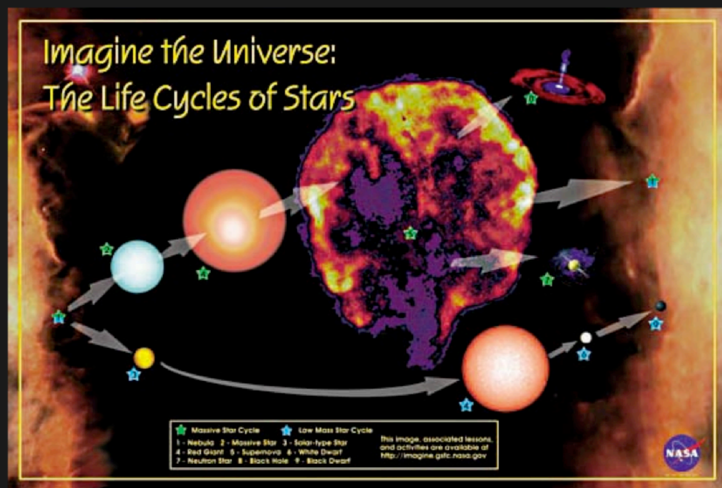
The Life Cycles of Stars

Dr. Jim Lochner, NASA/GSFC



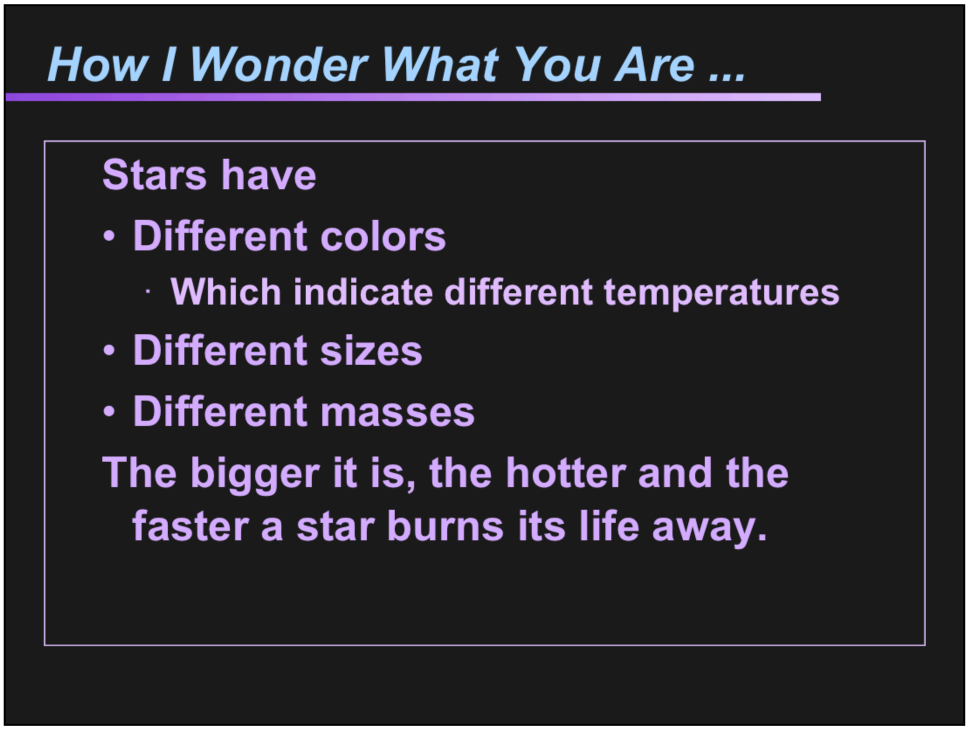
May 15, 2001

Imagine Life Cycle Poster Image

Hubble Heritage image of Sagittarius Star field. Note that along the horizontal axis, the image is 13.3 light-years across.

Ask audience what they notice by looking at this image. Hopefully they will notice the different colors. You can then ask them what the different colors mean [different temperatures]

Image from http://heritage.stsci.edu/public/Oct22/sgr1/sgrtable.html.



By looking at previous slide, audience should determine that stars have different colors, and deduce that this means different temperatures..

They won't be able to tell from the image that stars are of different sizes and masses, but they may be able to deduce that from the different temps.

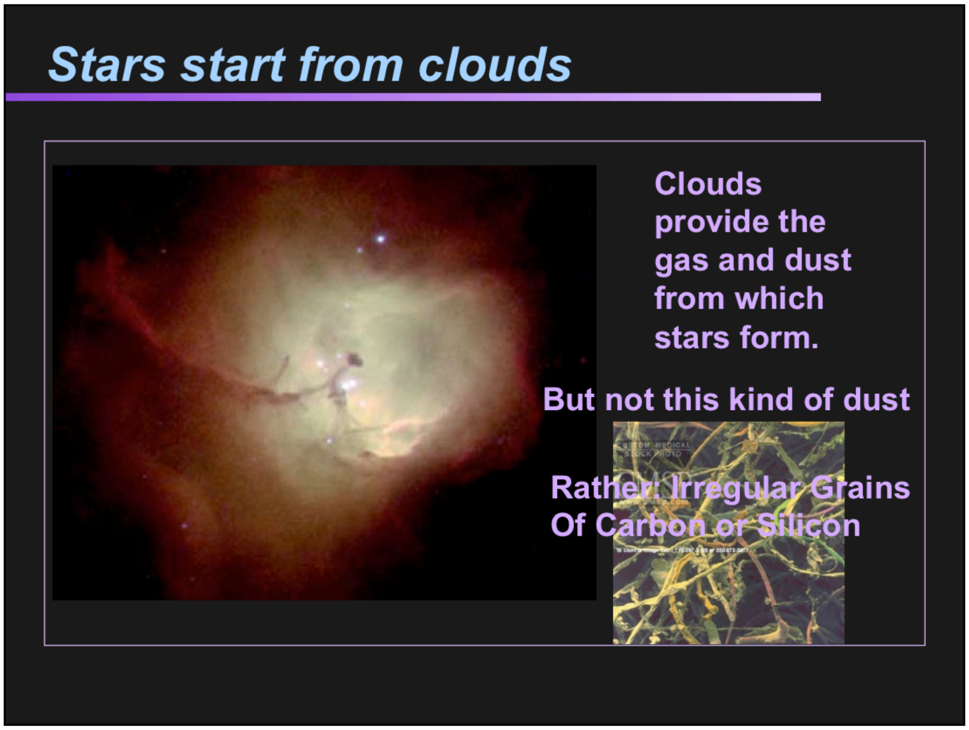
With different masses and sizes, make analogy that some people are tall and others are short.

M16 - Eagle Nebula Pillars

(from Hubble, http://oposite.stsci.edu/pubinfo/PR/95/44.html

These are columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. Dense clouds of molecular hydrogen gas (two atoms of hydrogen in each molecule) and dust that have survived longer than their surroundings in the face of a flood of ultraviolet light from hot, massive newborn stars (off the top edge of the picture).

