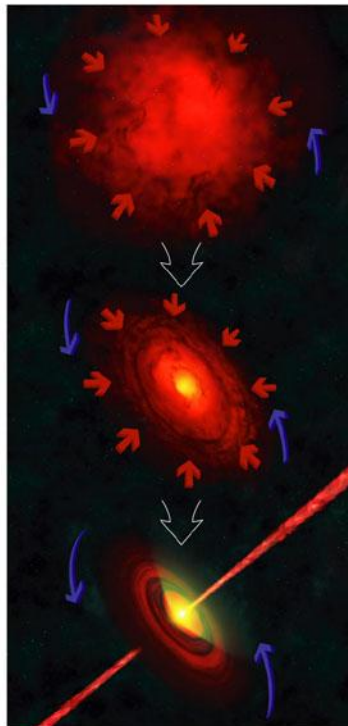


XIV. ASTRONOMY: STELLAR EVOLUTION

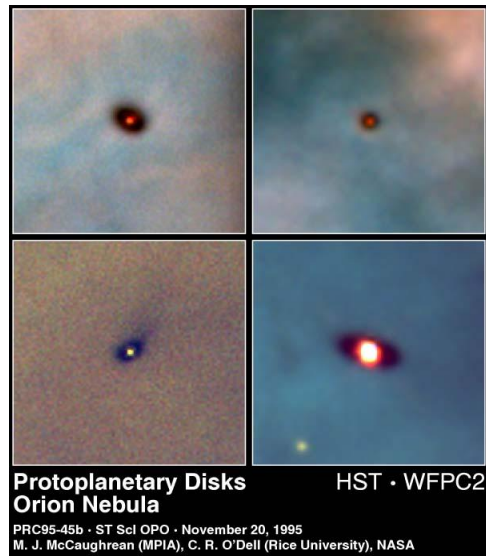
- A. To determine the probable life history of a typical star, we observe stars having many different ages and assume that they evolve in a similar manner.
 - 1. We must take into account their different masses; some aspects of their evolution depend critically on mass.
- B. Stars form from very large nebulae ---massive, self-gravitating clouds of gas and dust (tiny solid particles). All of the atoms, molecules, and particles exert a gravitational force on all others in the cloud.
 - 1. These particular nebulae are often called “giant molecular clouds” because they contain substantial amounts of molecular gas.
 - 2. The process of star formation is often hidden from view at optical wavelengths, due to the dense gas and dust.
 - a. Infrared and radio telescopes provide a much more direct view.
 - b. Eventually, winds generated by the young star clear out the surroundings, exposing it at optical wavelengths.
 - c. Often we see double-sided “jets” of material being ejected by very young stars.



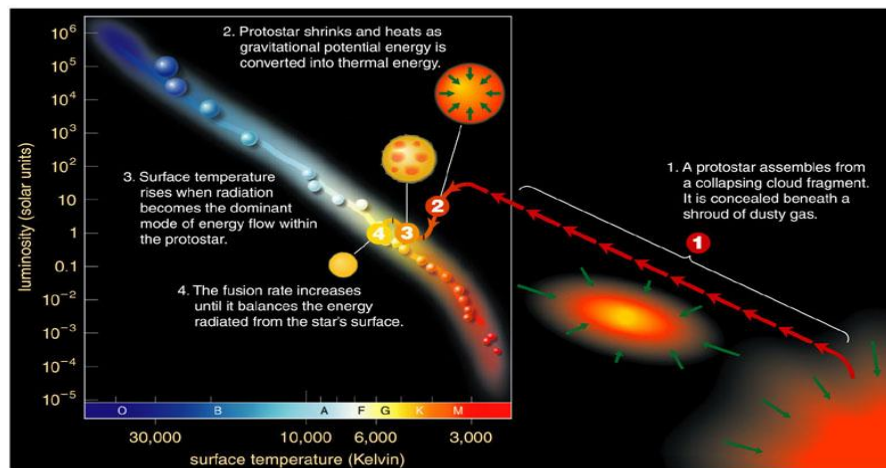
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- 3. If the cloud is sufficiently large or dense, it will begin to contract. Gravitational energy is released, and the material accelerates in free-fall.
- 4. Eventually the cloud fragments into many smaller parts, each with a mass comparable to that of a star. These “protostars” continue to contract, almost unopposed by internal pressure.

5. When a protostar becomes sufficiently dense, frequent collisions occur among its constituents particles; hence, part of the gravitational energy released during subsequent contraction goes into heating the gas, increasing its internal pressure.
 - a. In general, compression heats a gas. For example, a bicycle tire feels warm after air is vigorously pumped into it.
 - b. The rising internal pressure slows down the contraction rate until it becomes very gradual.
 - c. The object is now called a pre-main-sequence star.
6. During the contraction phase, a disk tends to form because the original nebula was rotating slightly.
 - a. Dusty disks have been found around young stars and pre-main-sequence stars in nebulae such as the Orion nebula. These are sometimes called protoplanetary disks.

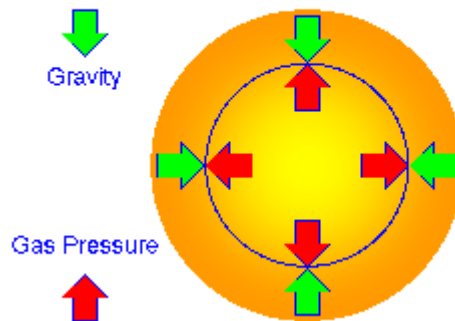


- b. This supports the theoretical expectation that planetary systems are common.
7. As energy is radiated from the surface of the pre-main-sequence star, its internal pressure decreases, and it gradually contracts.

