CHAPTER 4

MONSTERS IN THE SKY

Look up at the night sky. If you can escape city lights, flickering beams from myriad stars dance in the clear, dark heavens of the countryside. On a summer's night, you can see the broad sweep of our Galaxy, the Milky Way, and if you know where to cast your gaze you may perceive the misty outlines of a neighboring galaxy, the great galaxy in the constellation Andromeda -- a system like our own with hundreds of billions of stars. Humankind have wondered at the heavens probably since first gazing upward, but only in this century have we understood what lights the stars.

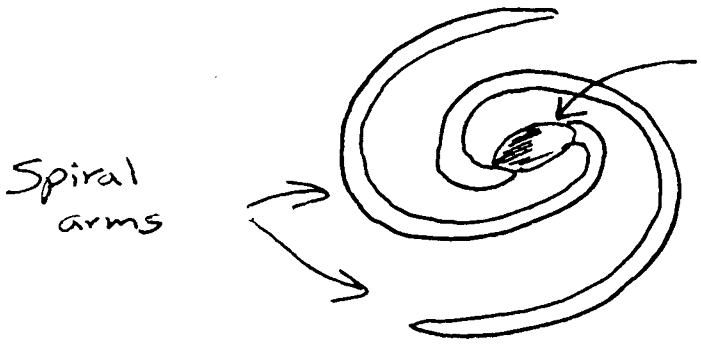
In this chapter we employ classical physics and the theory of relativity to trace the lives and fates of stars, including stars with planetary systems such as our own sun. Einstein's special theory of relativity, in particular, explains why they shine, and the general theory of relativity describes such exotica as neutron stars, pulsars -- blinking beacons in the sky -- and black holes, objects so dense not even light can escape their gravitational pull.

The realm of neutron stars, pulsars, and black holes is the realm of general relativity. Even near average-mass stars like our sun, relativistic changes are barely discernable. Only around celestial behemoths does the warping of spacetime become obvious.

UNITS OF STRUCTURE IN THE UNIVERSE

A star is as a grain of sand in the over-all structure of the Universe. On the scale of the Universe, the basic unit of structure is the galaxy.

Typical galaxies comprise hundreds of billions of stars and perhaps ten times as much additional mass in the form of gas, dust, and other more exotic matter (black holes, planets, and, perhaps, exotic elementary particles). Our own Milky Way is a typical spiral galaxy.



Typical galaxy, about 100,000 light years in diameter and containing 300 to 400 billion stars.

There are, in turn, about 100 billion galaxies in the observable Universe. Our nearest neighbor major galaxy, the great galaxy in Andromeda, is about 2.5 million light years distant. The farthest galaxy yet detected lies about 13 billion light years away.

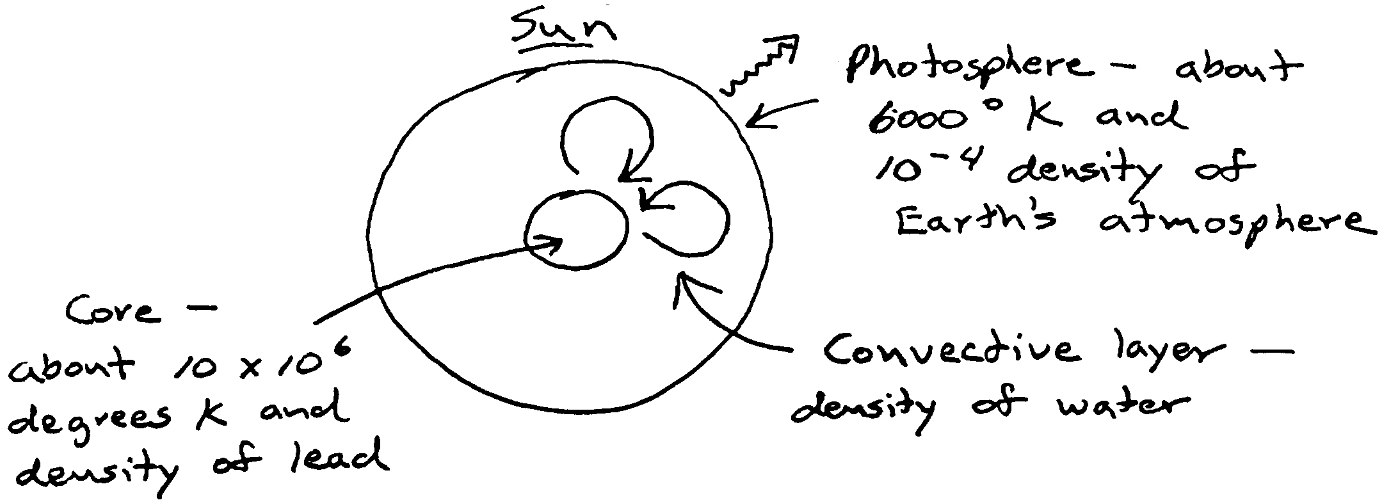
Galaxies themselves are distributed in clusters -- hundreds or thousands of galaxies ponderously orbiting a common center of mass, trapped by their mutual gravitational attraction.

STELLAR COMPOSITION

A typical star includes a mixture of gases, predominantly hydrogen and helium, the simplest chemical elements and the major components of the Universe as a whole. In fact, by proportion the Universe is (and most newborn stars are) about 75% hydrogen and 24% helium, with only traces of the other chemical elements. (How hydrogen and helium originated is our story in Ch.9.)

A star, unlike planet Earth, lacks a solid surface: it is a glowing ball of gas. It has an internal structure, however, determined by the temperature and gas density at different depths in the star. The inner layers are compressed by the outer layers, and different processes occur there.

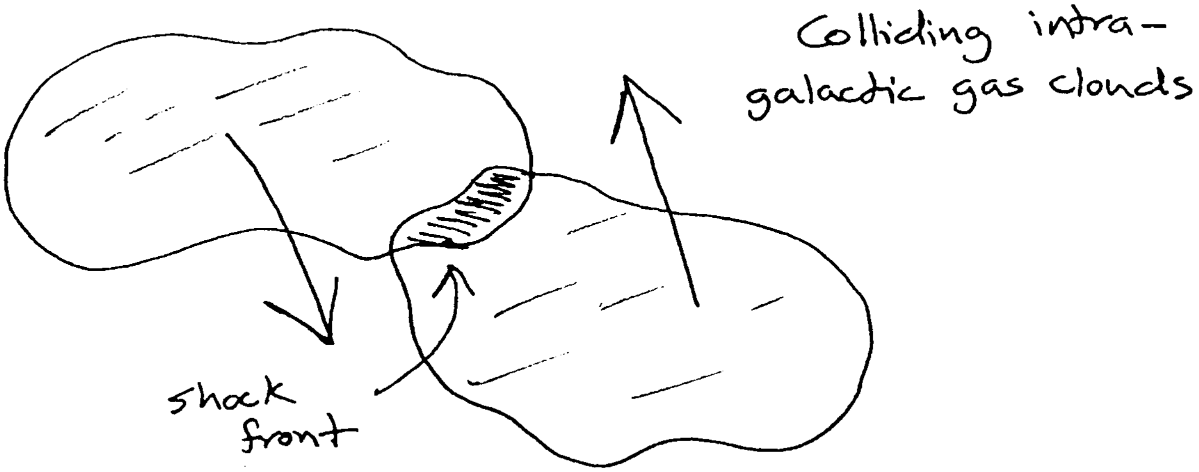
At the center of a typical star, such as our sun, is the core, a region compressed by the intense gravitational field to about twelve times the density of lead and in which temperature (about 10 million degrees Kelvin) and pressure are great enough to drive fusion reactions. Overlying the core is a convective layer, where boiling gasses transfer heat from the core to the photosphere. The photosphere is the radiative surface, where energy leaves the star as electromagnetic radiation, including light, and as a stream of high energy particles, the stellar wind.



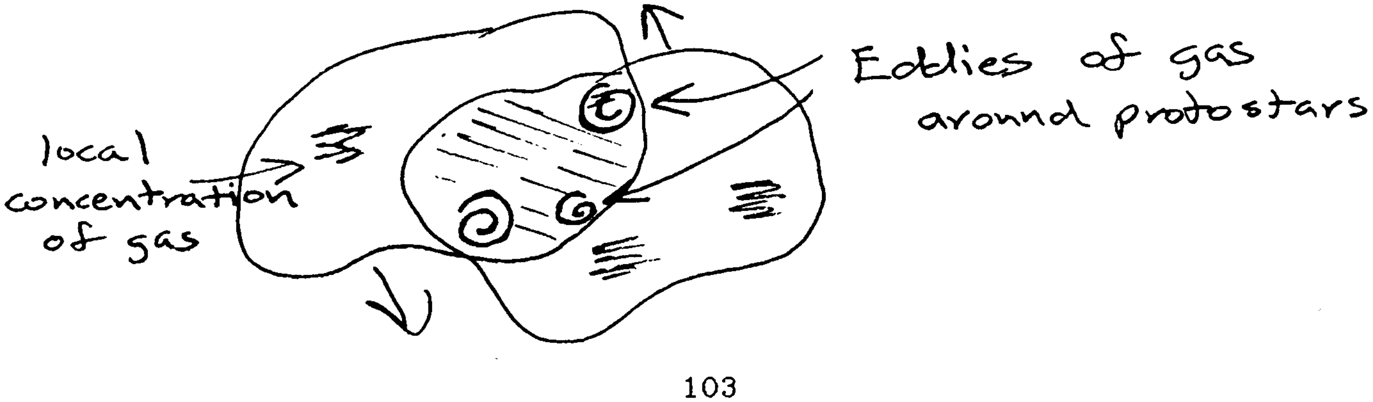
As a general rule, the mass of a star determines its structure and its fate. The more massive the star -- that is, the more hydrogen and helium it was given at birth -- the denser its core and the hotter it burns its nuclear fires. Paradoxically, the most massive stars live the shortest lives.