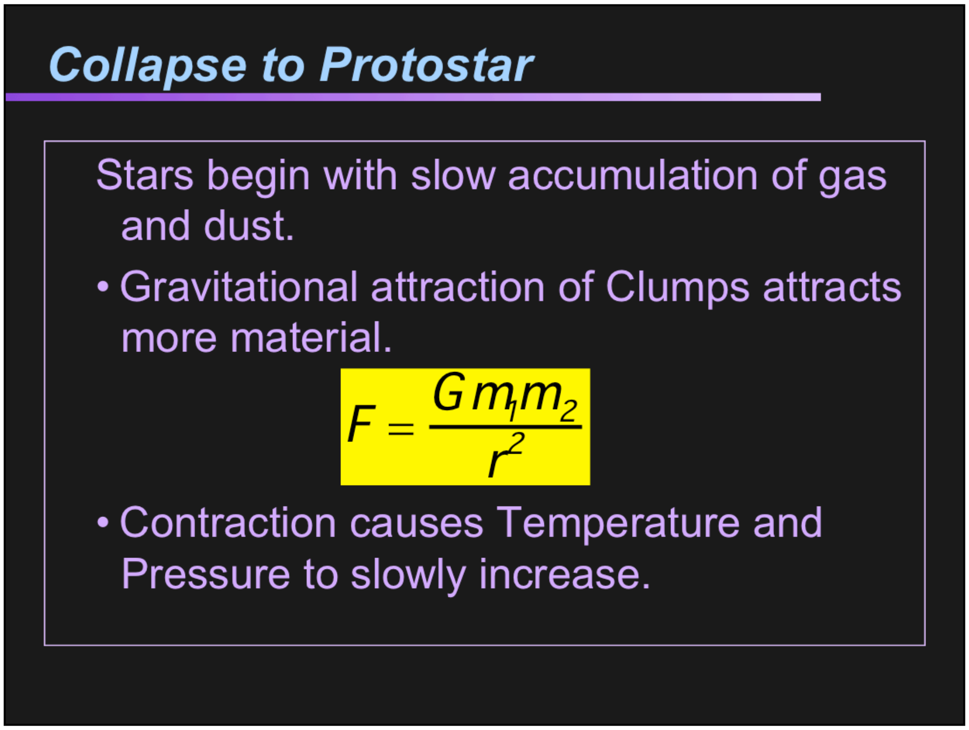
As the pillars themselves are slowly eroded away by the ultraviolet light, small globules of even denser gas buried within the pillars are uncovered. These globules have been dubbed "EGGs." EGGs is an acronym for "Evaporating Gaseous Globules," but it is also a word that describes what these objects are. Forming inside at least some of the EGGs are embryonic stars -- stars that abruptly stop growing when the EGGs are uncovered and they are separated from the larger reservoir of gas from which they were drawing mass. Eventually, the stars themselves emerge from the EGGs as the EGGs themselves succumb to photoevaporation.



N81 from Hubble Heritage - stellar nursery in SMC. These are massive stars whose stellar winds are hollowing out the nebula. Cooler clouds of molecular H and dust are silhouetted against the nebula. It offers a look at the turbulent conditions accompanying the birth of massive stars. See http://heritage.stsci.edu/public/2000oct5/n81table.html

Another candidate would be the Hubble Heritage image of Hubble-X in NGC 6822 (also a site of formation of massive stars). See http://heritage.stsci.edu/public/2001jan/table.html

Household dust is made up of skin, hair, cloth fibers, plants, spider silk, bits of sand and soil. This image is taken from the collection at http://catalog.cmsp.com/datav3/cg060001.htm



Protostars grow on the principle that "The rich get richer". As the clump grows, the gravitational force it exerts increases, and thus is able to grow more.

The equation gives the gravitational force exerted by mass m_1 on mass m_s. As the mass of m_1 increases, the force it exerts increases.

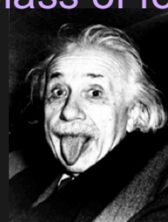
Nuclear Fusion !

At 15 million degrees Celsius in the center of the star, fusion ignites !

4 (^{1}H) --> ^{4}He + 2 e^{+} + 2 neutrinos + energy

Where does the energy come from ?

Mass of four ^{1}H > Mass of one ^{4}He



$$E = mc^2$$

Be sure audience members understand what the symbols mean. Especially that the superscripts for H and He are the atomic weights.

The energy comes from the slight difference in mass between four H atoms and one He atom. This excess mass gets converted to energy via Einstein's famous equation.

Fusion by the Numbers

$$4\,(^{1}H) \dashrightarrow {}^{4}He + 2\,e^{+} + 2\text{ neutrinos} + \text{energy}$$

Mass of 4 ^{1}H = 4 x 1.00794 amu

= 4.03176 amu

Mass of 1 ^{4}He = 4.002602 amu

Difference in mass = 0.029158 amu

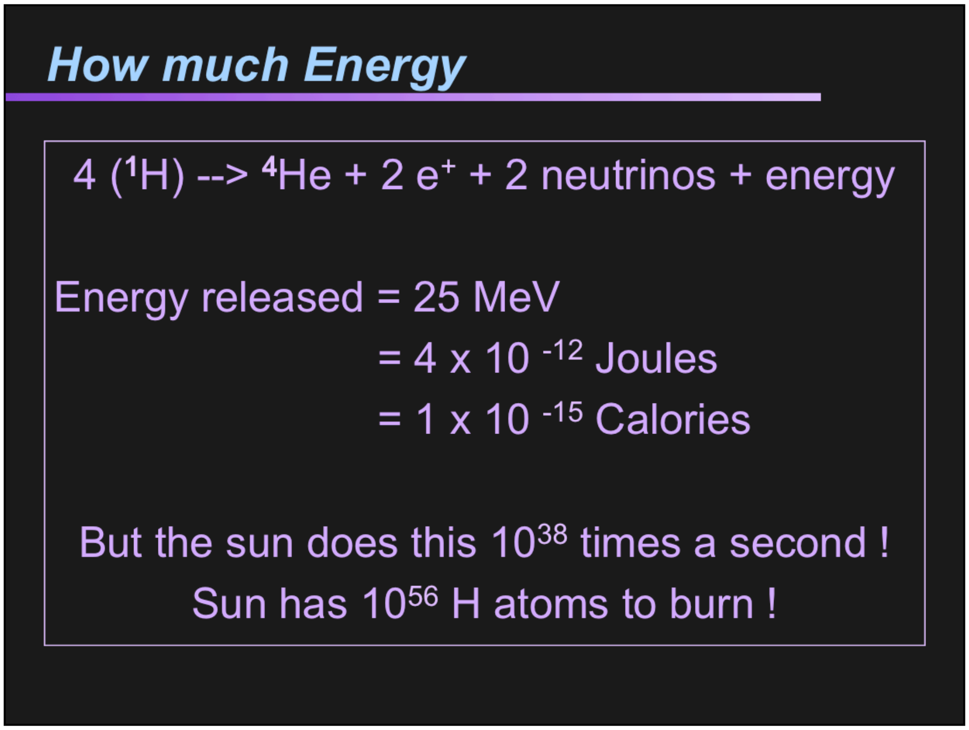
= 4.84×10^{-29} kg.