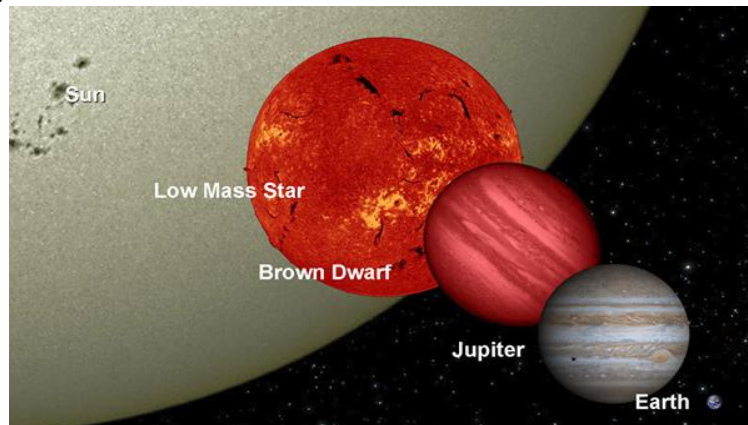


- a. This release of gravitational energy heats the interior, thereby increasing the internal pressure. It is also the source of the radiated energy.
- b. The internal temperature and pressure therefore rise as the object contracts.
- 8. If the object is sufficiently massive, the temperature in the core (i.e., the central region) eventually exceeds 10^6 K.
 - a. Nuclear reactions begin, producing energy at a rate equal to the rate of energy loss from the surface.
 - b. At this point, we say that a “**star is born**”: it reaches and settles on the main sequence. Contraction ceases, because the energy being released is nuclear rather than gravitational.
- 9. The star’s position on the main sequence (that is, it’s combination of luminosity and surface temperature) changes little during it’s lifetime.
 - a. Actually, stars grow somewhat more luminous during their main-sequence lives, because of changes in the composition of the core. The Sun, for example, is 30% more luminous now than shortly after birth.
 - b. The inward gravitational pull on any pocket of gas within the star is balanced by the outward push of pressure. This mechanical balance is called **hydrostatic equilibrium**.

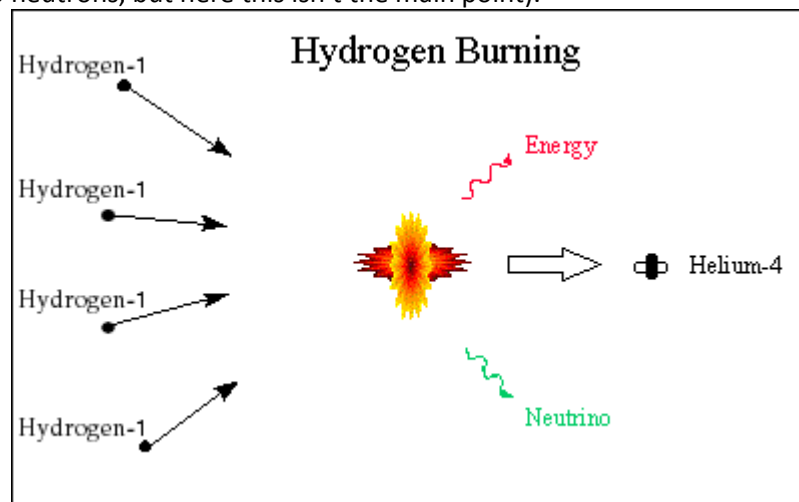
Hydrostatic Equilibrium



- 10. The entire contraction phase takes only about 0.1 % as long as the star’s main-sequence life.
- C. If the object is **not** sufficiently massive (greater than about 0.08 solar masses), nuclear reactions are not initiated. The object does not become a star.
 - 1. Instead, it is called a **brown dwarf**.

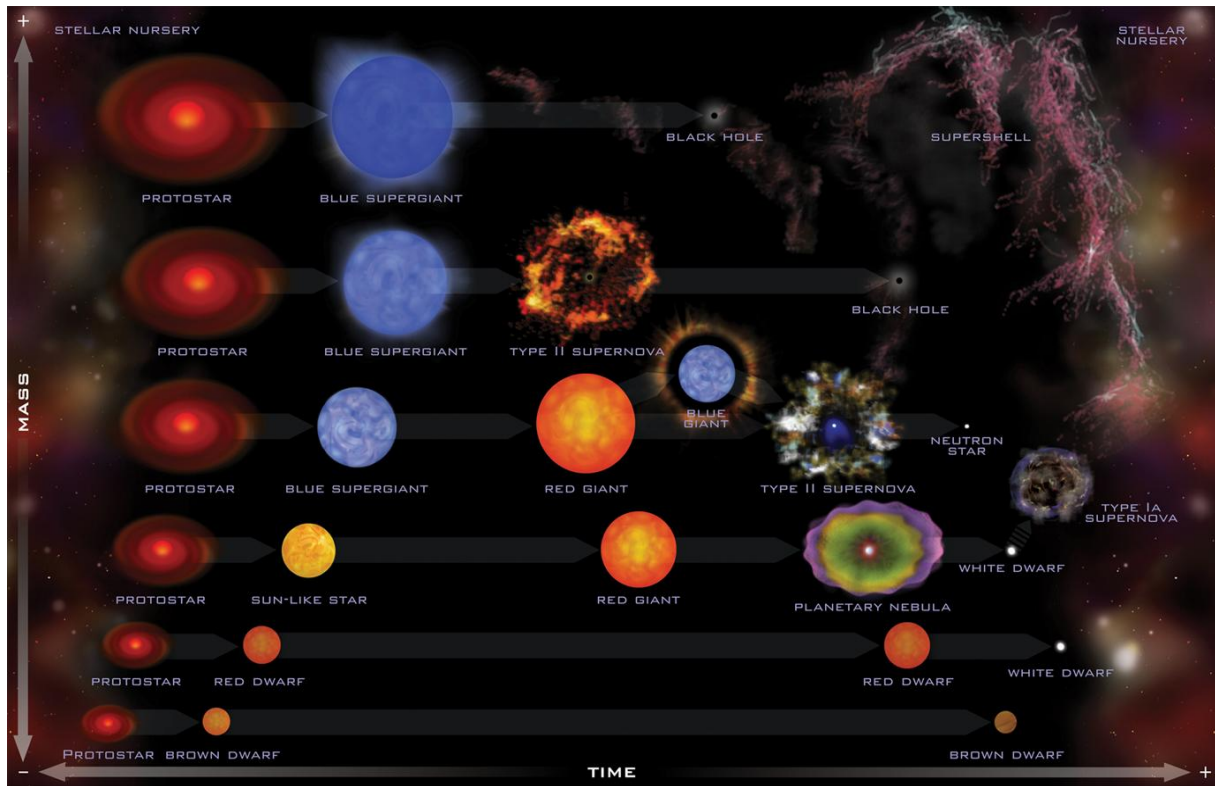


- a. Initially it shines due to gravitational contraction, but contraction halts when the interior becomes very dense.
- b. Subsequently, the only source of energy is the internal motion of the gas, and the object fades.
- 2. Brown dwarfs are very dim and difficult to find, but in the mid-1990s several were finally detected and confirmed.
- D. Main-sequence stars generate energy through nuclear fusion of hydrogen in their core.
 - 1. In the center of a star, the temperature is very high (e.g. 1.5×10^7 K in the Sun's core), so atoms are fully ionized (i.e., they lose all of their electrons).
 - 2. Protons (hydrogen nuclei) move with such high speeds that they can get close to each other and even collide, despite their mutual electric repulsion.
 - a. Occasionally they fuse together due to the "strong nuclear force".
 - b. There are several possible sequences of reactions, depending primarily on the temperature in the star's core, but the net effect is that 4 protons combine to produce 1 helium nucleus consisting of 2 protons and 2 neutrons. (2 of the protons turn into neutrons, but here this isn't the main point).