STAR BIRTH

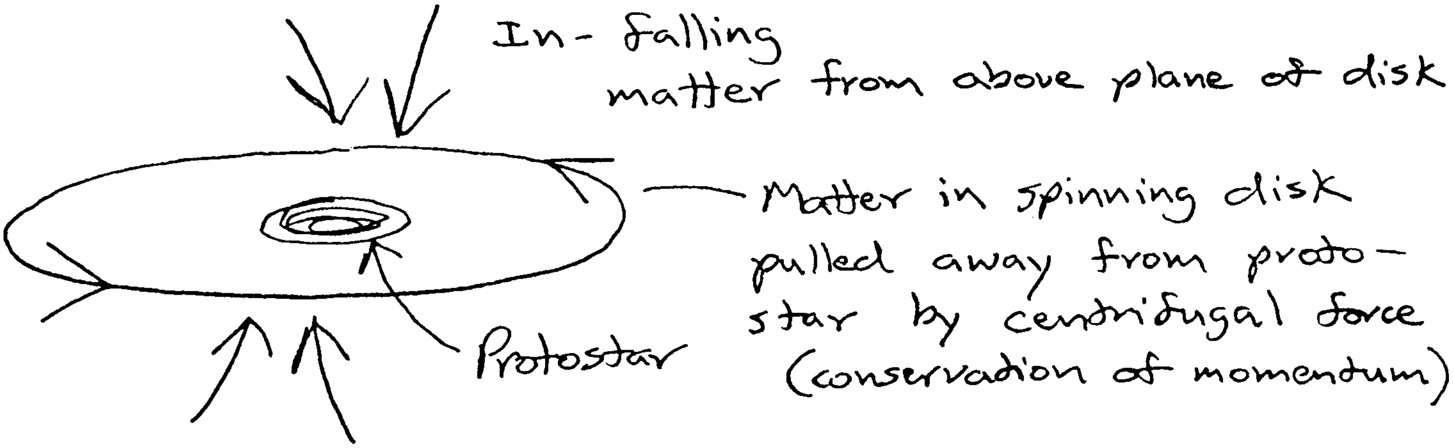
Stars are born from vast clouds of gas distributed in the galaxies, and stars are usually born in litters of hundreds or thousands from the same cloud. To start the process, some triggering event compresses the cloud. The trigger may be a nearby supernova explosion or a collision between two clouds. Such events pile up gas in the cloud into a shock front, like a bulldozer piling dirt. The gravitational field associated with shock front pulls yet more gas from the surrounding cloud.



Gas clouds have an uneven distribution of gas, and because the gas is in motion, like everything else in the Universe, eddies of turbulent gas form. A protostar (a denser-than-average concentration of gas) becomes the center of a maelstrom: like a skater pulling in her arms, in-falling gas swirls faster as it approaches the protostar.



The interplay between gravity and "centrifugal force" (the momentum of the spinning gas) creates planetary systems and multiple-star systems. The force of gravity is unopposed along the axis of spin, so material falls along the axis into the proto-star. In the plane of the spinning disk, however, centrifugal force opposes the force of gravity, just as a skater's arms, if she were to relax them, would fly away from her torso as she spins. Material surrounding the proto-star, then, becomes concentrated in the plane of the disk, where it may form a companion star or planets.



FUSION

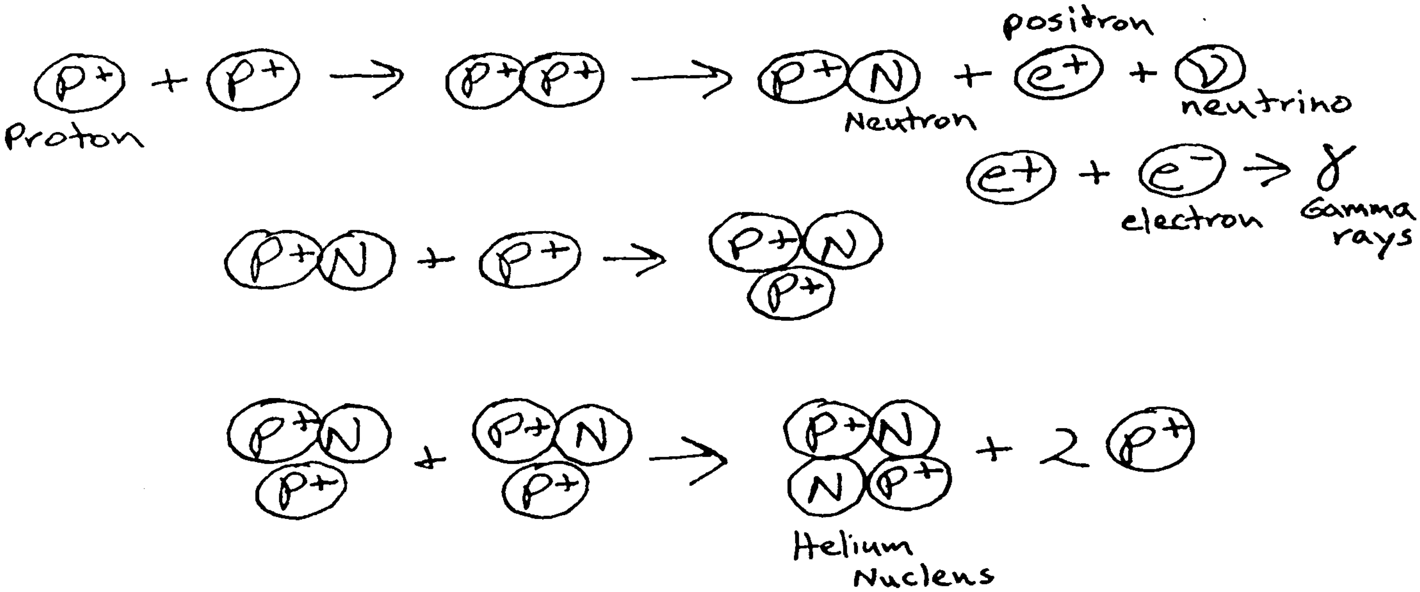
As gas accumulates in the proto-star, core density and temperature rise. When temperature and density reach a critical point, hydrogen fusion reactions ignite.

We can understand the rise in temperature qualitatively: If we drop a ball from three feet, it strikes the floor with a certain kinetic energy. Drop it from ten feet, it strikes with greater kinetic energy, since it has accelerated for a longer time in the Earth's gravitational field. Gas in a proto-star behaves similarly: as it falls into the proto-star, its kinetic energy increases.

Temperature is, in fact, a measure of the kinetic energy of the molecules, atoms, and subatomic particles in a system. In a star, in-falling gas gains kinetic energy, hence increases in temperature.

More formally, we can understand the increased temperature in terms of conservation of energy. Gas atoms initially were distributed at some (great) distance from the proto-star: they had a large potential energy. As they fall into the proto-star, that potential energy is converted into kinetic energy.

High temperatures (large kinetic energy) in the core of an evolving protostar strip atoms of their electrons, and the gas exists in a state called a "plasma" -- free electrons and free nuclei flying helter-skelter. Under such conditions, two protons may collide head-on with enough momentum to overcome their mutual electromagnetic repulsion, and they fuse: if they approach within 10^-13 cm., the range of the strong nuclear force, the strong nuclear force binds them together. (Within its range, the strong force is 100 times stronger than the electromagnetic repulsion.) In a series of reactions, four protons (hydrogen nuclei) eventually fuse to form one helium nucleus. In the process, some mass is converted to gamma rays, a form of energy -- just as Einstein predicted in the special theory of relativity.

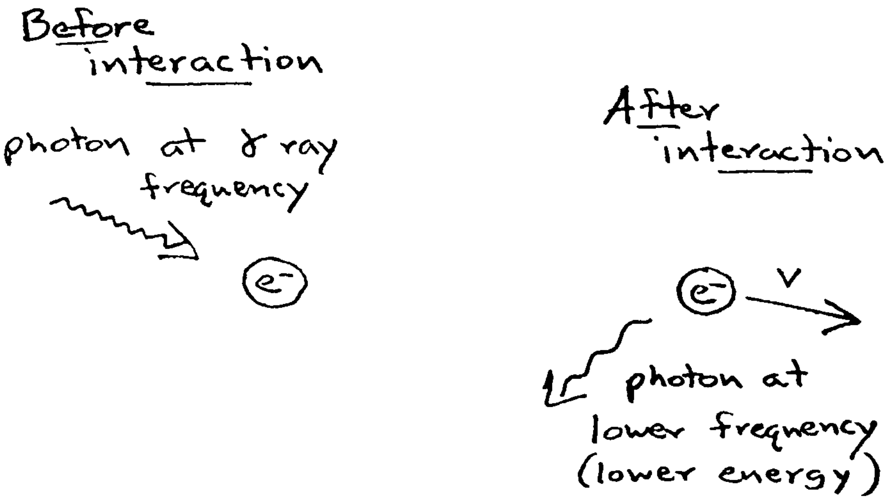


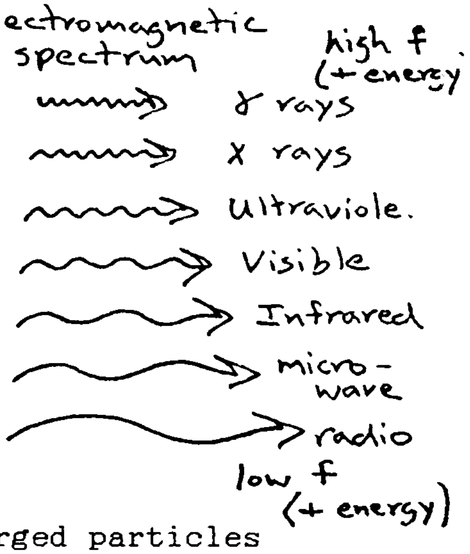
Ignition of fusion reactions in the core heralds the birth of the star.

