III. Stars

1. The Birth of Stars: Gravity tends to have the destabilizing effect of pulling matter into regions that are already more dense than their surroundings and pulling matter out of regions that are less dense than their surroundings. As best we can tell, stars form as a consequence of regions within vast clouds of dust and gas (called **stellar nurseries**) condensing under the attractive influence of mutual gravity until the temperature of the condensing material gets so high that thermonuclear reactions are triggered. The regions in which the condensing begins are regions that have, as a consequence of density fluctuations, slightly higher than average density. The temperature rises as the condensing goes on because the particles, atoms and molecules of the dust and gas clouds, as they are pulled closer and closer together, collide with one another more and more frequently and more and more energetically. Temperature, T, expressed in degrees Kelvin, is a measure of the average randomized kinetic energy per particle, $< K_{random} >_{av}$,

$$T \propto < K_{random} >_{av} ,$$

and the collisions tend to convert the relatively organized and increasing kinetic energy of the infalling motion into relatively randomized kinetic energy. At first the collapsing material starts to glow as a consequence of the collisions exciting atoms which then create photons of various frequencies as they de-excite. Once the temperature near the center of the collapsing material reaches a few million degrees (Kelvin or Celsius; it doesn't matter which) the **nuclear fusion** reactions (called **Hydrogen burning**),

$$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu , \qquad {}^2H + {}^1H \rightarrow {}^3He + \gamma ,$$

$$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H,$$ (called the proton – proton I sequence)

and, $^3He + {}^4He \rightarrow {}^7Be + \gamma$, $\qquad$ $^7Be + e^- \rightarrow {}^7Li + \nu$,

$$^7Li + {}^1H \rightarrow {}^4He + {}^4He ,$$ (called the proton – proton II sequence)

(net effect: four protons are converted into one ^4He nucleus)

ignite and start burning the Hydrogen of the protostar into Helium. To begin with the collapsing material contains about 75% Hydrogen and 24% Helium (this ratio appears to hold throughout the Universe) and these reactions start raising the Helium to Hydrogen ratio within the protostar. If the mass of the collapsing material is not much larger than our Sun's mass then, after about 20 million years of collapsing and heating up, the pressure and radiation generated by these processes will stop the gravitational collapse and the star will be stable for about ten billion years. Our Sun is just about halfway through its ten billion year stable regime.

If the collapsing mass is significantly greater than the mass of our Sun then the initial stages are run through more quickly. The proton-proton sequences fail to generate enough pressure to stop the collapse and when the core temperature reaches about 16 million degrees the carbon-nitrogen-oxygen (CNO) sequence dominates. This involves the fusion reactions,

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma,\ {}^{13}N \rightarrow {}^{13}C + e^{+} + \nu,\ \ {}^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma,$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma,\ \ {}^{15}O \rightarrow {}^{15}N + e^{+} + \nu,\ \ {}^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He\,.$$

Notice that in this sequence of reactions the initial ^{12}C is not consumed but rather triggers the sequence that results in converting Hydrogen to Helium. So this is still Hydrogen burning catalyzed by the presence of (minute) quantities of Carbon.

For new stars of greater and greater mass the fusion reactions in their cores that generate enough pressure to stop gravitational collapse involve the same reactions but occurring at faster and faster rates, so much so that the life of a star decreases as its mass goes up. The largest stars flare up and die within tens of millions of years rather than billions as with the Sun.

2. The Classification of Stars: Except for exploding stars, which we call **Novae** or **Supernovae**, the evolution of stars proceeds so slowly as to require much longer than the history of human civilization to observe. How, then, do we know anything about the evolution of stars? By being able to observe millions upon millions of stars in all the various stages of stellar evolution. But that situation does make the working out of stellar evolution very much like assembling a jigsaw puzzle from scattered puzzle pieces. Of any two presently existing stars, do they both belong to the same evolutionary sequence? Is one of them an earlier version of the other? How many different types of star and how many different evolutionary sequences are their?

Over the last two centuries astronomers and, more recently, astrophysicists have been trying to assemble that puzzle. Most of the assembling that we now have has been accomplished in the last sixty years and much of that in the last thirty years.

The two primary tools for classifying stars and their places in their evolutionary development are the **Spectral Type** classification scheme, established by the women of "Pickering's Harem", as they were called, with the major contribution made by Annie Jump Cannon and the **Hertzsprung-Russell Diagram** developed independently by the astronomers

2a. Spectral Type: Most of the electromagnetic radiation given off by a star is generated by the thermonuclear processes going on in the core of the star. Because the core and the surrounding material is very dense, our theories tell us that the radiation takes a long time to work its way to the surface of the star; in the case of our Sun about a million years. In the course of that tortuous journey, dominated by collisions and interactions, the distribution of the energy of the radiation over frequency, the so-called **spectrum** of the radiation, is greatly modified from its original form in the core to a form characteristic of the temperature of the surface (**Fig. III.1**). In particular, the wavelength, λ_{max}, or frequency, f_{max}, at which the radiation given off into space has the greatest intensity, satisfies Wien's law,

$$T\,\lambda_{max} = 2.9\ \text{mm}\ {}^0\text{K}\,, \qquad \text{or} \qquad f_{max} = (c\,/\,2.9\ \text{mm}\ {}^0\text{K})\ T$$

where T is the absolute temperature of the surface. Also the rate at which energy is radiated from the surface is given by the Stefan – Boltzman law,

$$F = \sigma T^{\,4},$$

Where F is the energy flux in (joules/sec)/unit area and σ is Stefan's constant,

$$\sigma \simeq 5.7 \text{ x } 10^{-8}\ \text{w/m}^2\ {}^0\text{K}^4 = 57\ \text{nw/m}^2\ {}^0\text{K}^4.$$

It is from relationships like these that we can infer the temperature of the surface of our Sun and other stars.