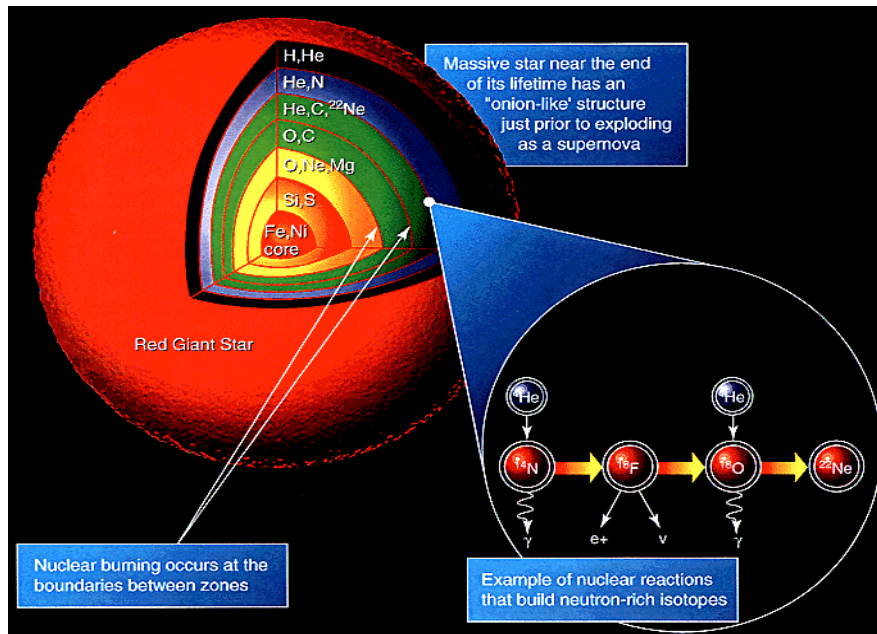


- c. The helium nucleus is *less massive* (by about 0.7%) than the 4 original protons, because the strong nuclear force **binds** the protons and neutrons together so tightly.
- d. The mass difference (m) is converted into an amount of energy given by Einstein's famous formula, $E = mc^2$.
- e. Most of the generated energy is in the form of gamma rays, which are converted to optical photons as they interact with matter on their way out from the center.
- f. The journey through the opaque star takes about 100,000 years, due to the almost innumerable interactions that convert the gamma ray into low-energy photons.
- g. If the core fails to reach a temperature of at least 10^6 K, the electric repulsion between protons is not overcome, and fusion of hydrogen to helium cannot occur. As mentioned above, this is a brown dwarf, with mass below $0.08 \times$ that of the Sun.
- 3. To produce its observed luminosity, the Sun converts about 700 million tons of hydrogen into helium each second.
 - a. There is plenty of raw material: by mass, the Sun is 70% hydrogen, 28% helium, 2% heavier elements. The core in which nuclear reactions occur has roughly 15% of the Sun's mass.
 - b. The Sun's main-sequence lifetime (during which hydrogen fuses to helium) will be about 10 billion years, and the Sun is now only 4.6 billion year old.

4. Despite its prodigious power output, and the method by which it achieves this (very similar to that of a hydrogen fusion bomb), the Sun is not exploding.
 - a. Rather, it is a controlled nuclear reactor: it generates energy at exactly the rate needed to maintain hydrostatic equilibrium.
 - b. All main-sequence stars behave in this stable manner.
- E. As part of the chain of reactions that converts 4 hydrogen nuclei (protons) into a helium nucleus, 2 of the protons turn into neutrons.
 1. The relevant reaction is that a proton becomes a neutron, a positron, and a neutrino.
 - a. A positron (e^+) is an antielectron; it rapidly annihilates with an electron (e^-), producing photons.
 - b. Neutrinos (ν , but not to be confused with frequency) are neutral particles that hardly interact with anything at all. Most neutrinos would pass unscathed through a light year of lead.
 - i) Neutrinos have a very small mass and travel slightly slower than light.
 - ii) They escape directly from the Sun, traversing its radius in just 2 seconds, unlike photons. They are probes of the current conditions in the Sun's core.
 2. The Sun should be producing neutrinos at a prodigious rate.
 - a. Even at Earth's distance from the Sun, a large number should be passing through us each second.
 - b. A tiny fraction of them interact with matter, and are potentially detectable.
 - c. For example, large tanks of various liquids have been built deep underground (where they are shielded from the solar wind, cosmic rays, etc.), and typically one neutrino per day should interact within the tank.
 - d. Significantly fewer are actually detected, yet tests have shown that the detectors are reliable. This is known as the "solar neutrino problem".
 3. It is likely that the "electron neutrinos" produced by the Sun change into a different type of neutrino during their journey.
 - a. In 1998, an independent experiment provided relatively direct evidence that "muon neutrinos" do indeed have non-zero mass and are the other type of neutrino.
 - b. A significant fraction of the so-called "dark matter" in the Universe might be neutrinos.
- F. What about stellar evolution beyond the main sequence?
 1. With some minor variations, essentially all single stars having $0.08 - 8 X$ the Sun's mass will evolve in a similar manner.
 - a. This is the vast majority of all stars; there are few very massive stars.
 - b. Since the Sun is a typical star in this mass range, we will focus our attention on one solar mass.
 - c. Binary stars can undergo more complex evolution.
 2. The main-sequence lifetime of a one solar mass star is about 10 billion years.
 - a. During this time, it is in hydrostatic equilibrium, with the inward pull of gravity being exactly balanced by the pressure pushing out.
 - b. Despite the leakage of energy into space (i.e., the star is shining), the interior maintains its high temperature and pressure because of nuclear fusion.
 - c. Each set of reactions has the net effect of converting 4 protons to a helium nucleus, releasing energy.
 - d. As the star ages, its luminosity gradually rises, but it is still considered a main-sequence star while there is hydrogen in its core.

