Chapter 2

A COSMOLOGICAL OVERVIEW

As we seem to be cherry picking topics, more or less, I'm going to put off the standard, math-driven presentation of Classical Newtonian Physics and burn a chapter over the question, "How did the universe get where it is, at least from the perspective of physics?" Enjoy. This will be the last chapter for quite a while that follows this math denude format.

Note: What makes science in general and physics in particular different from, say, history, is that science is based on *testable* hypotheses. If there is no way to test an assertion, it technically doesn't belong in physics.

What you are about to read is a mix of solid physics theory coupled with speculation. Specifically, it is not at all likely that we will ever be able to duplicate the energies associated with the Big Bang. The best we have been able to do so far has come from nuclear accelerators that can produce particle energies of around 1 TeV (that is, 1,000,000,000,000 electron volts), or approximately the *particle energy* of the universe 10^{-12} seconds after the Big Bang. As for what happened before that time, all we have are educated guesses.

Put a little differently, you are about to run into a lot of good, solid physics, but you are also about to run into some ideas that we have no idea how to test.

I will do my best to explain why physics thinks what it thinks in those realms, but all of you fundamentalist Christians (or, for that matter, fundamentalist Moslems) out there, don't despair. There *are* places in the story where you could well insert, " . . . and then *God* said . . ."

A.) In the Beginning . . . :

1.) In the Beginning (the theme of the movie *2001* should swell appropriately here), as far as western science is concerned, there was *absolutely nothing*.

a.) That is, what existed was a vacuum devoid of structure or time or even radiation (i.e., darkness throughout).

2.) Actually, we've already fudged a bit. There was *one* thing that did exist in the beginning. It was energy--the energy wrapped up in the vacuum.

3.) And what about that energy?

a.) On the surface, the energy in the primeval void seemed to be evenly distributed.

b.) But down at the super, super microscopic level (i.e., around the 10^{-34} meter mark), there were random, quantum mechanical fluctuations constantly going on.

B.) A Quick Reminder About Energy:

1.) There was nothing outside the vacuum of the primordial void, but that didn't mean there wasn't the possibility of work being done by the energy associated with the void.

2.) In the previous chapter, we established that energy and mass are two forms of the same thing.

a.) For example, it is possible in a laboratory situation to completely evacuate a container, creating a vacuum. If we irradiate that vacuum with just the right amount of electromagnetic energy (i.e., light-like energy), from nowhere will be created two bits of material--a *particle* and its *anti-particle*.

b.) This is called *pair production*, an example of which is the production of an electron and its anti-particle, a positron (a positron is a *positive electron*).

i.) In fact, the electromagnetic radiation with the right amount of energy to do this is in the gamma radiation range.

c.) Put a little differently, you can start with nothing and end up with something. Under the right conditions, pure energy has the ability to turn itself into solid matter.

Note: It goes the other way, also. Put a particle (an electron) and its anti-particle (a positron) together and you will get an explosion. It won't be a normal explosion with bits and pieces flying everywhere. Electrons are elementary particles--they aren't *made up* of smaller pieces to fly into. The explosion will leave absolutely nothing except the gushing forth of pure energy. The particles will have completely ceased to exist, literally converted themselves from matter into pure energy. This process is called *annihilation*.

d.) The bottom line: If you have energy and the right conditions, you have the possibility of creating matter.

C.) A Few Words About Quantum Mechanics (or a few more than a few):

1.) Quantum Mechanics is the study of the dynamics of very small systems--systems at the sub-atomic level.

2.) One of the peculiarities of structures, as shown through Quantum Mechanics, is that within extremely confined volumes:

a.) A simultaneous measurement of the *momentum* and *position* of an object cannot be done with absolute certainty, and energy can fluctuate in ways it could never do in the macroscopic world.

b.) These observations are summarized in what is called *the Heisenberg Uncertainty Principle.*

3.) The most common statement of the Heisenberg Uncertainty Principle has to do with observing a sub-atomic particle's velocity and position at the same time. A *hand waving* explanation of this follows.

a.) The momentum p of a body of mass m and velocity v is mathematically defined as $p = mv$.

i.) Yes, using a p to denote *momentum* is weird. The letter m was already used for mass, and who knows, maybe the guys who came up with the definition couldn't spell and thought it was really *pmomentum* . . .

ii.) What is important to notice is that the measure of a body's momentum, given its mass, is directly related to the measure of the body's velocity.

b.) To measure an object's velocity (hence momentum) and position, you have to somehow sense what the object is doing. The normal way to do this is to have the object absorb light energy. When the light is re-emitted in the form of "reflected" light, you can "see" where the object is and tell what it is doing.

i.) This is like bouncing light off a cat, thereby registering its position and velocity as the bounced light enters your eye.

c.) The problem with "seeing" subatomic particles in this way is that they are so small, "bouncing" radiation off them necessitates that they *absorb* some of the energy. In doing so, they change their position and momentum.

d.) The trick is, then, to bounce so little light off the electron that you can more or less pinpoint its position while not altering its momentum very much. Unfortunately, if you don't use much energy, hence insuring a small momentum uncertainty, you won't be able to see it very well insuring a large position uncertainty. In short, sensing an electron inevitably creates some degree of uncertainty in both the electron's position (this uncertainty is denoted as Δx) and the electron's momentum (this uncertainty is denoted as Δp).

e.) What Heisenberg postulated, and what was later confirmed, was that the product of the momentum and position uncertainties could never be smaller than, hence will always be greater than, a constant.

i.) That constant was related to what is called *Planck's constant*. (Yes, you'd think they'd have called it *Heisenberg's constant*. They didn't because Planck encountered the same number in his earlier study of *black body radiation*.)

ii.) Symbolized as h, Planck's constant is numerically equal to 6.626×10^{-34} joule·seconds. The constant actually needed is Planck's constant divided by 2π. This is symbolized as $\hbar$.

f.) In other words, Heisenberg's Uncertainty Principle, in a nutshell, can be written as:

$$(\Delta x)(\Delta p) \geq \hbar .$$

g.) What is particularly interesting about this is that you can devise an experimental procedure to pinpoint the position of, say, an electron *with extreme precision* (i.e., with minuscule position uncertainty Δx), but in doing so you will know very little about the particle's momentum (. . . which is to say, Δp will be very large). Why? Because it must be true that $(\Delta x)(\Delta p) \geq \hbar$.

h.) On the other hand, you can devise an experimental procedure to pinpoint the momentum of an electron with extreme precision (i.e., with minuscule momentum uncertainty Δp), but in doing so you will know very little about the particle's position (that is, Δx will be very large). Why? Because it must be true that $(\Delta x)(\Delta p) \geq \hbar$.

i.) The point is that *position uncertainty* and *momentum uncertainty* are linked in a kind of dance.

