SDSU Astronomy 101 Prof. W. Welsh

STARS & STELLAR ASTRONOMY

Distances to Stars

Space is Big! Stars are at astronomical distances from us!
Stars are far away.... the nearest star is ~4 ***light years*** away. A **light year** is the distance light will travel in a time of one year: 9.5 x 10^{15} meters (= 9.5 x10^{12} km) or about 5.9 trillion miles. Remember: ***a light-year is a distance, not a time!***

Distances to nearby stars can be determined by measuring their parallax. Parallax is the apparent shift in position of an object with respect to more distant objects due to change in location of the observer.

The orbit of the Earth around the Sun gives the baseline of the triangle of 1 AU.
If **p** is the measured parallax (in arcseconds), then the distance is **d = 1/p** if d is measured in **parsecs**.
A parsec is 206265 AU
= 3.09 x10^{13} km = 3.26 light years

Stellar parallax is the most accurate and direct way to measure distances to stars. However, it is *extremely difficult* to measure parallax because the ***angles are so small***. Sp not many stars have had their parallax measured. How small is the parallax angle? The largest is only 0.77 arcseconds. (An arcsecond is 1/60 x 1/60 of a degree.)

A parsec (pc) is a convenient distance for astronomers, since it comes directly from measuring the parallax angle in arcseconds.

The Brightness of Stars

The Stellar Magnitude System

Goes back thousands of years to Hipparchus: The brightest stars were called magnitude 1, the faintest stars magnitude 6. The system was modernized to be more precise:

Each magnitude increment corresponds to an increase in brightness by 2.512
A change of 5 magnitudes is exactly a change of brightness by 100.

The system was extended to include objects that were too faint to see without a telescope. So you can now have mag > 6 (fainter) and mag < 1 (brighter).

Apparent and Absolute Magnitudes

Brightness of a star as seen from Earth depends on:

1. how bright the star really is (size and temperature)
   - Stefan-Boltzmann law $L = 4 p R^2 s T^4$
2. distance to the star
   - brightness goes as $1/d^2$ an inverse-square law, just like gravity
3. transparency of space between the star and the Earth
   - gas & dust absorb light

Absolute magnitude (M) is the apparent magnitude (m) if the star were exactly 10 pc away. Mathematically,

$$m - M = 5 \log d - 5$$

where d is the distance in pc.
For example, the Sun has an apparent magnitude m = -26.7 and absolute magnitude of M = +4.8. If the Sun were 10 pc away, it would only be mag m=4.8, which is rather faint.

Temperatures of Stars

By Wien's law, **λ_{max}= 2.9 x 10^{-3} m / T**, the color tells us roughly the temperature. Cooler stars are red, hotter stars are blue. (Remember: we get the color and brightness of stars via photometry.) But stars are not exactly blackbodies, so Wien's law is not exactly obeyed. Also, for hot blackbodies, the wavelength of the peak shifts so far into the UV that you can't measure it from the ground anymore. So you can't tell the temperature from the color if it is very blue. Precise temperatures require *spectroscopy* to measure spectral lines. Different lines require different energies, and the energy is related to the temperature. By measuring which lines are present, you can tell the star's temperature and the composition. For example, some stars may show sodium (Na) lines while some do not. Sodium can only show lines (in the optical) if the temperature is low (a few thousand K). If it is too hot, sodium lines vanish because all the atoms are ionized. So detecting sodium tell us it is a cool star. If there are no sodium lines, it must be a hot star.

Spectral Classification of Stars

Folks like Joseph von Fraunhofer and Annie Jump Cannon devised a scheme of classification based on the appearance of the star's spectrum. Although confusing, we still use the same classification today (just like the magnitude system and constellation names created thousands of years ago). The spectral types of stars are: OBAFGKM

O stars are the:
hottest: 35,000 - 50,000 K
brightest: >50,000 L□
most massive: > 25 M□
shortest "lifetime": 10 million years
most rare

M stars are the:
coolest: 2,500 - 3,900 K
faintest: 0.03 L□
smallest: 0.5 M□
longest "lifetime": billions of years
most common
O stars are blue; M stars are red.

Each spectral class is divided into 10 sub-divisions. For example, there are B0, B1, B2, B3.....B9 type stars. The higher the number, the cooler the star: K7 is cooler than K3. The Sun is an ordinary G2 star. A G2 star will last about 10 billion yrs. The Sun is currently about 4.5 billion years old.

The H-R Diagram

The Hertzsprung-Russell diagram is one of the most important concepts in astronomy. The H-R diagram is simply a plot of the *stellar spectral type* (x-axis) and *absolute magnitude* (y-axis). Since spectral type and temperature are related, the *H-R diagram is a plot of stellar luminosity versus temperature.*
x-axis: Temperature (increases to the left !!)
y-axis: Luminosity (brightness increases upwards)
Stars could have been all over this figure, but they are not.
Instead, most stars (90%) they lie in a tight band called the *main sequence.*
è the brightness and the temperature of most stars are related.
In addition to the main sequence, there are other areas where stars lie. These define the ***luminosity class*** of the star.