$E = Dmc^2 = (4.84 \times 10^{-29}\text{ kg})(3 \times 10^{8}\text{ m/s})^2$

$E = 4.4 \times 10^{-12}$ J

This slide is optional, depending on the mathematical background of the audience, and how much detail they need to see.

Here we explicitly show the difference in mass between the H and He, and how it gets converted to energy. Note that 1 amu = 1.66053×10^{-24} g



1 MeV is the voltage necessary to move 1 million electrons through 1 volt

Re- 1 ev = 1.6 x 10^{-19} J. 1 cal = 4.184 J
The “Calories” given in the slide are kcal, the same as used on food labels.

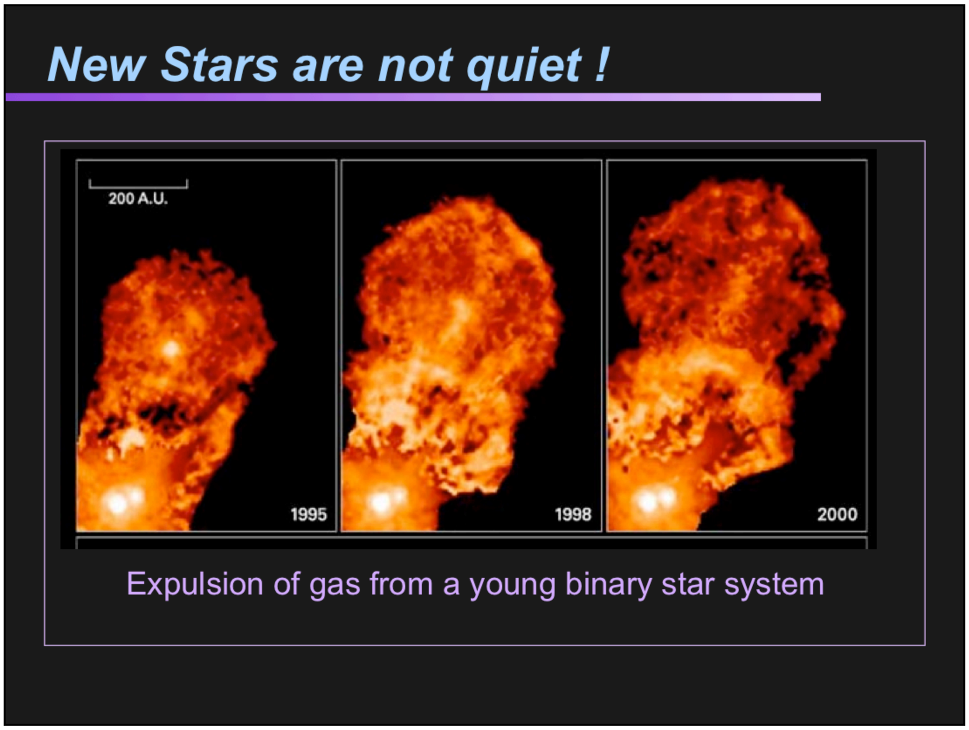
We know the rate at which the sun consumes H because we can measure its energy output. We know how many H atoms it has from knowing the sun’s mass (2 x 10^{30} kg).

A Balancing Act

Energy released from nuclear fusion counter-acts inward force of gravity.

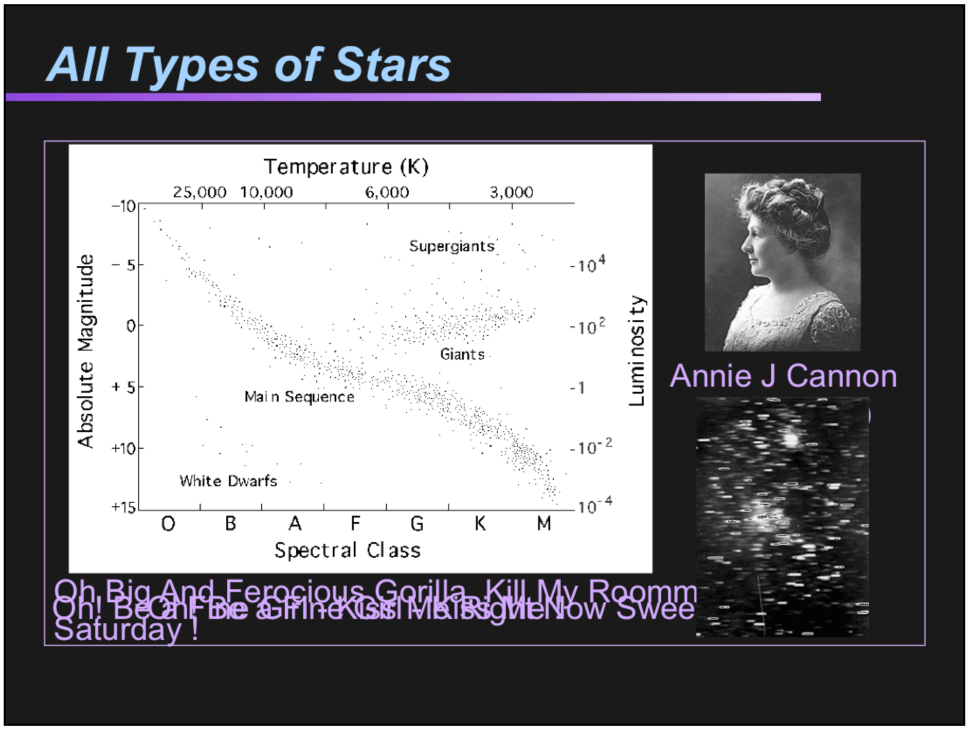
Throughout its life, these two forces determine the stages of a star's life.

This is an important principle which governs the life stages of a star.



The young binary system XZ Tau. Gas from an unseen disk around one or both of the stars is channeled through magnetic fields surrounding the binary system and then is forced out into space at nearly 300,000 miles per hour (540,000 kilometers per hour). This outflow, which is only about 30 years old, extends nearly 60 billion miles (96 billion kilometers).