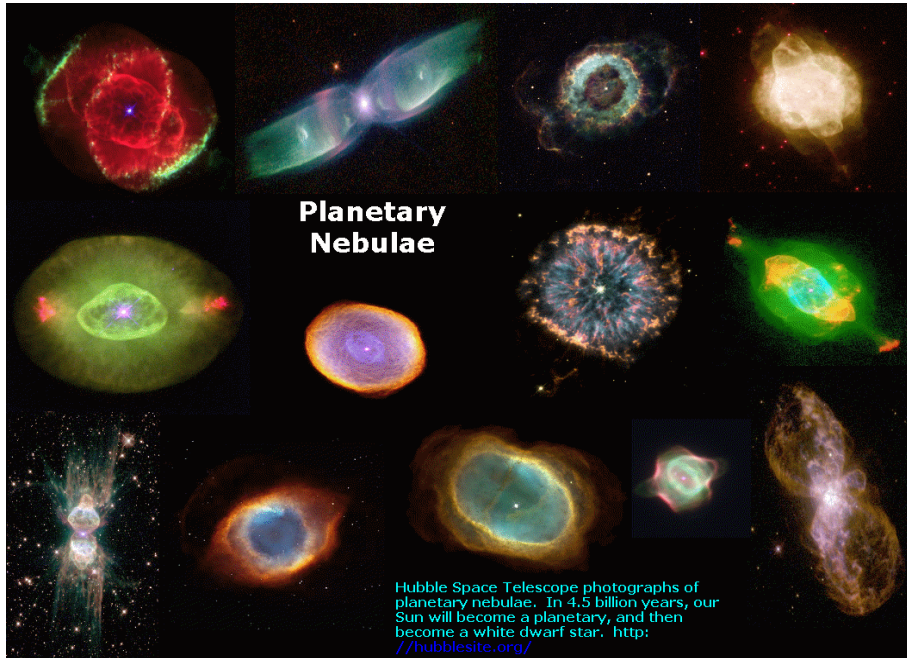


- G. Eventually, a helium core with about 10% - 15% of the star's mass builds up.
1. The temperature is too low for fusion of helium nuclei into heavier elements.
 - a. Helium nuclei have 2 protons each, so they repel each other more strongly.
 - b. Only at higher temperatures do the nuclei move with sufficient speed to get close together and bind.
 - c. A hydrogen-burning shell surrounds the helium core, gradually increasing the core's mass.
 2. Energy continues to leak out of the core, since the surroundings are cooler.
 - a. The pressure in the core therefore decreases, and it begins to gravitationally contract.
 - b. This liberates more energy; it also heats the core and the hydrogen-burning shell.
 - c. Nuclear reactions in the shell proceed faster, liberating more energy per second than during the main sequence.
 - d. This heats the surrounding envelope and causes it to expand.
 - e. As the star bloats, it's surface cools, and it becomes a **red giant**.

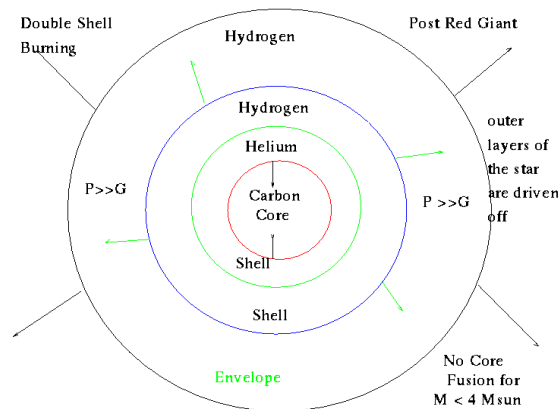


- f. For example, the radius of the Sun will reach perhaps half the distance to Mercury.
 - g. The Sun will be over 100 X more luminous than during the main-sequence stage, and Earth will get fried.
 - h. The transformation to a red giant happens quickly---less than 10% of the star's main-sequence lifetime. This is why few stars are found in the transition region of the HR diagram.
3. Meanwhile, the contracting helium core continues to heat up, and eventually reaches a temperature of about 10^8 K.
 - a. 3 helium nuclei can then fuse to form a carbon nucleus, releasing energy.
 - b. Also, a carbon nucleus can often fuse with another helium nucleus, forming an oxygen nucleus and releasing energy.
 - c. This phase is analogous to the hydrogen-fusing main sequence, but with helium.
 - d. It is relatively short lived (about a million years); the Sun is very luminous, and it quickly consumes it's fuel. Also, per reaction, much less energy is liberated when carbon and oxygen form that when helium forms; thus, more reactions per second are needed to maintain hydrostatic equilibrium, and the fuel supply quickly dwindles.
 4. A carbon-oxygen core builds up within the helium core.
 - a. The temperature is too low for fusion; carbon and oxygen nuclei have 6-8 protons, respectively, so they strongly repel other positive charge.
 - b. A helium-burning shell surrounds the carbon-oxygen core, and a hydrogen-burning shell surrounds the helium shell.
 - c. Energy continues to leak out of the carbon-oxygen core, and it contracts.
 - d. This heats the core and the surrounding layers, causing the helium and hydrogen shells to fuse faster and liberate still more energy; the Sun becomes even more luminous.
 - e. Once again, this heats the surrounding envelope and causes it to expand.
 - f. The star bloats to an even larger red giant. At this stage, the Sun will encompass the orbits of Mercury and Venus.
 5. The star now becomes unstable, and it's outer layers are ejected in a series of relatively non-violent outbursts.

- a. The expanding shells of gas are ionized by the UV radiation emitted by the surface of the remaining star, which is very hot because it used to be the interior of the star.
- b. The hot, ionized gases glow at optical wavelengths: emission lines are seen in the spectrum.
- c. This is called a “planetary nebula”: viewed through a small telescope, the bubbles of gas around such stars often resemble the disks of planets.

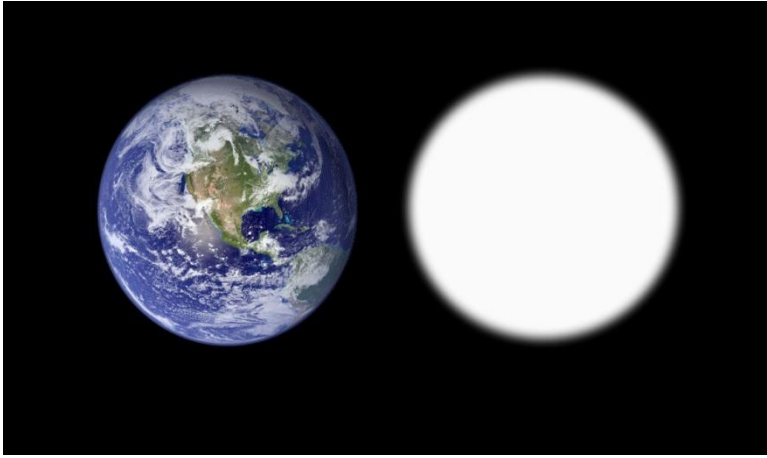


- d. They are very beautiful, with a wide variety of forms that depend on parameters such as the number of discrete ejections, the presence of circumstellar material, the star’s rotation rate, the distance of the companion star (in binary systems), etc.
6. The remaining star consists mostly of carbon and oxygen, a layer of helium and perhaps a thin outer layer of hydrogen.