THE BALANCE OF FORCES

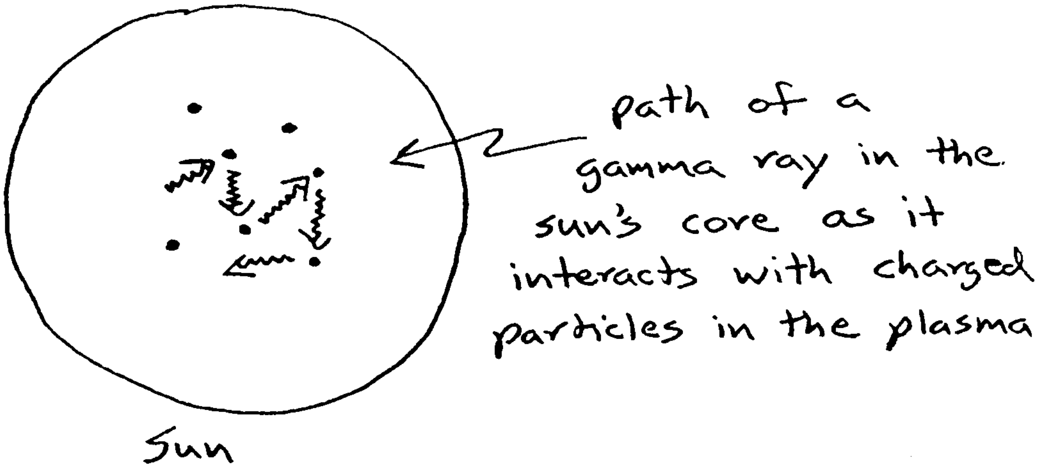
A star is a balance between the force of gravity, trying to collapse the star, and the radiation pressure released in fusion reactions, trying to balloon the star. If fusion reactions in the core increase, the star swells. If fusion reactions slow and the core cools, the star contracts.

It is important to note that electromagnetic radiation exerts a pressure. The gamma rays produced by fusion interact with the plasma, and a gamma ray imparts some of its energy to any electron or proton it strikes. In the process, the particle gains kinetic energy, and the gamma ray drops to a lower energy (lower frequency). The high-velocity electron or proton then pushes with greater force on any neighbor it happens to impact, and helps to support the weight of the star's outer layers.





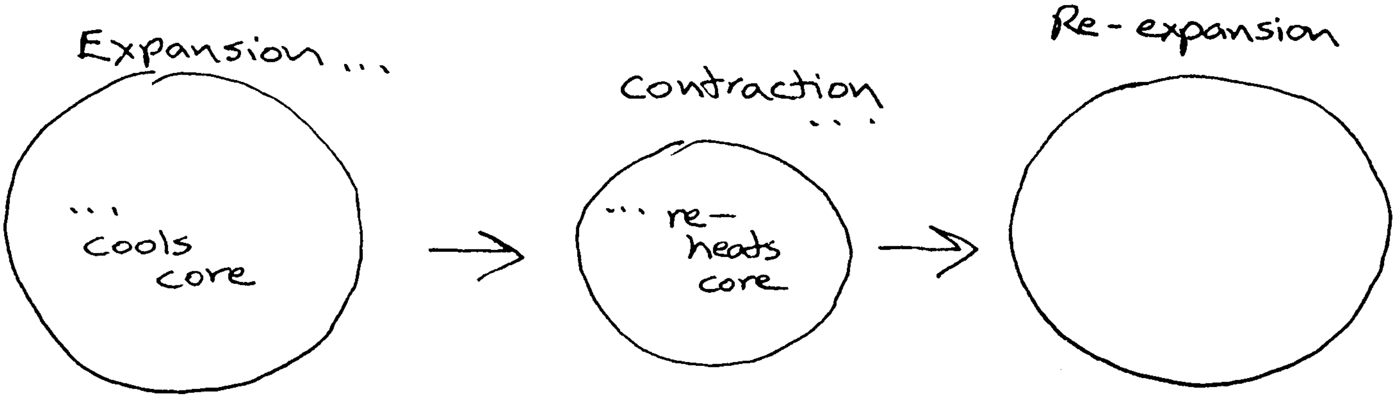
On average, because they ricochet off charged particles in the plasma, gamma rays produced in the core of our own sun take one million years to reach the surface and escape into space.



Most neutrinos, on the other hand, pass directly out of stellar cores and do not contribute to the structural equilibrium. Neutrinos interact with other particles only via gravity and the weak nuclear force, which has a range of only 10^-16 cm. Even in the dense core of the sun, it is unlikely a neutrino will approach another particle that closely, so it leaves the core unhindered. (We will discuss the particles and forces in more detail in Ch.6 and 7.)

unless it approaches closer than 10^{-16} cm, a neutrino will not interact with another particle

During its birth pangs, a star may oscillate violently. Eventually, it settles down to relative quiescence, but even respectable middle-age stars, like our sun, oscillate. They expand and contract, driven by the push/pull of fusion vs gravity: if the core cools, the star collapses a bit. The collapse itself reheats the core (by the conversion of potential to kinetic energy discussed above and by increased fusion). The hotter core causes the star to expand, but expansion cools the core, and the cycle starts all over again.



Eventually, the core runs out of fuel, and the star collapses more dramatically, initiating a new phase in the life of the star -- or its ultimate demise.

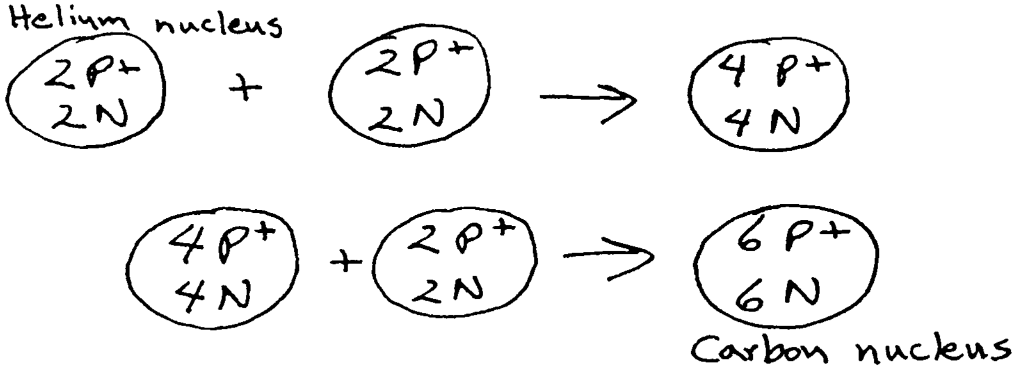
THE LIVES OF STARS: BROWN DWARFS AND WHITE DWARFS

The life span of a star and its ultimate fate are determined by its mass at birth. The more massive stars have shorter lives and violent ends, and they leave more exotic remnants.

The smallest mass capable of supporting fusion is about 0.01 solar masses. Stars less than about a tenth the mass of the sun have long lives -- tens of billions of years -- and end their existence as "brown dwarfs." Once they have converted all the hydrogen in their cores to helium, they simply flicker out.

Stars the mass of the sun to about 8 times the sun's mass live a few billion years. (The sun itself was born about 5 billion years ago and has an expected life span of another 5 billion years.) They end their existence as white dwarfs.

It is worth exploring the sun's life cycle in a bit more detail, since it illustrates important general points. When the sun exhausts the hydrogen in its core and the core cools, it will collapse. The sun is so massive that the collapse will drive core density and temperature high enough to fuse helium into carbon.

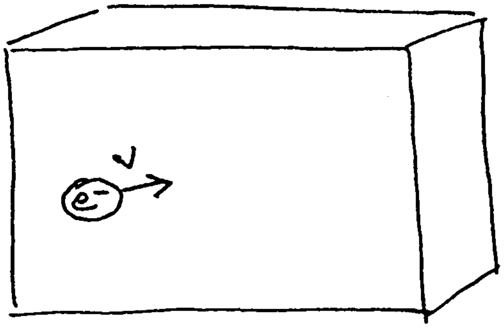


The excess heat generated by the collapse and by helium fusion will ignite fusion in the hydrogen shell surrounding the core. During this phase, the sun's atmosphere, heated by the events underneath, will expand enormously and become a "red giant," swallowing planets out to about Mars.

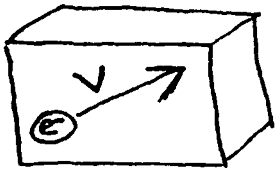
Once the sun has converted its core helium to carbon, its core will collapse once again. Energy released by the final collapse will blow off the sun's outer layers, leaving a bare core, a "white dwarf," gradually radiating away the energy of its final collapse.

DEGENERATE ELECTRON PRESSURE

"Degenerate electron pressure" stabilizes a white dwarf against further collapse. As we shall discuss in more detail in the next chapter, electrons (and all other subatomic particles) resist confinement: the more an electron is restricted, the faster it moves.

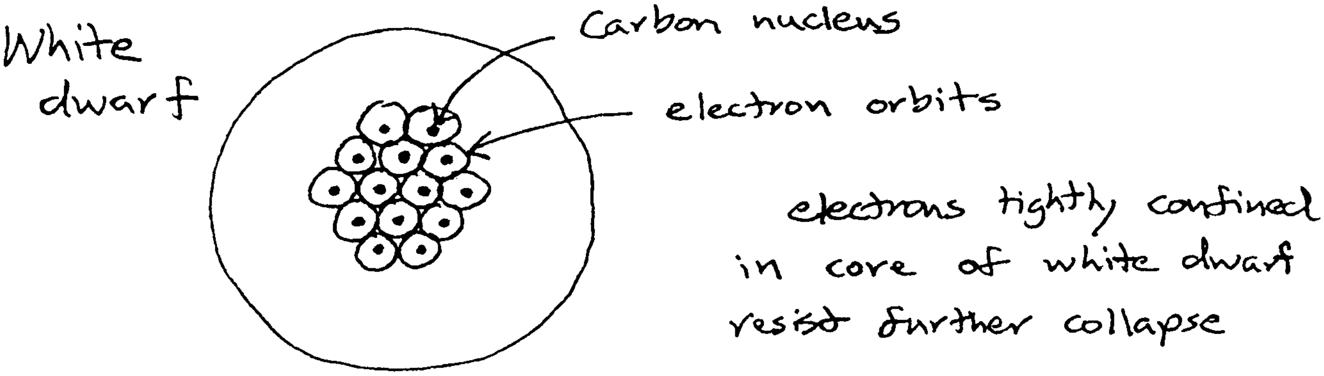


Relatively un-confined electron has low momentum



Confined electron has higher momentum

In a white dwarf, the plasma has been compressed and the electrons are tightly confined. Hence they have large momenta. The pressure generated by the electrons' momentum supports the star against further collapse.