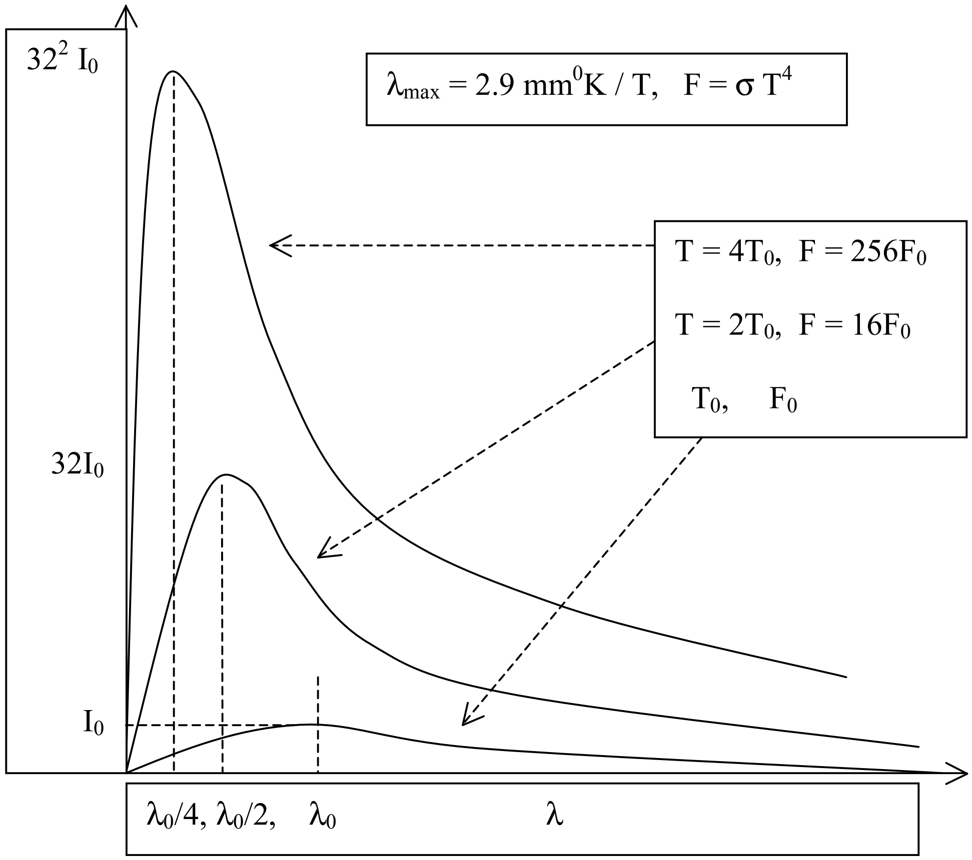


Fig. III.1: Thermal (Black Body) radiation curves for surfaces of various temperatures.

Beyond these features a close analysis of the radiation from a star reveals that the distribution of intensity over wavelength is marked by several, sometimes very many, thin dark lines where the intensity is unusually weak. The wavelengths corresponding to the lines were very stable from star to star, being altered by small amounts only when the entire spectrum was similarly displaced. The darkness of the different lines, however, varied more dramatically, both from star to star and from line to line within a star. But the variations were systematic enough to permit stars to be placed in classes, with each star in a given class exhibiting the same kind of spectrum and collection of dark lines except for possibly small spectrum wide displacements. This is the basis for the famous OBAFGKM classification of stellar spectra (**Fig. III.2**).

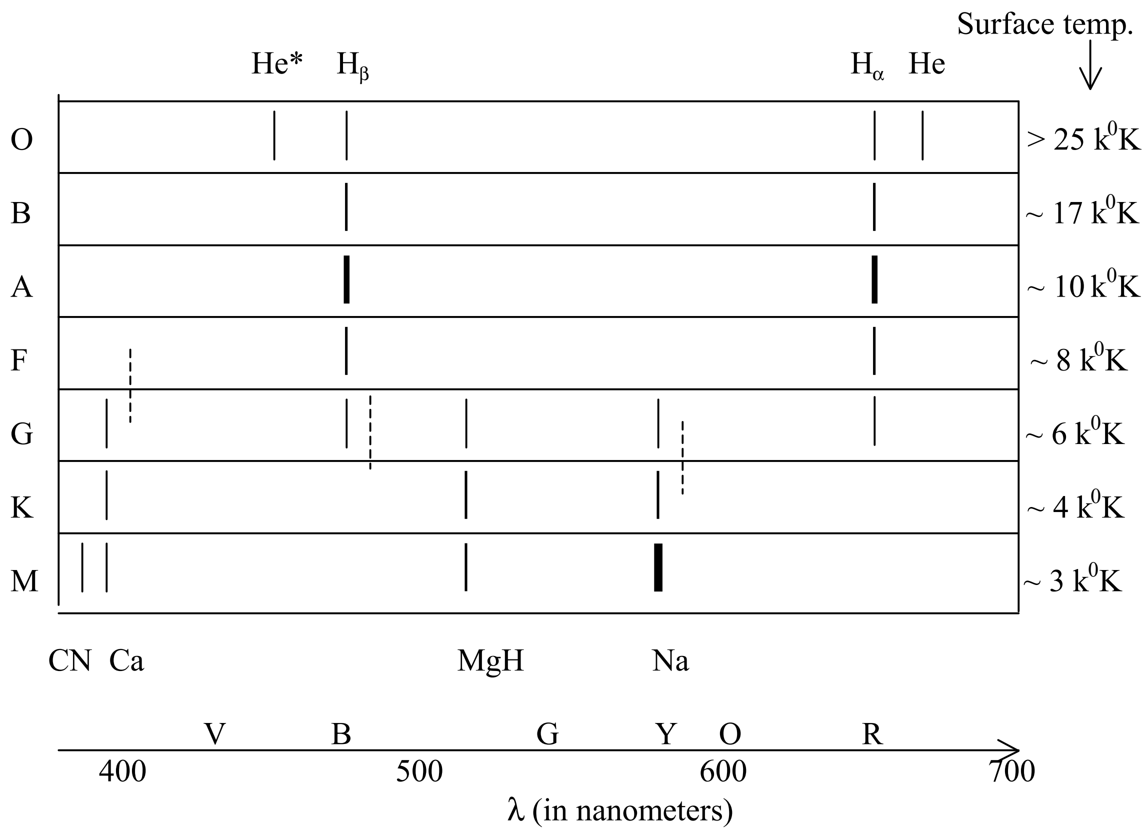


Fig. III.2: Stellar spectral classifications with some of the strongest absorption lines and characteristic surface temperatures. The dashed vertical line in the row for G stars indicates the approximate location of λ_{max} , the wavelength at which the radiation is most intense. For the other star types λ_{max} is off the scale, outside of the visible spectrum.

We understand these dark lines to be produced by the absorption of radiation coming off the surface by *relatively* cooler atoms and some molecules in the outer atmosphere of the star. Atoms and molecules both emit and absorb radiation at wavelengths and rates that are very characteristic of the type of atom or molecule involved. These wavelengths and rates are precisely measured in laboratories. By comparing the dark lines in the stellar spectra with the laboratory measurements we can identify what atoms and molecules are present in the stellar atmospheres and how much of each kind. From