4.) What is important to our discussion is that this dance exists between other parameters. For instance, the Heisenberg Uncertainty Principle connects energy fluctuations and time during which the fluctuations occur. Specifically:

a.) In a highly confined volume, a spontaneous fluctuation ΔE can happen during time Δt as long as the energy content of the fluctuation satisfies the Heisenberg Uncertainty Principle for energy and time. That, specifically, is

$$(\Delta E)(\Delta t) \geq \hbar .$$

b.) Reiterating, this means that without violating *conservation of energy*, it is possible to have a completely random energy fluctuation ΔE over a time period Δt as long as $(\Delta E)(\Delta t) \geq \hbar$ is true.

i.) When this happens, the bundle of energy that comes into existence is called a *virtual particle*.

ii.) THIS IS NOT LIKE ANYTHING YOU WILL EVER RUN INTO IN THE MACROSCOPIC WORLD. If it did, you could expect virtual rabbits to just pop into existence out of nowhere, then have them pop back out of existence without any apparent causal impetus.

c.) All of this was summarized by P.C.W. Davies in his book, The Accidental Universe, when he wrote:

> "Although the permanent creation of a new particle of rest mass m_o requires an input of energy m_oc^2 (this is just Einstein's $E = mc^2$), such a particle can be temporarily created in the absence of an energy supply. The reason for this concerns the Heisenberg uncertainty principle which allows the law of conservation of energy to be suspended for a duration Δt by an amount ΔE, where $(\Delta E)(\Delta t) \approx \hbar$. It follows that m_oc^2 can be "borrowed" for a time $\Delta t \approx \frac{\hbar}{mc^2}$ to make a temporary, so-called virtual particle. Of course, this temporary particle enjoys only a fleeting existence before disappearing again. It cannot, therefore, travel very far . . ."

d.) The point here is that it is perfectly possible at a subatomic level (i.e., within the world of Quantum Mechanics) to have random, spontaneous energy spikes that are large, but that exist for only a very short period of time.

5.) So back to "the beginning."

a.) Modern physics theory holds that a super, super, super large, radical, energy fluctuation occurred by freak chance--a trillion trillion trillion trillion (etc.) to one shot--at a super, super microscopic point within the primeval vacuum.

b.) The energy content of the fluctuation was so great that it triggered the creation of matter.

c.) The presence of that matter warped the geometry of the region which, in turn, drew fantastic amounts of free energy to the point.

d.) That energy was converted to matter, drawing still more energy.

e.) In a rapidly escalating reaction (the whole process took less than 10^{-43} seconds to happen), all that would eventually become our physical universe gushed forth in one nearly instantaneous, gigantic BIG BANG.

6.) As described in a 1985 *Astronomy* magazine article entitled "In the Beginning . . . ":

> ". . . So we are left with the remarkable possibility that, in the beginning, there existed nothing at all, and that nearly all of the matter and radiation we now see emerged from it. This process has been described by University of California physicist Frank Wilczek: "The reason that there is something instead of nothing," he said, "is that 'nothing' is unstable." A ball sitting on the summit of a steep hill needs but the slightest tap to see it in motion. A random energy fluctuation in space is apparently all that was required to unleash the incredible latent energy of the vacuum, creating matter and energy and an expanding universe from quite literally nothing at all."

D.) A Quick Word About Light:

1.) Although we will talk in considerably more detail about light later, for now you need to know that light can act like a wave or like a particle, depending upon the circumstance.

2.) When light is treated like a wave, it is characterized either by its *wavelength* or by its *frequency*. So what's the deal with waves?

3.) Picture a water wave as viewed from the side. What is notable in the undulation are crests and troughs.

a.) The *wavelength* of a water wave or, for that matter, any wave, is defined as the distance between two crests, or the distance between two troughs, or the distance between any point and the place where that point's geometry repeats itself.

4.) *All* periodic wave forms have a wavelength associated with them.

a.) The symbol for a wave's wavelength is the Greek letter *lambda*, written λ.

b.) The unit in the MKS system for a wave's wavelength is *meters per cycle*.

Note: Actually, the term *cycle* is not really a unit--I include it for the sake of descriptive clarity. Technically, therefore, the unit for wavelength should be *meters*.

c.) When dealing with very short wavelengths, the unit that is often used is the *angstrom*.

i.) An *angstrom* is equal to 10^{-10} meters.

ii.) The symbol for the angstrom is *Å*.

5.) The wavelengths of light that are visible to the human eye range from 4000 Å (violet light) to 7000 Å (red light).

6.) *All* periodic wave forms also have a *frequency* associated with them.

a.) The symbol for a wave's frequency is the Greek letter *nu*, written ν.

b.) The *frequency* of a wave is defined as the number of crests or troughs that pass by a given point *per unit time*.

c.) The unit in the MKS system for a wave's frequency is *cycles per second*. This is also given the name *Hertz* (abbreviated Hz).

Note: Again, remember that *cycles* is not technically a unit. In fact, many books present the unit for frequency as *inverse seconds* (i.e., *1/seconds*, or $(seconds)^{-1}$).

7.) There is a relationship between a wave's frequency and its wavelength.

a.) That relationship is $v = \lambda \nu$, where v is the velocity of the wave, λ is the wave's wavelength, and ν is the wave's frequency.

b.) For light, the relationship becomes $c = \lambda \nu$, where c is the speed of light (i.e., 186,000 miles per second, or 3×10^8 meters per second).

Minor Note: What $v = \lambda \nu$ suggests is that a wave with a very high frequency will have a very short wavelength, and a wave with a very low frequency will have a very long wavelength.

c.) Using $c = \lambda \nu$, the frequency range of optical light becomes 7.50×10^{14} Hz (violet light) to 4.29×10^{14} Hz (red light).

8.) When light is viewed as a particle, it is thought of as a bundle of energy.

a.) So viewed, light is characterized by the amount of energy E wrapped up in the bundle.

b.) A bundle of light energy is called a *photon*.

9.) For a given bit of light, there is a relationship between the light's wave characterization (i.e., its frequency) and its particle/photon characterization (i.e., its energy content).

a.) That relationship is $E = h\,\nu$, where E is the photon's energy, ν is the light's frequency, and h is Planck's constant h ($=6.63 \times 10^{-34}$ joule·sec).

b.) It is important to note that light waves at high frequency (i.e., short wavelength) are associated with photons of high energy, and light waves at low frequency (i.e., long wavelength) are associated with photons of low energy.

E.) Energy and Temperature:

1.) Before we start with the evolution of the universe, we need to say a little more about energy and temperature.

2.) An electron volt, abbreviated as *eV*, is the amount of energy required to accelerate an electron through a one volt electrical potential difference.

a.) Note that there is a 12 volt electrical potential difference between the terminals of your car battery, and 1.5 volts across the ends of a AA battery.

b.) Numerically, 1 eV is equal to 1.6×10^{-19} joules, which is to say, not a lot unless you happen to be an electron.

c.) The binding energy of Carbon atoms in wood is around 1 eV, so if you burn a log in the fireplace, you get out about 1 eV's worth of energy per atom in the reaction.

3.) Temperature is a measure of the average kinetic energy of the atoms and molecules making up a system. In other words, if you have a gas, its temperature tells you the average kinetic energy of each gas molecule as it moves about within the volume.

a.) Molecules of air in a room have kinetic energy of around $\frac{1}{40}$ eV. If their energy was 1 eV, the room would glow. Fluorescent lights accelerate mercury atoms to several eV's. This is why *they* glow.