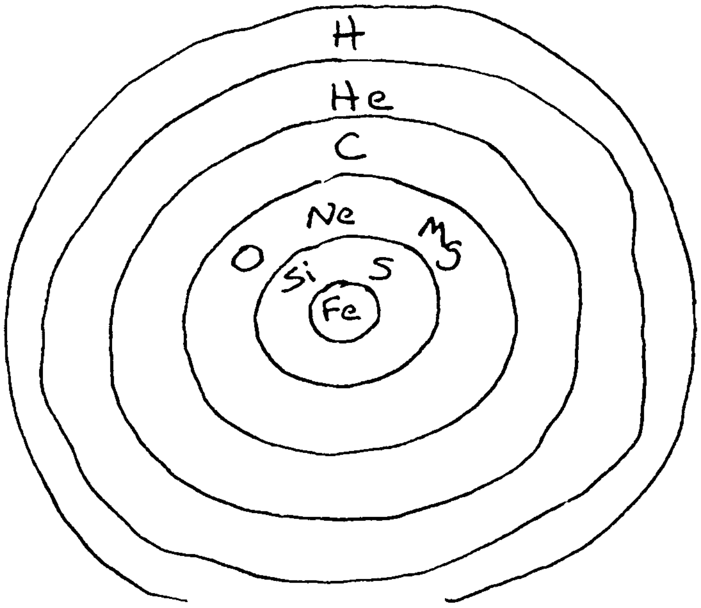


The "Pauli exclusion principle" provides another mechanism stabilizing white dwarfs: no two electrons can occupy the same energy state. In a white dwarf, all available energy states are filled, and no electron can be squeezed into a lower state. The electrons support the overlying weight of the star.

THE LIVES OF STARS: NEUTRON STARS

Stars born with about 8 to 30 times the mass of the sun live a few tens to hundreds of millions of years. They burn their cores furiously, driven by the intense pressures and temperatures created in their self-gravitational field. Such stars can fuse progressively heavier elements in their cores. Fusion ceases with the creation of iron, however. The star then collapses and rebounds in the cataclysmic explosion we call "supernova," perhaps the most dramatic event in the heavens. The remnant is a neutron star.

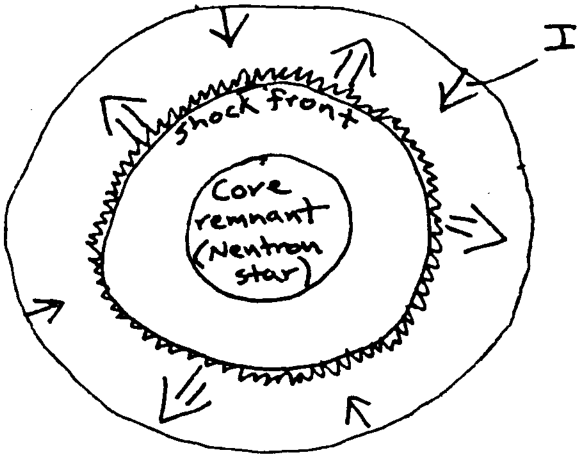
We've described how our sun, in its old age, will fuse helium to carbon. A more massive star can fuse carbon to oxygen, oxygen to silicon, and finally silicon to iron. Fusion produces other, intermediate nuclei as well, including neon and magnesium along with the oxygen, sulfur along with the silicon. At the end of each phase of fusion the star collapses and heat generated by the collapse ignites fusion in the next phase. The star develops an onion-skin structure, as higher core temperature and density ignite the adjacent, outward layer.



"Onion skin" structure of an end-stage massive star

To fuse iron requires more energy than is released by the fusion process, so a star with an iron core cannot sustain stable fusion. Radiation pressure in the core fails, and the star's outer layers plummet toward the core, reheating and condensing it. Within a few seconds, the core is compressed to the density of an atomic nucleus. Infalling matter bounces off the super-dense core, and the resulting shock wave blows off the star's outer layers. In the process, energy delivered by the shock wave fuses material in the overlying layers into the heaviest nuclei, such as lead and uranium. In fact, it is in supernovas that all the heavy elements in the Universe -- including those found on Earth -- are formed.

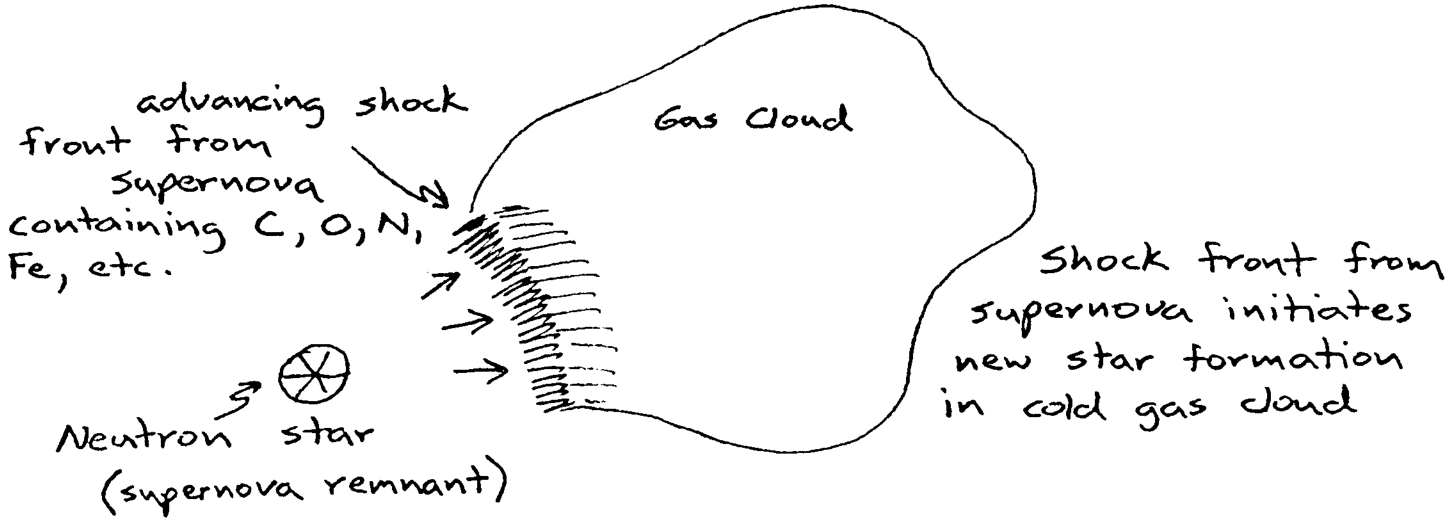
For a few seconds, the energy released by the supernova exceeds the combined energy output of all the other stars in the Universe!



In-falling surface layers

SEEDS OF LIFE

The outer layers of the supernova, six or more solar masses, initiate new star formation and carry with them the seeds of life. Moving at relativistic velocities, the ejecta plow into nearby gas clouds, compressing the gas and initiating a new cycle of star formation. The new stars and their planetary systems incorporate the heavy chemical elements produced in the supernova and its progenitor.



Our sun is a second- or third-generation star. That is, it contains atomic nuclei fused by its mother (star) and, perhaps, grandmother. The planets also incorporated those elements as they condensed from the swirling gas around the proto-sun. All the heavy elements on Earth -- every atom heavier than hydrogen and helium -- were forged in the core of an ancestral star. All the carbon, oxygen, nitrogen, phosphorous, calcium, and other heavy atoms of life on Earth were forged in stars. We are, indeed, "children of the stars."

NEUTRON STARS AND PULSARS

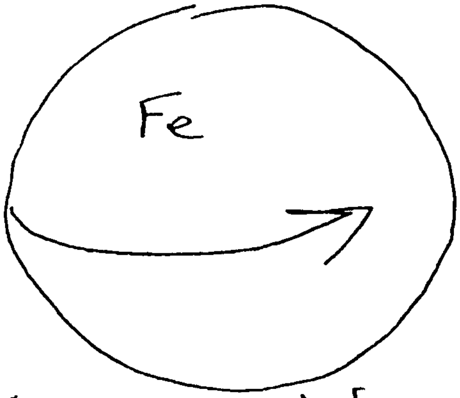
If the iron core of the supernova progenitor is between 1.4 and 3 solar masses, stellar collapse precipitating the supernova can overcome degenerate electron pressure and "squeeze" the electrons "inside" of protons. If an electron is forced close enough (less than about 10^-16 cm) to a proton, it may react with the proton, producing a neutron and a neutrino. The supernova remnant is a neutron star, a spinning ball of nuclear matter only a few kilometers in diameter but containing the core mass.

The diameter of the neutron star is roughly in the same proportion to the diameter of the original core as an atomic nucleus is to the diameter of an atom -- about 10^-13/10^-8, or 1/100,000. If the Earth collapsed to nuclear density, it would be about one-tenth of a mile in diameter.

Neutrons, like electrons, resist confinement, and degenerate neutron pressure supports the weight of a neutron star (except when the stellar remnant exceeds about 2 solar masses -- our next story.)

After the supernova event, three traces of the progenitor star remain. Along with the mass of its core, angular momentum is conserved in the supernova event, and the magnetic field remains.

During collapse, the core conserves angular momentum. All stars spin -- our own sun revolves about once every 27 days (though it has a different spin at the poles than at the equator). Some of the angular momentum is transfered to the ejecta in a supernova, but as the core collapses, like a skater pulling in her arms, it "spins up," increasing its rate of rotation. If our sun collapsed to nuclear density, and all the angular momentum was preserved in the remnant, it would spin about 42,000 times per second.

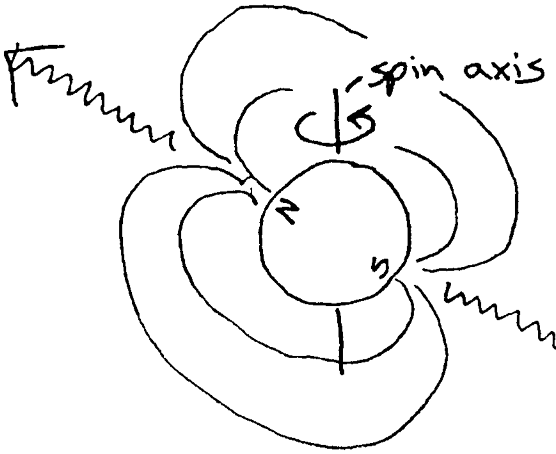


Neutron stars typically spin on the order of one revolution per second, but some spin as rapidly as a thousand times per second.

