Lecture 5: The H-R diagram, standard candles and cosmic distances

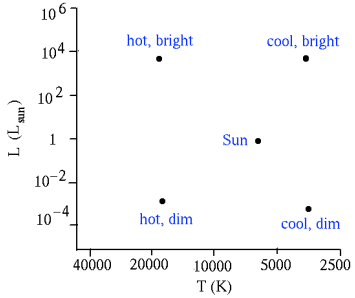
- The Hertzsprung-Russell diagram
- Classes of stars: main sequence, giants and dwarfs
- Spectroscopic parallax
- Stellar masses, and the mass-luminosity relation
- Standard candles and the astronomical distance ladder

Luminosity vs temperature of stars - the Hertzsprung-Russell diagram

Vertical axis:

luminosity of star

- could be measured as power, e.g., *watts*
- or absolute magnitude
- or in units of Sun's luminosity: $L_{star}/L_{\odot}$



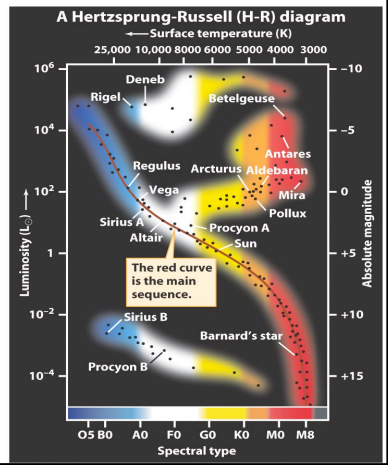
Horizontal axis: surface temperature

- T traditionally increases to the LEFT
- Or use spectral type: OBAFGKM
- Or colour (e.g. B-V), with blue to left

Hertzsprung-Russell (H-R) diagrams reveal different classes of stars

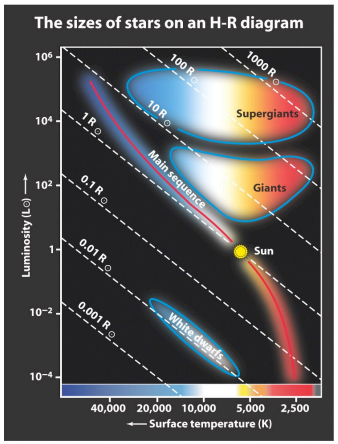
Stars are not scattered at random on the H-R diagram:

- Most stars lie on the main sequence, which runs from hot, luminous stars (top left) to cool faint ones (bottom right)
- Most of the other stars are grouped into three other regions
- What can we deduce about their properties from their location on the H-R diagram?



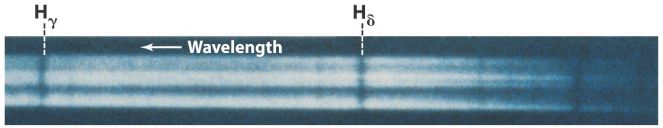
Hertzsprung-Russell (H-R) diagrams reveal different classes of stars

- Remember that for a spherical blackbody emitter, luminosity, temperature and radius are related by: $L=4\pi R^2 \sigma T^4$
- Hence stars of a fixed size would populate a line from top left to bottom right - the main sequence is almost such a line
- However, it is steeper - hotter stars on the MS are also *larger*
- The two populated regions above the MS are much larger stars: the giants and supergiants
- The region below the MS consists of very small stars - these are the white dwarfs

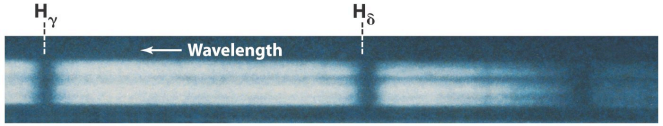


Determining luminosity class from stellar spectra

By carefully examining a star's spectral lines, astronomers can determine the luminosity class of a star - i.e. whether it is a main-sequence star, giant, supergiant, or white dwarf.