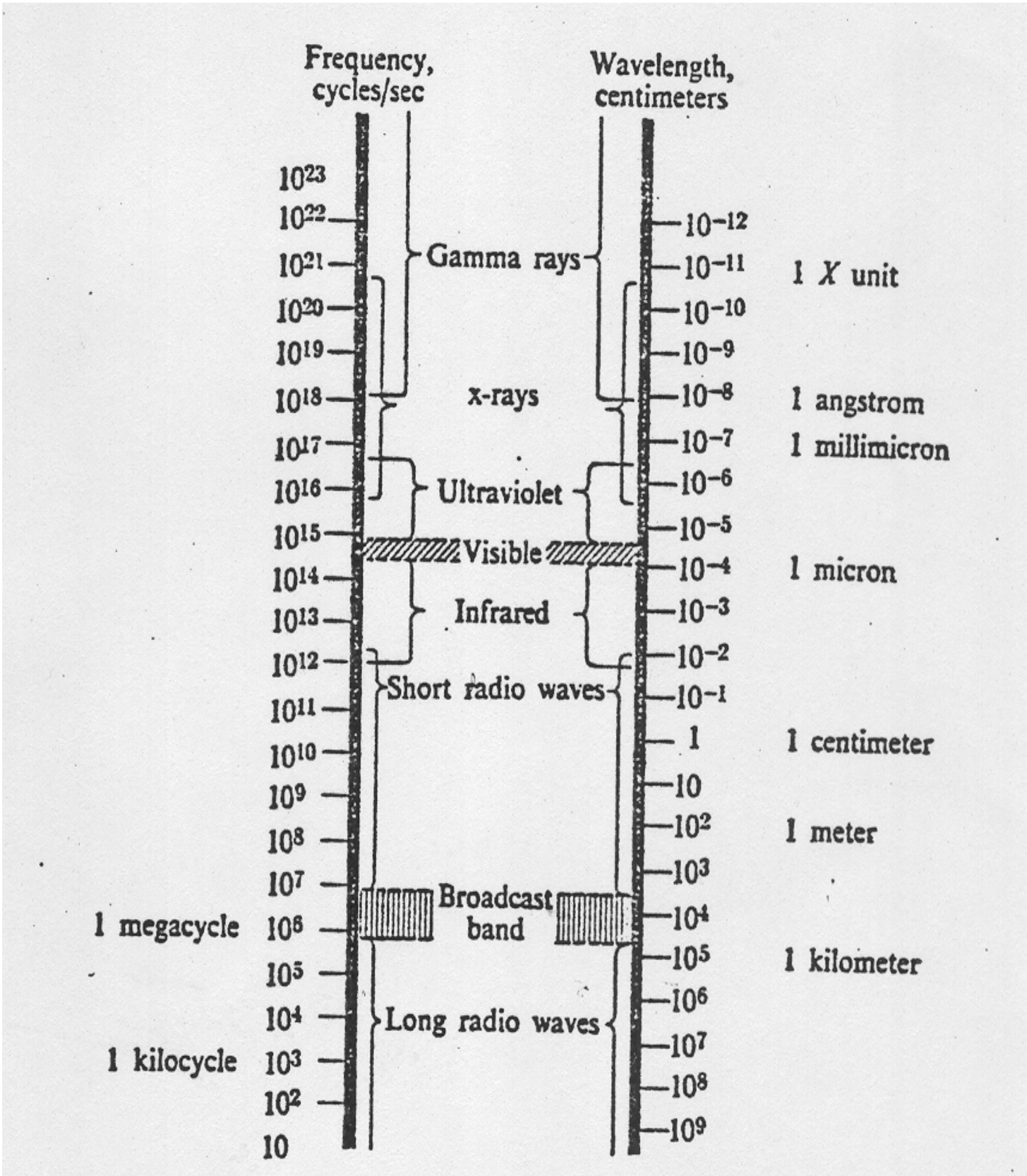


Fig. III.3: The Electromagnetic Spectrum, from thousand kilometer radio waves to milli-angstrom Gamma rays.

these observations we corroborate our theoretical predictions that stars are mostly made of hydrogen and helium nuclei, some of which attach to electrons to form hydrogen and helium atoms in the cooler outer atmospheres. Stars with the hotter surfaces don't display much else in their spectra, but stars with cooler surfaces display heavier atoms like the indicated Na and Ca, and even some molecules like the indicated MgH and CN.

Fig. III.2 shows only the visible part of the electromagnetic spectrum while modern instruments enable us to examine both longer (infrared, microwave and radio) wavelengths and shorter (ultra-violet, X-ray and gamma ray) wavelengths (**Fig. III.3**). With these instruments we observe many additional absorption lines in some of these non-visible wavelengths and they add to the identification of stellar types and their composition. There are also many sources of radiation in the Universe that radiate much more intensely outside the narrow band of visible wavelengths and were first discovered by **radio telescopes** or **X-ray telescopes**, etc. Unfortunately, we will not have time to discuss most of these sources.

2b. The Herzsprung-Russell diagram: (**Fig. III.4**) represents stars by points on a diagram in which luminosity is plotted against surface temperature. By far most of the stars we see lie along or near to a curve sloping downward from left to right in the middle of the diagram which is called the **main sequence curve**. These stars are called main sequence stars and it was originally thought that stars began their evolution hot and bright near the upper left end of the curve and evolved down the curve towards a cooler, dimmer state. We now think this idea is all wrong.

Our theories of star formation, stellar structure and evolution indicate that as stars form they begin above and to the right of the curve and as they contract and heat up they quickly move to a place on the curve determined mainly by their mass and size, the larger stars towards the upper left of the curve as the diagonal dashed lines would indicate. The stars spend most of their time at this fixed place on the curve while they burn their core hydrogen supplies, the larger stars burning much faster than the smaller ones. Our Sun has been there for about 4.5 billion years so far and is expected to remain there for another 5.5 billion years. Main sequence stars significantly smaller than our Sun will take hundreds of billions of years to burn up their core hydrogen supplies while the larger, hotter, brighter, bluer stars near the upper left of the main sequence are rather young stars that will not last long (millions of years) before their core hydrogen is gone and they leave the main sequence curve.

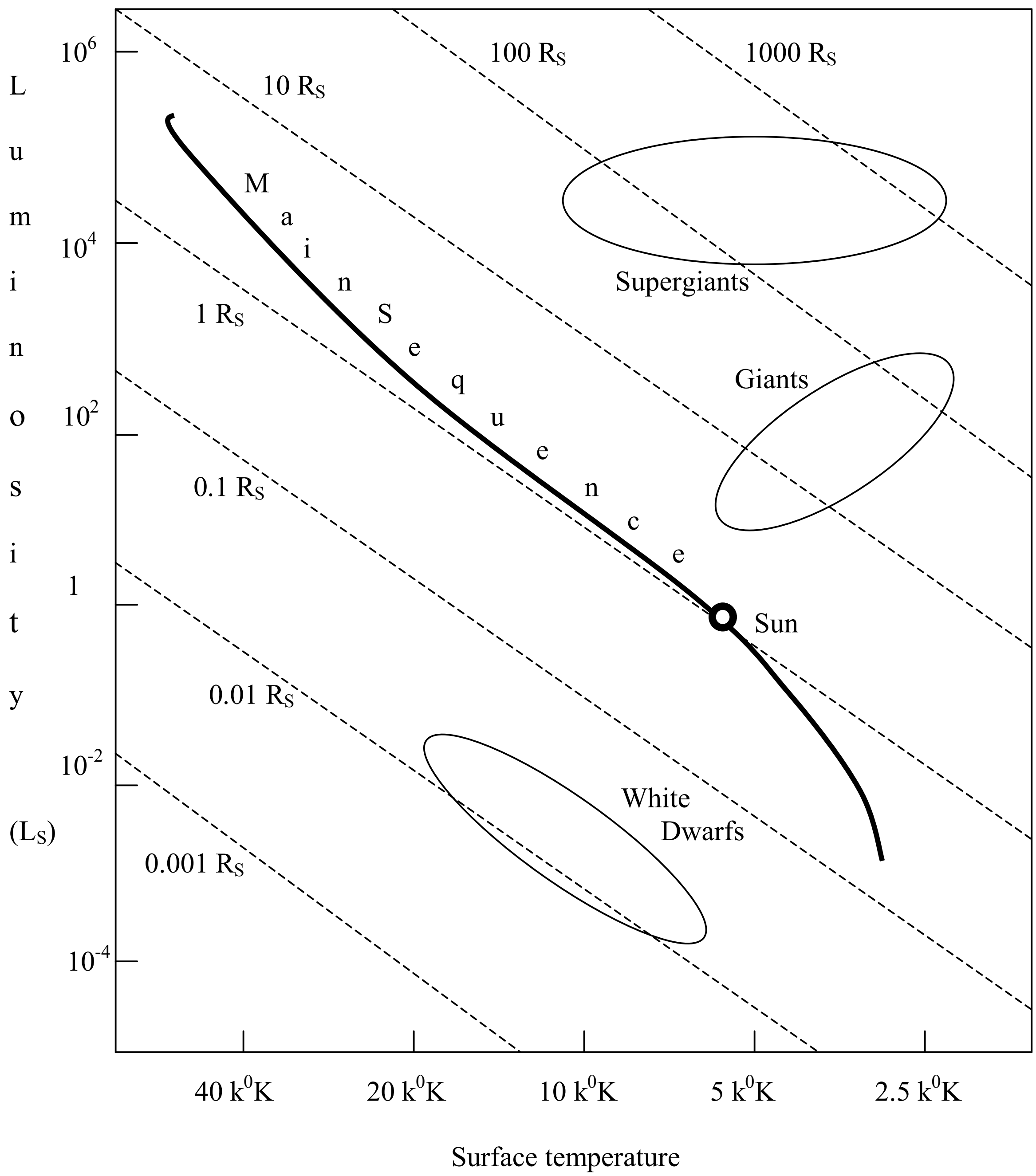


Fig. III.4: The Herzsprung – Russell diagram for star types and stellar evolution.