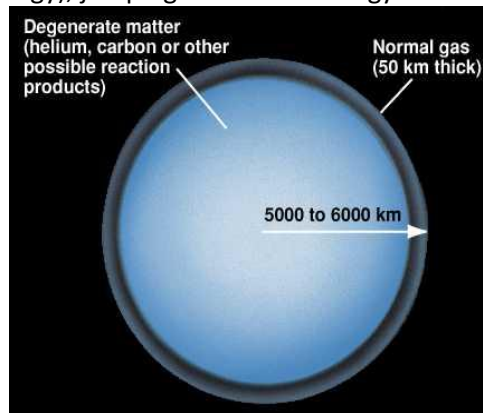
- a. In the Sun’s case, it’s mass will be about 0.6 solar masses.
- b. Its mass is always below 1.1 solar masses, even if the star’s initial mass was up to 8 solar masses; the rest of the mass was lost, mostly during the planetary nebula stage.

- c. The temperature is not sufficiently high to fuse carbon and oxygen to heavier elements, and the helium-burning and hydrogen-burning shells were ejected.
- d. Thus, the star quickly cools down and becomes much less luminous.
- e. It is called a white dwarf, and its typical size is comparable to Earth.



H. A white dwarf is a very strange star held up by “electron degeneracy pressure”; it doesn’t contract.

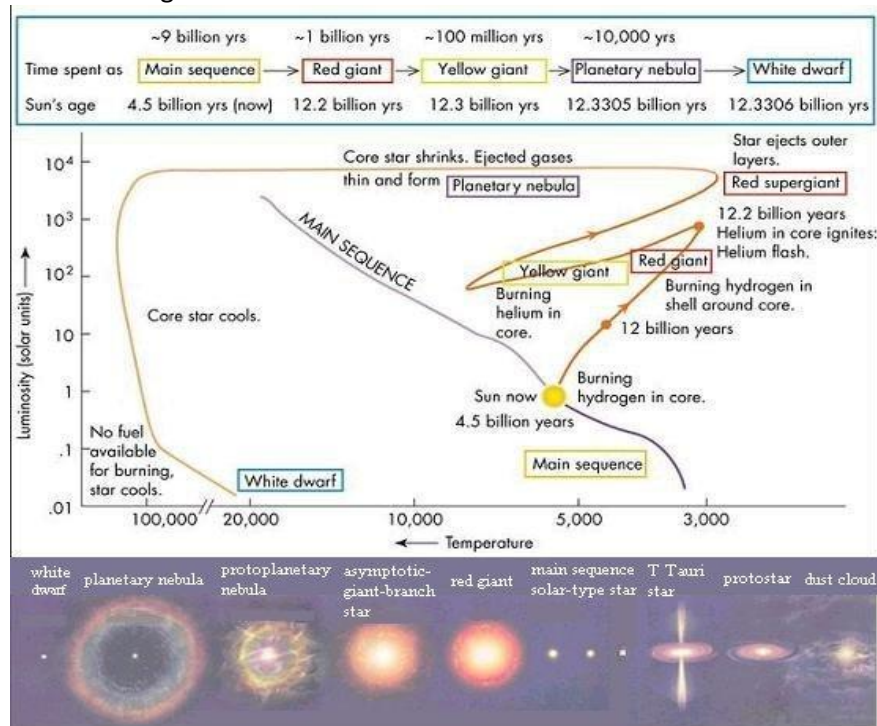
- 1. Most of the electrons are moving very fast, but the laws of quantum Mechanics prevent them from losing energy.
 - a. All lower energy levels are already filled to capacity by other electrons; only 2 electrons are allowed in each level. This is what we mean by the term “degenerate matter”.
 - b. Electrons in the high energy levels are moving so fast that they exert great pressure.
 - c. An interesting property is that massive white dwarfs are actually **smaller** than the less massive one.
- 2. The atomic nuclei are not degenerate: they can lose their energy of random motion (i.e., their thermal energy), jumping into lower energy states.



- a. A white dwarf shines only because nuclei lose energy. There are no nuclear reactions.
- b. Thus, white dwarfs are “retired stars,” spending their “life savings” of thermal energy.
- 3. Typical white dwarfs observed in our Galaxy have surface temperature about 2-4X that of the Sun and luminosity about 0.001 – 0.01X that of the Sun.
 - a. Eventually, after about 10^{10} years, the white dwarf’s luminosity is very low because its temperature is low.
 - b. Such objects are sometimes called “black dwarfs”, but the distinction from a white dwarf is arbitrary; a black dwarf is simply a cool white dwarf.



- c. They are still supported by electron degeneracy pressure, and they remain the same size.
 - d. They wander around in galaxies almost forever, cold and dark.
4. To summarize, the Sun will evolve into a red giant, then a larger red giant, followed by a planetary nebula, and finally a carbon-oxygen white dwarf. All this is conveniently plotted on a HR diagram.



- a. The main-sequence stage is by far the longest of the Sun's active lifetime (excluding the white dwarf, when it is not undergoing nuclear fusion).
- b. Stars in the range 0.45 – 8 solar masses follow essentially the same evolutionary sequence, but at various rates: stars more massive than the Sun evolve more quickly, and those less massive evolve more slowly.
- c. Stars less massive than 0.45 solar masses do not achieve sufficiently high temperatures to produce a carbon-oxygen core; they instead become helium white dwarfs.
- d. Stars in the range 8 – 10 solar masses become so hot that they produce an oxygen-neon-magnesium core. If most of the surrounding layers are lost, the remaining object becomes an oxygen-neon-magnesium white dwarf.

- e. In no case can a white dwarf exceed 1.4 solar masses, known as the Chandrasekhar limit.

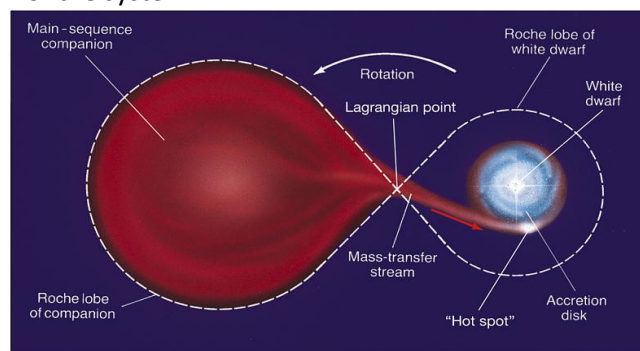
TABLE 20.1 Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (Yr)	Central Temperature (10^6 K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	15	6000	10^5	7×10^5	1	Main-sequence star
8	10^8	50	4000	10^7	2×10^6	3	Subgiant branch
9	10^5	100	4000	10^8	7×10^7	100	Helium flash
10	5×10^7	200	5000	10^7	7×10^6	10	Horizontal branch
11	10^4	250	4000	10^8	4×10^8	500	Asymptotic-giant branch
12	10^5	300	100,000	10^{10}	10^4	0.01	Carbon core
		—	3000	10^{-17}	7×10^8	1000	Planetary nebula*
13	—	100	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

*Values refer to the envelope.