4.) Temperature is related to energy as $E = (n)kT$, where n is a number between 1 and 3 that depends upon whether you are talking about photons or gas molecules, T is the temperature in *degrees Kelvin*, and k is called Boltzman's constant. Boltzman's constant is equal to *1.38×10^{-23} joules per molecule per degree Kelvin* or *8.6×10^{-5} eV per molecule per degree Kelvin* (don't memorize these constants--if you need them on a test, I'll supply them).

a.) The point is, if the temperature is high, the energy content of the system will be high.

5.) In the center of the sun, the *energy per atom* is around 1 keV. This corresponds to a temperature of 10^7 degrees Kelvin.

Note: The letter *k* stands for *kilo*, so 1 keV is the same as 1000 eV's.

a.) The letter *M* stands for *Mega*, or million, so 1 MeV is 1,000,000 eV's. This is a thousand times more energetic than the atoms in our sun. It also corresponds to a temperature of 10^{10} degrees Kelvin.

Note: It is common for physicists to say things like, 'The temperature was 1 MeV." This appears on the surface to be a little strange because an MeV is a measure of energy and temperature is a measure of . . . well, temperature. It is not as off the wall as it seems, though, as the temperature is proportional to the energy. If you know one, you know the other.

b.) The letter *G* stands for *Giga*, or 1,000,000,000, so 1 GeV is 1000 MeV's or a million times more energetic than atoms in our sun. It also corresponds to a temperature of 10^{13} degrees Kelvin.

c.) The letter *T* stands for *Tera*, or 1,000,000,000,000, so 1 TeV is 1000 GeV's. This is the energy level of our most powerful particle accelerator. It corresponds to a temperature of 10^{16} degrees Kelvin.

6.) At the Big Bang, temperatures and pressures were unimaginable. As time proceeded and the stuff of the universe spread outward, the volume of the universe increased. We need to say a little bit about this spreading before we can make any sense at all of the size of the universe at various points in its early evolution. The hang-up has to do with the propagation of light in an expanding universe. That, and a misunderstanding about what Einstein said about the speed of light.

F.) Faster Than the Speed of Light?:

1.) Tough as it may be to believe, current astronomic observation suggests that the universe is expanding faster than the speed of light. That is, it appears that there are stars we can see today that, at some point in the future, will be outside our "event horizon" (I'll explain what that means shortly) and no longer visible to us. The problem is, if Einstein said that *no physical object can travel faster than the speed of light*, and if we *believe* Einstein, how can we support a belief that the *universe* is expanding faster than the speed of light?

2.) The problem is in understanding what Einstein actually maintained. What Einstein said was that nothing will ever *pass you by* moving faster than the speed of light.

3.) Let's say you set up an experiment in your laboratory in which an object travels by your measuring apparatus.

a.) What Relativity says is that if you measure that object's velocity, it will never be *equal to* or *greater than* the speed of light no matter what.

b.) In fact, if the experiment incorporated a *signal* traveling across the room instead of an object, Relativity maintains that the signal's velocity will never be *greater than* the speed of light.

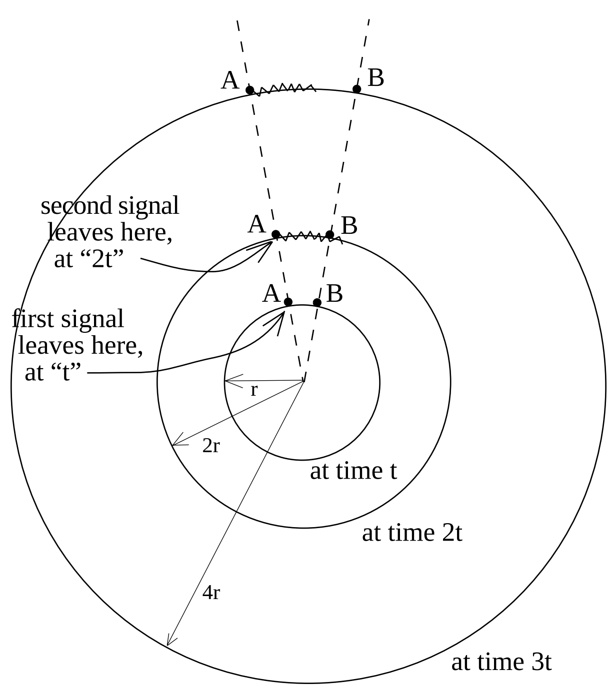
4.) So let's assume we have two stars, *star A* and *star B*. How can we explain *star B's* disappearing beyond *star A's* event horizon?

The best way to see what is happening is to take another look at our balloon universe.

5.) Assume our universe is, as far as we are concerned, the two dimensional surface of a balloon. Assume also that our balloon universe doubles its size every *t* seconds.

On the balloon sit two ants, one at *point A* and the other at *point B*. Assume the ants communicate with one another by sending messenger ants between them, and assume there is an absolute speed limit that no messenger ant can exceed.

a.) At time *t*, the balloon's surface is as shown as the inner circle on the sketch. *Ant A* sends a messenger ant toward *ant B*. By the time *t* seconds have passed (i.e., at time *2t*), the balloon has doubled its size. Traveling at maximum speed, the messenger ant reaches the distance shown (we will call that *maximum distance* the messenger ant's *event horizon*). As that distance is beyond *ant B*, *ant A* concludes that *ant B* is reachable and, in fact, exists.



b.) At time *2t*, the balloon's surface is shown as the second circle from the center on the sketch. *Ant A* sends another messenger ant toward *ant B*. By the time *t* seconds have passed (i.e., at time *3t*), the balloon has doubled its size again. Traveling at maximum speed, the messenger ant reaches the distance shown (again, its event horizon). As that distance does *not* reach *ant B*, *ant A* concludes that *ant B* is unreachable and, as a consequence, is not sure whether *ant B* still exists or not.

c.) Between time *2t* and *3t*, a student of *ant A* reviews what is happening and says, "What the hell! *Ant B* went from being reachable to being unreachable, which means *ant B* must have been moving faster than a messenger ant can go. But I thought nothing could go faster than the speed limit. What's going on?"

d.) *Ant B* appears to be moving to *ant A*, but in fact *ant B* is *stationary* and not moving relative to the balloon at all. What's actually moving? It's the geometry of the balloon. It is expanding, carrying *ant B* and *ant A* apart in the process.

Evidently, it is possible for a *point* on the expanding universe to be moving faster than the speed limit relative to a *distant* point (versus a *near* point in the lab).

e.) The law wasn't being broken. All it said was that if an ant passed you by as you sat in your local laboratory frame of reference, the ant couldn't be moving faster than the speed limit. That wasn't violated. If *ant A* measured the speed of a passing messenger ant, *ant A* would have found that speed to be below or equal to the speed limit. And if *ant B* did a similar thing in *his* laboratory, he would have observed the same.

f.) The crux of all of this is that space can expand faster than the speed of light, and if there are objects sitting still in space, so be it.

6.) So taking our analogy back to our universe, the messenger ant was the event horizon. *Ant A* was us. *Ant B* was some celestial object that was initially inside our event horizon but that passed beyond our event horizon at some point in time.