3. The Aging and Death of Stars: As a star runs out of its primary fuel of Hydrogen in its core the core collapses further, growing hotter as it shrinks and igniting the p – p reaction sequence in a shell surrounding the core. This heats the outer regions of the star which expands to become a **Red Giant**, much larger and much brighter than our Sun. Eventually the shrinking core reaches temperatures of 100 million degrees at which point **Helium burning** begins. This process involves the reactions,

$$^{4}He + {}^{4}He \rightarrow {}^{8}Be\ ,\ \ {}^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma\ ,\ \ {}^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma\ ,$$

and with these reactions heavier nuclei, carbon and oxygen, are produced.

Except for the trace amounts of carbon and oxygen created in the Big Bang, all the carbon and oxygen in the Universe, so far as we know, was created in helium burning inside stars. All the carbon and oxygen in your body had their nuclei created during helium burning inside aging stars.

When our Sun runs out of Hydrogen it will start to burn Helium. The increased temperature and pressure will cause the outer reaches of the Sun to swell to 50 to 100 times its present size. The inner solar system, including the Earth will be burnt to a cinder or completely vaporized. After burning its Helium fuel in about two billion years the core of the Sun will collapse again, this time, before temperatures reach new ignition levels, collapse will be stopped by **electron degeneracy pressure**, a quantum mechanical effect involving the **Heisenberg uncertainty principle** and the **Pauli exclusion principle**. The Sun will then be a **white dwarf**, very hot and gradually cooling and dimming with a radius comparable to that of the Earth and enormous density ~ 10 billion $kg./m^3$.

Stars are always ejecting into space a certain amount of their mass, at a slow rate, percentage wise, while burning hydrogen. Once they enter the expansion to red giant status and helium burning the rate of **mass ejection** climbs and can be very substantial by the time core helium burning ends. If the mass left when core helium burning ends is less than 1.4 M_{Sun} then the burned out core will collapse to a white dwarf star as the Sun will. But for stars exceeding 1.4 M_{Sun} in core mass, once core helium burning ends, the subsequent collapse is not stopped by electron degeneracy pressure but continues with ever increasing temperatures until, at about 600 million degrees, **carbon burning** begins, which produces oxygen, neon, sodium and magnesium. If the core mass stays above 1.4 M_{Sun} then core carbon burning will be followed by further collapse until **neon burning** begins at 1.2 billion degrees, producing higher oxygen and magnesium concentrations. Next follows **oxygen burning** at 1.5 billion degrees which produces mainly sulfur. Finally, with collapse generating a temperature of 2.7 billion degrees, **silicon burning** ignites and generates a variety of nuclei from sulfur to iron.

The Iron nucleus is the most stable nucleus that exists. Larger, heavier nuclei can undergo nuclear breakup, or fission, in stages, until they reach iron. Lighter, smaller nuclei can undergo nuclear merging, or fusion, in stages, until they reach iron. Iron is the last stop. But if that is the case, where do the nuclei for the rest of the periodic table of the elements come from? Are they not cooked in the stars also? They are, but the process is significantly different from ordinary fusion. For some details see the **Appendix**.

With each new stage in core burning corresponding regions of shell burning are occurring and repeating expansions to red giant size or larger are occurring. Near the end of its life a high mass ($\geq 25\ M_{Sun}$) star may have an outer radius of 500 million km (about that of Jupiter's orbit) with a comparatively very small iron core encased in six shells sustaining, from the outermost shell towards the core, hydrogen burning, helium burning, carbon burning, neon burning and silicon burning (**Fig. III.5**).

After all the burning that can generate enough heat and pressure to prevent severe contraction is over or diminishing, the massive star core contracts again and if mass ejections from the envelope leave the total contracting mass above 1.4 M_{Sun}, the contraction continues to such high core densities that most of the electrons are absorbed into most of the protons to form neutrons with very large liberations of neutrinos, ν, which escape,

$$e^- + p^+ \rightarrow n + \nu \quad .$$

The neutrons are then squeezed into a quantum degenerate state and this generates so much pressure, independent of temperature, that it can stop the contraction if the mass is less than an uncertain limit between 2 and 3 times M_{Sun}. Such a dead star is called a **neutron star** with its entire mass compressed into a ball only tens of kilometers in diameter!