From http://oposite.stsci.edu/pubinfo/PR/2000/32/pr-photos.html



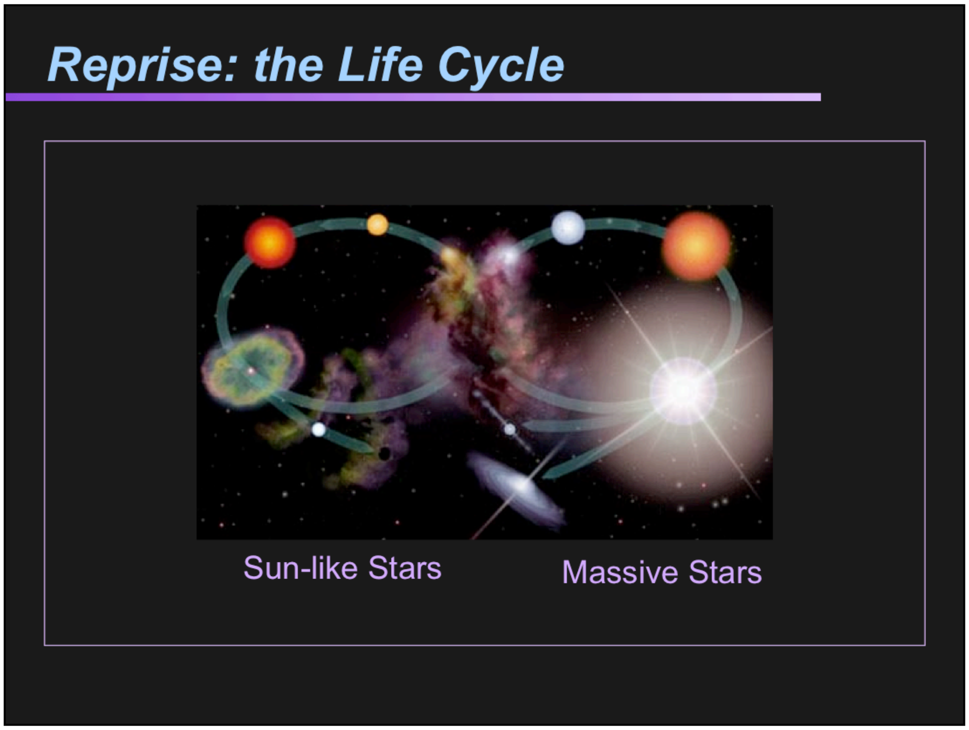
HR diagram shows range of stellar sizes, masses, temperatures, luminosities

Born in Dover, DE. Hard of hearing but loved to play piano. Her mother sparked her interest in astronomy by teaching her the constellations. She went to Wellesley College and studied physics and astronomy, and learned spectroscopy. After graduating in 1884, she returned home, took up photography and travel.

In 1894 her mother died, and she returned to Wellesley as a junior instructor. In 1896 she began work at the Harvard College Observatory for Edward Pickering, joining the staff of women "computers" (50 cents/hr). These women recorded the astronomical data, catalogued variable stars, and classified spectra.

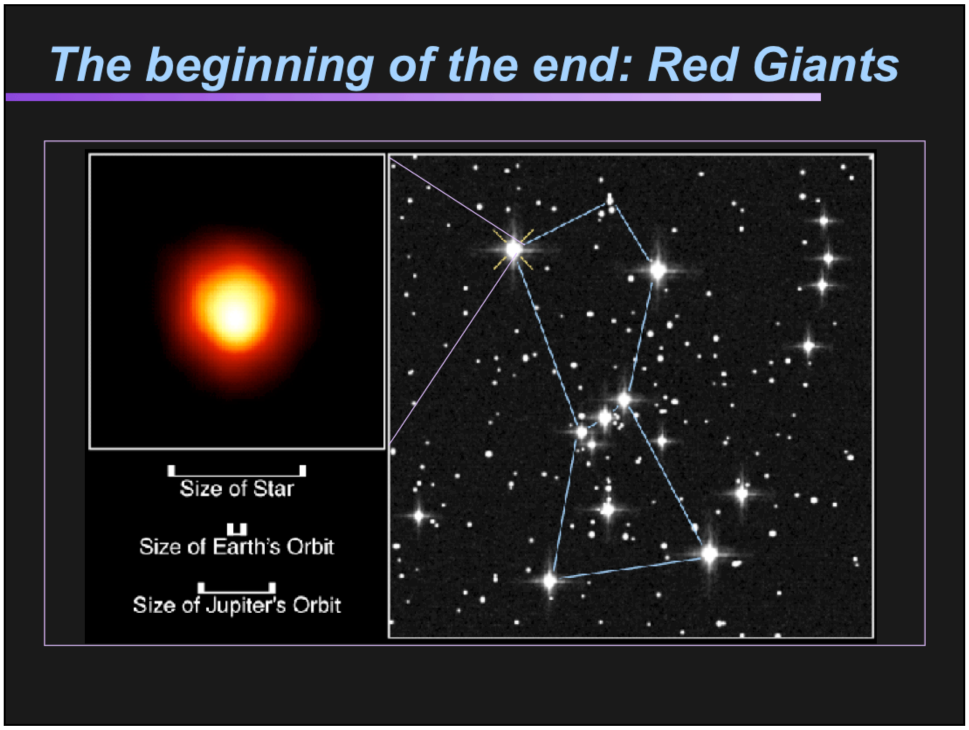
In 1911, Cannon was appointed curator of the observatory's photographic plates. For the next 4 years she classified all the stars on the plates down to 9th mag. She classified 5,000 stars per month, and when done had classified 225,300 stellar spectra. The results were published in 9 volumes from 1918-1924. She developed the spectral classification used today.

Upon receiving the Draper Award from the Nat'l Academy of Science (first woman ever to receive their highest honor), Harlow Shapley commended her as "author of nine immortal volumes, and several, thousand oatmeal cookies, Virginia reeler, bridge player."



Stars are either low mass or high mass. Their mass determines their fate.

One might note that stars are not quiescent even during the time they steadily fuse Hydrogen. For example, our own sun is very active.



End of H fusion - red giant stage

Betelguese - see http://oposite.stsci.edu/pubinfo/PR/96/04.html

Red Giants

After Hydrogen is exhausted in core,

- Core collapses, releasing energy to the outer layers
  - Outer layers expand
- Meanwhile, as core collapses,
  - Increasing Temperature and Pressure ...

More Fusion !