7.) So for the record, what *did* Einstein say about the speed of light?

a.) Relativity says that if you set up an experiment in which you measure the speed of any object that passes through your local frame of reference, you will never measure the speed of that object to be *equal to* or *greater than* the speed of light.

b.) Relativity also says that if you set up an experiment in which you measure the speed of an information carrying signal that passes through your local frame of reference, you will never measure the speed of that signal to be *greater than* the speed of light.

c.) Einstein says nothing, at least not at the level we are talking, about what you are going to see if you look at an object located outside our local frame of reference . . . which is to say, *across the expanse of the universe.*

8.) Finally, for the amusement of it, let's say inflation *is* happening and you are looking at the light from some object that is billions of light years away. If it passes through and beyond our event horizon, what will we observe from your frame of reference?

a.) As the object approaches our event horizon, we will observe the object's "red shift" (we'll talk more about what this is later) getting larger and larger. This will tell us that the object's velocity, relative to us, is getting closer and closer to the speed of light (remember, just as was the case with the ants on the expanding balloon, *space* can be separating *faster* than the limiting speed, which in our case is the speed of light).

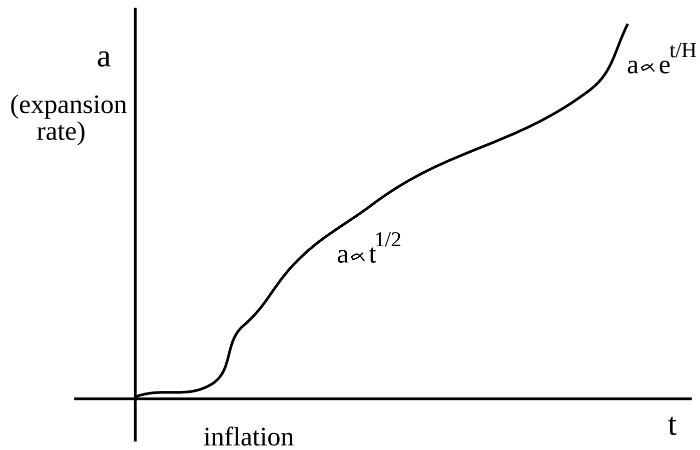
b.) As the red shifting gets larger, the object will get dimmer.

c.) And just as the object passes through the event horizon--a point at which its velocity would *be* the speed of light--it will completely disappear and we will *never see it move faster than the speed of light* . . . the consequence of which is that Einstein does not need to roll over in his grave.

9.) Bottom line: The paradox is eliminated if you remember that the statement *nothing can go faster than the speed of light* should read *no object or signal can <u>pass you</u> <u>by</u> moving faster than the speed of light*. That, and the fact that you are looking at the motion of objects as they exist *in an expanding universe*, not as they exist in a stationary universe.

G.) Cosmic Expansion:

1.) It turns out that all that is needed to identify the expansion of the universe is what is called *the expansion factor*, symbolized as an *a*. This factor has not been a constant in time. The rough graph shown presents how this factor has varied.



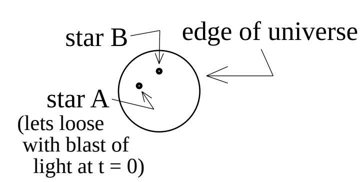
2.) What is interesting is that the sudden spurt--it's called *inflation*--at the end, the one that is proportional to $e^{t/H}$, suggests that within 20 billion years we will no longer *see light from galaxies outside our own* (this, ignoring the fact that we will all be dead by that point in time, anyway). This rather bizarre bit of amusement is explained as follows.

a.) Think of the expanding universe as a balloon that is being blown up bigger and bigger. Assume also that there exists on the balloon two light producing points.

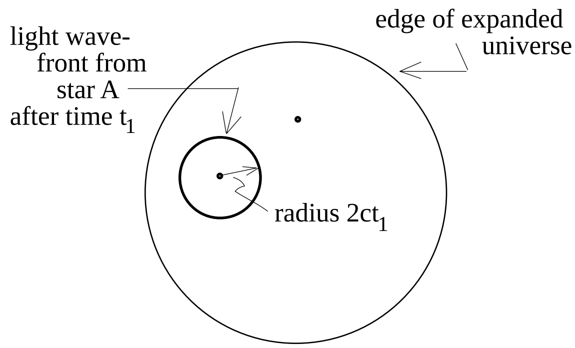
i.) For the sake of argument, we will assume these are stars that have at least one inhabitable planet orbiting them. Remember though, the only place light can go is *on the surface of the balloon.*

b.) *Star A* lets loose with a blast of light at $t = 0$ (this could be at the Big Bang or later--it doesn't matter for what we are doing).

c.) We wait for a time t_1. During that time, the light's wave front travels to the point shown in the second sketch.



d.) If the universe was *not* expanding, the radius of the light's wave front, called the radius of the *event horizon*, would be *ct*. It turns out that that isn't the case.



if you aren't inside the radius $2ct_1$, you won't register the presence of star A

Note 1: This *ct* expression came from the old *distance* equals *speed* times *time* formula, where the speed part in this case is the speed of the light *c*.

Note 2: The real universe is, at the very least, three dimensional, so really, light propagates out from a point source spherically. On our two-dimensional balloon surface, light propagates out as a circle.

e.) In any case, the radius isn't *ct*. The problem is that the universe is expanding. Taking that into account, it turns out that the radius of the light's wave front will be *2ct*.

f.) If you are on the planet orbiting *star B*, will you see the light from *star A* at time t_1? No! The light from that star will not have reached you yet, so as far as you are concerned, that star doesn't exist.

i.) In fact, the only planets that will register the existence of *star A* will be those that reside *inside the light circle* (i.e., inside the *event horizon*).

g.) Will the light from *star A* ever reach you?

i.) It will if the radius of the event horizon is growing faster than the expansion of the universe.

h.) And is that the case?

i.) For most of the age of the universe, that has been the case.

ii.) How so? If you look back on the expansion factor graph, a major portion of the expansion has been proportional to $t^{1/2}$.

iii.) With the radius of the event horizon being *2ct*, the light circle is expanding faster than the universe (think about it, *2ct* grows faster than $t^{1/2}$) and the planet orbiting *star B* will, sooner or later, see the light from *star A*.

i.) Put a little differently, if we ignore the upturn that seems to exist at the end of the *expansion factor* graph, the amount of stuff *that we can see* in the universe should be growing as time proceeds even though there is probably still stuff *outside* that area we *can't* see.

j.) So assume you are looking at light that was emitted just after the Big Bang. At any given point in time t_2 after the Big Bang, there will be two radii of interest.

i.) The first is the event horizon radius. This identifies the distance light has traveled during the course of the universe's existence up to t_2. It also identifies what we would have been able to see of the universe *at that point in time*--at t_2. Remember, we can only see the stuff that is *inside* the event horizon.

ii.) The second is the radius of the stuff in the universe that we *can see now* but couldn't see then. This tells us how big the universe we see now was when the time was t_2.

k.) What is bizarre is that recent evidence suggests that the expansion rate has somehow increased as $e^{t/H}$. The radius of the event horizon is still growing at a rate of *2ct*, but now the stars are moving away from one another in consonance with the expansion of the universe as $e^{t/H}$.

i.) In other words, the universe is running away from the event horizon and we will *never see star B* if we haven't seen it yet.

ii.) Also, stars we *can* see now will cease with time to be evident.