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- I. Single stars evolve in a simple manner.
1. In particular, their main-sequence lifetime depends primarily on their mass, and to a much lesser extent on other variables such as the chemical composition.
 2. Most stars, however, are in binary systems, and the stars can exchange matter.
 - a. Surrounding each star is a region known as the “Roche lobe”, in which it’s gravity dominates over that of the other star.
 - b. The Roche lobes of the two stars join at a point between them.
 - c. Consider 2 main-sequence stars. As the more massive star evolves to the red giant phase, it fills it’s Roche lobe, and gas can flow toward the lower-mass companion.
 - d. The recipient can gain considerable mass, and it subsequently evolves faster than it would have as a single star.
 - e. Note that the flowing matter forms an *accretion disk* around the recipient star due to the rotation of the system.



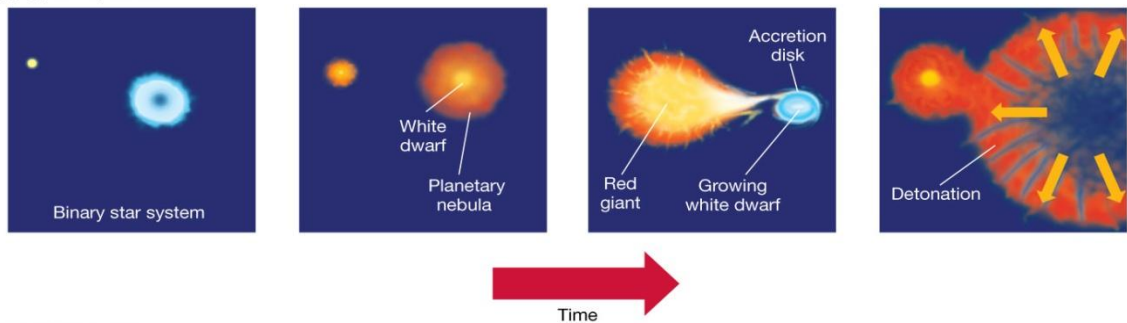
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3. If one star is already a white dwarf and the companion fills it’s Roche lobe (e.g. it is on it’s way to the red giant phase), a **nova** can result.
 - a. Nova is short for “**nova stella**”, or “new star”.
 - b. Actually, however, it is an old star that brightens by a factor of a hundred to a million in a few days or weeks.
 - c. It subsequently fades over months or years.
 - d. This phenomenon can recur in a given binary system.

4. The brightening of a nova can occur in at least two ways.
 - a. As gas accumulates in the accretion disk, the disk becomes unstable and suddenly dumps material onto the white dwarf. The gravitational energy is converted to photons.
 - b. Matter accumulates on the white dwarf, and suddenly undergoes nuclear fusion. This can brighten the system far more than the release of gravitational energy. The fusion produces a few of the heavy elements in the periodic table.
- J. Stars in binary systems may occasionally brighten as novae, but the white dwarf survives the eruption.
 1. Some stars, however, violently destroy themselves by exploding.
 - a. The ejected gases expand with speeds that can exceed 10,000 km/s.
 - b. Over the course of a few days or weeks, they become much more luminous at visible wavelengths---up to 10 billion times the solar luminosity.
 - c. For a few weeks, they can rival the brightness of a small galaxy.
 - d. They fade over the course of years.
 2. Besides being powerful and fun to watch, these exploding stars ("supernovae") are important for many reasons.
 - a. They sometimes produce neutron stars and black holes, compact remnants that allow us to explore the laws of physics conditions unattainable in laboratories.
 - b. The expansion heats surrounding gas to temperatures of tens of millions of degrees, in some cases ejecting it in gigantic bubbles or fountains.
 - c. They send waves of compression through dense clouds of gas, triggering gravitational contraction and initiating the formation of new stars.
 - d. They produce high-energy charged particles ("cosmic rays") that can cause mutations in living cells, and hence contribute to the evolution life.
 - e. Being so luminous, they can be used to measure distances of galaxies billions of light years away, allowing us to determine the past history and fate of the Universe.
 3. From a human perspective, supernovae are most important because they produce and disperse heavy elements into the cosmos.
 - a. The elements are synthesized by nuclear fusion before and during the explosion.
 - b. The ejected gases expand, producing supernova remnants like the Crab nebula from the explosion of 1054 A.D.
 - c. After tens of thousands of years, the chemically enriched gases merge with other clouds of gas.
 - d. If a sufficiently large cloud is produced, it can gravitationally contract to form chemically enriched stars and planets.
 - e. The oxygen that we breathe, the carbon in living tissue, the calcium in our bones, the iron in our red blood cells, and the gold and silver in our jewelry were produced long ago, deep inside stars.
 4. Supernovae are rare: they occur perhaps once or twice per century in a typical galaxy.
 - a. Thus, we are unlikely to see very nearby ones; most galaxies are distant.
 - b. We need to examine hundreds of galaxies to find a few supernovae each year.
 - c. Several amateur astronomers, most notably the Reverend Robert Evans in Australia, are quite successful at finding supernovae by visually examining or photographing galaxies.
 - d. A good example was SN 1994D, the fourth supernova discovered in 1994: located in a galaxy about 60 million ly away, it looks brighter than a foreground star perhaps 600 ly away.

- i) Since $(6 \times 10^7 / 600)^2 = (10^5)^2 = 10^{10}$, the supernova was about 10 billion X more luminous than a normal star.
5. There are 2 main types of exploding stars.
- Those that show hydrogen in their spectra are called Type II.
 - Those that do not show hydrogen in their spectra are called Type I.
 - There are other differences as well, such as in their “light curves” (plots of brightness versus time).
 - There are various subdivisions among the 2 types. Most notably, when referring to “Type I,” we actually mean “Type 1a”.
- K. Type I supernovae occur in all kinds of galaxies, including ones that have few if any massive stars.