At 100 million degrees Celsius, Helium fuses:

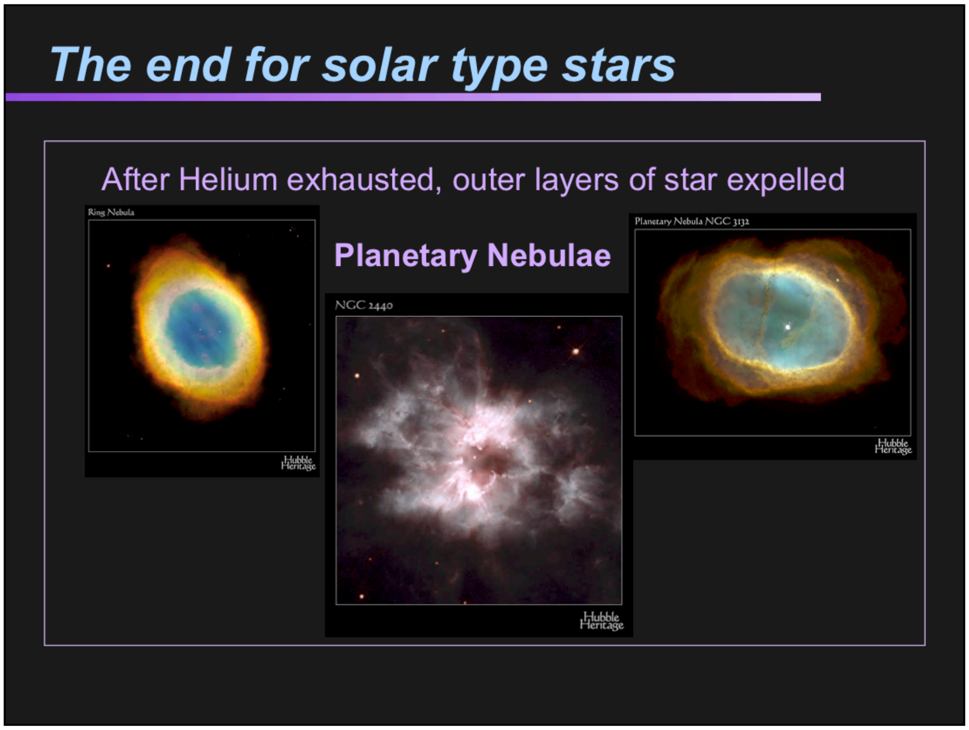
$3\,(^{4}He) \rightarrow {}^{12}C + \text{energy}$

(Be produced at an intermediate step)

(Only 7.3 MeV produced)

Energy sustains the expanded outer layers of the Red Giant

Note that fusion of He requires a much hotter temperature than fusion of H.



Planetary nebula - after He consumed, core collapses again. Outer atmosphere expelled, and then ionized (I.e. glows) by the hot remaining core

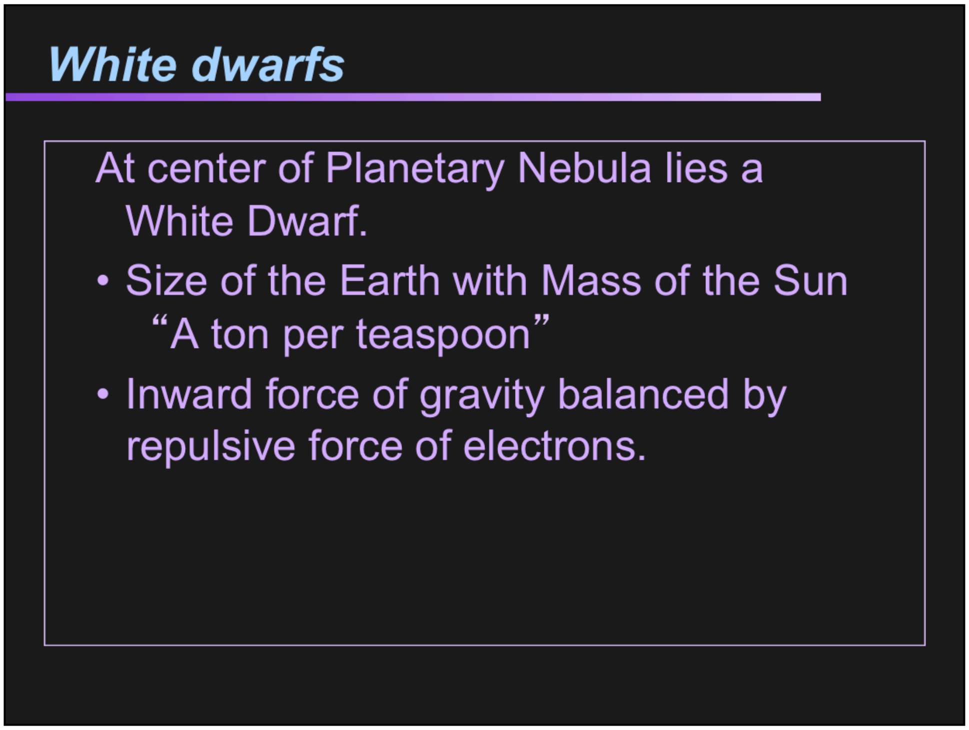
From Left to Right:

Ring Nebula - true colors, representing different elements. helium (blue), oxygen (green), and nitrogen (red).

NGC 2440 - The central star of NGC 2440 is one of the hottest known, with surface temperature near 200,000 degrees Celsius. The complex structure of the surrounding nebula suggests to some astronomers that there have been periodic oppositely directed outflows from the central star, but in the case of NGC 2440 these outflows have been episodic, and in different directions during each episode. The nebula is also rich in clouds of dust, some of which form long, dark streaks pointing away from the central star. In addition to the bright nebula, which glows because of fluorescence due to ultraviolet radiation from the hot star, NGC 2440 is surrounded by a much larger cloud of cooler gas which is invisible in ordinary light but can be detected with infrared telescopes. NGC 2440 lies about 4,000 light-years from Earth in the direction of the constellation Puppis.

NGC 3132 - colors represent temperatures. Filaments made of dust condense out from the cooling gas. These filaments are rich in carbon

[Images from Hubble Heritage: http://heritage.stsci.edu/public/gallery/



Basic characteristics of white dwarfs: about the size of the earth, with a mass of about the sun. 1 million g/cm^3 = "1 ton/teaspoon"

White Dwarfs are stable because inward force of gravity is balanced by the repulsive force of the electrons.

