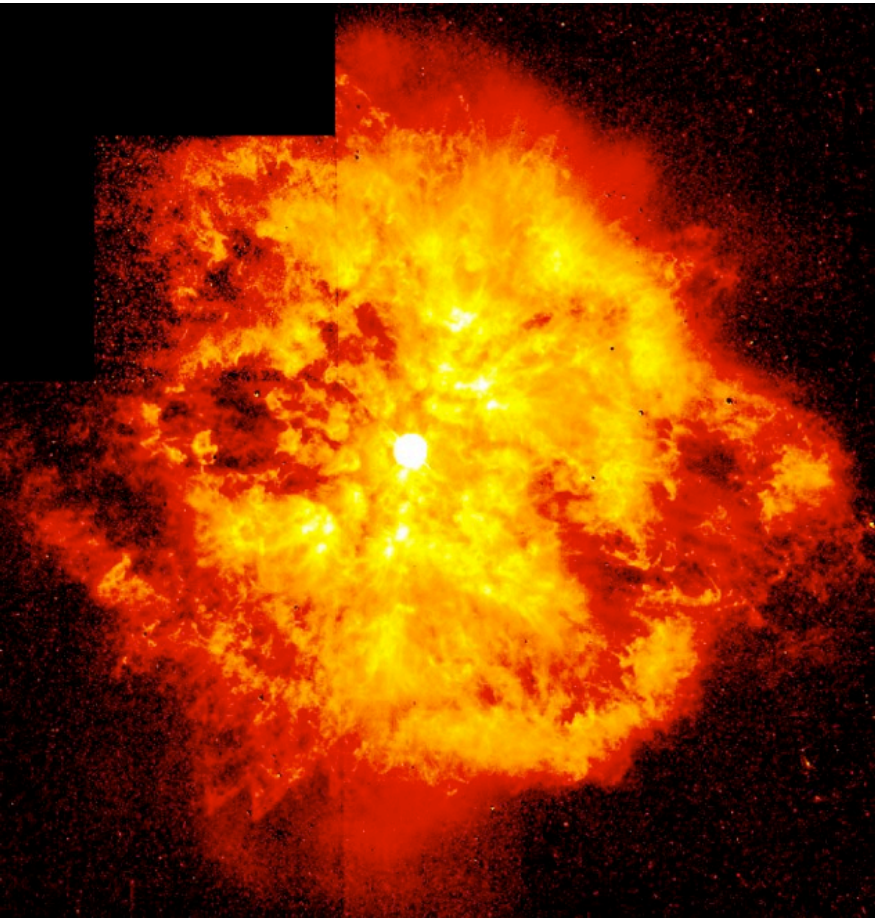
There may even be a binary companion in the system, in which case it was probably the more evolved (hence heavier!) companion which lost all the material.



Stars as massive as Eta Carinae, and the “Pistol Star” discovered by HST, shine so brightly that the pressure of the radiation they produce is tearing the star apart.

Infrared image of the “Pistol Star”, which lies in a small cluster of stars near the Galactic Centre. The star is about 100 times the mass of the Sun; the surrounding nebula is formed from mass lost from the star.

All very massive stars have large winds. Wolf-Rayet stars may be the remnants of luminous blue variable stars. These stars are hot supergiants with strong winds, but their spectra are very bizarre, with almost no hydrogen. They appear to have completely lost their outer layers, leaving the underlying layers exposed.



HST image of the Wolf-Rayet star WR124, showing the star surrounded by hot clumps of gas being ejected at high speed.

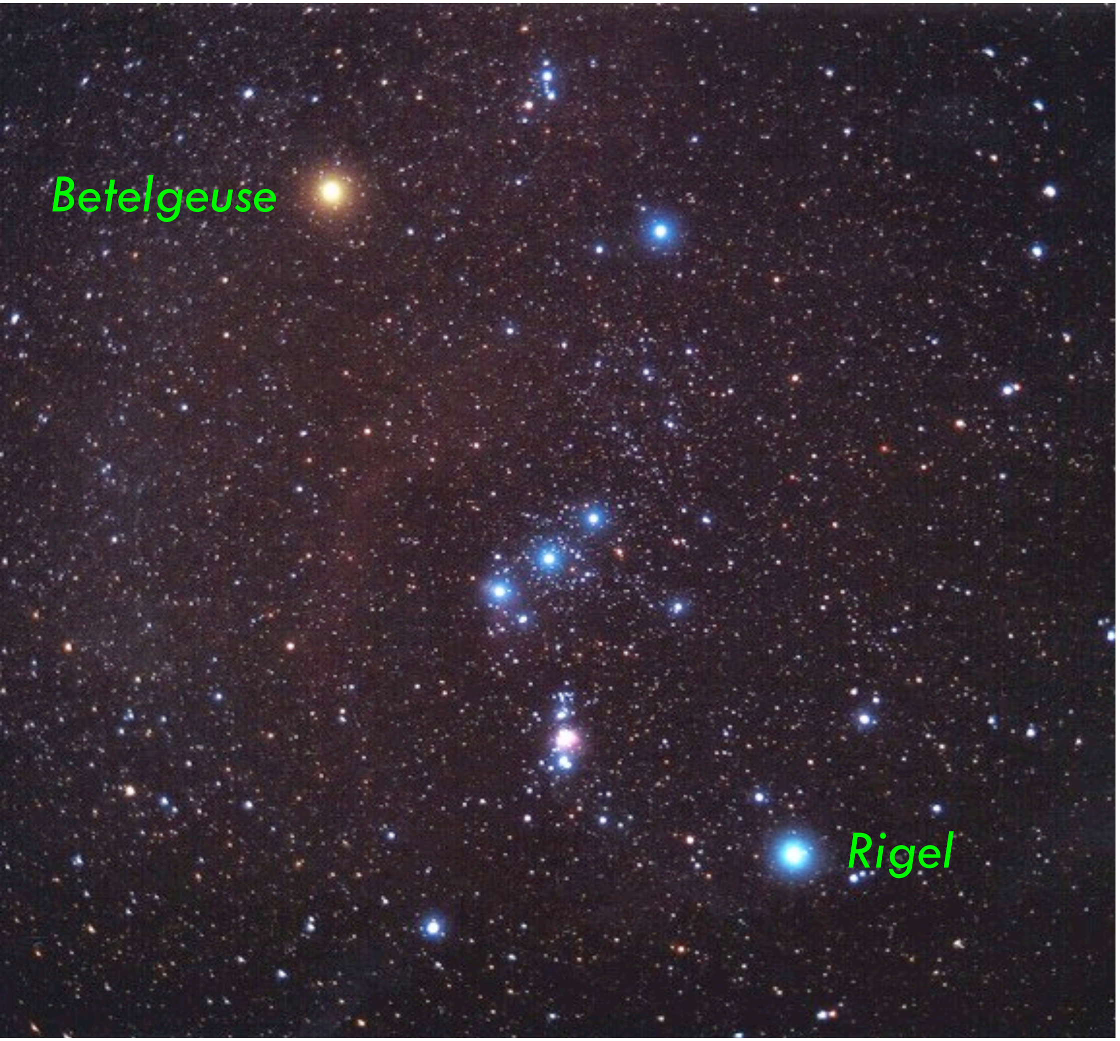
The enormous amount of matter lost from Wolf-Rayet stars is often visible as a grand nebula, illuminated by the hot star within.

“Thor’s Helmet” (NGC 2359), a bubble-like nebula blown from the hot Wolf-Rayet star in its centre.

The Bubble nebula (NGC 7635) is the boundary between an intense wind from the central O giant star and the dense cloud.