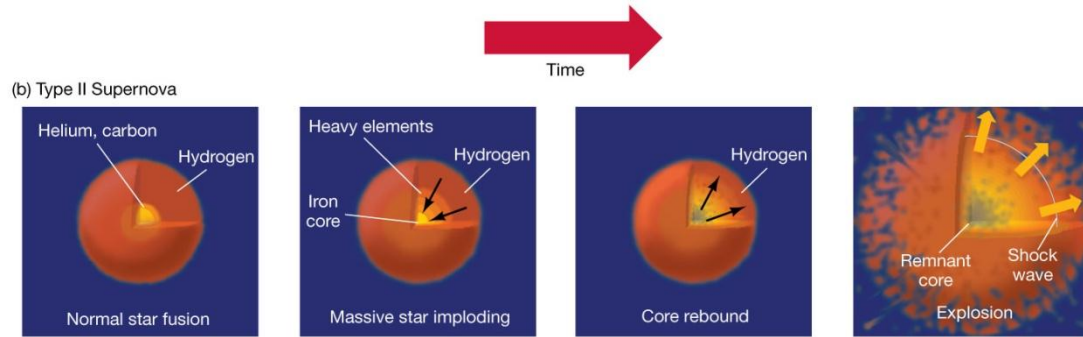
(a) Type I Supernova



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- Thus, their “progenitors” (the stars that produce them) are old, or reasonably old ---ages of perhaps a few hundred million to a few billion years.
- Type I supernova is thought to be produced by a white dwarf in a binary system, but only a small fraction of such systems have the properties necessary to yield an explosion.
 - If the companion star is sufficiently close to the white dwarf, it’s outer envelope can be larger than the Roche lobe.
 - As in the case of novae, gas then flows from the companion to the white dwarf.
 - The nature of the companion star is unclear, but it could be a normal star, or a star on it’s way to becoming a red giant, or perhaps even another white dwarf.
 - In general, the matter accumulated on the surface of the white dwarf will be expelled in a nova event (in which nuclear reactions occur only at the surface of the star).
 - Under some circumstances, however, the nova process may be bypassed, and the mass of the white dwarf steadily grows.
 - If the mass of the white dwarf reaches a critical value of about 1.4 solar masses, the white dwarf becomes unstable, and a series of uncontrolled nuclear reactions ensues. This upper limit to the mass of a white dwarf is known as the Chandrasekhar limit, after S. Chandrasekhar who derived it on a voyage from India to England, where he was to be educated.
 - Heavy elements are synthesized from carbon and oxygen, thereby liberating a huge amount of energy. This unbinds the star, and it explodes.
 - About half of the white dwarf’s mass is fused into radioactive nickel nuclei.
 - This subsequently decays into radioactive cobalt, and finally into stable iron, releasing energy at each stage.
 - The supernova glows for over a year due to this decay process, becoming progressively fainter after the initial rise that lasts weeks.
 - Since the star entirely obliterates itself, no compact remnant remains.

- j. The stellar ejecta, enriched in relatively heavy elements (up to iron and its neighbors) produced during the explosion, expand outward and gradually form a supernova remnant. Tycho's supernova of 1572 may have been Type I, and we can now observe the expanding remnant.
 - k. One of the best known and nearest white dwarfs is Sirius B, the companion of Sirius, the brightest star in the sky. (8.7 ly away)
- L. Type II supernovae tend to occur in regions that contain many very massive stars, such as the arms of spiral galaxies.

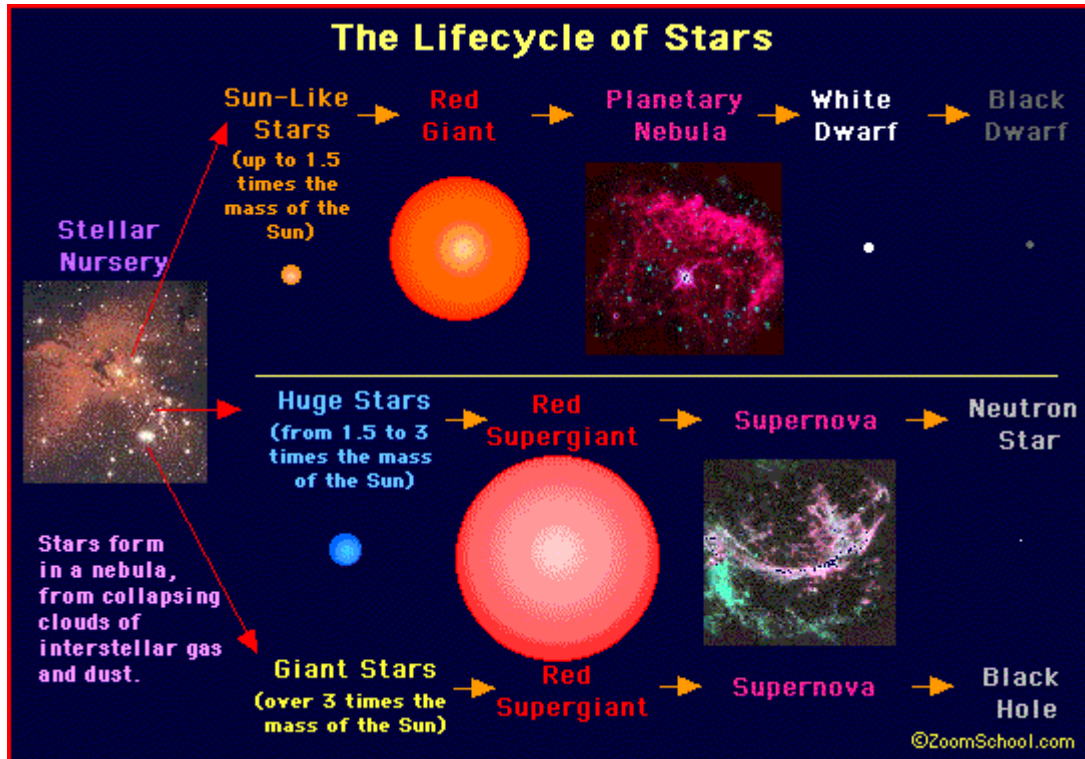


1. They arise from stars at least 10X the mass of the Sun.
2. Despite being so massive, such stars don't live very long, because they use their store of nuclear fuel at a disproportionately rapid pace. A 15 solar mass star, for example, lives only about 10 million years (compared with the Sun's main-sequence lifetime of about 10 billion years).
3. Near the end of its life, a star initially more than 10X the mass of the Sun becomes a supergiant ---generally a cool red one.
 - a. It develops an internal structure similar to that of an onion: there are layers of progressively heavier elements going in from the outer atmosphere to the core.
 - b. The heavy elements were synthesized by fusion of lighter elements.
 - i) Hydrogen fused to helium during the main-sequence stage.
 - ii) Next, helium fused to carbon and oxygen, as our Sun will do.
 - iii) Carbon subsequently fuses to form neon and magnesium, and so on.
 - iv) Effectively, the ashes of one set of nuclear reactions became the fuel for the next set.
 - c. This process is able to go all the way up to iron, liberating energy at each stage and keeping the star hot inside. The very high temperatures and pressures in the core of a supergiant make this possible.
 - d. The iron core cannot fuse to form heavier elements, because energy would be absorbed rather than liberated, accelerating the demise of the star. Iron and elements of similar mass have the most tightly bound nuclei.
 - e. The mass of the iron core increases due to nuclear fusion in the surrounding shell. When it reaches about 1.4 solar masses (similar to the Chandrasekhar limit of a white dwarf), it becomes unstable.
 - f. Gravitational collapse ensues. The protons and electrons combine to form neutrons and neutrinos, and the latter escape from the star.
4. The collapsing core overshoots its equilibrium size and rebounds outward, like someone jumping onto a trampoline.
 - a. It collides with the inward-falling surrounding layers and propels them outward.