Fate of high mass stars

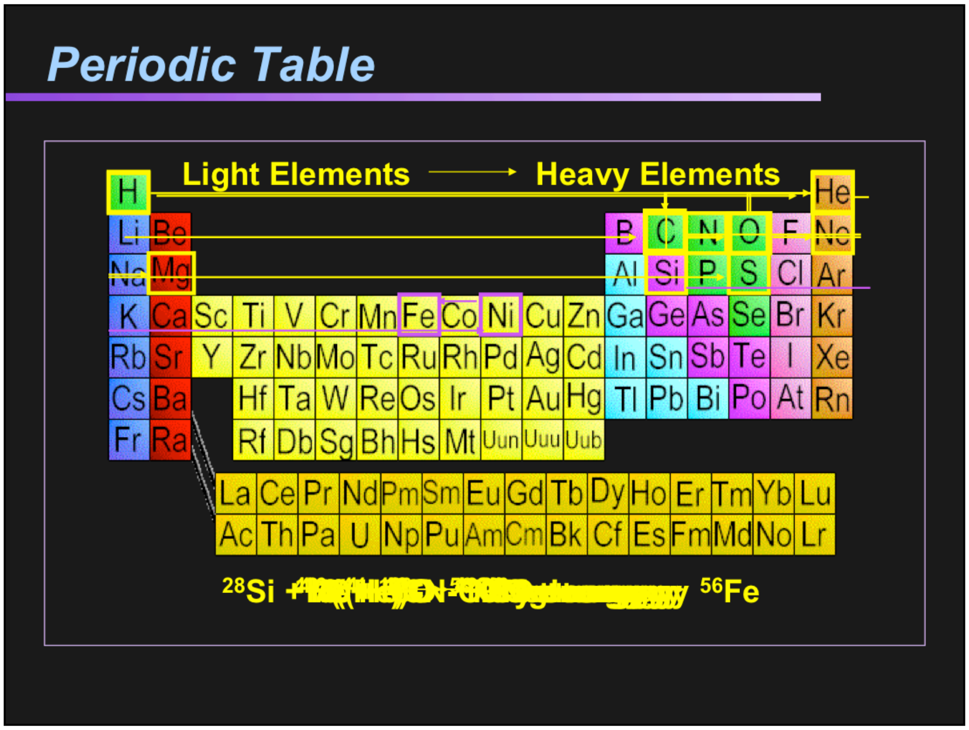
After Helium exhausted, core collapses again until it becomes hot enough to fuse Carbon into Magnesium or Oxygen.

- $^{12}C + ^{12}C \rightarrow ^{24}Mg$

  OR $^{12}C + ^{4}H \rightarrow ^{16}O$

Through a combination of processes, successively heavier elements are formed and burned.

After the red giant stage, there is a series of collapses and further nuclear burning. Fusion creates heavy elements from light elements.



Periodic table is from http://www.chemicalelements.com/

We've seen (click #1) ^{1}H -> ^{4}He and (2) ^{4}He -> ^{12}C.

These are further representative reactions that occur in massive stars:

(3) Carbon to Magnesium (^{12}C -> ^{24}Mg)

(4) Helium and Carbon to Oxygen (^{4}He + ^{12}C -> ^{16}O)

(5) Oxygen to Silicon (^{16}O -> ^{32}Si) or Oxygen to Sulfer and He

(6) Helium and Oxygen to Neon (^{4}He + ^{16}O -> ^{20}Ne)

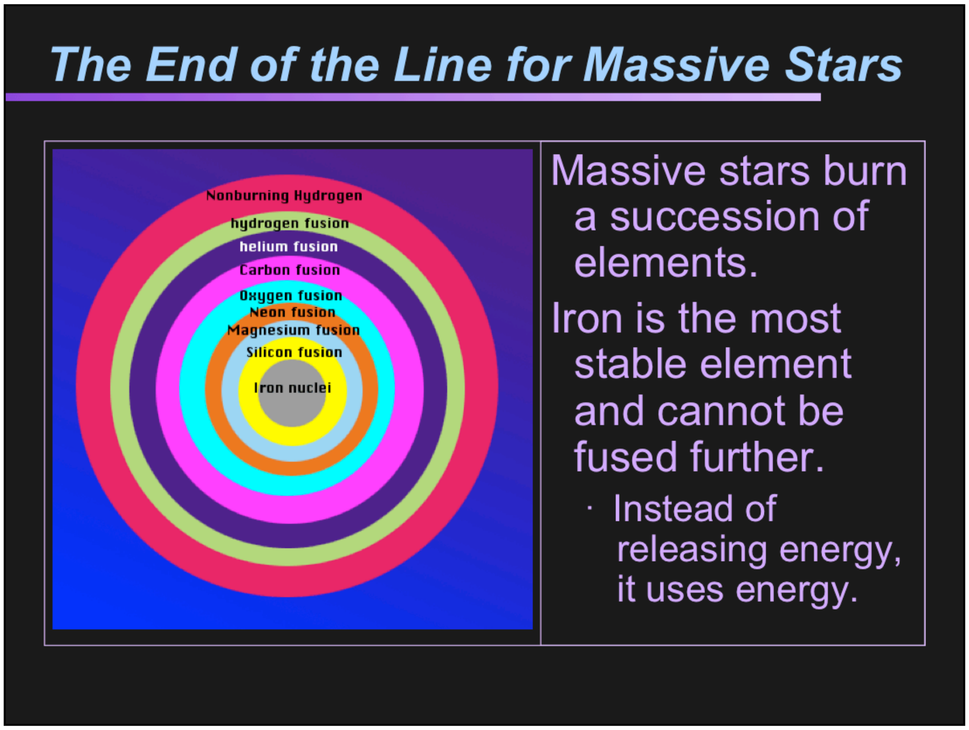
(7) Also note the CNO cycle which uses C,N,O, as catalysts for H-> He in hotter stars. These are noteworthy as the building blocks of life.

(8) Helium and Silicon to Nickel (which decays to Cobalt and then to Iron via successive positive beta decays) (^{28}Si + 7(^{4}He) -> ^{56}Ni -> ^{56}Co + e^{+} -> ^{56}Fe + e^{+}

Iron and neutrons to isotopes of Iron (not shown)

Through fusion, nearly all the elements up to Iron are created

Periodic table is from http://www.chemicalelements.com/



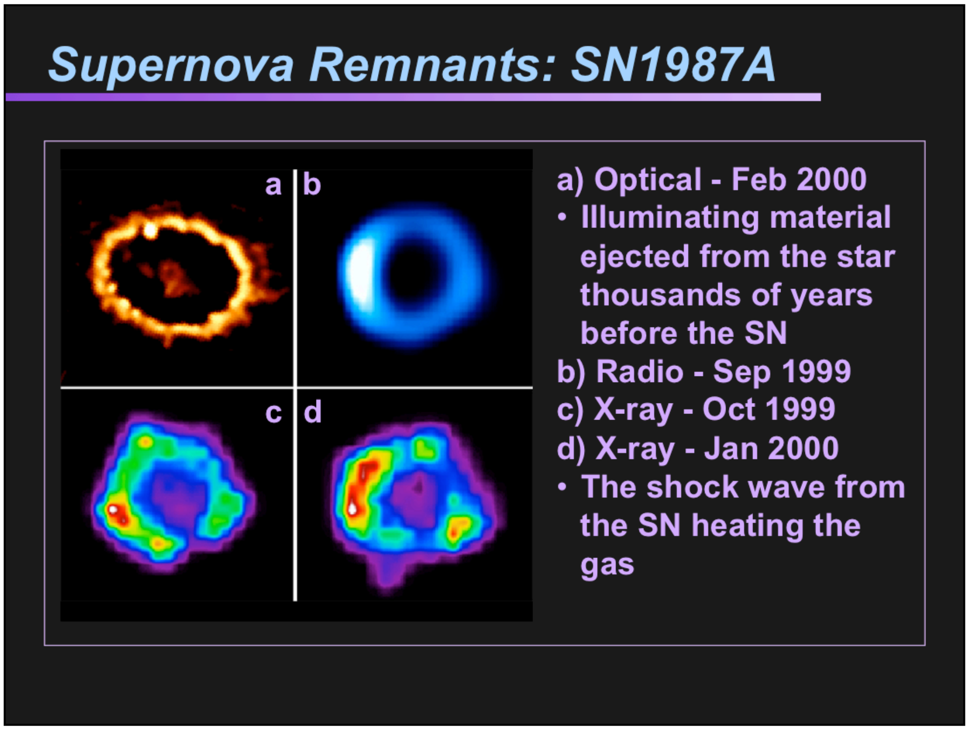
Fusion stops at Iron, and star collapses under its own weight.