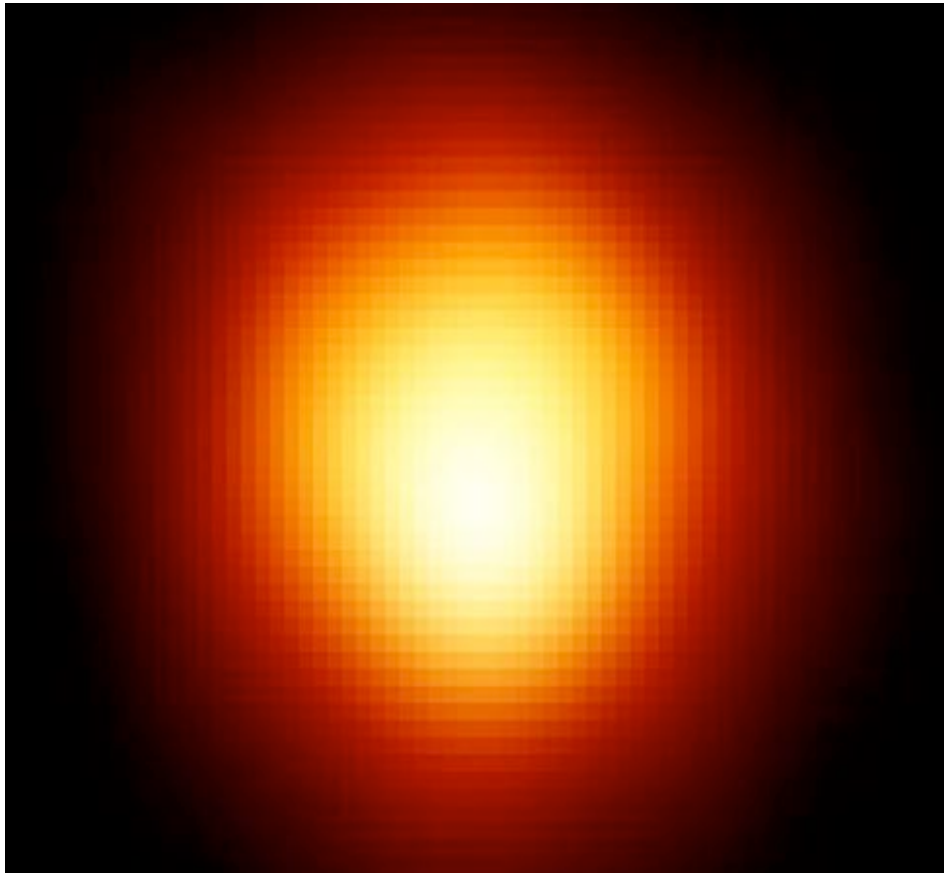

This HST image of the Bubble Nebula shows the O star, which is about
40 times the mass of the Sun.

The *red supergiants* are the largest stars in the Galaxy. In Orion, Rigel is a blue supergiant, while Betelgeuse, the brightest star, is a red supergiant.



In order to be similar brightness, Betelgeuse must be much larger than Rigel.

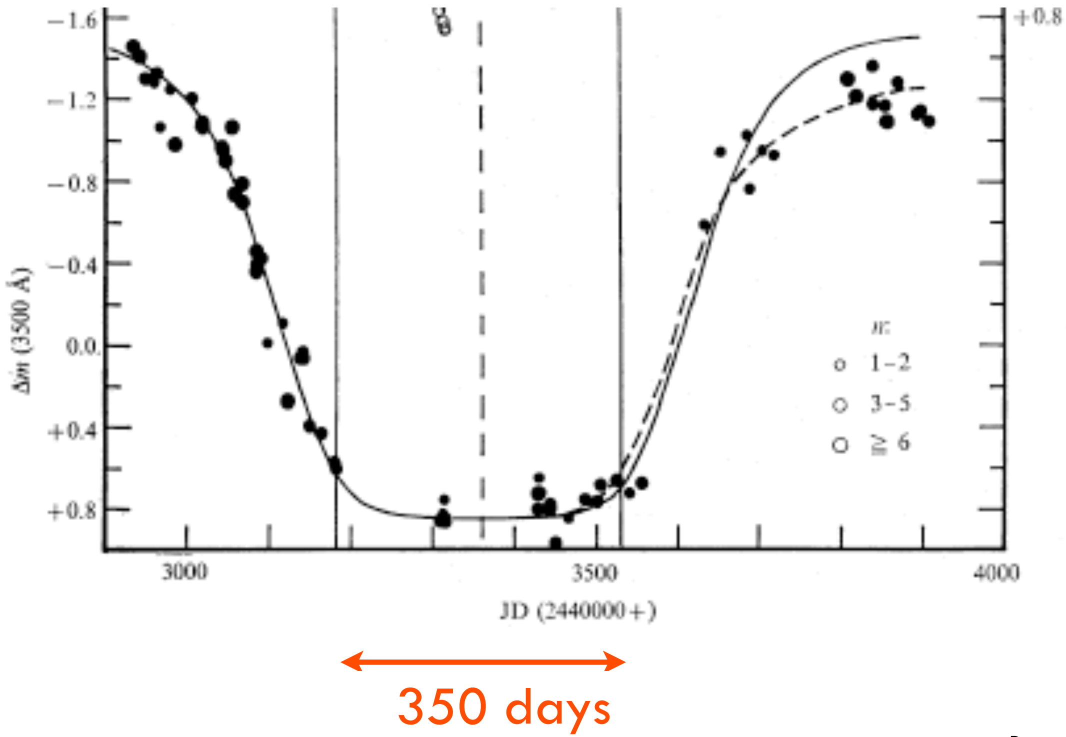
Betelgeuse is one of the few stars which we can resolve with HST. It is 0.05 arcseconds in diameter which, at the distance to Betelgeuse (130 pc) corresponds to 6 AU, or past the main asteroid belt in our solar system.



The largest star visible to the naked eye is μ Cephei, also known as Herschel's "Garnet Star". This star is roughly 4 billion km across; if it replaced our Sun, it would extend beyond the orbit of Jupiter.