3.) What keeps a rotating galaxy from flying apart is gravity. We have observed galaxies that are rotating way too fast to stay together, yet they do. We think this is due to what is called *dark matter*. In fact, it is estimated that 4% of the universe is made up of stuff we know about (i.e., protons, etc.), 23% is made up of *dark matter*, and 72% is made up of *dark energy*. For *inflation* to happen, *and it has been observed to be happening right now*, there must be something accelerating the universe outward. We believe this has to do with dark energy.

a.) As a clarification, normal radiation pressure burns energy as it does work to make the universe expand. In that case, the universe's energy goes down. What's more, as you lose energy, the expansion slows down.

b.) *If* the expansion of the universe is speeding up, and it seems to be doing that, you need something that has a *negative* radiation pressure that puts energy *into* the universe as it expands. This something is believed to be what physicists have called *dark energy*.

c.) Dark matter acts like regular matter. We just don't know what it is.

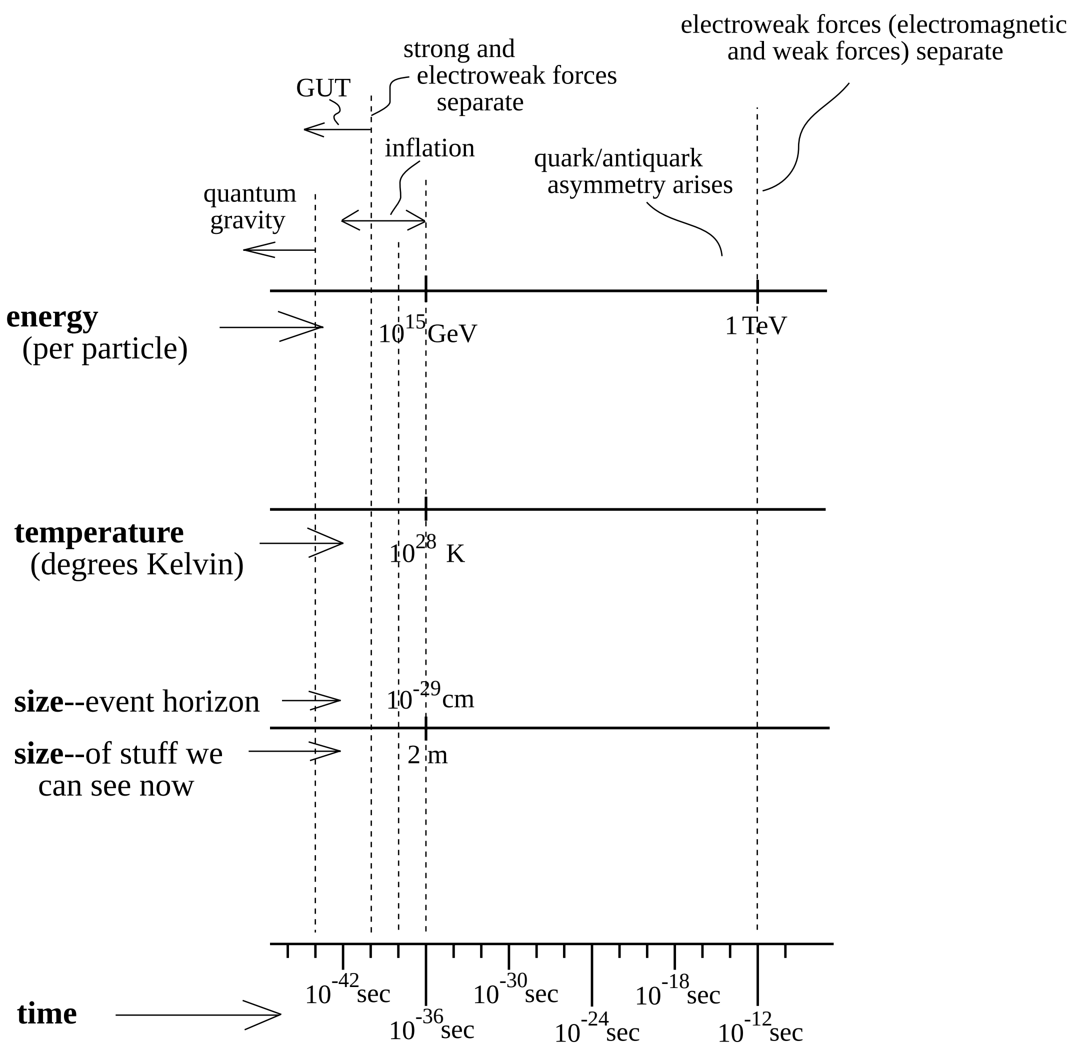
H.) So What Happened *In the Beginning*?

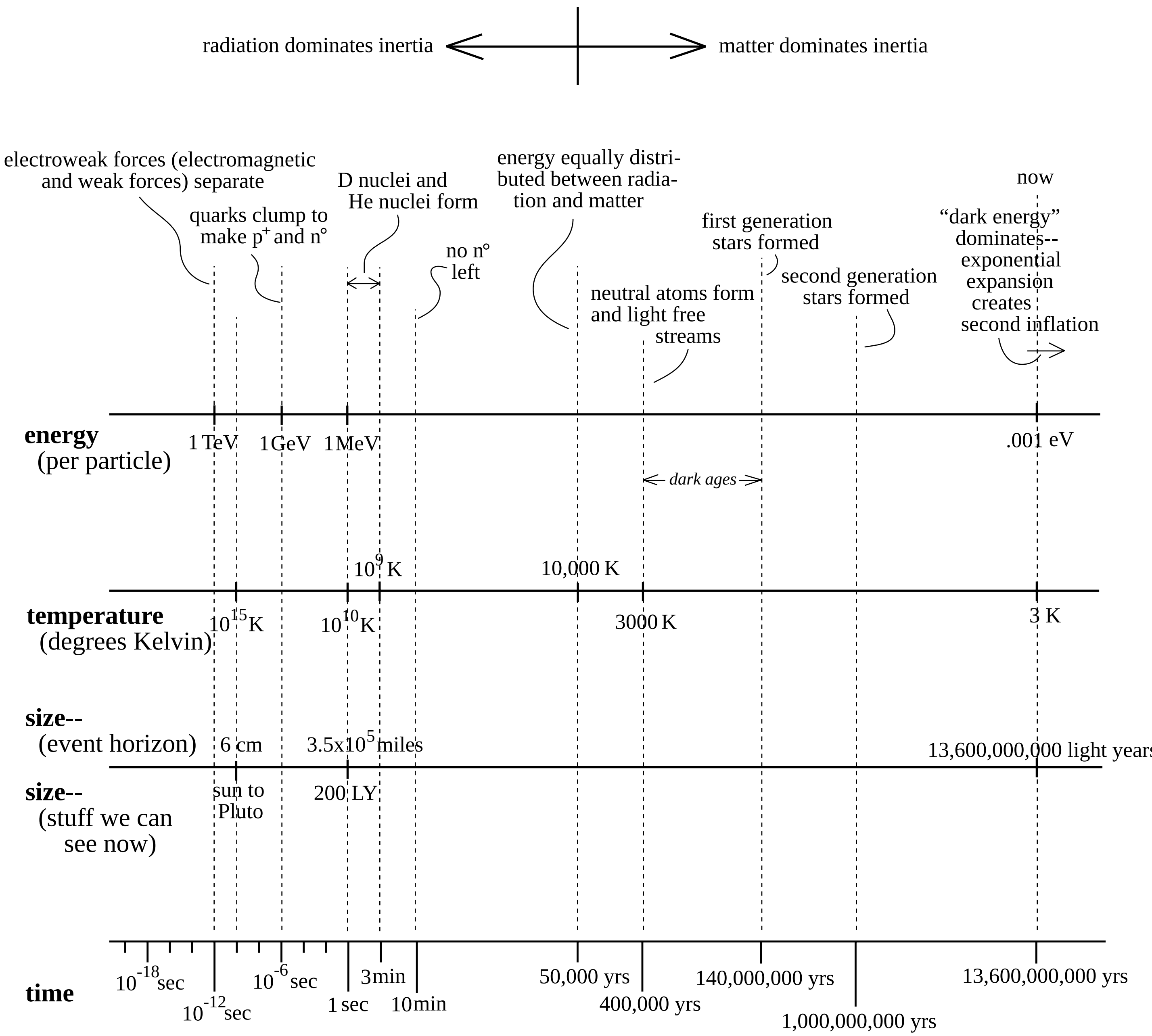
1.) To begin with, up to around 10^{-43} seconds after the Big Bang, the universe was governed by what are called *quantum gravitational effects*. Quantum Mechanics ruled, but Relativity was there, also. We have not yet been able to meld these two models into one coherent theory, so we have not been able to extrapolate in a theoretical sense back beyond the 10^{-43} second point. This cut-off point is called the *Planck time*.