The star contains products of the fusion processes.

SN1987A before and after image from Anglo-Australian Observatory. It's in the LMC, 160,000 light-years distant.

When fusion process no longer produces energy to support the star, the core of the star collapses. With nothing to stop it, the atoms are crushed together, and the infalling material bounces off the superdense core, causing the explosion.

A supernova produces 10^{40} erg/s (a million times more than the sun). The supernova disperses the elements it has created. In addition, the energy of the explosion creates elements heavier than iron.



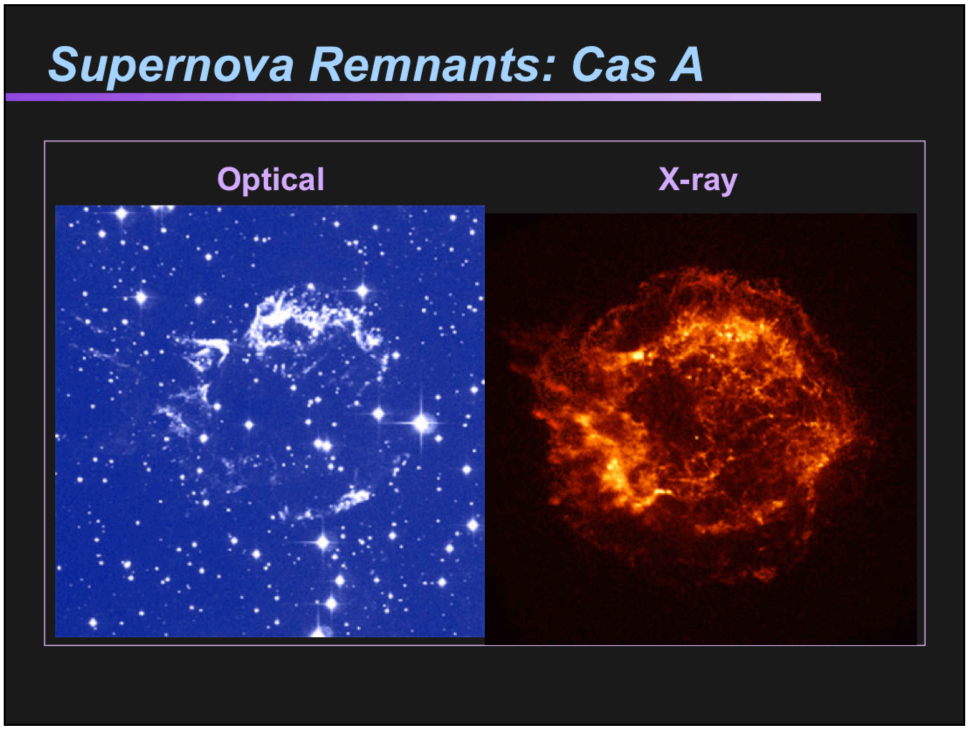
Optical and X-ray images of Supernova 1987a

Hubble image shows brightening of ring of material that was ejected from the star thousands of years before the supernova.

The Chandra images show the shock wave (traveling at 4,500 kilometers per second = 10 million miles per hour), smashing into portions of the optical ring. The gas in the expanding shell has a temperature of about 10 million degrees Celsius, and is visible only with an X-ray telescope.

In 2001, SN87A underwent transition from a few isolated hot spots in the optical to having many interaction sites distributed around the ring. See IAUC 7623

Hubble/Radio/Chandra image of SN1987A from http://chandra.harvard.edu/photo/cycle1/sn1987a/

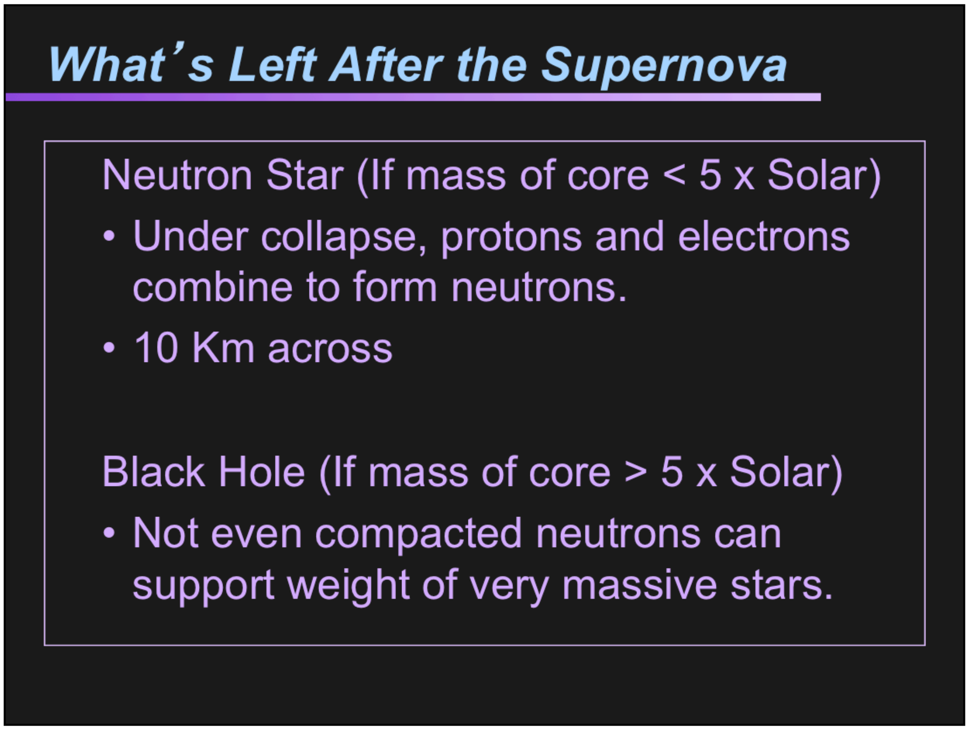


Cas A is 300 years old. The remnant is about 10 light-years in diameter, and 10,000 light-years away.