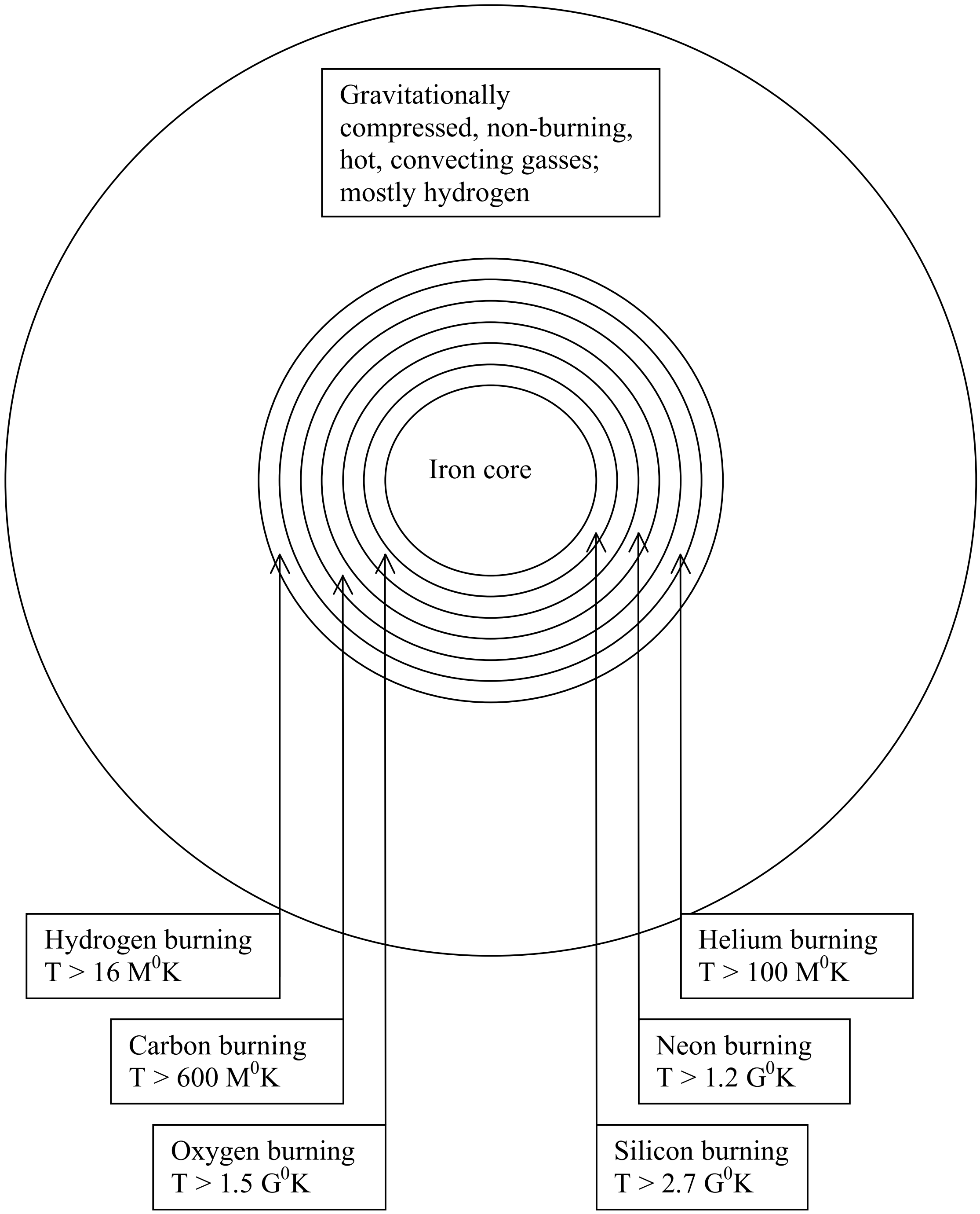


Fig. III.5: The fusion burning shell structure of an ageing giant star that will eventually collapse into a neutron star or a black hole. The diagram is not to scale. The core and the burning shells should all be much smaller compared to the outer surface radius.

4. Neutron Stars and Black Holes: Neutron stars were theoretically predicted back in the 1930s by the young astrophysicist **Subrahmanjan Chandrasekhar**, but the idea was ignored as not being realizable in nature. Instead it was believed that no matter how massive a main sequence star might be, when it left the main sequence and finally burned out it would somehow always eject enough mass from its outer regions to contract into a white dwarf, just as our Sun will. But that attitude was to change in the wake of the 1967 discovery of the Cambridge University graduate student in astronomy, **Jocelyn Bell**.

Having spent many months working on the construction of a new radio telescope, Bell noticed strange rapid signal pulsations from the (obscure?) constellation of Vulpecula when the telscope was turned on. The frequency of the pulsations was about 3 per second and very steady. So much so that the thought occurred: were they signals from an alien civilization? This led to the signals being dubbed LGMs for Little Green Men. Soon, however, other such steady, rapidly pulsating signals were found coming from many directions in the sky and at widely different frequencies. Many of them were pulsating much faster than Bell's original signal; the record holder to date pulsates about 1000 times per second. Surely these were not all signals from alien civilizations. They came to be called **pulsars**.

The search for theoretical models of something that could send such steadily, rapidly pulsating signals soon narrowed to rapidly spinning neutron stars carrying intense magnetic fields. All stars rotate to some degree, a natural consequence of their formation from swirling material. But the rotation rates are usually modest. Our Sun rotates once every 25 to 35 days (depending on which part of the Sun one is considering). Neutron stars spin furiously by comparison because of the conservation of angular momentum during the collapse and contraction of the large star that becomes the neutron star. The process is analogous to the increasing rate of spin of a figure skater when she pulls her arms and/or legs in (**Fig. III.6**). Remember that the final neutron star is only tens of kilometers in diameter while still consisting of more than 1.4 M_{Sun} in mass. If the mass of our Sun was uniformly distributed throughout its volume and it then contracted to a sphere of 10 km radius, the final spinning rate would be once every few ten thousandths of a second.

A neutron star carries an intense magnetic field due to the current generated by the *comparatively* small number of left over protons that didn't get converted into neutrons when the collapse occurred. The very intense field is shaped, roughly, like that of a bar magnet through the center of the neutron star. If, as is the case with the Earth, the direction of the bar magnet is not the same as the axis of rotation (Geographical North pole is different from Magnetic North pole), then the bar magnet and its magnetic field is whirled around very fast and this can produce a beam of radiation along the magnetic axis (**Fig. III.7**). We see only those pulsars that have beams that sweep over the Earth as the neutron star spins. If this theory is correct, there must be many more neutron stars that we never directly see.

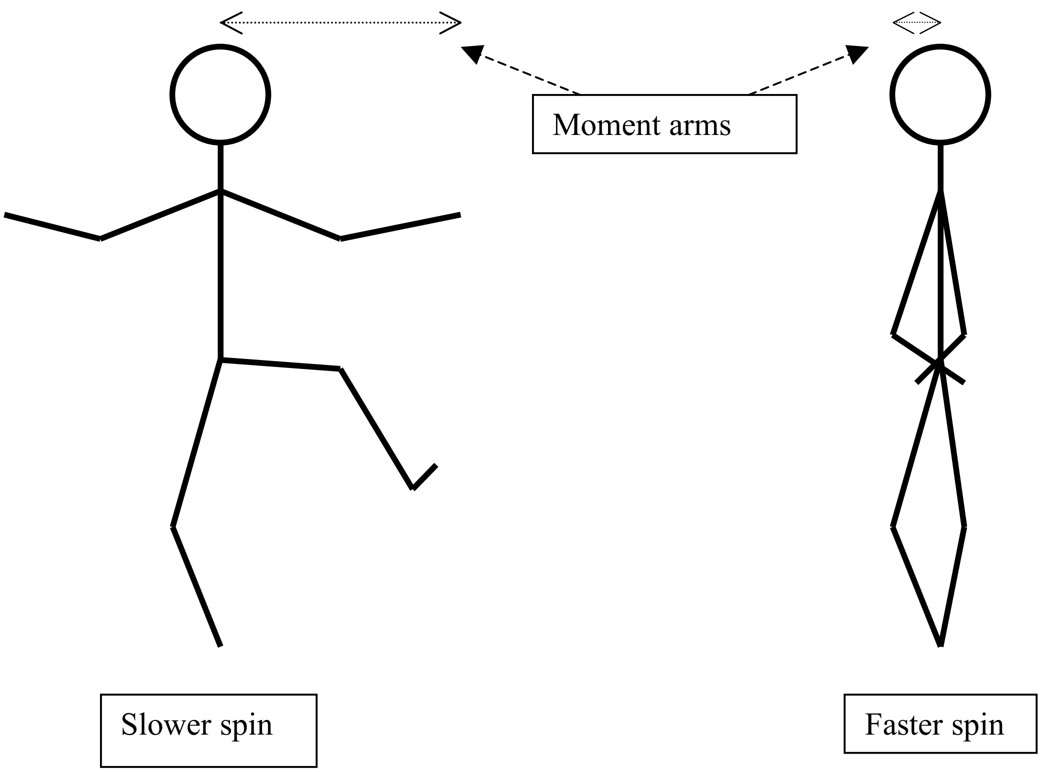


Fig. III.6: The conservation of angular momentum results in higher rate of rotation when the mass distribution contracts around the axis of rotation.