If the magnetic axis of the neutron star lies off the spin axis, the star may become a pulsar: the spinning magnetic field accelerates charged particles in nearby plasma, and those particles radiate. Neutron stars are surrounded by plasma -- debris left over from their own demise or gas pulled off a companion star. Pulled by its intense gravitational field, plasma plummets toward the neutron star.

In-falling plasma radiates by two mechanisms. First, charged particles in the plasma are channeled along the magnetic field lines, toward the star's magnetic poles. As they fall, they radiate. (See section on electromagnetic radiation, below.) Since the magnetic axis rotates with the star, its beam sweeps around the sky. If the beam happens to be aligned with Earth, we see the star as a pulsar, flickering on and off precisely as the star revolves -- a kind of lighthouse in the heavens.

In the second mechanism, the rotating magnetic field acts as an electrical generator, accelerating charged particles in the plasma one direction as the north pole sweeps past, the opposite direction when the south pole sweeps by. The accelerated particles radiate.

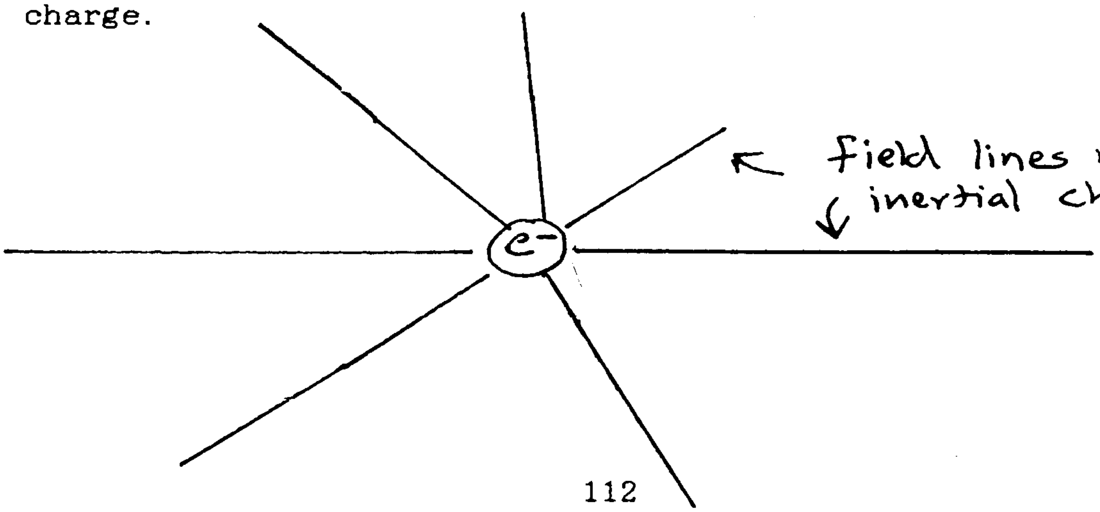


radiation directed outward from magnetic poles. Beams sweep around sky as star rotates.

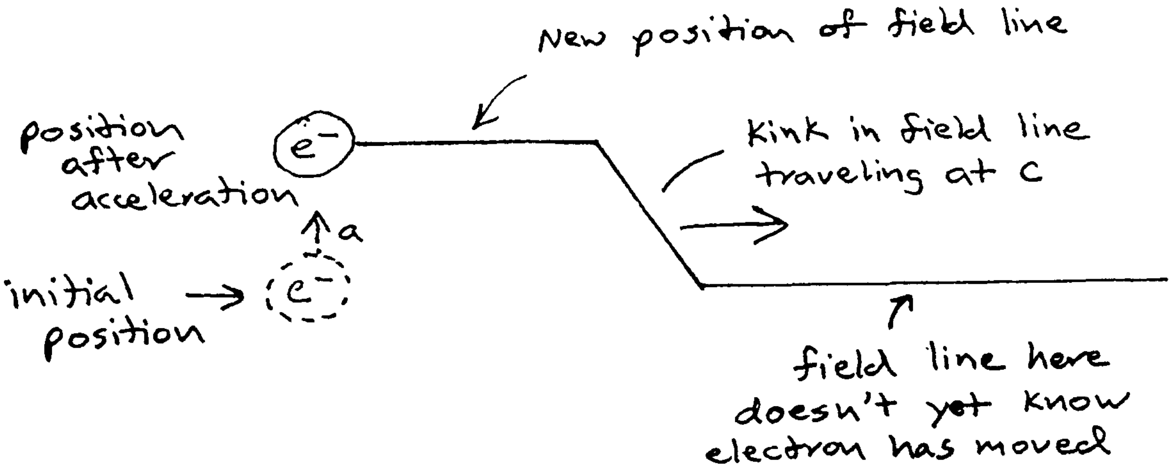
MECHANISMS PRODUCING ELECTROMAGNETIC RADIATION

An accelerated electric charge emits electromagnetic radiation, and the energy of the radiation depends on the amount of acceleration. We can diagram this phenomenon by drawing the field lines around an accelerating charge.

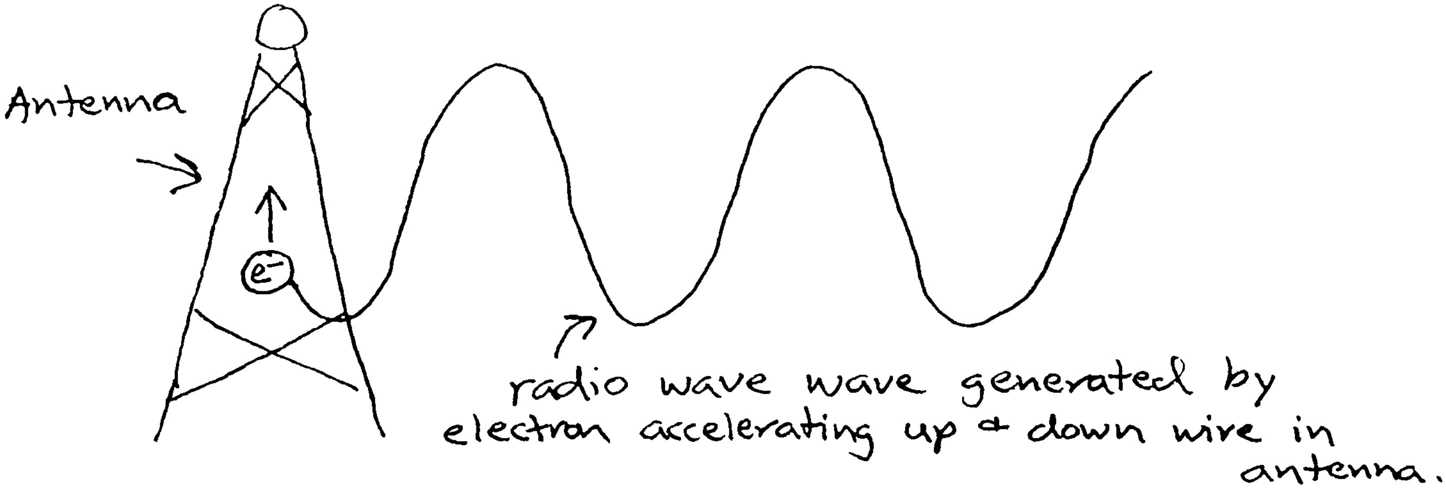
The electric field originates at the charge, and the field lines emanate radially from the charge. Since information cannot travel faster than light, field lines at some distance from the charge do not "know" the charge has moved for some time -- the time it takes light to travel that distance. There is, then, a "kink" in the field lines, traveling at the speed of light. This traveling wave is the electromagnetic radiation emanating from the accelerated charge.



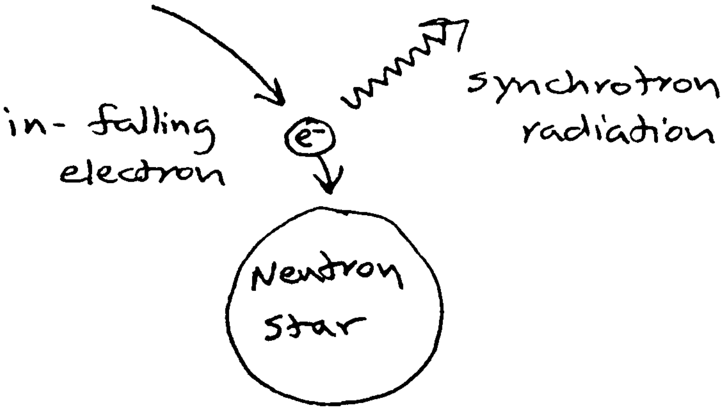
field lines near inertial charge



As a familiar example, radio transmitters accelerate charges up and down an antenna, and the resulting electromagnetic waves carry the broadcast.



Charged particles, such as electrons, falling into a gravitational field also accelerate and, therefore, radiate. If the gravitational field is very strong, the charges emit high energy electromagnetic radiation, in the X-ray region of the spectrum. This process is called "synchrotron radiation."



THE LIVES OF STARS: BLACK HOLE FORMATION

Stars born with greater than 30 times the mass of the sun live only a few million years. They may end as supernovas, leaving the most bizarre of remnants -- a black hole, or they may simply wink out as a black hole without the supernova's fireworks.

The most massive stars lead lives similar to the neutron star progenitors: they fuse progressively heavier nuclei in their cores, eventually producing iron. If the iron core exceeds two solar masses, degenerate neutron pressure cannot support the overburden, and gravity crushes the star completely. The star collapses into infinite density at a geometric point.

There are other mechanisms that may produce black holes:

-- In-falling matter in a supernova may compress a borderline-mass core into a black hole.