2.) After 10^{-43} seconds, we have some idea as to what happened as we are really dealing with a high energy, high pressure gas, which is an area of physics we know something about.

3.) From the 10^{-43} second point on, there was a wild melange of energy and particle mixing and unmixing as the stuff of what would become the physical universe spewed out. Within a very short period of time, all of the building blocks of the physical universe "froze out" into place, and the laws that govern this universe were set in stone.

4.) What was the deal with distances and temperatures in the early universe? It is all summarized on the two charts provided below. The second chart summarizes what we know in the energy and temperature ranges we currently can generate with our best particle accelerators. The first chart is pure theory as we cannot yet duplicate that energy and temperature range. Look at the chart (we will go over it in class).





radiation dominates inertia
matter dominates inertia
electroweak forces (electromagnetic and weak forces) separate
quarks clump to make p^+ and n°
D nuclei and He nuclei form
no n° left
energy equally distributed between radiation and matter
neutral atoms form and light free streams
first generation stars formed
second generation stars formed
now
"dark energy" dominates-- exponential expansion creates second inflation
energy (per particle)
1 TeV
1 GeV
1 MeV
.001 eV
dark ages
temperature (degrees Kelvin)
10^{15} K
10^{10} K
10^9 K
10,000 K
3000 K
3 K
size-- (event horizon)
6 cm
$3.5x10^5$ miles
13,600,000,000 light years
size-- (stuff we can see now)
sun to Pluto
200 LY
time
10^{-18} sec
10^{-12} sec
10^{-6} sec
1 sec
3 min
10 min
50,000 yrs
400,000 yrs
140,000,000 yrs
1,000,000,000 yrs
13,600,000,000 yrs

I.) Star Formation:

1.) Stars are formed due to the wholesale, gravitational collapsing of huge quantities of stellar gas.

a.) As the gases collapsed inward, temperatures at the core skyrocketed. At 10,000,000 degrees Kelvin, hydrogen fusion "ignited" and the protostar becomes a full fledged star.

b.) As the fusion process proceeds, the star begins to produce helium and enormous amounts of radiated energy via $E = mc^2$.

2.) First generation stars, which were completely hydrogen and helium in content, first came into existence sometime around 140,000,000 years after the Big Bang.

a.) Interestingly, their presence heated the universe enough to ionize it (i.e., atoms lost electrons). It also heated the gas enough to allow its pressure to hold up against gravity for awhile. It wasn't until expansion cooled the gas that gravity was able to re-establish its dominance and additional star and star clusters again began to form.

b.) The universe finally expanded and cooled enough to allow for the re-recombination of atomic ions into neutral atoms. When that happened around 10^9 years after the Big Bang, hydrogen and helium atoms again gravitationally collapsed into huge, massive balls. And when temperatures and pressures got large enough at the core of these structures, fusion ignited and second generation stars came into existence.

3.) When second generation stars came into existence, the universe was big enough so that no ionizing took place (except, possibly, locally), so from there on star production continued unrestricted.

4.) When these second generation stars died, they produced all of the elements heavier than iron (we'll talk about what happens in stellar evolution later) and the stuff that would make up third generation stars.

a.) Our sun is a third generation star that formed 5 billion years ago when the universe was around 8 billion years old.

b.) When third generation stars are formed, it is possible that small volumes of material coalesce but don't become a part of the central mass. These small structures aren't heavy enough to gravitationally squeeze their centers to high enough pressures and temperatures to ignite nuclear fusion, but they can solidify into massive bodies. We call these structures *planets*. (In fact, planets are not very important in a stellar sense . . . except to us.)

J.) Stellar Evolution:

1.) So let's say a star is born and begins to live its life. What happens as its life proceeds?

a.) The fusion process at the star's core converts hydrogen into helium liberating enormous amounts of energy in the process.

i.) In other words, as the star lives, its hydrogen content goes down as its helium content goes up.

ii.) Remember, our sun converts 657,000,000 tons of hydrogen into 653,000,000 tons of helium every second, converting 4,000,000 tons of matter into pure energy via $E = mc^2$ in the process.

b.) There are, therefore, two forces acting in a star. Gravity is trying to collapse it in, and the energy from the fusion process is trying to push it out. In short, the star finds itself in a state of relative equilibrium.

c.) At some point, the star will begin to run out of hydrogen fuel. When that happens, the fusion process begins to slow, the outward pressure begins to diminish, and gravity begins to compress the star even more than it already has.

d.) As the star compresses, compressive heating happens. If the star is large enough, the core temperature will reach 100,000,000 degrees Kelvin due to this compressive heating and *helium* fusion will start.

e.) This is where things get a little weird. At this stage, one would think that helium and hydrogen would fuse to make things like lithium and beryllium and boron, etc., but that's not what happens.

i.) If a hydrogen and helium were to fuse together, they would produce ^{5}Li (this is lithium with five nucleons--three protons and two neutrons). The problem is that the half life for ^{5}Li is 10^{-21} seconds. In other words, as soon as an ^{5}Li is made, it falls apart. In fact, it takes a couple of extra neutrons to make the stable form of lithium, ^{7}Li, which is an atom that is very rare and that was formed only during the Big Bang.

ii.) A similar problem exists when two helium atoms (i.e., two protons and two neutrons each) combine to make ^{8}Be (this is beryllium with eight nucleons--four protons and four neutrons). The half life of ^{8}Be is 10^{-16} seconds. (The stable form of beryllium is ^{9}Be with one more neutron than ^{8}Be.)

iii.) To get boron (^{9}B) with five protons and four neutrons, you would have to have two helium (^{4}He each) fuse to make one very unstable beryllium ^{8}Be, then immediately have one hydrogen ^{1}H fuse with that beryllium before it decays into something else. Though there is very little ^{8}Be around due to its instability, that reaction could happen. The problem is that the end result--^{9}B--is unstable itself. (The stable forms of boron are ^{10}B and ^{11}B.)