Finally, if the core mass of a dying star is greater than somewhere between $2M_{Sun}$ and $3M_{Sun}$ (the exact theoretical value is very difficult to pin down), no known physical process can stop the gravitational collapse and the whole collapsing system reaches such high densities and generates such an intense gravitational field that it literally disappears within a spheroidal surface from which not even light can emerge. The star has become a **black hole**!

Black holes form whenever gravity warps the structure of space-time so much that a spheroidal closed surface exists for which the transfer of any energy or matter from inside the surface to outside the surface is prohibited. Energy and matter can pass through the surface from the outside to the inside but, once in, can never come back out. And the closer anything gets to

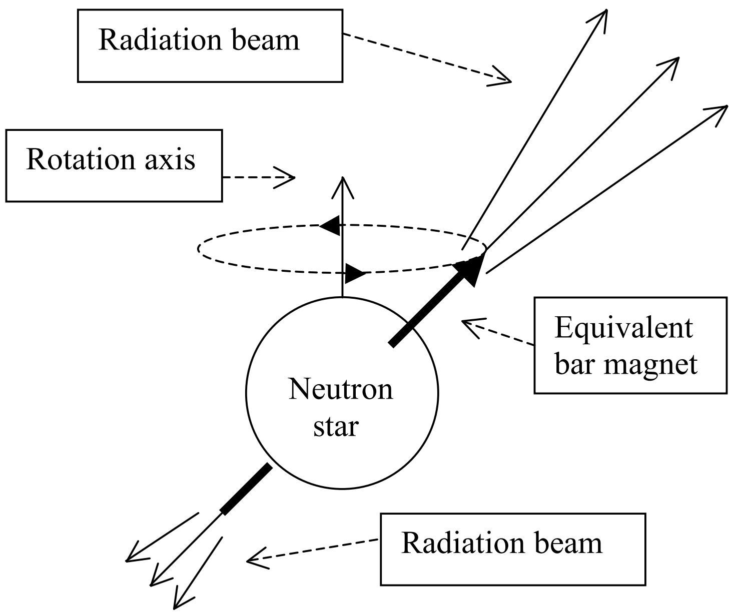


Fig. III.7: Spinning neutron star with radiation beams.

the separating surface, the more energy it must possess to have any possibility of not being sucked through the surface. As a consequence of this feature no events or processes that may occur within the surface can signal their occurrence to the exterior or influence exterior events in any way. For these reasons the surface is called an **event horizon**.

If the black hole contains a mass of M, and is not rotating, then the circumference, C, of the event horizon surrounding it is given by,

$$C = 4\pi\, G\, M / c^2.$$

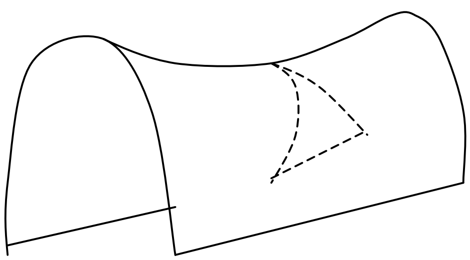
I've given the formula for the circumference rather than the radius of the event horizon because the geometry of space and time near and inside the horizon is very different from familiar Euclidean geometry. We say that spacetime is curved. What might that mean?

5. Einstein's Theory of Gravitation: When Einstein invented his first relativity theory, the **Special Theory of Relativity**, published in 1905, he employed the principle that the speed of any light beam in vacuum was the same relative to all observers (If you've never studied relativity before, this principle should sound crazy and absurd to you. Unfortunately, we can't clarify the matter here.). From this principle and the assumed equivalence, for the purpose of describing the laws of nature, of the perspectives of any observer in unaccelerated motion, Einstein concluded the impossibility of any object or causal influence moving faster than the vacuum speed of light. This conclusion brought his theory into immediate conflict with Newton's theory of gravity which had worked awfully well for over two hundred years!

The problem was that in Newton's theory of gravity any modification of the distribution of mass in any locale would have an *immediate* gravitational effect on all other pieces of matter, no matter how far away from the original locale the pieces might be. The causal influence of Newtonian gravity propagated with infinite speed! Admittedly, this extreme aspect of Newton's theory was never directly tested in all the two hundred years of corroboration of Newtonian gravity that had occurred. But since none of the tests that *had* been made came into obvious conflict with the infinite speed aspect, it was not going to be easy to modify gravitational theory so as to incorporate Einstein's speed limit and still get right all the things that Newton's theory explained.

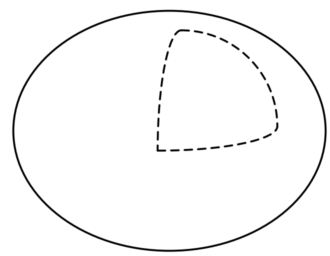
After about ten years of intense effort, not only by Einstein, the new theory of gravity was presented as the **General Theory of Relativity** in 1916. In this theory, instead of matter producing a force of attraction for all other matter, gravity was treated as not really being a force at all! Instead the distribution of mass and energy (Einstein had derived the equivalence of energy and mass in his Special Theory) produced an alteration or distortion or warping in the geometry of space and time and 'pieces' of mass-energy that were not influenced by any real forces moved along the 'straightest possible' trajectory-histories, or **worldlines** that existed in the warped geometry. In the vicinity of large concentrations of mass-energy, these 'straightest possible worldlines' look to us like the accelerated motions of gravitational orbits. Later the great gravity theorist, **John Wheeler**, would sum up General Relativity by saying “Matter tells space-time how to curve and space-time tells matter how to move.”

We can get some feeling for how curvature changes geometry by considering two dimensional surfaces. We are all familiar with curved surfaces, unlike four dimensional spacetime, or even curved three dimensional space, which we can not directly visualize. The three surfaces of **Fig. III.8** are designated to be surfaces of negative curvature (the saddle surface), positive curvature (the ellipsoid) and zero curvature, or flat (the plane). On each surface if one forms triangular shapes out of three segments of the straightest possible kinds of curves that exist on each surface, then one always finds that the sums of the vertex angles of the triangular shapes



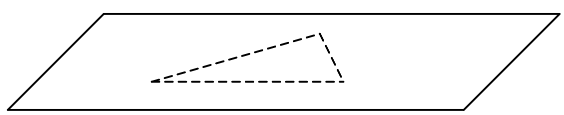
Σ angles < 180^0

Saddle surface of negative curvature with straightest possible triangle



Σ angles > 180^0

Ellipsoidal surface of positive curvature with straightest possible triangle



Σ angles = 180^0

Flat surface of zero curvature with triangle

Fig. III.8: Surfaces of various curvatures with straightest possible triangles which provide two dimensional analogues to the curved geometries in Einstein’s General Theory of Relativity.

are less than 180^0 on the saddle surface, more that 180^0 on the ellipsoid and exactly 180^0 on the plane. Features like this, albeit more varied, continue to characterize the geometrical properties of objects in three and four dimensional curved spaces.

In the vicinity of massive or dense stars Einstein's theory requires space and time to be curved, the more so the more massive or dense the star. External objects move on the straightest possible curves in the distorted space-time and these curves are what we recognize as gravitational orbits. The purely spatial part of the curvature is usually positive and so the sums of triangular vertex angles exceed 180^0 and circular circumferences are less than 2π times their radii.