X-ray: outer shock wave is from the initial supernova explosion ripping through the interstellar medium at 10 million miles per hour. Temperatures may reach 50 million degrees. The inner shock is the ejecta from the SN heating up the circumstellar shell, heating it to 10 million degrees

The optical image of Cas A shows matter with a temperature of about ten thousand degrees. Some of these wisps contain high concentrations of heavy elements and are thought to be dense clumps of ejected stellar material.

Cas A x-ray and optical images from http://chandra.harvard.edu/photo/0237/



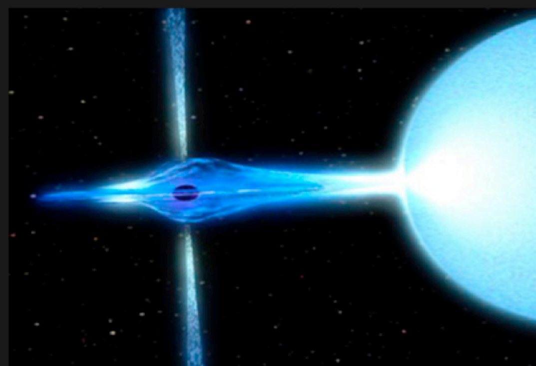
Neutron Stars and black holes

Neutron Stars form as protons and electrons in the "superdense" core combine to form neutrons. Re- the core is collapsing under it's own weight.

If there's too much mass, the formation of neutrons cannot stop the collapse. The neutrons themselves combine and "disappear" under the collapse.

A whole new life: X-ray binaries

In close binary systems, material flows from normal star to Neutron Star or Black Hole. X-rays emitted from disk of gas around Neutron Star/Black Hole.



If the neutron star or black hole is part of a binary star system, material from the normal star flows to the compact star, emitting x-rays. The system has a whole new life as an x-ray binary.

Illustration from http://www.gsfc.nasa.gov/gsfc/spacesci/structure/spinningbh/spinningbh.htm

Also see http://imagine.gsfc.nasa.gov/docs/features/news/30apr01.html

SN interaction with ISM

Supernovae compress gas and dust which lie between the stars. This gas is also enriched by the expelled material.

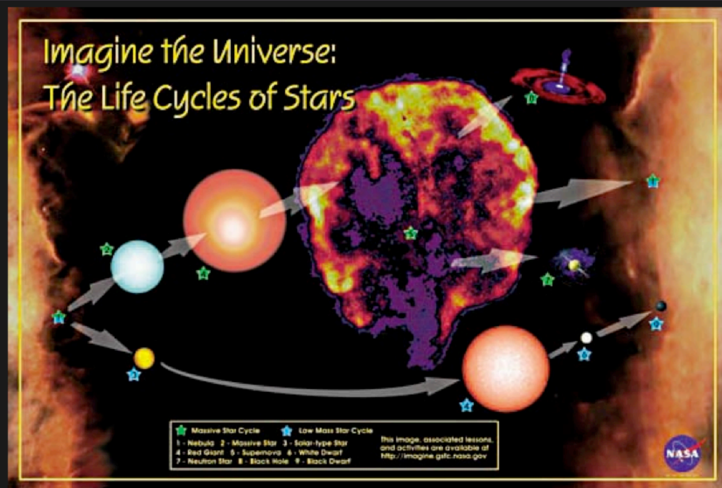
This compression starts the collapse of gas and dust to form new stars.

Shocks from SN’s cause collapse of clouds in the ISM and it starts over.

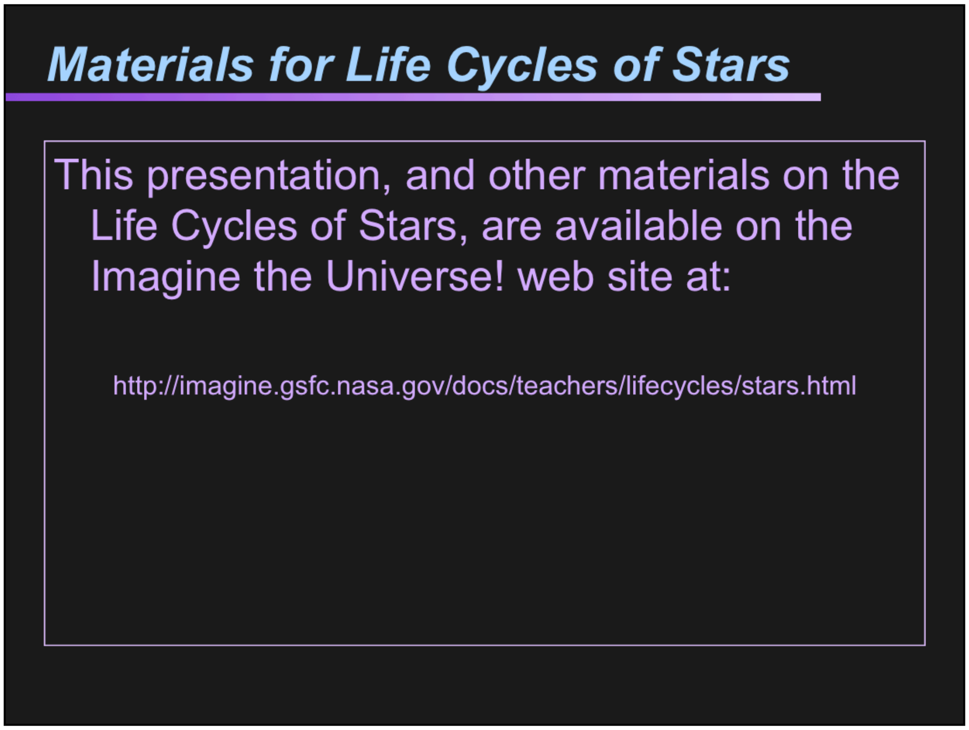
Hodge 301 is the cluster of massive stars in the lower right of this image of the Tarantula Nebula. It lies in the LMC. Many of the stars in Hodge 301 are so old that they have exploded as supernovae. These stellar explosions have blasted material out into the surrounding region at high speeds. As the ejecta plow into the surrounding Tarantula Nebula, they shock and compress the gas into a multitude of sheets and filaments, seen in the upper left portion of the picture. Also present near the center of the image are small, dense gas globules and dust columns where new stars are being formed today, as part of the overall ongoing star formation throughout the Tarantula region. These features are moving away from Hodge 301 at speeds of more than 200 miles per second. Hodge 301 is also bathed in the X-rays resulting from the shocks of all its supernovae.

The Hubble Image of Hodge 301 is from http://heritage.stsci.edu/public/gallery/galindex.html

Which Brings us Back to ...



This brings us back to our life cycle !


Materials for Life Cycles of Stars
This presentation, and other materials on the Life Cycles of Stars, are available on the Imagine the Universe! web site at:
http://imagine.gsfc.nasa.gov/docs/teachers/lifecycles/stars.html