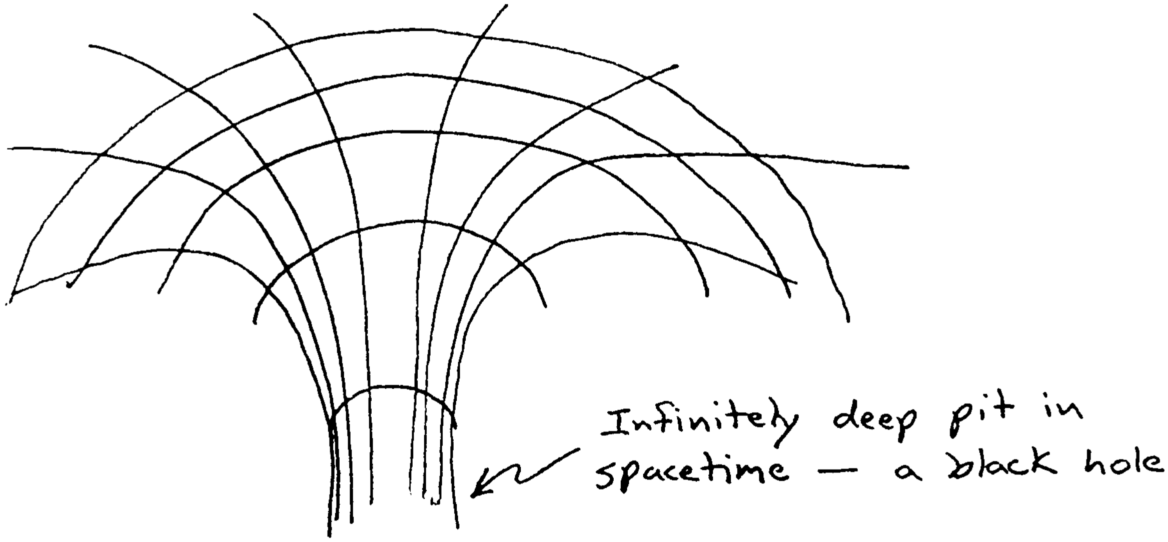
-- A neutron star may steal enough mass from a nearby companion to exceed the degenerate neutron pressure.

-- At the big bang (the origin of the Universe) extreme pressures and densities may have created numerous small black holes (masses about the mass of a mountain). No such primordial black hole has been detected, and their existence remains conjectural.

-- Black holes apparently occupy the nuclei of most, if not all, galaxies. It is not known, how they formed, whether they preceeded the galaxies, as kernels for the galaxies' accretion, or coalesced from the matter of established galaxies.

BLACK HOLES

Black holes are among the most intriguing predictions of general relativity. They are regions of spacetime from which nothing, not even light, can escape. In the terminology of relativity, a black hole is the region around a mass density so great that it creates an infinitely deep and steep "pit" in spacetime. Spacetime is curved so much that the path of light in the black hole bends back into the hole, and clocks at the edge of the black hole slow down to a stop. (Clocks inside the black hole theoretically run backward -- time reverses.)

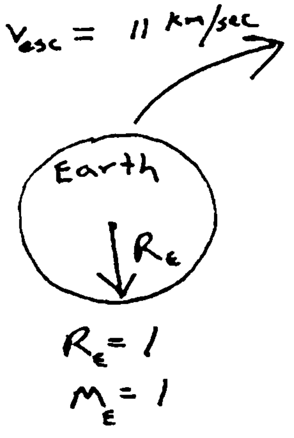


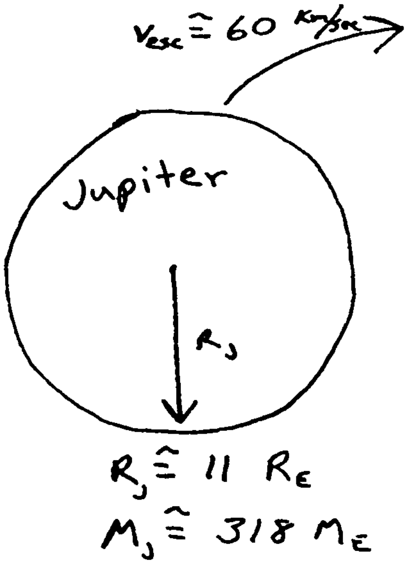
We can visualize a black hole somewhat more easily in terms of escape velocity. The escape velocity (v) from the surface of a massive object is proportional to the square root of the mass and inversely proportional to the square root of the radius of the object (see the section on escape velocity in Ch.3):

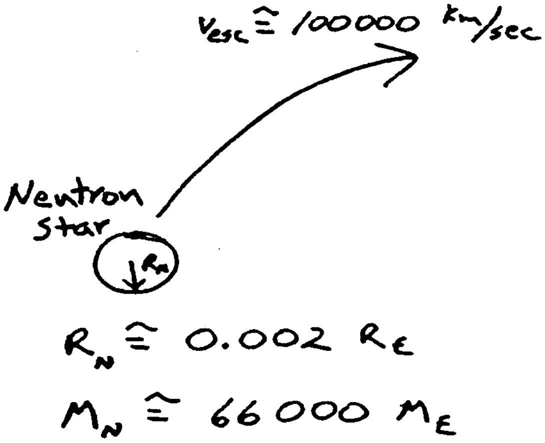
$$V_{esc} = \sqrt{2GM/R}$$

The more massive an object, the higher the velocity needed to escape from its surface. The smaller the radius, also, the higher the escape velocity. It follows that the highest escape velocities obtain in the vicinity of compact (small radius) extremely massive objects, such as collapsed stars.

The escape velocity from Earth -- the velocity required to launch a satellite into orbit -- is about 11 kilometers per second. Escape velocity from Jupiter is about 60 km/sec, and from the sun about 350 km/sec. From a neutron star, the escape velocity is of the order 100,000 km/sec.





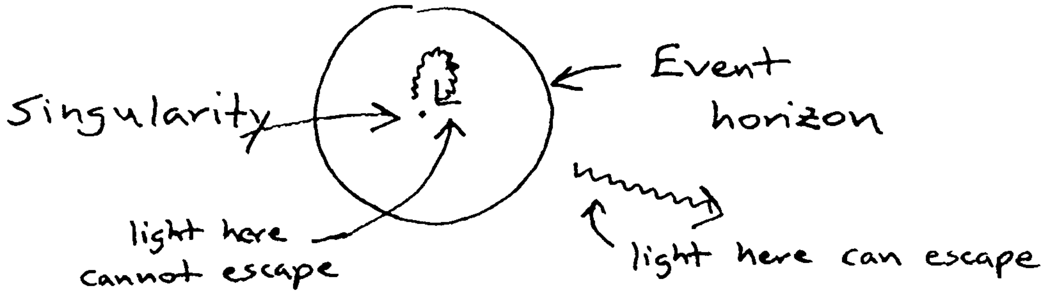


Now imagine an object so massive, or occupying such a small volume, that the escape velocity exceeds the speed of light. No information can escape it. In essence, it lies outside our Universe. It has folded spacetime around itself and pinched itself off from the rest of us.

BLACK HOLE STRUCTURE

A black hole has a simple structure: it consists of a singularity and an event horizon.

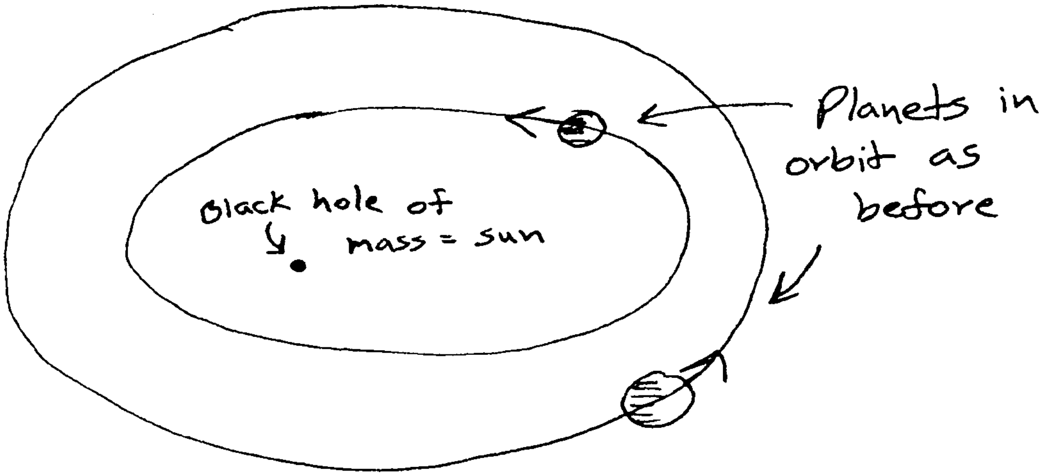
The singularity is the geometric point into which all the black hole's mass has collapsed. At some distance outward from the singularity lies the event horizon, the spacetime surface at which the escape velocity just equals the speed of light. Information cannot reach us from below the event horizon: it defines the boundary of the black hole.



BLACK HOLES ARE POINT MASSES

There is a popular notion that black holes act as "cosmic vacuum cleaners," gobbling up everything in the vicinity. This is misleading.

If the sun collapsed to form a black hole (it won't), the planets would continue their orbits as before (though there would be some transient effects of passing gravity waves generated by the collapse). Outside the event horizon of a black hole, other masses behave the same as if an equally massive star occupied that region in spacetime.



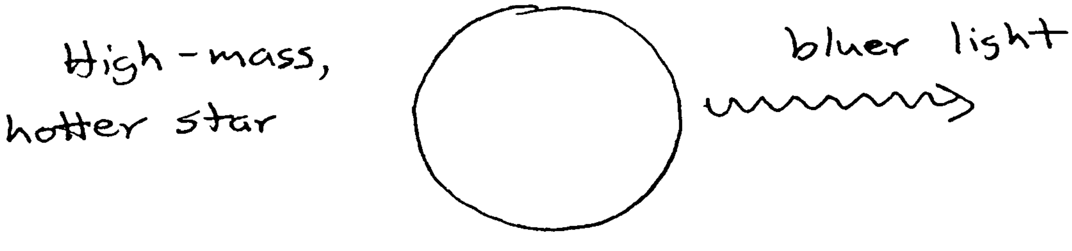
DETECTION

If nothing escapes a black hole, how can we detect it? Certainly we cannot "see" inside a black hole, but there are other clues to its presence.