In ordinary stars we can partially visualize the curved geometry by considering surfaces cutting "straight" through the center of the star (**Fig. III.9**). Outside the star the surface is very nearly flat, the more so as we

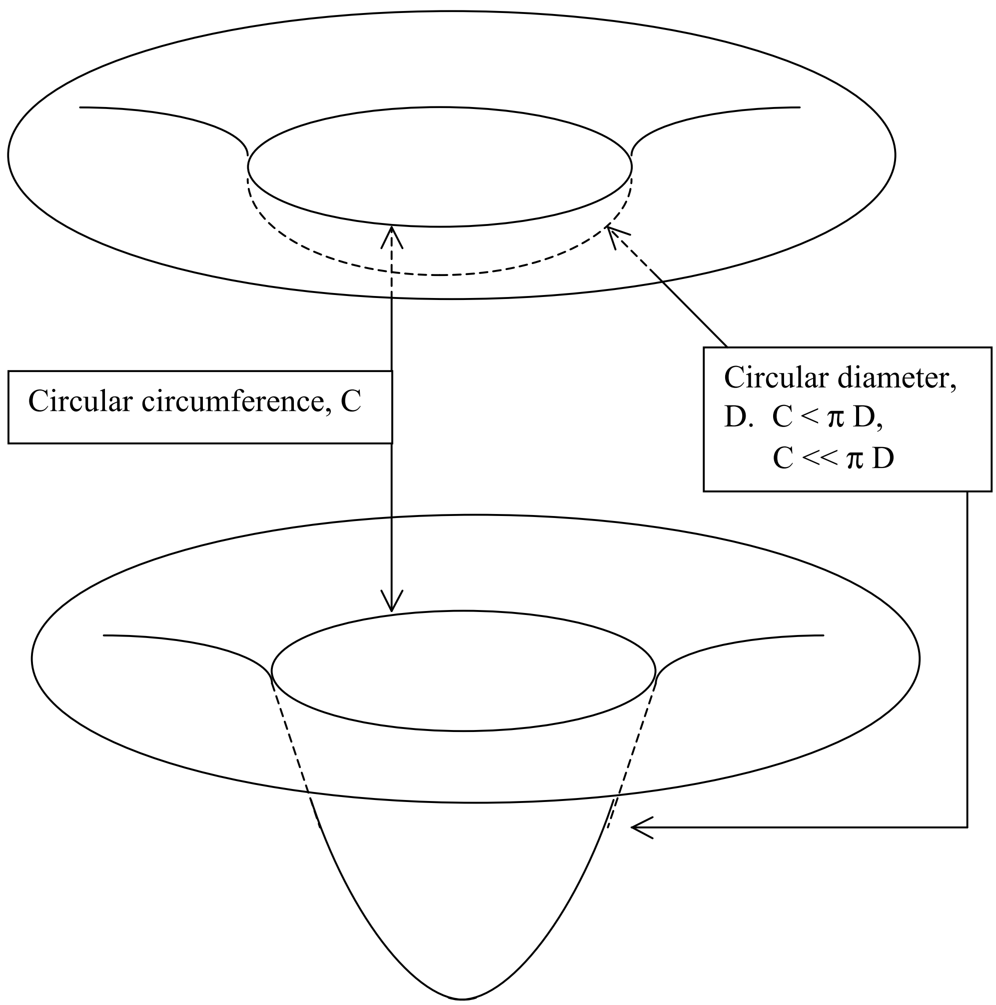


Fig. III.9: The spatial geometry of flattest possible two dimensional sections through the interiors of stars of different densities.

move away from the star. But inside the star a noticeable distortion occurs which reduces, below π, the ratio of circular circumferences to their diameters.

The effect is more accentuated in more dense stars. It's quite strong in neutron stars. In the case of a black hole it's extreme. The circumference of the event horizon is finite but it's radius is infinite!

It is also the case, although harder to wrap ones mind around, that space and time are, in a sense, rigidly attached to the event horizon. For example, in Einstein's theory, clocks mark time more slowly as they are located more downstream in a gravitational field. One can not regard this as merely a dysfunctionality induced in clocks by gravity since it is the case for any rhythmic process and, indeed, for any process whatsoever. ***All processes*** *run their course more slowly downstream in gravitational fields relatively to upstream in such fields, and, consequently, relative to the absence of gravitational fields.* Since time itself is measureable only by physical processes, usually periodic processes, the previous statement is equivalent to saying that time itself 'runs' or 'flows' more slowly downstream than upstream in gravitational fields.

In particular, in the case of the event horizon of a black hole, time stops *relative to exterior regions*, i.e., an exterior observer would never actually observe any object to have passed through the horizon in a finite amount of time. Instead, the exterior observer would see all processes to proceed slower and slower as an infalling system approached the event horizon. An infalling observer, however, notices nothing strange about its local flow of time but rather, shortly before passing through the horizon, infers the exterior observers time flow to speed up (This assumes that he survives, long enough, the ultimately fatal **tidal forces** of radial stretching and circumferential squeezing that accompany all intense gravitational fields (**Fig. III.10**). Oddly, the larger the black hole, the longer he will survive. The really nasty black holes are the smaller ones which will tear you apart well before you reach the event horizon.).

Similarly, if a black hole is formed from the collapse of a rotating star and, thus, is a rotating black hole, *the adjacent space rotates with it* in the sense that to orbit the event horizon in the same direction of the black hole rotation requires less energy than orbiting the horizon against the direction of the black hole rotation. Similarly to ordinary rotating objects, the shape of the event horizon of a rotating black hole is that of an oblate ellipsoid.

For a long time the extremely bizarre features of black holes made acceptance of their real occurrence in stellar collapses very rare. Neither Einstein nor Eddington ever believed they could really occur and it was primarily the work of Oppenheimer and Wheeler in this country and **Landau** and **Zeldovich** in the Soviet Union that eventually (by the late 50s) convinced the physics community that they would occur in nature. For a variety of reasons that we do not have time to consider here, we now believe