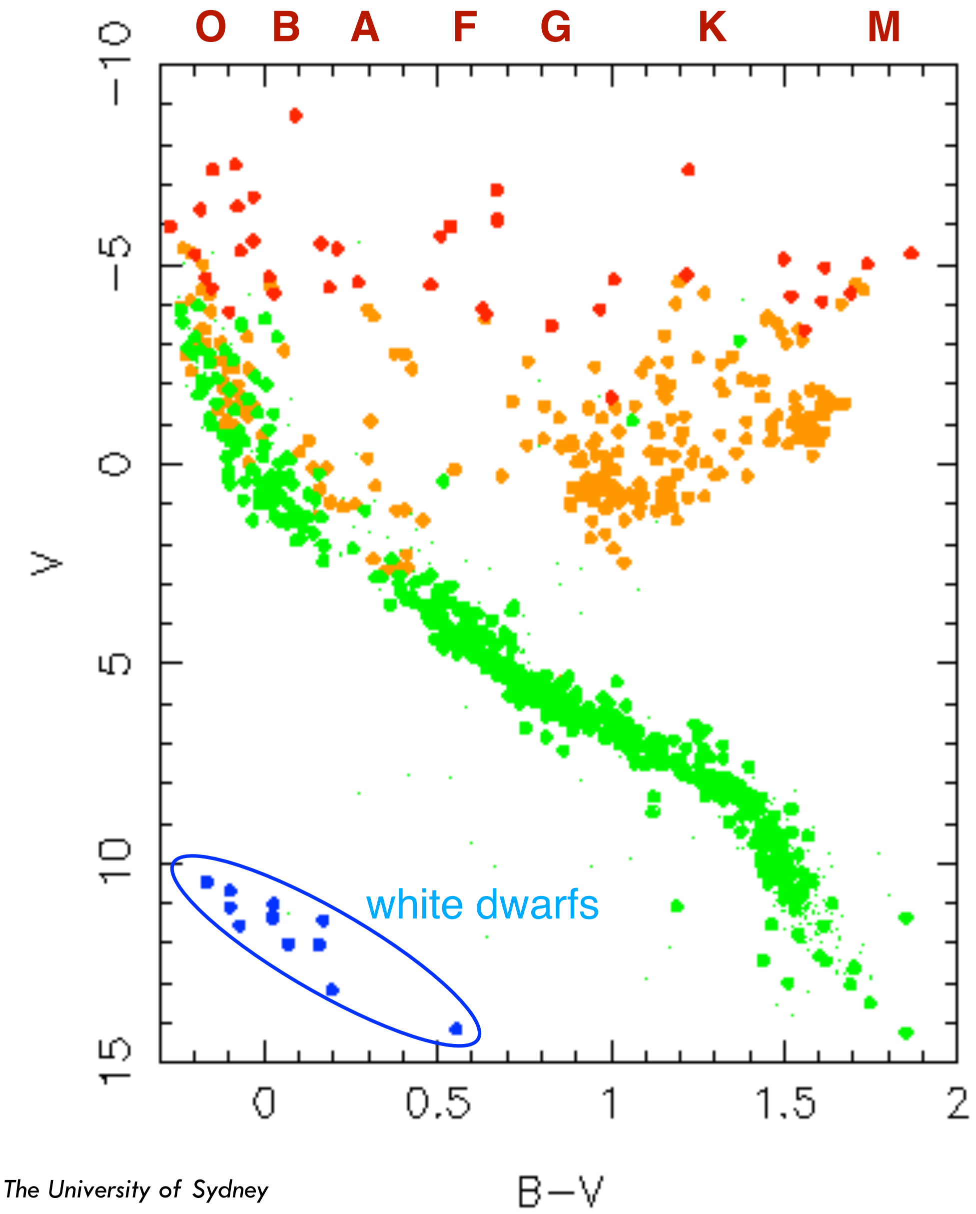
The large, dusty emission nebula IC 1396, with μ Cephei in the upper left.

Even larger is VV Cephei, which is an eclipsing binary consisting of a hot O dwarf and a cool M supergiant. The orbital period is 20 years; when the O star passes behind the supergiant, it disappears for an amazing 1.2 years. This implies it has a radius just smaller than the orbit of Saturn.



Light curve of VV Cephei, showing the dimming of the light from the binary as the O star disappears for over a year.

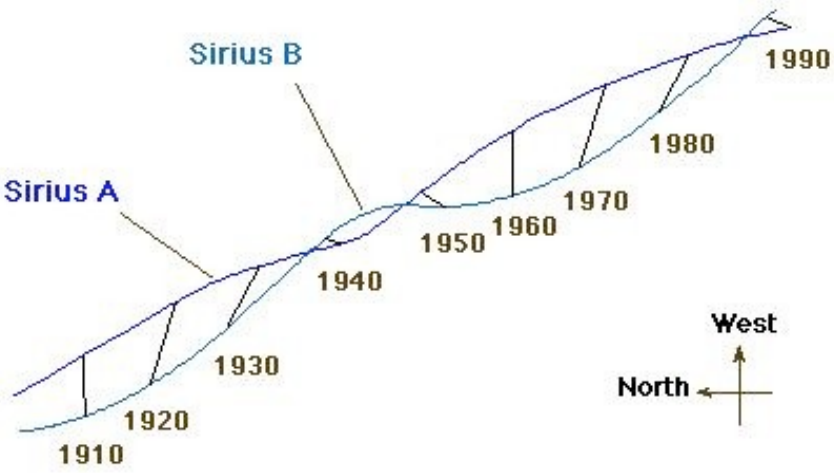
The smallest stars

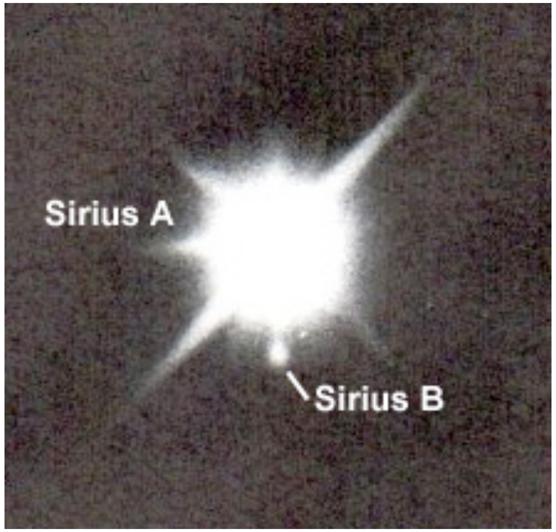


Now let's travel to the other extreme: the realm of the smallest stars.

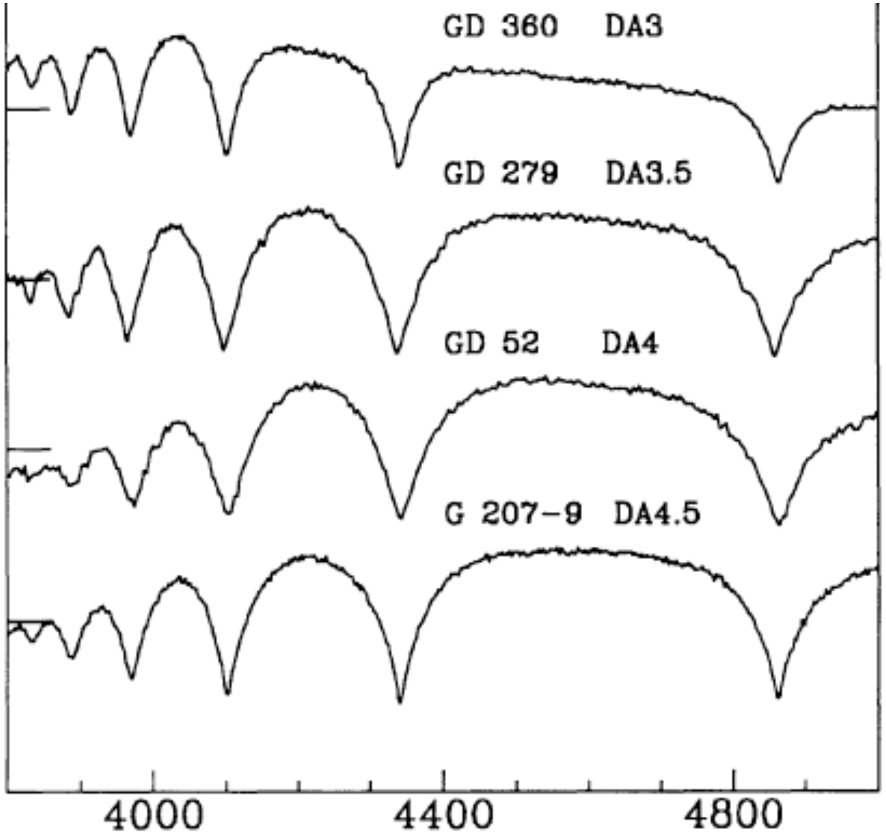
White dwarfs are the remnants of stars like the Sun, after they finish life on the main sequence.

Famous white dwarfs include the companions to Sirius and Procyon – Sirius B and Procyon B. Their existence was suspected when Bessell, in 1844, found that neither Sirius nor Procyon moved through space in a straight line.