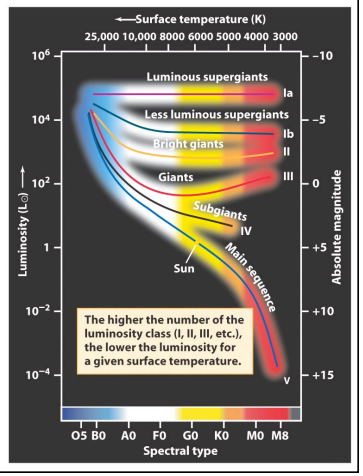
(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines



(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

Spectroscopic parallaxes

- If the approximate luminosity of star can be determined from its spectral lines, coupled with position on the HR diagram, then comparing this with its apparent magnitude allows its distance to be estimated (see notes from Lecture 3).
- This method of distance estimation is (unfortunately) referred to as spectroscopic parallax - it is not a parallax method at all! It does give very useful distances, though, since it can be used out to d~10 kpc, where standard parallaxes cannot currently be measured.

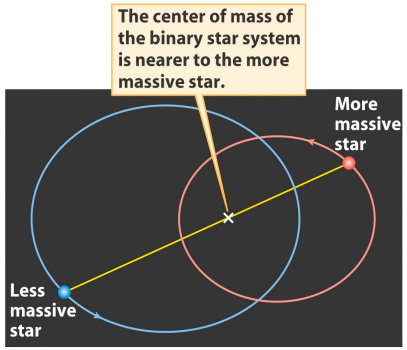


Stellar masses

- We would also like to know the *masses* of stars
- Information about stellar masses can be deduced from the motion of stars in binary systems
- Binary stars move along interlocking orbits, such that the centre of mass of the system remains stationary
- If the orbital size and binary period can be measured, then the total mass of the binary pair follows from the equation

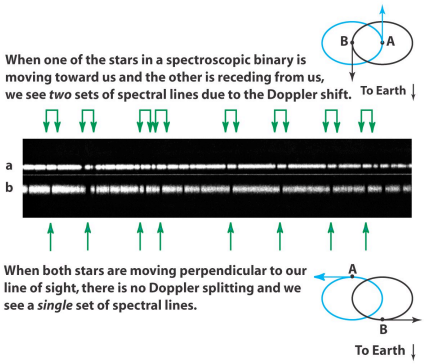
$$M_1+M_2 = a^3/P^2$$

where a is the semi-major axis of the separation vector (in AU) and P the orbital period in years



A binary star system

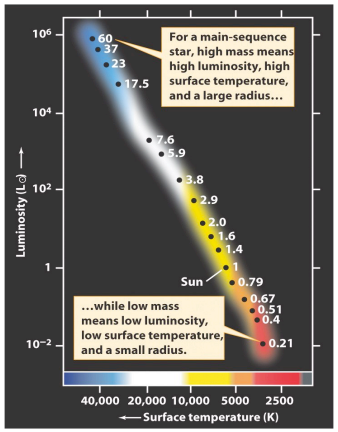
Spectroscopy makes it possible to study binary systems in which the two stars are close together



- Some binaries can be detected and analysed, even though the two star images cannot be resolved
- A spectrum binary appears to be a single star but has a spectrum with the absorption lines for two distinctly different spectral types
- A spectroscopic binary has spectral lines that shift back and forth in wavelength due to the Doppler effect, as the orbits of the stars carry them first toward then away from the Earth
- Analysis of these spectral shifts allows velocity and period to be derived, and hence M_1+M_2

Mass-luminosity relation for main sequence stars

- Once spectral masses are known we can study the way in which mass changes along the main sequence
- Main sequence stars are stars like the Sun but with a range of masses
- The greater the mass of a MS star, the greater its luminosity (and also the greater its radius and surface temperature)
- The mass-luminosity relation expresses a direct correlation between mass and luminosity for main-sequence stars. It is found that L scales strongly with mass, approximately as $L \propto M^{3.5}$
- Since luminosity rises faster than the amount of fuel available, massive hot MS stars have much shorter lifetimes



Standard candles

Suppose that all stars had exactly the same luminosity….