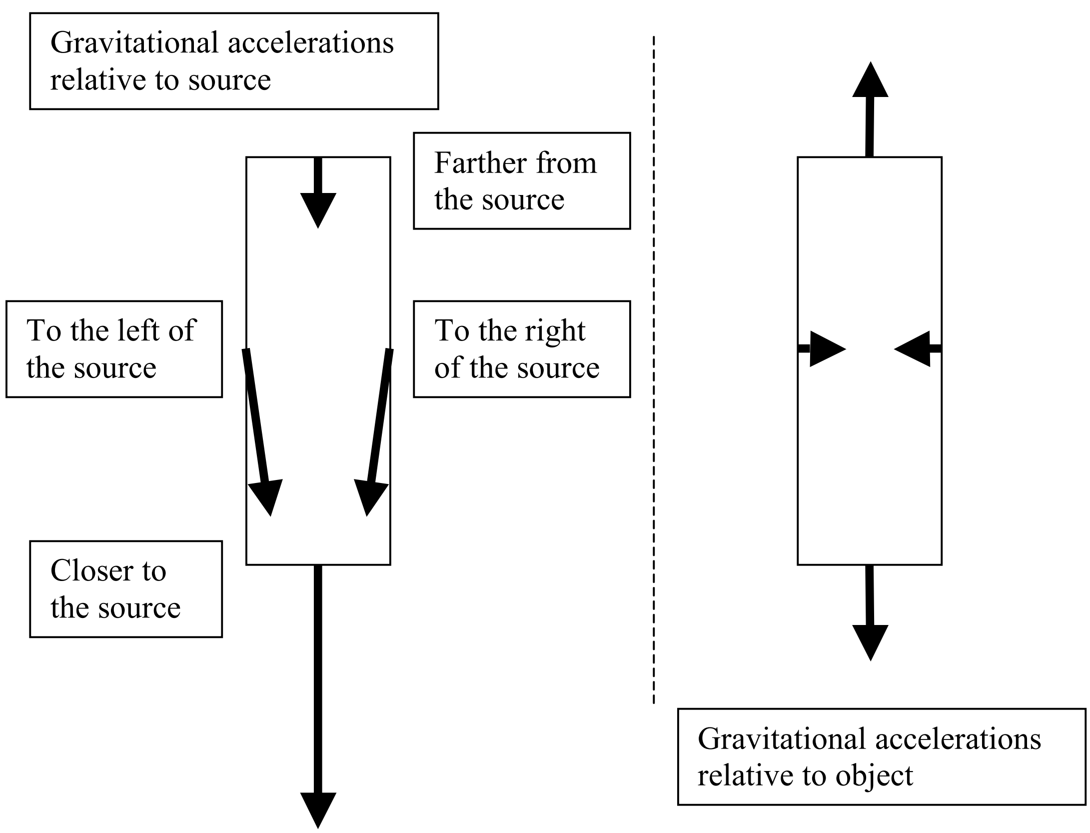


Fig. III.10: Differential accelerations induced by gravity on an extended object and resisted by the cohesive electromagnetic and nuclear forces that hold the object together. If gravity is sufficiently intense, the object will be torn apart. These effects are called tidal forces because they are responsible for the tides on Earth due to the gravity of the Moon and the Sun.

they are commonplace and plentiful. In particular, we presently have strong evidence that the centers of most large galaxies, including our own, are occupied by **supermassive black holes**.

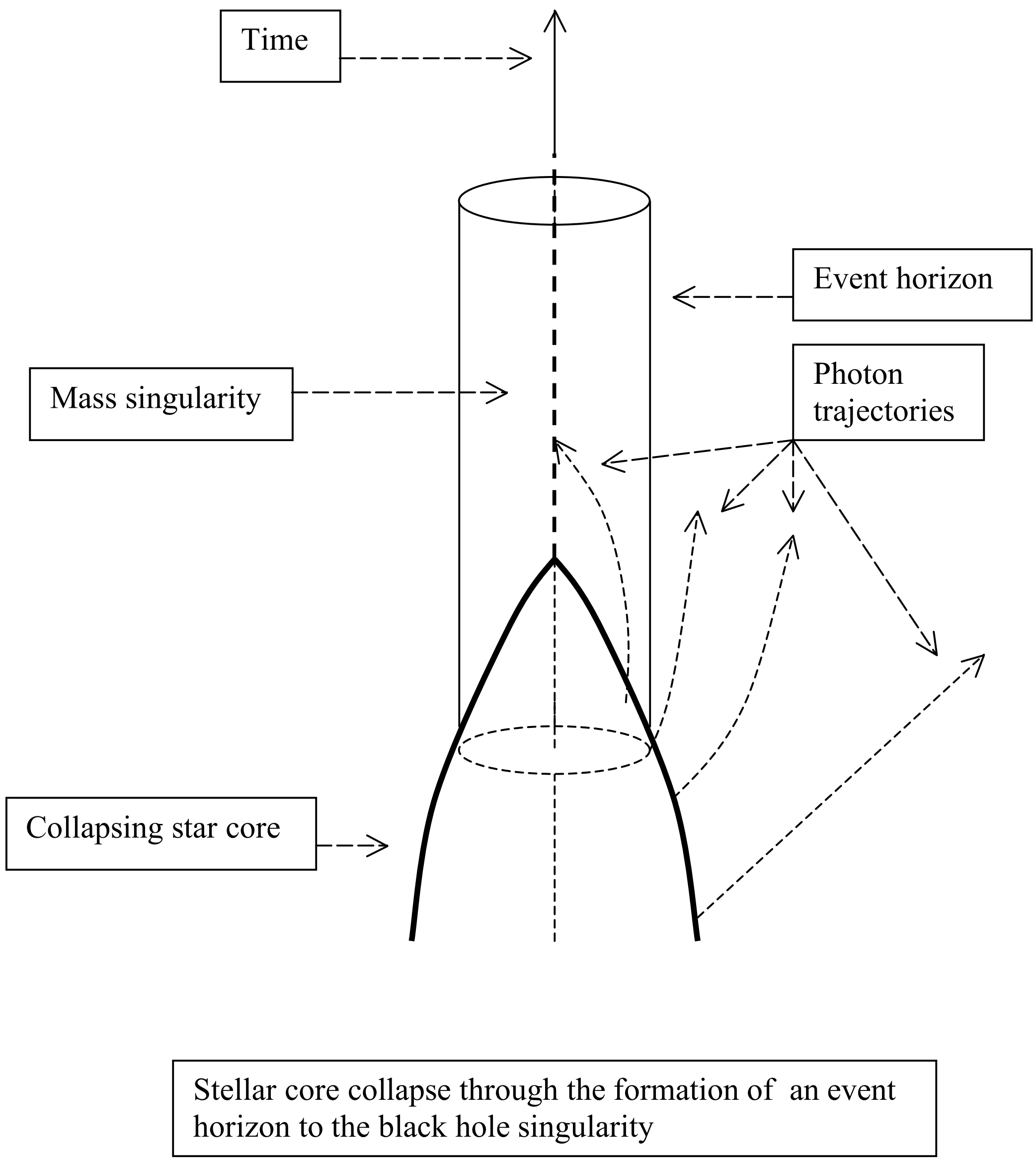


Fig. III.11: Space-time diagram for stellar core collapse to a black hole with the core surface passing through the event horizon to the mass singularity. The distorted world lines of photons are indicated.

Appendix: Nucleosynthesis of the elements beyond Iron

In the thermonuclear fusion chaos there are free neutrons to be found. If neutrons remain free, then, on average in about 1000 seconds, they spontaneously decay into a proton and electron and an anti-neutrino. The free neutrons can come from being knocked off, by collisions, from high atomic weight isotopes (in which they may not be too tightly bound). Some of these neutrons can then be absorbed by Iron nuclei and other nuclei near iron in atomic number, giving rise again to high atomic weight isotopes of those same elements. In such isotopes some neutrons, even though no longer free, can decay. Each time this happens the electron and anti-neutrino are spit out but the proton stays in the nucleus and the atomic number of the nucleus (the number of protons in the nucleus) increases by one unit. Starting from Iron, a higher member of the periodic table is produced, first Cobalt, next Nickle, then Copper and so on. Unlike the fusing nuclei with their positive electric charges, the electrically neutral neutrons don't have to fight against electrostatic repulsion to get absorbed. So they don't have to be moving very fast, 'though in the fusion furnace they usually are. If a neutron decay occurs after each absorption and before the next one, the process is called s-absorption where the s is for slow. This takes place in the last stages of a star burning heavy elements. But there is also a rapid absorption process, called r-absorption, in which several neutrons will be absorbed by a nucleus before any of them decay. This process is common during novae or super novae explosions of stars.

Even though the neutrons are *fusing* with the nuclei, many astrophysicists do not call these processes fusion, reserving that term for the fusing of two positively charged nuclei. Instead, production of the higher elements by neutron absorption and decay is included under the broader umbrella term of nucleosynthesis.