f.) So where do stable beryllium and boron come from? It all has to do with carbon.

g.) To produce carbon through fusion, you have to have three helium atoms fuse almost simultaneously. That is, two have to fuse to make ^{8}Be, then within 10^{-16} seconds a third helium has to collide with the otherwise short-lived beryllium to make ^{16}C. What makes this different from the *two helium and one hydrogen* fusion that produced ^{9}B is that ^{16}C is stable. And, in fact, this is the way carbon is produced at the core of a star.

h.) So where do stable beryllium and boron come from (am I repeating myself)?

i.) When stars die, big ones literally blow up in what is called a supernova (we'll talk about this shortly). As the star supernovas, star stuff and a shock wave move outward from the exploded star at around 10,000 kilometers per second. As the shock wave passes through the interstellar material filling the space around the recently deceased star, it heats that material up enormously.

ii.) So let's assume it is a 20 solar mass star that blows. There will be approximately *10^6 protons per cubic meter* in the interstellar material (this is about one atom per cubic centimeter), so the wave will travel somewhere around 6 parsecs over a 600 year period before it starts to slow down. (At this point, it will have swept up 20 solar masses of interstellar matter, doubling the mass it is pushing.) As it expands, it slows down more and more until, after approximately a million years, it finally slows to the speed of sound in the interstellar medium.

iii.) During this period, protons in the interstellar material outside the shock wave will be spiraling along magnetic fields in space, as usual. When these protons run into the shock wave, they will bounce off irregularities in the magnetic field that are produced by the existence of the shock wave.

iv.) As protons reverse their direction, they also pick up speed. (This is a lot like a slow moving tennis ball being slammed by a tennis racket. The racket not only reverses the direction of the ball, it also speeds it up.) They then slam into other irregularities in the magnetic field, reversing direction again and again and again, picking up more and more speed as they go.

v.) This happens continuously over the million years it takes the shock wave to slow down to the speed of sound in the interstellar medium. By that time, the protons have been accelerated to relativistic speeds.

vi.) If one of these high energy protons (they are called *cosmic rays*, though that is misleading because they aren't rays at all) strikes a stable carbon atom, it just might knock one or two protons and, maybe, a few neutrons out of the carbon's nucleus (this is called *spallation*--fast moving objects knocking a little bit of stuff out of something).

vii.) If *one* proton is ejected, you end up with an atom that has *five* protons total. This is a *boron* atom. If *two* protons are ejected, you end up with a *beryllium* atom.

viii.) In other words, stable beryllium and boron atoms come from carbon atoms that have been split due to high energy collision during supernova.

i.) At some point, the star will begin to run out of helium, the fusion process will slow, contraction will produce non-nuclear heating, and if the star is big enough, fusion of the next *most populous element* will begin.

j.) This process can continue over and over again until the star's core is iron (Fe). Elements above iron do not give off energy when created through fusion, so no star will ever go that route (in trying, they would extinguish themselves).

2.) Observation: What this means is that all of the elements between carbon and iron in our universe were made via fusion at the core of a second generation star.

3.) As a minor side point, radioactive carbon dating is based on a similar idea--atoms being hit by cosmic rays, then changing into something else. Specifically:

a.) High energy protons (i.e., a cosmic ray) hit ^{14}C atoms making them decay into ^{13}C. Because this process happens continuously, the ratio of ^{14}C to ^{13}C in the atmosphere is constant and known.

b.) Plants and animals take in carbon of all types throughout their life cycle. When a plant or animal dies, this stops and the ratio of ^{14}C to ^{13}C in the body is fixed at the ratio that exists in the atmosphere.

c.) ^{13}C is an unstable isotope of carbon. It has a half life of 5730 years. What this means is that after the plant or animal has died, ^{13}C begins to diminish in the physical structure.

d.) By measuring the ratio of ^{14}C to ^{13}C in a tissue or bone sample, scientists can work backwards to determine when the ratio was that of the atmosphere. This gives us a way to date old, organic things.

K.) The Death of our Star:

1.) Let's assume the fusion process in a star whose core is less than 1.4 solar masses has gone as far as it can go. The core is predominantly iron and the fusion process is now dying down.

2.) Gravitation begins to take over and the star begins to collapse. As it does, the internal pressures get larger and larger. What stops the implosion is called *electron degeneracy pressures*.

a.) Electrons are odd creatures in that there can only be *one electron* occupying a particular *quantum state* within an atom.

b.) As the pressures at the core increase, atoms are crowded more and more together. What stops the crowding is the "unwillingness" of electrons to degenerate into shared quantum states. This halts the implosion.

3.) What we end up with in cases like this is what is called a *white dwarf*.

4.) Our sun will end up this way.

L.) Supernovae:

1.) Let's assume the fusion process in a star whose core is greater than 1.4 solar masses but less than 1.6 solar masses has gone as far as it can go. The core is predominantly iron and the fusion process is now dying down.

2.) Gravitation again begins to take over and the star begins to collapse. As it does, the internal pressures get larger and larger.

3.) Because the star's core is heavy, the electrons that are fighting quantum intrusion get so energetic that they go relativistic (i.e., their kinetic energy way exceeds their rest mass energy mc^2) and can't hold. That is, the electrons implode in toward their nuclei with energies greater than 1 MeV. When they reach the nucleus, they combine with protons to make neutrons.

4.) Once the nucleus has become solid neutrons, the neutrons fight their own quantum incursion. That is what stops the implosion.

5.) In the end, it is not uncommon to have a ball of neutrons that is 6 or 7 miles across and that has a mass density of 10^{15} gms/cm^3.

> **a.)** This means a tablespoon of neutron star, as measured on earth, would weigh around *two and a half trillion* pounds (that's 2,500,000,000,000).

6.) As long as the core is not over 1.6 solar masses, the *quantum* repulsion of the neutrons can counter gravity and the structure will hold.

7.) It is not uncommon for a 1.4 to 1.6 solar mass core to be at the center of a 15 to 20 solar mass star. When such a star dies, what happens to all of its outer shell mass?

> **a.)** Until the collapse, the outside shell has been held up by the energy provided by the fusion process at the center. When the core collapses, that energy is no more and the shell begins to collapse.
>
> **b.)** As the core collapses, though, there is lots of gravitational binding energy given off. It is not uncommon for the star to release 100 times the amount of energy it has given off *over its entire life* in, maybe, 10 seconds.
>
> **c.)** If even 1% of that energy is coupled with the in-falling envelope, there will be enough energy to completely blow the envelope out.
>
> **d.)** When this happens, we have what is called a *supernova.*

8.) It is during a supernova that nature provides the energies needed for all of the heavier elements to be fused (remember, all elements heavier than Iron need to *take in* energy when they fuse).

9.) IN OTHER WORDS, with the exception of hydrogen and helium (and lithium, beryllium and boron), all of the atoms in our universe came from stars.

a.) The lighter atoms--atoms from carbon to iron--came as a consequence of fusion at the core of living stars.

b.) The heavier atoms--atoms from iron to uranium--came when stars blew as supernovae. (Elements heavier than uranium may have formed, but they decayed too quickly to stay around naturally in the world.)

c.) Put a little differently, the atoms that make up you and your friends and the gold in your fillings and pretty much everything that physically exists around you, it is almost all *star stuff*.