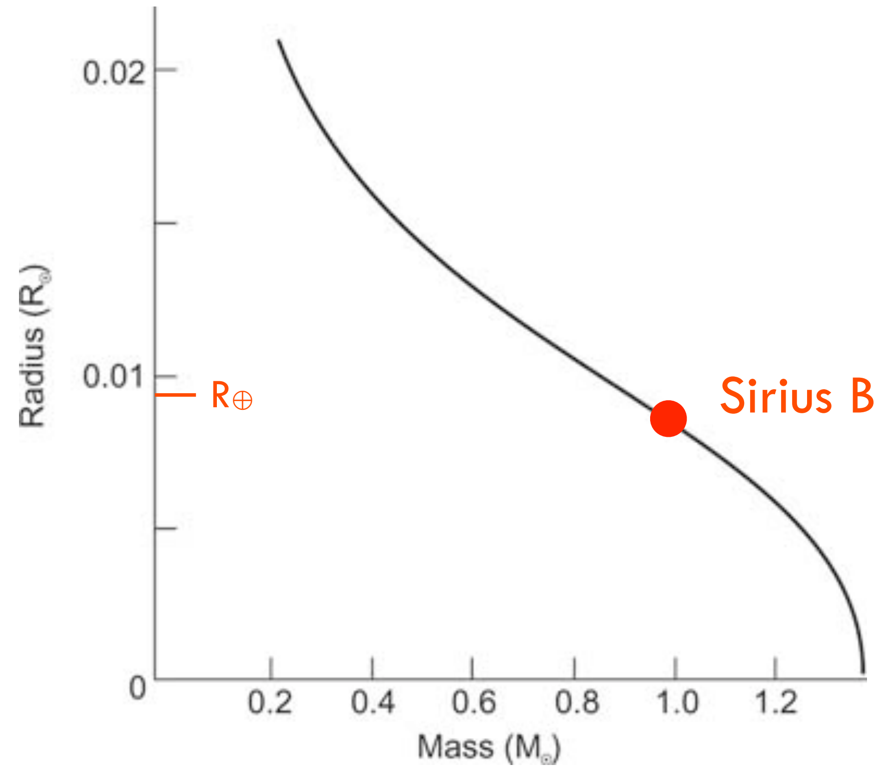
White dwarfs have hot spectra, like A stars, but are enormously fainter. This must mean they are extremely small, with sizes closer to that of the Earth (7000 km) than that of the Sun.



The lines in the spectra of white dwarfs are extremely broad, which is evidence of their high surface gravity.

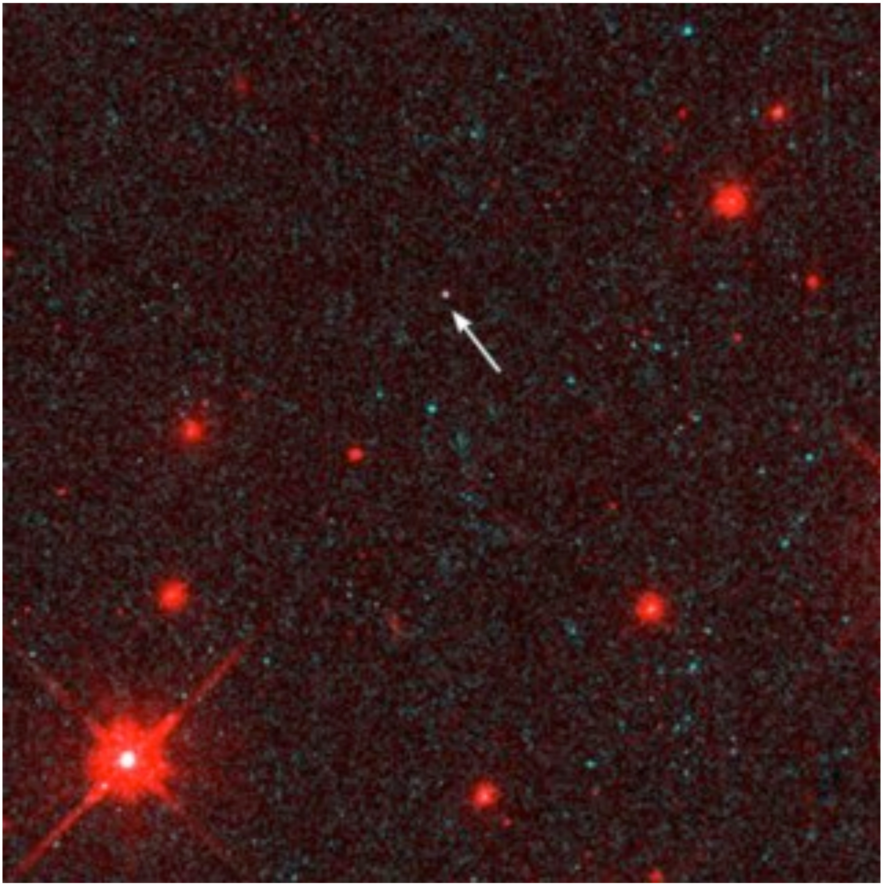
Most white dwarfs have masses slightly more than half that of the Sun, though a few are heavier than the Sun.

Unlike ordinary stars, the more massive a white dwarf is, the *smaller* its size.



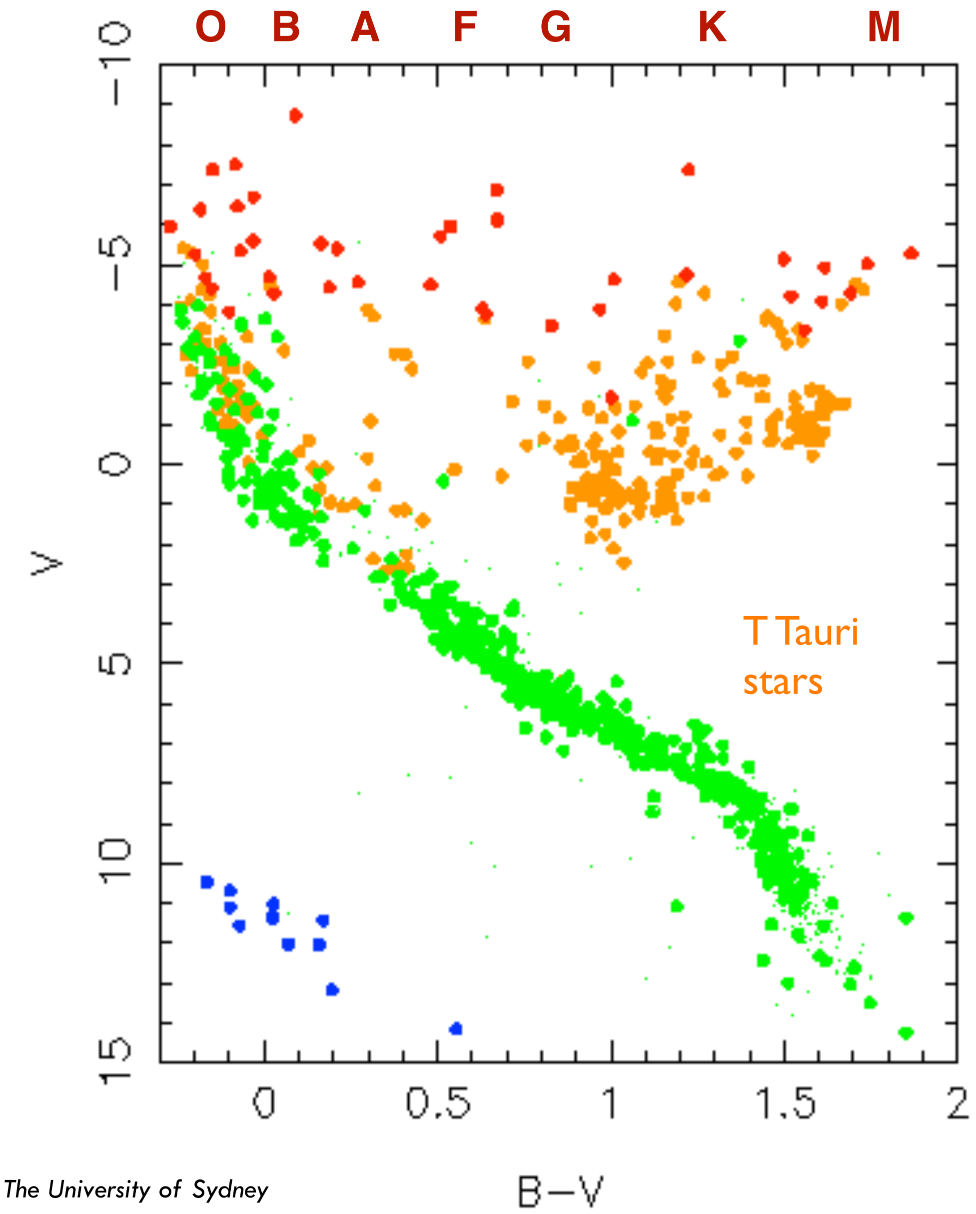
Even smaller...

