WEEK 8: CSI UCSC: ASTRO EDITION SOLUTIONS

This week you are going to play detective and investigate why and how different kinds of stars die in our Universe.

1. Cause of Death

(1) Why is a star on the main sequence stable? Why doesn't it collapse or explode?
A star on the main sequence is stable because it is steadily fusing hydrogen into helium in the core. There is a force balance in the star (outward force equals the inward force).

(2) Which two forces are in balance for a main sequence star?
While self-gravity pulls the star inward and tries to make it collapse, thermal pressure (heat created by fusion) pushes outward. These two forces cancel each other out in a main sequence star, thus making it stable.

(3) What's the heaviest element that can be created through fusion in a star (not through a supernova explosion)?
The heaviest element that can be fused in a star is Fe (iron). When you fuse hydrogen into helium (or helium into carbon/oxygen, etc.), you get energy OUT of fusion. However, you have to put energy IN to fuse iron into heavier elements. A star wants to use fusion as a source of energy (not as a way to give up/waste energy), so it's just going to stop fusion once it gets to an iron core.

(4) Which force "wins" the battle when a star eventually runs out of fuel in its core, and as a consequence, what happens (and what eventually stops this)?
Gravity wins the battle when the star runs out of fuel in the core (ex. the Sun runs out of hydrogen), and as a result the core starts to contract. As the core contracts, the density and the temperature increase. Once it gets dense and hot enough, heavier elements can start to fuse (ex. the Sun can now fuse helium into carbon/oxygen), which means the star has found a new source of energy and thermal pressure. Thus the core stops contracting. The envelope, however, will expand, turning the star into a red giant.

2. Case Study 1: White Dwarfs

Remember that low mass stars, such as our Sun, die to become white dwarfs.

(1) What other remnant usually accompanies a white dwarf?
A white dwarf, which used to be the core of the star, comes embedded in a planetary nebula, which is basically a cloud of gas that used to make up the fluffy outer layers of the red giant.

(2) Which two forces are in balance for a white dwarf?
Inward self-gravity is balanced by electron degeneracy pressure. Remember that electron degeneracy pressure comes about because electrons don't like being close to each other; i.e., electrons are anti-social!

(3) What is the maximum mass of a stable white dwarf?
The maximum stable mass of a white dwarf is 1.4 $M_\odot$. *Electron degeneracy pressure is not sufficient to fight self-gravity once a white dwarf exceeds this mass.*

(4) So how is it possible that a 5 solar mass star will end up as a white dwarf?
Remember that a white dwarf comes from what used to be the core of the star, and a planetary nebula comes from what used to be the outer layers of the star. This means that the mass of the star you initially start out with is going not only into the white dwarf, but also into the planetary nebula. There is also some mass lost from the star during the red giant phase because there are stellar winds.

3. Case Study 2: Neutron Stars

Remember that massive stars die to become neutron stars.

(1) Which two forces are in balance for a neutron star?
Inward self-gravity is balanced by neutron degeneracy pressure. Remember that neutron degeneracy pressure is very similar to electron degeneracy pressure. Neutrons are also anti-social!

(2) What phenomenon precedes the birth of a neutron star?
A violent explosion called a supernova precedes the birth of a neutron star.

(3) What is a pulsar?
A pulsar is a rapidly rotating neutron star whose electromagnetic beams emerging from its magnetic poles are misaligned with the neutron star's rotation axis such that the beam points in and out of the line of sight of an observer. **Here** *is a good animation.*

(4) What is the typical size of a neutron star? What is the density of a maximum-mass neutron star in g/cm^3?
The typical size of a neutron star is 10 km, and the maximum mass of a neutron star is roughly 2 $M_\odot$. Density is mass divided by volume:

$$D = \frac{M}{V} = \frac{M}{\frac{4}{3}\pi R^3} \ ,$$

where we assume that the neutron star is a sphere, and the volume of a sphere is given by $\frac{4}{3}\pi R^3$ (R is the radius). So we have:

$$D = \frac{2\mathrm{M}_\odot}{\frac{4}{3}\pi(10\ \mathrm{km})^3} = \frac{2(2\times10^{33}\ \mathrm{g})}{\frac{4}{3}\pi(10^6\ \mathrm{cm})^3}$$

So the density of a neutron star is roughly 10^{15} g/cm^3=10^{18} kg/m^3.

4. Case Study 3: Black Holes

Remember that really massive stars die to become black holes.

(1) Which force has triumphed in a black hole?
Gravity has triumphed in a black hole. Not even neutron degeneracy pressure was sufficient to fight against gravity, and since the star cannot muster up anything else, gravity wins.

(2) Where do you think a black hole gets its name from?
Black holes get their name because not even light can escape from within a black hole. Since there's no light being emitted by the black hole, we can't see it directly, and hence it looks black.

(3) Can we detect black holes directly? Name two detection methods.
We have to detect the presence of the black hole indirectly. The first detection method is to study the orbits of stars going around the black hole. If you observe the stars for a long period of time, you can trace out their orbits and infer the presence of the central black hole. You're basically observing the gravitational influence of the black hole sitting there amongst the stars. The second method is to look at the X-ray emission. When a black hole is devouring gas or torn up stars, there'll be a disk of gas swirling around the black hole. Since the gas is swirling around really fast, there will be friction, and there will be X-ray emission. Astronomers can detect this X-ray emission and infer the presence of there black hole.

(4) How small a volume do you have to squeeze your body into if you want to become a black hole? Why will you become a black hole this way?
To become a black hole, you have to squeeze all of your mass to a size equal to your Schwarzschild radius. Once you get to this scale, gravity prevails and you'll just collapse. The Schwarzschild radius is given by the following formula:

$$R_S = \frac{2GM}{c^2} \ ,$$

where G is the gravitational constant, M is the mass you're interested in, and c is the speed of light. Plugging in the mass of a typical human being, 70 kg (roughly 150 lb), you get:

$$R_S = \frac{2(6.67\times10^{-11}\ \mathrm{Nm^2/kg^2})(70\ \mathrm{kg})}{(3\times10^8\ \mathrm{m/s})^2} = 10^{-26}\ m.$$

You need to squeeze yourself to a size of about 10^{-26} m if you wish to become a black hole.

5. Special Case Study: Supernovae

(1) Compare Types I and II supernovae. What kinds of objects explode and what are their explosion mechanisms?
There are two main types. The first one is Type Ia supernova, which comes from a white dwarf in a binary system with another star. A white dwarf may steal material from the companion star, and its mass will start to grow. If its mass exceeds 1.4 $M_\odot$*, then it will be unstable and explode (discussed above). The second type of supernova is Type II, also known as a core-collapse supernova. This is the supernova explosion that precedes the birth of a neutron star or a black hole resulting from the collapse of the iron core.*

(2) Explain Carl Sagan's famous quote "We are made of starstuff."
We are made of starstuff because the elements in our bodies (such as carbon, oxygen, nitrogen) came from fusion processes inside the first generation of stars. These stars eventually died and spewed different kinds of elements into the interstellar space, which then got mixed into clouds of hydrogen that later formed new stars and planets.