- Then, the brightness of the stars would only depend on their distance.
- By measuring the apparent brightness, we could calculate the distance to the star using the inverse square law of light.
- Of course, stars have a large range of luminosities, and their apparent brightness depends on distance, temperature, size (surface area), extinction, etc.

- However, there are certain classes of astronomical objects which have a small range of luminosities
- These objects are called standard candles
- The measured apparent brightness of a standard candle can be used to determine its distance using the known luminosity and the inverse square law

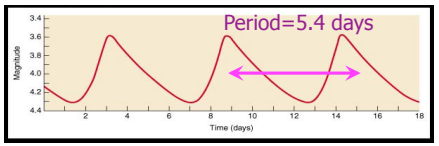
Pulsating variables and Cepheids

- Pulsating variable stars are giant evolved stars that grow and shrink in size
- Cepheid variables (named after δ Cephei, the first one known) are large yellow stars
  - They have luminosities 1,000-10,000 times greater than the Sun.
  - They have periods of 3-50 days.
  - They vary in luminosity from a few percent to a factor of 10.
  - Polaris is a well known Cepheid (period 4 days).
- Henrietta Leavitt at Harvard studied Cepheids in the Large Magellanic Cloud and found that their pulsation period was related to their magnitude

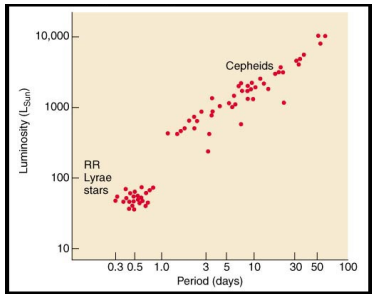
Henrietta Leavitt (1868–1921)

Period-Luminosity relation

For example, if one Cepheid has a period of 3 days and another has a period of 30 days, the star with the longer period is 2 magnitudes or about 6 times brighter.



- Since all the stars are in the same stellar system (the LMC), they are all the same distance from Earth.
- Therefore, the brightness differences indicate that the total luminosity of a Cepheid is related to its period of variation.

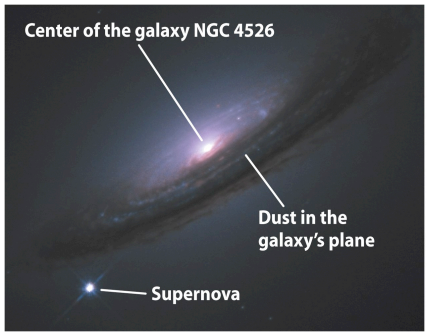


The distance ladder

- Cepheids are especially useful as distance indicators because they are luminous enough (up to 10^4 $L_\odot$) to be studied in other fairly nearby galaxies
- Although Leavitt found that the apparent brightness of the Cepheids was related to the period, no one knew what the true luminosity of the Cepheid variables in the LMC, because its distance was unknown
- A variety of other techniques, such as spectroscopic parallax were used to calibrate the Cepheid P-L relation
- Much confusion resulted from the fact that there turn out to be two different classes of Cepheids, with different P-L relations
- Hipparchos eventually provided true parallaxes for a useful sample of Galactic Cepheids

The distance ladder

- To extend the distance ladder to more distant galaxies, other indicators have to be used, for example…
- Type Ia supernovae provide the brightest standard candles known, and can be detected to high redshifts
- Approximate relations have also been discovered between the luminosity of galaxies and their dynamical properties - an example is the Tully-Fisher relation, which relates the luminosity of a spiral galaxy to its rotation velocity



The distance ladder

A selection of distance determination methods:

- Trigonometric parallax
- Spectroscopic parallax
- Cluster main sequence fitting
- Cepheid variable stars
- Type-Ia supernovae
- Tully-Fisher relation

Read more about this in "Universe"