But white dwarfs are not the smallest stars. Neutron stars are more than 1.4 times the mass of the Sun, and are only 15 km across. We can see a few of them (barely!) using optical telescopes; but most are only known because of the regular pulses of radio waves they produce: the *pulsars*.



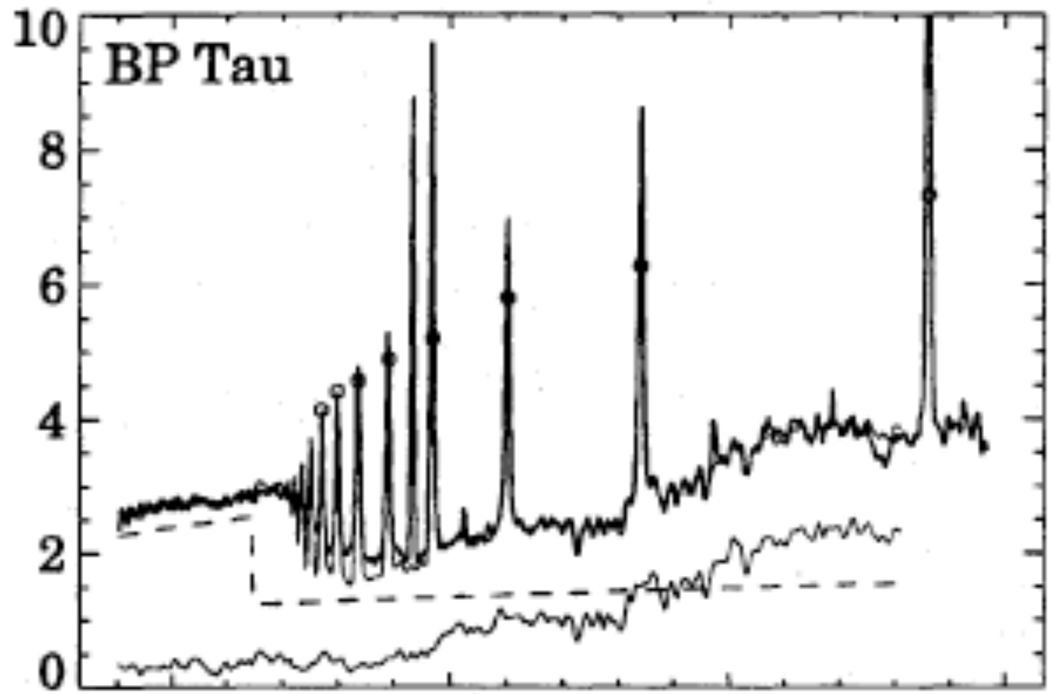
First image of a lone neutron star: HST picture of RX J 185635–374.

Newborn stars

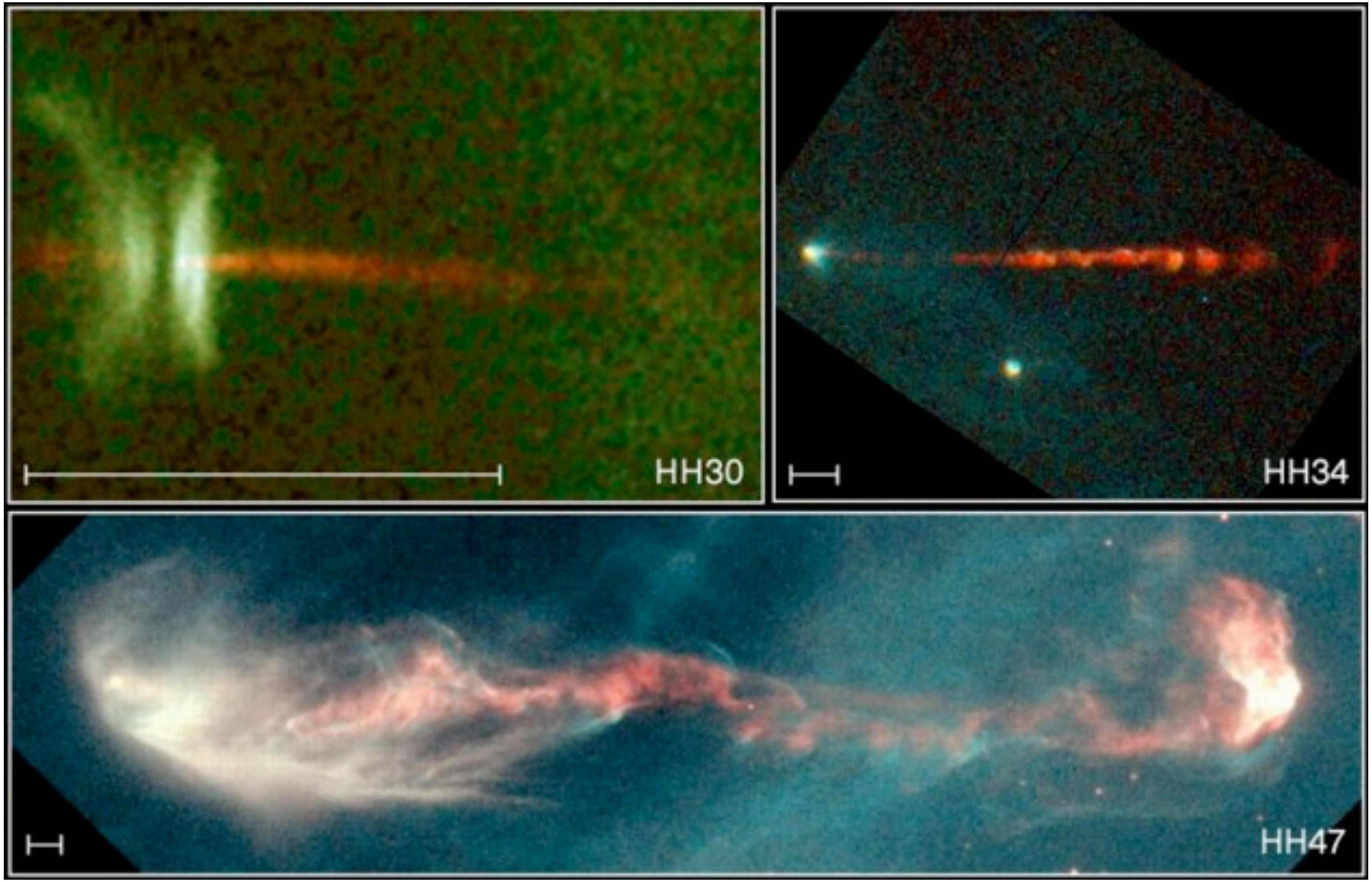


There is a set of stars above and to the right of the main sequence: the *T Tauri stars*. These are stars still in the process of forming from their birth clouds: they have not yet reached the main sequence.