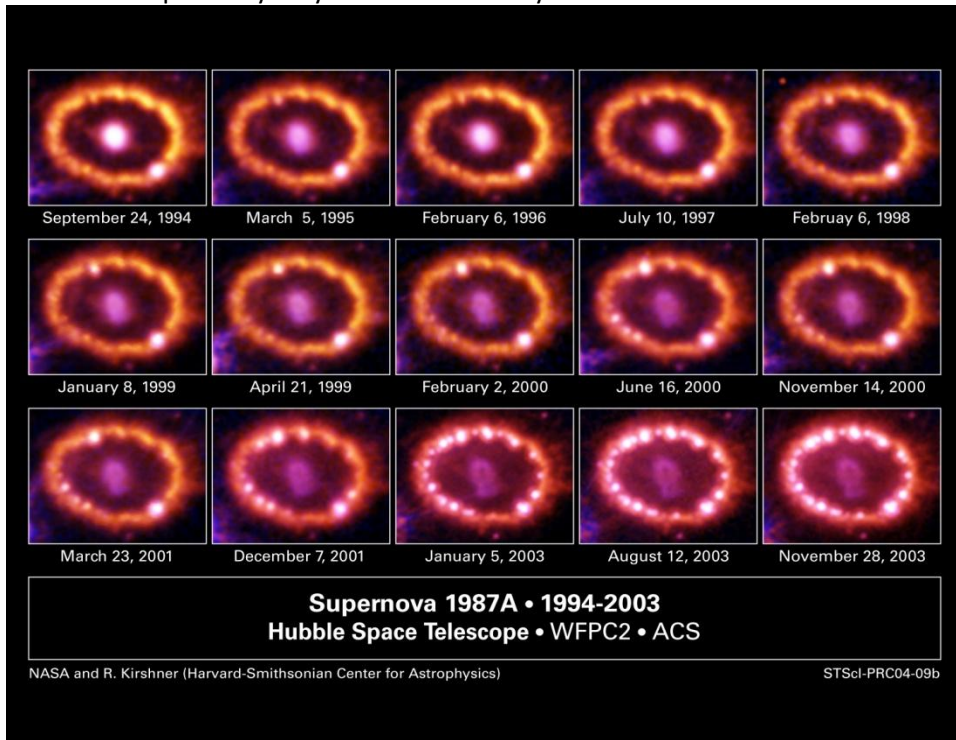
- b. For a stunning analogy, hold a tennis ball on top of a basketball several feet above the ground, and drop both of them simultaneously. The tennis ball will rebound to a great height.
- c. The collapsed core also emits an avalanche of neutrinos, some of which interact with the surrounding layers and push them out. This is actually more important than the mechanical “bounce” described above.
- d. A supersonic blast known as a shock wave travels through the star at about 10% of the speed of light.



- e. The result of all this is a successful explosion of most of the star; only the collapsed core remains intact as a strange “neutron star” of radius about 10 km. The ball of neutrons is extremely dense: one tablespoon of it on earth would weigh about a billion tons.
 - f. So much energy is released during the explosion that elements heavier than iron are synthesized, mostly by the rapid capture of free neutrons. For example, this is the origin of the gold and silver in our jewelry, as well as the uranium and plutonium in nuclear weapons.
5. In some cases, stars whose initial mass is in the range 8-10 solar masses may explode by a similar mechanism.
- a. Their cores do not fuse up to iron, but only to oxygen-neon-magnesium, or perhaps to somewhat heavier elements.
 - b. If a companion star steals the envelope of gases, then the core might not reach instability, and it becomes a white dwarf.
 - c. However, in single stars or widely spaced binaries, the core eventually becomes unstable and collapses to form a neutron star.
 - d. The consequences are similar to those describe above.



- M. In February 1987, a supernova became visible in the Large Magellanic Cloud (LMC), a satellite galaxy only 170,000 ly away.
1. It was indeed a supergiant star that began its life with about 20 solar masses. Prior to the explosion, some mass was lost due to winds and mild expulsions. Thus, the star was somewhat less massive when it exploded.
 2. The star was probably only about 10 million years old at the time of its death.



3. Neutrinos were detected.
 - a. The neutrinos actually preceded by a few hours the arrival of visible light from SN1987A.
 - b. This confirmed the explosion mechanism was a core collapse followed by ejection, and the a neutron star was created.
 - c. 99% of the gravitational energy was converted to neutrinos and antineutrinos.
 4. Later, SN1987A confirmed that heavy elements are synthesized during the explosion.
- N. Questions:
1. Describe the process by which stars are thought to form.

2. Discuss the source of energy emitted by a contracting pre-main-sequence star.

3. State what is happening in the core of a main-sequence star to liberate energy.

4. Explain why it is said that the Sun is a controlled nuclear reactor.

5. Define the term "brown dwarf".

6. Summarize the results of experiments designed to detect neutrinos from the Sun, and their interpretation.

7. State the approximate age of the Sun.

8. Describe what will happen to the Sun after it uses up the hydrogen in its core.
9. Define what is meant by a planetary nebula.
10. Discuss the reason a white dwarf does not gravitationally collapse, and the source of the energy that it emits.
11. Summarize the complete evolution of the Sun.
12. Explain why a star's rate of evolution can change if it is in a binary system.
13. Describe a nova and its physical origin.
14. What is the difference between a protoplanetary disk and a planetary nebula?
15. How can we be so confident in our theory of the Sun's future evolution?
16. Describe the observational properties of an exploding star (supernova).

17. Summarize the ways in which supernovae are important.
18. State the main reason supernovae are relevant to life on Earth.
19. Explain how supernovae are discovered in other galaxies.
20. Define the 2 main types of supernovae.
21. Discuss the physical mechanism that produces each type of supernova.
22. Identify the origin of neutron stars.
23. Describe the discovery and significance of Supernova 1987A.