Luminosity Classes

For a given temperature, the brightness of a star determines its luminosity class.
Remember, brightness depends on temperature and size (Stefan-Boltzmann law):

Luminosity = surface area x flux

$$L = 4 \pi R^2 \quad \sigma T^4$$

So the luminosity class really is a ***size class.***
Stars on the main sequence are class V (five).
Brighter stars are sub-giants (IV) and giants (III).
Even brighter are the supergiants (II and Ia, Ib).
Small, faint, burned-out remnants of stars are called ***white dwarfs***.
The Sun is a G2V star.

Stellar Evolution

Stars form relatively quickly, spend most of their existence on the main sequence, then grow old and "die". Why? **Stars evolve because they run out of fuel.** ("fuel" is H; the "engine" is fusion) When hydrogen in the core runs out:

- The core contracts and gets hotter
  - At these hotter temperatures and densities, fusion of He into C takes place
  - "CNO thermonuclear fusion cycle" creates N, O, Na, ... and other medium-weight elements
- The outer layers expand; the star becomes a giant
  - luminosity class III (also called a "red giant")

But eventually He runs out too. Fusion slows down and the core shrinks again….The end is near!

The Death of a Star: Part I. Low-mass Stars

Low-mass stars like the Sun expand and eject all of their outer layers
- a “planetary nebula” is thrown off into space.
- “Star stuff” is returned to the interstellar medium, enriched in C,N,O and other medium-weight elements. The compressed C,N,O core is all that is left: “white dwarf”

White Dwarf: A white dwarf is the remnant of the stellar core. It generates no new energy. It just *slowly* cools and fades.
The maximum mass is 1.4 $M_\odot$ (Chandrasekhar limit).
made of ultra-dense degenerate matter: *pressure does not change with temperature*
- peculiar property: the more mass, the smaller the size!
- a teaspoon would weigh 5 tons! (think of stacking many mattresses on top of each other; as you add more, the pile shrinks)

The Death of a Star: Part II. High-mass Stars

In high-mass stars (like O and B stars), the core gets hot enough to fuse C, N, O, Ne, etc. This creates heavier elements like silicon (Si), etc., and eventually iron (Fe).
But Fe does not yield energy when it fuses! So the core temperature suddenly drops.
The core collapses in a *fraction of a second.* This creates incredibly high pressure and density! More fusion occurs, creating heavy elements (“nucleosynthesis”).
The compressed core “rebounds”, creating a tremendous explosion - a ***supernova.***
Can be as bright as a billion Suns!
Ejected material is enriched in heavy elements like Fe, Ni, and all the other elements.

Neutron Stars

Sometimes a super-compressed part of the core remains intact after the supernova explosion. If the collapsing core is < 3 $M_\odot$, a **neutron star** is formed.
Core is crushed into a super-high-density “ball of neutrons”
- 1 teaspoon would weigh 1 billion tons!
- A 1.4 $M_\odot$ neutron star is only 10 km wide!

Neutron stars can possess an incredibly strong magnetic field. Conservation of angular momentum means that neutron stars rotate very rapidly, usually rotating in less than a second. Radio waves from neutron stars can seem pulsed due to the rotation of the neutron star (like a lighthouse beacon): these types of neutron stars are called pulsars.

Black Holes

If the collapsing core is > 3 $M_\odot$, nothing can stop the collapse. Even the neutrons get crushed together. Gravity is so strong, that *nothing* can escape…a black hole is formed!
Gravity at the “surface” of a black hole is so strong that *not even light* can get out.
Inside of a BH is isolated from the rest of the Universe. No information can come out.
Usual laws of physics may no longer apply - we do not know what happens beneath the *event horizon* because our understanding of relativity and quantum mechanics is incomplete.

No direct images of black holes have been taken (yet). But we are almost certain BH exist:

- in stellar corpses left over from supernovae
- in the center (nucleus) of most galaxies
- and now, gravitational waves.

We can infer the presence of a BH based on its <u>gravitational affect</u> on other objects:

accreting gas
companion star (in a binary star pair)
star orbits at the center of a galaxy

Final Note: Black ***holes do not suck!*** Outside the event horizon, gravity acts in the usual Newtonian way.

Interacting Binary Stars

Some binaries are so close together they influence each other: ***interacting binary stars.***
They heat and tidally distort each other. If close enough, the gravity from the more massive star can strip mass from its companion star. Mass gets transferred from one star to the other (stellar cannibalism!).
White dwarf mass-transferring binary systems are called *"cataclysmic variable stars"* because they tend to change their brightness by such large amounts.

Accretion Power

Accretion is the capture of matter by gravity. Usually a flat disk shape is formed (because of conservation of angular momentum). Think of an accretion disk as a whirlpool. As matter falls downward, it releases energy: "accretion power".
The amount of energy released depends on the density of the accreting object.
Viscosity in the accretion disk converts gravitational potential energy into thermal (heat) energy and electromagnetic radiation.
Accretion onto a compact object like a white dwarf yields a tremendous amount of energy
Neutron stars and black holes have such high density that ***accretion releases much more energy than thermonuclear fusion***! As much as 50x more! So neutron stars and BHs in interacting binaries are very bright and give off lots of X-rays and are therefore called "X-ray binary stars"

White Dwarfs & Supernovae

A WD can gain mass from its companion in an interacting binary star via accretion. But the maximum mass for a white dwarf is 1.4 $M_\odot$ (the "Chandrasekhar limit"). Gaining more mass might cause the WD to collapse, then explode as a supernova.
Thus there is a second pathway to creating a supernova: pushing a WD over its limit!