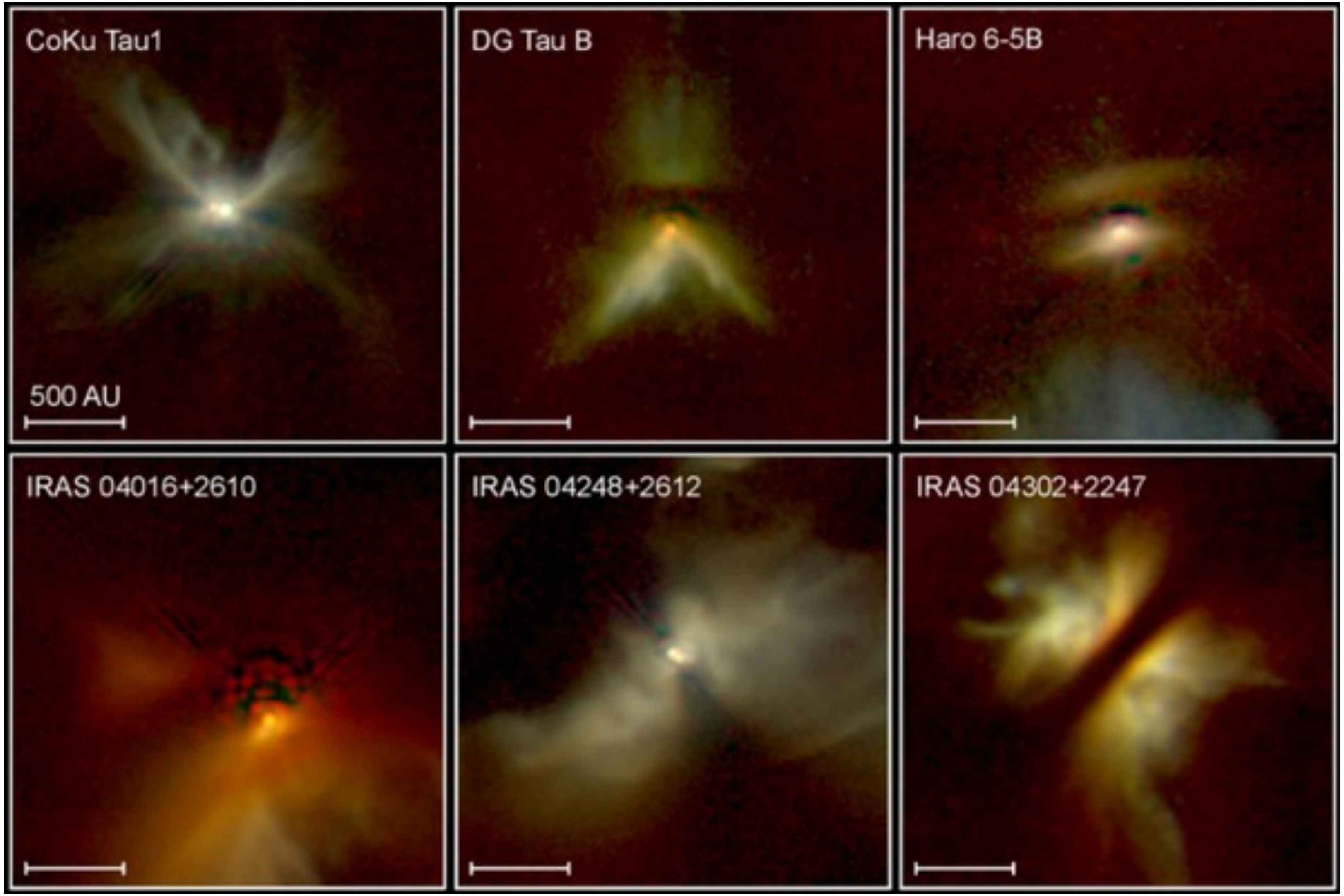
T Tauri stars have G, K or M-type spectra, but with strong emission lines on top, as well as absorption signatures, indicating material is both falling in and being ejected away. They show large infrared "bumps", indicating lots of dust in the system.

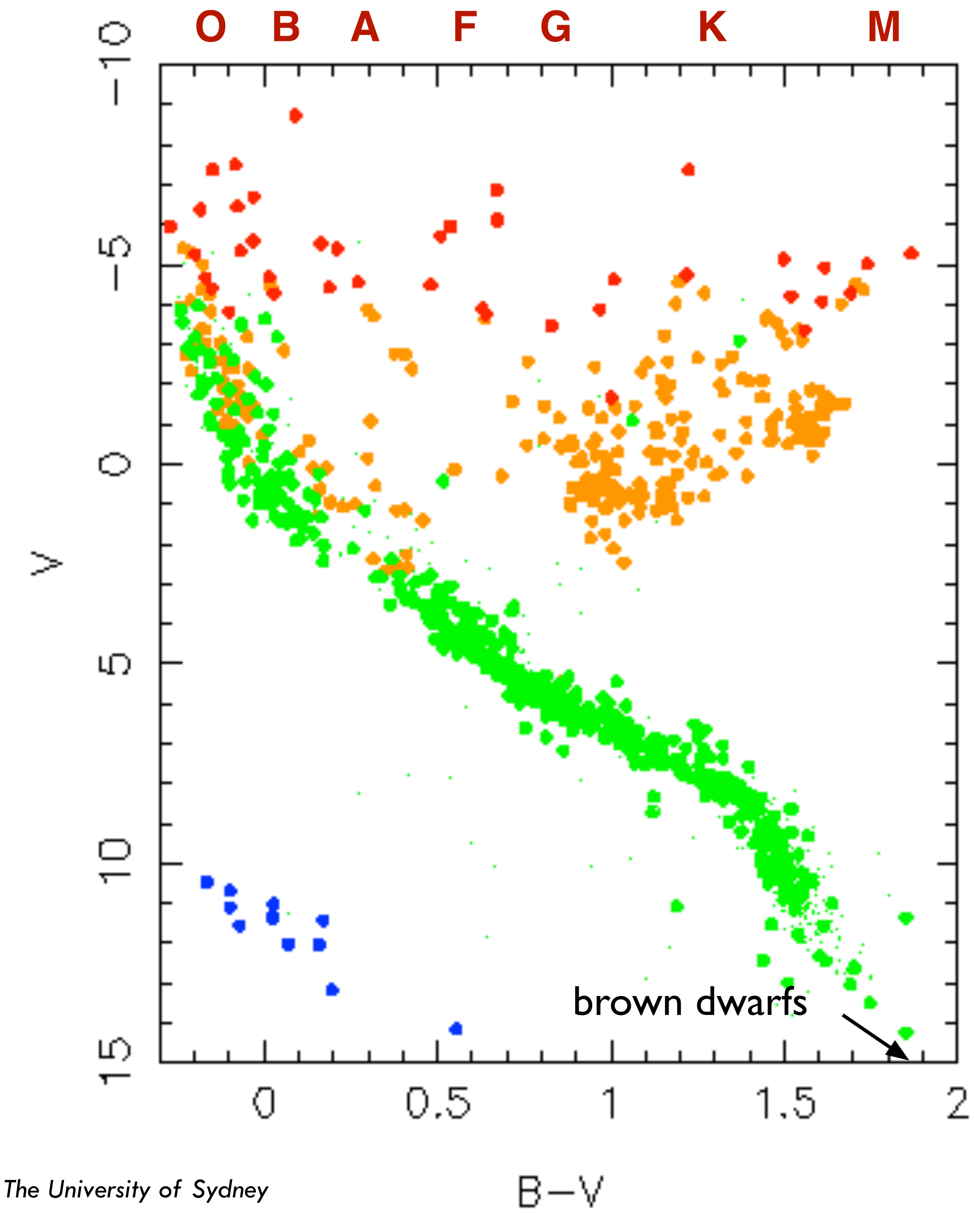


HST images of T Tauri stars show jets and disks.