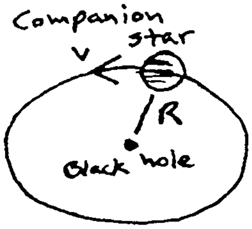
Theoretically, a black hole can carry three measurable quantities: mass, electric charge, and angular momentum. We can "weigh" a black hole by measuring its gravitational effect on other, nearby masses. We can calculate charge by measuring the electric field, and we can measure black hole spin by effects on local spacetime. (A spinning black hole drags local spacetime and wraps spacetime around itself.) Of these three, astronomers are most likely to detect the mass effects: spin distorts spacetime only in immediate proximity to the event horizon, and a black hole would most likely be electrically neutral, since a net charge attracts opposite charge from outside.

The mass of a black hole, of course, affects other, nearby masses. Seeking black holes, astronomers look for evidence of a large, unseen mass orbited by a visible companion. Most stars, born in bunches from the same cloud, occur in gravitationally bound systems of two or more, so the chances of detecting a black hole are not so remote as one might think.

By measuring the orbital velocity of the visible companion and estimating its mass, astronomers can calculate the mass of the black hole. It is possible to measure the orbital velocity directly, with a series of observations over time, tracking the visible companion in its orbit. And astronomers can estimate the companion's mass fairly accurately by studying its light: low-mass stars, with cooler cores, emit redder light and more massive stars, with hotter cores, emit bluer light -- just like iron in a blast furnace glows dull red as it starts to warm, then blue-white at the highest temperatures of the furnace. Chemical elements evident in the star's spectrum also give information about the star's age and mass: more massive stars, and older stars, contain heavier elements. (More about atomic spectra in the next chapter.)



Knowing the mass of the visible companion, astronomers calculate the mass of the black hole by orbital mechanics: the centrifugal force due to momentum of the visible companion must balance the gravitational force pulling it toward the (presumed) black hole.



Centrifugal force   Gravitational force

$$F_c = F_G$$

$$mv^2/R = \frac{GmM}{R^2}$$

$$v^2 = GM/R$$

$$M = v^2R/G$$

where M = mass of black hole
m = mass of companion
v = velocity of companion
R = distance from companion to black hole

This derivation shows that the mass of the black hole is proportional to the square of the companion's orbital velocity and proportional to the distance between the companion and the black hole. We can understand this qualitatively: A companion star must orbit the black hole rapidly enough -- or at large enough distance -- to keep from falling into the black hole.

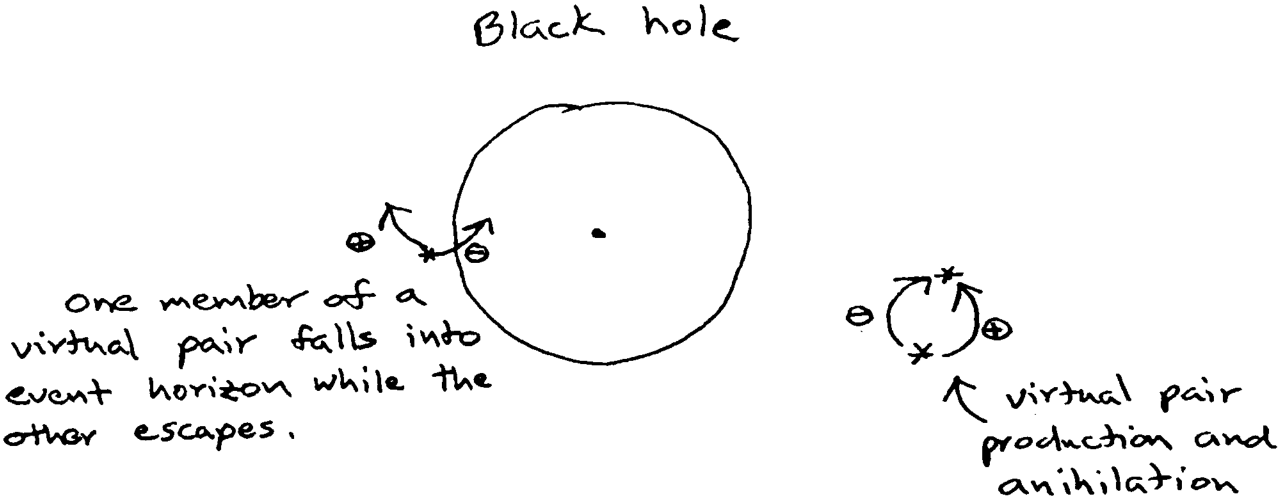
The mass of the black hole also determines the spectrum of synchrotron radiation from the region. Charged particles screaming into the black hole, under tremendous gravitational acceleration, emit high-energy X-rays. Detecting synchrotron X-rays, then, gives astronomers a clue to the hole's presence.

Astronomers have detected several stars with unseen companions that are black hole candidates. One is the X-ray source Cygnus X-1, in the constellation Cygnus (the Swan, or Northern Cross), in which a visible star orbits an invisible companion that emits high-energy X-radiation and is about five solar masses.

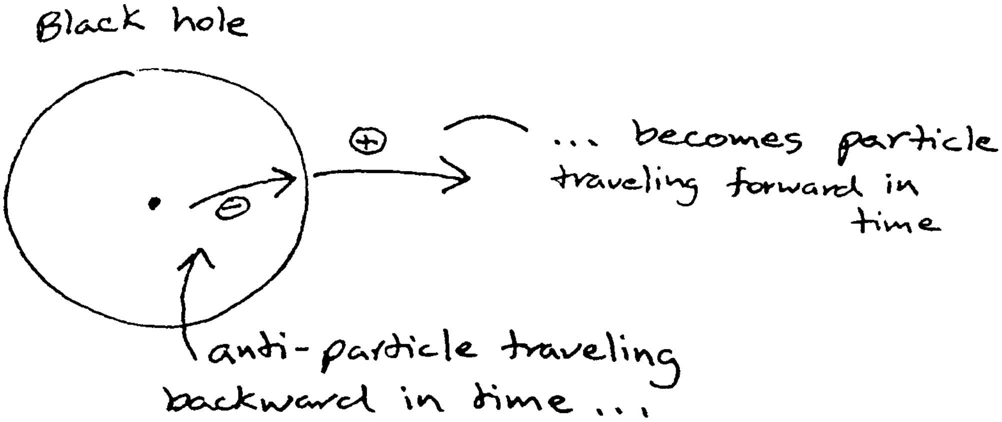
HAWKING RADIATION

A surprising theoretical discovery by the British physicist Stephen Hawking indicates that black holes may evaporate: they radiate mass/energy <u>other</u> than synchrotron radiation. According to Hawking, black holes radiate particles produced by the quantum mechanism of "virtual pair production." The phenomenon of Hawking radiation brings us to a meeting point of general relativity and quantum mechanics.

Pairs of virtual particles pop into existence everywhere, including at the event horizon of black holes. (We'll find out why in the next chapter.) If a virtual pair emerges near the event horizon, there is a chance one of the pair will fall into the black hole and the other escape.



Another, equivalent, interpretation of this phenomenon is that an anti-particle travels backward in time from inside the black hole to the event horizon, where it emerges as a particle traveling <u>forward</u> in time in our Universe. In this way, the black hole radiates away its mass. This "time parity" is a well established tenet of particle physics: an anti-particle traveling backward in time is equivalent to its associated particle traveling forward in time. Nature makes no distinction.



Practically speaking, average-size black holes radiate undetectably small amounts of energy by the Hawking mechanism, but as the mass of a black hole decreases over the eons, it radiates more and more vigorously. A black hole may eventually evaporate and end its existence in a flash of high-energy particles and anti-particles, most of which annihilate and produce gamma rays.

WHERE THE VERY LARGE MEETS THE VERY SMALL

We are standing at a cusp in physics, a meeting point of relativity and quantum mechanics. The laws of the very large merge with the laws of the very small: black holes -- monsters in the sky -- evaporate according to mechanisms affecting the smallest constituents of matter.

Let's explore, next, the realm of the smallest bits and pieces of the Universe.

SUMMARY:

Special and general relativity describe the physics of stars and their remnants -- white dwarfs, neutron stars, and black holes.

Stars are born from galactic gas clouds, and the life span of a star depends on its mass: more massive stars have shorter lives. The fate of a star also depends on its mass: the smallest stars end their lives as brown dwarfs; stars about the mass of the sun end as white dwarfs; stars born with between 8 and 30 solar masses end as neutron stars; and more massive stars end as black holes.

A black hole is an object so massive and confined to such a small radius not even light can escape from it. There are, however, effects we can detect, due to the gravitational field of the black hole and synchrotron radiation. These offer clues to the existence of black holes, and several candidates have been found.

In that they radiate Hawking particles, black holes provide a theoretical meeting ground of relativity and quantum mechanics -- the laws of the very large and the very small.

REVIEW QUESTIONS
CHAPTER 4

1. Trace the evolution and eventual fate of a star with a birth mass of the sun. Trace the evolution and fate of stars of 10 solar masses and 50 solar masses.

2. What is the escape velocity from our sun? (The sun's mass is about 1.99 X 10^30 kg. and its radius is about 6.96 X 10^5 km. The gravitational constant, G, is 6.7 X 10^-11 m^3/kg-sec^2.) At what radius would the sun become a black hole?

3. Comment on the statement "mass itself drives the thermonuclear reactions which convert mass to energy inside a star."

4. Calculate the velocity of a hydrogen nucleus (proton) falling from infinity to the core of the sun. Convert this velocity to temperature. (Use the information in number 2 above. Proton mass = 1.67 X 10^-24 g. Gravitational potential energy is equal to GMm/R. Assume potential energy is completely converted into kinetic energy. One degree Kelvin is equivalent to about 1.4 X 10^-16 ergs of energy.)

5. Calculate the degenerate pressure of electrons at the very center of a star of 1.5 solar masses. (The electrons must support the over-lying weight of the star.)

6. How much energy is required to blow off 8 solar masses of overburden during a supernova? Assume the neutron star remnant has 2 solar masses and a radius of 10 km. Use the information in number 2 above. Gravitational potential energy is equal to GMm/R.