10.) As a minor side note, there are different "types" of supernovae.

a.) Some large stars in binary systems do not have hydrogen in their outer shell because it has been stolen by a white dwarf partner. When they blow, they are called Type Ib supernovae.

b.) A Type II supernova is one in which the outer shell still has hydrogen.

c.) If a binary system is made up of a white dwarf and a larger star (maybe a red supergiant), the white dwarf will suck material from the other star's envelope (this is called *accreting*). In doing so, it will increase its mass.

i.) If the mass of the white dwarf reaches 1.4 solar masses, it will begin to collapse.

ii.) It is not uncommon for the white dwarf to *not* be made up of iron but, rather, to be made up of elements like neon or oxygen.

iii.) As the collapse happens, there is energy to fuse these elements to make still larger elements like nickel and iron, and there is enough energy to blow the star in a supernova. This kind of supernova is known as a *Type Ia* (no hydrogen involved like a *Type Ib*, but due to an exploding white dwarf, not due to the exploding of the core of a massive star).

M.) Elementary Forces in General:

1.) All of the elementary forces were set in stone at the Big Bang. It is believed that there were one or two primary forces that existed first, and that as the temperatures and energies of the universe diminished, those forces splintered into the forces we know about in today's world.

2.) The forces that exist today are the gravitational force, the electromagnetic force, the strong force and the weak force.

N.) Precision:

1.) We will finish with another quote from Davies from *The Accidental Universe*.

> "The numerical values that nature has assigned to fundamental constants, constants such as the charge on an electron, the mass of a proton, the speed of light, the Newtonian gravitational constant, etc., may be mysterious, but they are crucially relevant to the structure of the universe that we perceive. As more and more physical systems, from nuclei to galaxies, have become better understood, scientists have begun to realize that many characteristics of these systems are remarkably sensitive to the precise values of the fundamental constants.
>
> More intriguing still, certain crucial structures, such as solar-type stars, depend for their characteristic features on wildly improbable numerical accidents that combine together fundamental constants from distinct branches of physics.
>
> Recent discoveries about the primeval cosmos oblige us to accept that the expanding universe has been set up in its motion with a cooperation of astonishing precision."

2.) Please note that the optimal phrases in this eloquent commentary are wildly improbable numerical accidents and cooperation of astonishing precision.

a.) Translation: Your universe is a marvel. Appreciate it as such!

O.) Forward to Next Series of Chapters:

1.) What we have been doing over the last two chapters has been very much in the vein of *physics for poets*. We have, in a qualitative sense, focused on the observations and conclusions physicists have made about the physical world as they have attempted to mathematically model that world.

2.) It is time for us to step away from this *off the wall*, speculative side of physics and begin to look at the models themselves.

3.) For those of you who lament this, don't despair. We will, mid-year, get wild and crazy once again and look at the mother of all wildness, Einstein's Theory of Relativity. In any case, it's time to put on your analytical thinking caps. We are about to begin what every "normal" Honors Physics class in the country is doing . . . and you *vill* (sic) enjoy it!

QUESTIONS & PROBLEMS

Note: Although it might be possible to tease a few math problems out of the reading, I'm not going to do that. What I am going to do is similar to what I did in the last chapter--list a series of *very specific* questions you could be asked on your test (I'm being specific because there is an enormous amount of information on those two time-lines--you only have to remember particular bits of each). As these are more research questions than anything else (all the answers *are* all found in the chapter), you will not find solutions at the end of the book.

2.1) Our best nuclear accelerators can accelerate subatomic particles up to what maximum energy (per particle)? This corresponds to the energy (per particle) in the universe at what point in time after the Big Bang?

2.2) According to physics, what was there *in the beginning*?

2.3) What is antimatter?

2.4) What is *pair production*? If you wanted to produce an electron and positron, what kind of energy or radiation would you need to do the job?

2.5) What is *annihilation*? What do you get when two particles annihilate each other?

2.6) Why can *pair production* and *annihilation* happen? That is, what is it about the universe that allows both to exist? How did Einstein quantify this idea (i.e., what's the only equation you know that came from him . . . and be sure you know what the variables in the equation mean!)?

2.7) How is momentum defined?

2.8) What does Heisenberg's Uncertainty Principle state concerning momentum measurements and position measurements? (Write out the relationship, but also be able to explain it.)

2.9) What does Heisenberg's Uncertainty Principle state concerning energy measurements and time measurements? (Write out the relationship, but also be able to explain it.)

2.10) Why is the time/energy version of Heisenberg's Uncertainty Principle important to the Big Bang?

2.11) What are the symbols and units for frequency and wavelength?

2.12) What is the relationship between a wave's wavelength, frequency, and wave velocity? (Be able to write out the equation and know what the parameters stand for.)

2.13) What is a photon?

2.14) What is the relationship between the energy E of a bundle of energy associated with, say, blue light, and the frequency of that light?

2.15) What is an electron-volt?

2.16) How much kinetic energy (in eV's) do air molecules have at "room temperature?"

2.17) What does temperature measure?

2.18) What does *keV* stand for? What does *MeV* stand for? What does *GeV* stand for? What does *TeV* stand for?

2.19) Is it possible for the universe to expand faster than the speed of light?

2.20) How often, according to theory, has cosmic "inflation" occurred? When were those occurrences? What was its consequence the first time it happened? What was its consequence the last time it happened?

2.21) What is the difference between the *event horizon* and the *stuff we can see now*?

2.22) What is the Planck time, and what is its significance?

2.23) From the first chart:

a.) At what time and particle energy did the electromagnetic and weak forces separate? Would physicists claim that this is speculation or fact?

b.) How big were the *event horizon* and the *stuff we can see now* at 10^{-36} seconds?

2.24) From the second chart:

a.) At what time and energy did quarks clump to make protons and neutrons?

b.) During what period did deuterium and helium nuclei form? At the beginning of that period, what was the size of the *event horizon* and what was the size of *the stuff we can now see*?

c.) When did the universe run out of free neutrons? Why was this significant?

d.) How long after the Big Bang did radiation dominate over matter?

e.) At what temperature and time did the first neutral atoms form?

f.) At what time did the first stars form?

g.) What is the current *event horizon*?

2.25) What is the difference between a *first generation star* and a *second generation star*?

2.26) What did the second generation stars produce when they died?

2.27) What two forces act against one another in a normal, healthy star?

2.28) What happens when a star's fuel begins to deplete?

2.29) What kind of elements can be produced during the lifetime (but not death) of a very large star?

2.30) Beryllium is a relatively small atom. Was the Be that exists on earth today originally formed during the fusion process in a normal, healthy star? If not, why not? And if not, where did the Be that is around come from? Also, are there any other elements with a similar story?

2.31) What is the largest element a large, normal, healthy star can produce, assuming you don't include its death?

2.32) When our star dies, what will it turn into?

2.33) What is a neutron star? How big is it, how dense is it, what are its defining characteristics, and how is it produced?

2.34) From whence came the heavier elements (elements heavier than iron) in the universe?

2.35) There are two kinds of supernova. What are they and how are they different?

2.36) What are the four "elementary" forces?