HST images of T Tauri stars show jets and disks.



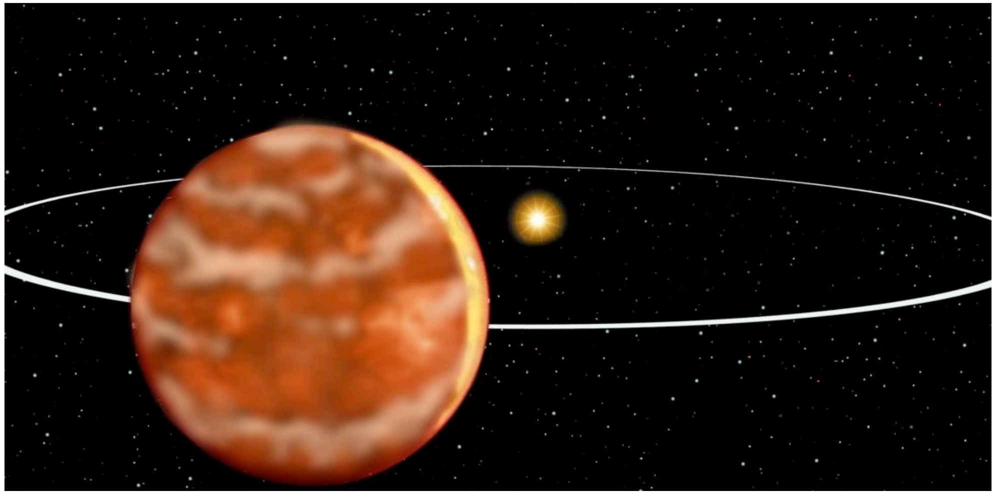


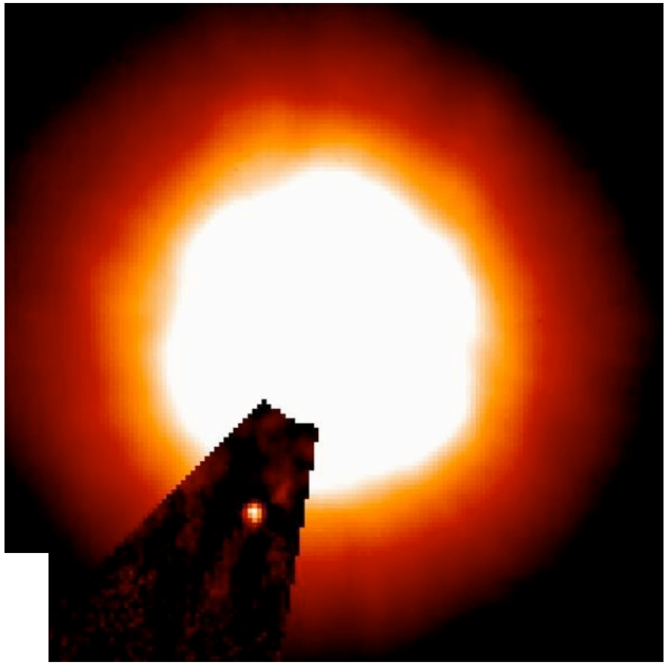
Failed stars

Below the end of the main sequence are the not-quite stars: *brown dwarfs*, which are too light for the stars to burn hydrogen.

Brown dwarfs were only discovered in 1995, after much searching. Since then, more than 1800 have been found. Two new spectral classes have been invented to describe them: classes L and T.

We'll discuss brown dwarfs more fully when we talk about star formation.





Gemini adaptive optics image of the brown dwarf around 15 Sge, and artist's impression of the system.

Next week

Next week, we'll spend some time looking at some of the basics of quantum mechanics; the physics of the very small (atoms) is necessary to understand the very large (stars).

Then we'll start investigating stars proper.

Further reading

For the whole course:

- For astronomical images, you can't do better than the "**Astronomy Picture of the Day**" website, http://apod.nasa.gov/apod/. Not only does this have a fabulous archive of the most amazing pictures (and a new one every day), each image also has links to many other interesting sites where you can follow up the topic. I've used APOD as the source for many of the images here, mostly because it's so convenient. If you prefer to have your pictures in a form you can hold (and show off to friends), a selection has been published as a book, in "**Universe: 365 Days**" by R. J. Nemiroff and J. T. Bonnell (Harry N. Abrams, 2003), with a follow-up volume called "**Astronomy: 365 Days**" (2006)

For tonight's lecture:

- James Kaler has written several books about stars. "**Extreme Stars: At the Edge of Creation**" (Cambridge UP, 2001) is a wonderful look at stars at the various extremes: the hottest, the youngest, the faintest, etc. He has a more detailed book called "**Stars and their Spectra: An introduction to the Spectral Sequence**" (Cambridge UP, 1989), if you want to get into the nitty-gritty. He has an amazing ability to put into words just what the various stars are like (I have borrowed some of his more dramatic comparisons), but he does occasionally get bogged down in detail. My advice is, on the first reading, if you find your eyes crossing slightly as he tells you about details of stars you've never heard of, just skip a bit till you get to the next good bit!

- The same author has a website called "Stars: Portraits of Stars and their Constellations" ("*dedicated to showing that all stars are not the same*") at http://stars.astro.illinois.edu/sow/sow.html, which has a host of interesting information about the various types of stars.

- Bryan Gaensler (ex-Sydney University) has a book called "**Extreme Cosmos**" (NewSouth, 2011), which has lots more amazing facts and figures about the most extreme objects in the universe.

- To see the spectra of stars in detail, check out "The FAST Stellar Spectral Atlas" by Perry Berlind, at https://www.cfa.harvard.edu/~pberlind/atlas/atframes.html. He has examples of the spectra of all kinds of s and peculiar.