7. Suppose astronomers find a visible star of 5 solar masses in orbit around an invisible companion. The visible star orbits with an average velocity of 10^6 m/sec, and the average radius of its orbit is 670 X 10^9 m. Could the invisible companion be a black hole? Show your work.

8. How can the mass of a star collapse to a geometric point? Where does all the mass go?

9. Diagram the spacetime curvature around a black hole.

10. Astronomers estimate the diameter of distant objects by their "flicker time:" the light from certain stars and galaxies varies in intensity over seconds to days. What does the flicker time tell us about the maximum size of an object?

11. What is synchrotron radiation? What determines the energy (frequency) of the synchrotron photons?

12. Discuss the notion that the Universe itself may be a black hole.

13. Diagram the mechanism that produces electromagnetic radiation by comparing the field lines of inertial and accelerated electric charges.

14. The electric current in a common house circuit oscillates at sixty cycles per second (alternating current). What is the wavelength of electromagnetic radiation produced at that frequency?

15. Outline the mechanism by which the heavy atomic nuclei, such as carbon and iron, are produced in the cores of stars.

16. Trace the events in a supernova explosion, from the time at which the progenitor star has produced an iron core. In your answer, discuss how the shock front develops, the role of the shock wave, the role of neutrinos, and the mechanism by which a neutron star is formed.

17. Comment on the idea that "we are children of the stars."

18. Why does it take so long for electromagnetic radiation to reach the surface of the sun from the core? Why can neutrinos produced in the core pass essentially unimpeded into outer space?

19. In order for astronomers to detect a pulsar, the pulsar must have a particular orientation in relation to the Earth. Why, and what is the special orientation?

DEMONSTRATIONS
CHAPTER 4

1. Stellar oscillation:

Partially fill a balloon with air, then warm it gently ovar a candle or bunsen burner (be careful not to burn the balloon). What happens?

Now put the balloon in a refrigerater or ice water. What happens?

In this demonstration, we substitute an external heat source (or heat sink) for the internal energy source (fusion) in a star. What about the balloon is analagous to the force of gravity?

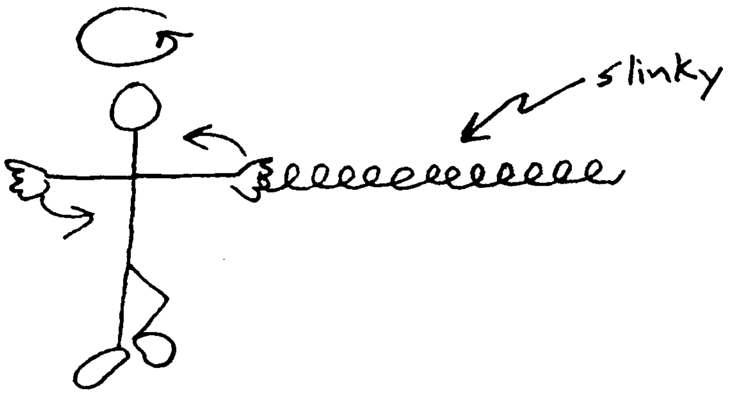
2. Cooling with expansion:

Hold the back of your hand close to your open mouth, and exhale gently. Feel the warm air, raised to body temperature in your lungs.

Now purse your lips and blow a jet of air at the back of your hand. What is the temperature of the jet compared to body temperature? Why?

3. Gravitational collapse along the spin axis:

Find a relatively loose spring, such as a slinky or coiled telephone cord. Spin yourself around, with the spring extended away from the axis of your body. What happens to the spring? Why?



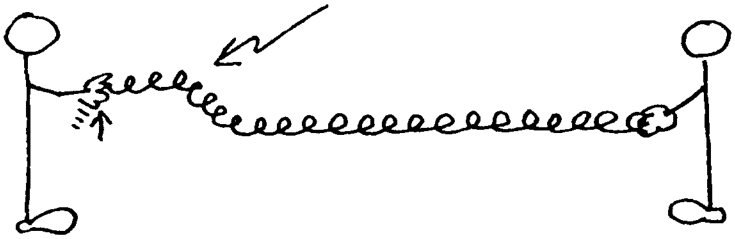
Now spin yourself around, but with the spring held close to your torso, along the axis of spin. What happens to the spring?

If you were a spinning proto-star, what would happen to material extended in the disk perpendicular to your spin axis? What would happen to material located along (parallel to) your spin axis?

4. Generation of electromagnetic waves by an accelerated electric charge:

Fix a slinky or coiled telephone cord to a damped anchor (an anchor that moves with the rope and suppresses any reflection -- perhaps a friend can hold the far end and damp the waves as they arrive). Hold the free end.

Imagine your hand is an electric charge, and the coil is a field line of the electromagnetic field extending away from the charge.



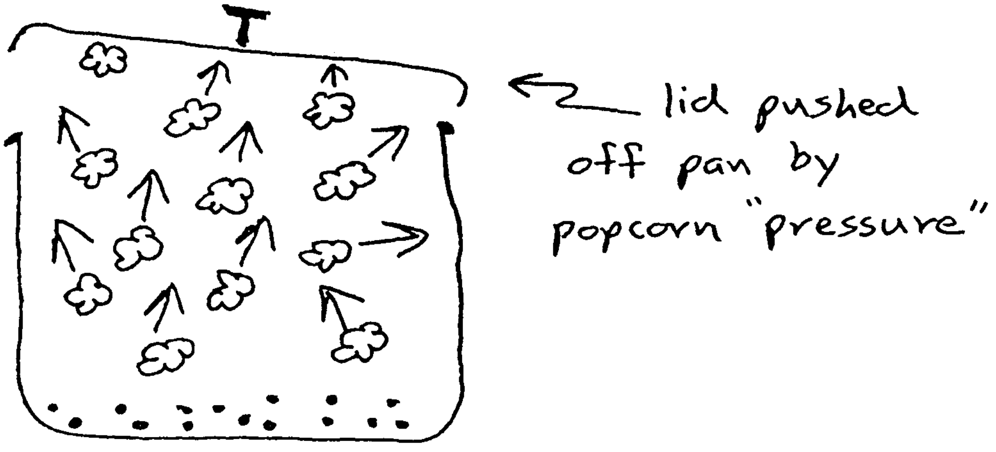
wave traveling down slinky
after you abruptly raise one end

Move your hand abruptly up or down, and watch the wave that travels along the coil. It is analagous to the electromagnetic wave (traveling at the speed of light) from an accelerated charge.

Now oscillate the coil at a fixed frequency, and observe the pattern of traveling waves on the coil. The waves are analagous to electromagnetic waves radiating from a radio antenna, as electrons oscillate up and down the antenna, driven by the station's transmitter. What happens to the wavelength as you increase the frequency?

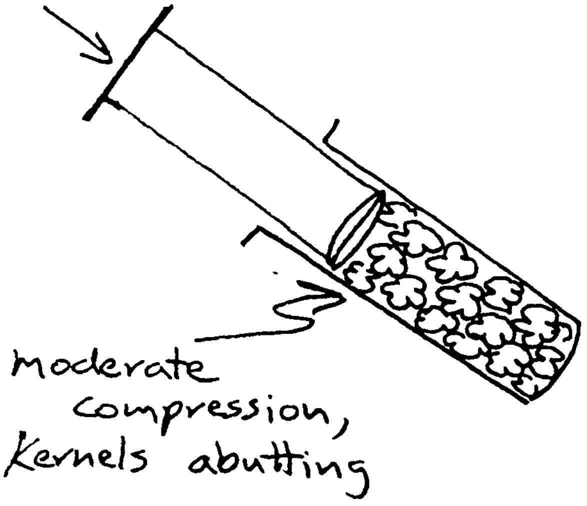
5. Degenerate electron pressure:

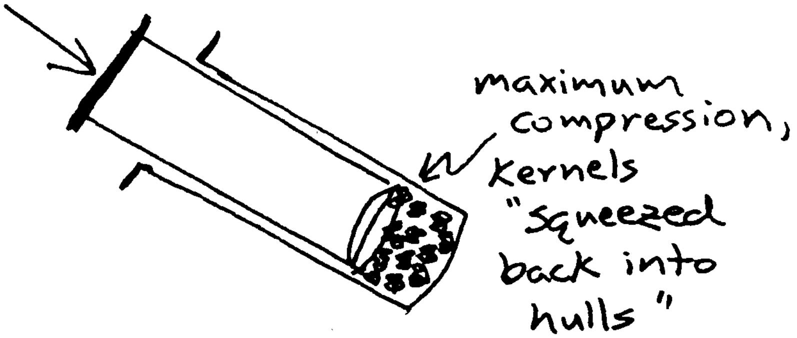
Pop a pan of popcorn under a light lid or piece of aluminum foil. If there is enough popcorn, it will lift the lid off the pan. This "popcorn pressure" is analogous to the thermal pressure generated by hot plasma at the core of a star.



Now compress the popped corn. You can use a piston, such as a large syringe, to compress several kernels. Imagine the kernels are free electrons and that as we press them closer together, we are pushing them into more confined states.

At first, the system is analogous to the core plasma, with free kernels rattling around the syringe. When compressed so that the kernels abut one another, the system approximates the degenerate electron pressure in a white dwarf: the confined electrons resist further collapse. As the kernels are compressed still further (imagine pressing the kernels back into their hulls), the system is analogous to the degenerate neutron pressure supporting a neutron star: we have squeezed the "electrons" inside the atomic "nucleus," transforming protons to neutrons, which resist further collapse.





6. Black-body radiation -- dependence of color on temperature:

Heat a thin steel wire in a flame. (The wire loops used in hospital microbiology labs work well, heated over a bunsen burner.) What happens to the wire's color as its temperature increases?

7. A simple demonstration of chemical spectra:

Sprinkle table salt into the flame of a bunsen burner.or candle. What color does the salt produce? Try other chemicals, such as copper sulfate, and note the colors when they flame.

Astronomers can determine the chemical composition of a star by looking (with more sophisticated apparatus) for the characteristic colors of chemical elements in the star light. (See also the demonstration of atomic spectra in Ch.5.)