- The American Association of Variable Star Observers has a page on Eta Carinae at http://algol.aavso.org/vsots_etacar. If you'd like to try looking at it for yourself, there's a nice chart showing where to find it at the European Southern Observatory "Catch a Star" site, https://www.eso.org/public/outreach/eduoff/cas/cas2002/cas-projects/italy_etacar_1/carina.htm

- The evidence for Proxima Centauri being bound to α Cen is in "Are Proxima and α Centauri Gravitationally Bound?" by Wertheimer & Laughlin (2006), AJ 132, p. 1995 http://adsabs.harvard.edu/abs/2006AJ....132.1995W

Sources for images used:

- Title image: NGC 602 from HST http://hubblesite.org/newscenter/archive/releases/star-cluster/2007/04/
- Stars in Scorpius: from APOD 2012 September 12, http://apod.nasa.gov/apod/ap120912.html
- The Hubble Ultra-Deep Field: from http://www.hubblesite.org/newscenter/archive/releases/2004/07/
- NGC 3982: from HubbleSite http://www.hubblesite.org/newscenter/archive/releases/galaxy/2010/36/
- Overview of Galaxy: from A. Finkbeiner, "Galaxy formation: The new Milky Way", Nature 490 News Feature
- Orion in gas, dust and stars: image by Rogelio Bernal Andreo (Deep Sky Colors), from APOD 2009 Sep 29 http://antwrp.gsfc.nasa.gov/apod/ap090929.html
- Black hole binary animation: http://imagine.gsfc.nasa.gov/Videos/BlkHoleIntro.mov
- Southern cross: image by Yuri Beletsky, from APOD 2007 May 17 http://apod.nasa.gov/apod/ap070517.html
- Distances of stars in the Southern Cross: from "Distances" by Peter Caldwell, http://users.netconnect.com.au/~astronet/dist.html. Used with permission.
- I made the Hipparcos H-R diagram using data from the Hipparcos web site at http://astro.estec.esa.nl/Hipparcos/
- Spectral types as coloured bars: adapted from "Spectral Classes" by Michael Lemke and C. S. Jefferey http://www.sternwarte.uni-erlangen.de/www/tot/spek/SPEK_E.HTML
- Spectral types as intensity plots: from "The Properties of Stars", http://www.jb.man.ac.uk/distance/life/sample/stars/
- The comparison between the brightnesses of stars on the main sequence is from James Kaler, "Extreme Stars", p. 20
- The α Centauri triple system: from ESO Press Release 05/03 http://www.eso.org/outreach/press-rel/pr-2003/pr-05-03.html
- Size of Proxima Cen: from Wikipedia http://en.wikipedia.org/wiki/Proxima_Centauri
- Barnard's Star: from Stars, Galaxies, and the Universe http://csep10.phys.utk.edu/astr162/lect/motion/proper.html
- Gliese 1214b: from APOD 2013 September 10 http://apod.nasa.gov/apod/ap130910.html
- M and A star spectra: from "The FAST Stellar Spectral Atlas" by Perry Berlind, http://cfa-www.harvard.edu/~pberlind/atlas/atframes.html.
- Red dwarf interior: from "Introduction to Stars, Galaxies and the Universe" by Richard Pogge, http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Unit2/mainseq.html
- Solar flare: from "SOHO: Exploring the Sun", http://sohowww.nascom.nasa.gov/gallery/top10/
- 61 Cygni: from Windows to the Universe, http://www.windows.ucar.edu/tour/link=/the_universe/61CygniAB.html
- Gliese 710: from Astronomy Picture of the Day, 2001 July 7 http://apod.nasa.gov/apod/ap010707.html
- Starspots on AB Doradus: from "Mapping starspots and magnetic fields on cool stars: The AB Dor Picture Gallery" by Andrew Collier Cameron, http://star-www.st-and.ac.uk/~acc4/coolpages/imaging.html
- Scorpius: image by Akira Fujii, http://www.davidmalin.com/fujii/source/af4-10_72.html; after a drawing by James Kaler, "Stars and their Spectra", Figure 9.2
- Pleiades: picture by Roberto Colombari, from Astronomy Picture of the Day 2013 September 18, http://apod.nasa.gov/apod/ap130918.html
- Artist's impression of a Be star: from "Astronomer Studies the Flashy, Complex 'Be Star' ", http://www.usc.edu/dept/engineering/TTC/newsarchives/feb99_bestar.html
- The Rosette Nebula: from Astronomy Picture of the Day, 2000 Jan 11, http://apod.nasa.gov/apod/ap000111.html
- Main sequence star properties: from Nick Strobel's Astronomy Notes, http://www.astronomynotes.com/starprop/s12.htm, and "Extreme Stars" by James Kaler, p. 19.
- Line profiles in giants and dwarfs: from Astronomy 62: Introduction to Astrophysics by Ann Esin, http://www.physics.hmc.edu/faculty/esin/a062/lectures/lumclasses.gif
- SUSI: from the SUSI Home Page, http://ftp.nofs.navy.mil/projects/npoi/science/diam.htm
- Interferometer fringes: after diagram in "A Sharper View of the Stars" by Arsen R. Hajian and J. Thomas Armstrong, in Scientific American, March 2001.

- Sizes of stars: from "The Optical Interferometer: Completing the Work of Galileo" by Tyler Nordgren http://www2.lowell.edu/rsch/npoi/publications/diam.php
- Carbon star IRAS 06088+1909: false-colour infrared JHK Atlas image mosaic courtesy of 2MASS/UMass/IPAC/IPAC-Caltech/NASA/NSF, http://www.ipac.caltech.edu/2mass/gallery/images_iras.html
- Eta Carinae nebula: from the NOAO Image Gallery, courtesy NOAO/AURA/NSF, http://www.noao.edu/image_gallery/html/im0044.html
- Eta Carinae and the Keyhole Nebula: by Brad Moore, from Astronomy Picture of the Day, 2006 March 16 http://apod.nasa.gov/apod/ap060316.html
- Eta Carinae light-curve: from "Optical monitoring of Eta Carinae" http://etacar.fcaglp.unlp.edu.ar/
- HST and Chandra images of Eta Carinae: from Chandra X-ray Observatory Photo Album, http://chandra.harvard.edu/photo/0099/index.html
- The Pistol Star: from the Hubble Site, press release October 8, 1997, http://hubblesite.org/newscenter/newsdesk/archive/releases/1997/33/
- WR 124: from the Hubble Site, press release November 5, 1998, http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/38/
- NGC 2359, "Thor's Helmet", NOAO/AURA/NSF, from Astronomy Picture of the Day 2002 December 5, http://antwrp.gsfc.nasa.gov/apod/ap021205.html
- Bubble Nebula: image by Russell Croman, from Astronomy Picture of the Day 2005 November 7, http://antwrp.gsfc.nasa.gov/apod/ap051107.html. HST infrared image of the Bubble nebula: from the Hubble Site Archive, http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/04/
- Orion: image by Matthew Spinelli, from Astronomy Picture of the Day 2003 February 7, http://antwrp.gsfc.nasa.gov/apod/ap030207.html . Used with permission.
- mu Cephei: image by Matt BenDaniel, http://starmatt.com/gallery/astro/ic1396.html. Used with permission.
- Light curve for VV Cephei: from Saito et al., "Photometric Study of VV Cephei during the 1976-78 Eclipse", PASJ 32, 163 (1980), available at http://adsabs.harvard.edu/abs/1980PASJ...32..163S
- Image of Sirius and Sirius B: Lick 3m image, from "The 10 Brightest Stars" by Pedro Braganca, http://www.space.com/scienceastronomy/brightest_stars_030715-1.html. Wobble of Sirius: from "Astronomy 162: Stars, Galaxies and Cosmology", Astrometric Binaries, http://csep10.phys.utk.edu/astr162/lect/binaries/astrometric.html
- White dwarf spectra: from "An Atlas of optical spectra of white-dwarf stars" by Wesemael et al. 1993, PASP 105, 761 http://adsabs.harvard.edu/abs/1993PASP..105..761W
- T Tauri spectra: from "T Tauri stars in blue" by Valenti et al. 1993, AJ 106, 2024 http://adsabs.harvard.edu/abs/1993AJ....106.2024V
- HST images of jets from young stars: from the Hubble Site Archive, , News Release STSci-1995-24 http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/24/
- HST infrared images of disks around young stars: from the Hubble Site Archive, News Release STSci-1999-05 http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/05/
- Brown dwarf around 15 Sge: Gemini press release http://www.gemini.edu/project/announcements/press/2002-1.html
- Quantum image: from http://z-a-n-i-a-n.deviantart.com/art/Quantum-411038259