COSMOLOGY TIME LINE

INTRO: This time line is intended to serve as a framework for a set of short descriptions of the various eras through which the universe passed in its evolution from a primordial, hot, dense fluid-like medium to the galaxy clusters and the mega-parsec scale voids and walls of clusters we observe today, 14 billion years later. It is thought that throughout this whole time the universe has been expanding, so we will incorporate the time-dependent expansion scale, a(t), which is set to one at the present and takes on progressively smaller values as one follows the time line into the past. The scale a(t) cannot be made absolute because we do not know the absolute size of the universe, either now or at any time in the past.

The “known” universe is the part of the universe we can directly detect through electromagnetic signals: radio, microwave, submillimeter, ir, optical, uv, xuv, x-ray, and gamma. And we should also include other known quantities that travel at the speed of light. These are relativistic (light) neutrinos and gravitational waves, and possibly other particles we have not yet discovered. As we use ever better instruments to gaze into and resolve weaker and more distant sources we look back into a progressively red shifted and time shifted universe with progressively more primordial conditions: early morphology in galactic structure and interaction, the increased role of quasars and supernovae, and smaller quantities of the heavier chemical species. But since signals get weaker as they propagate into the three dimensions of space, and their energy per quantum drops off with the expansion of space, there may be a limit to how far out in space (and back in time) our instruments can take us. At the present time in our technological history we are resolving galaxies which emitted their light 500 million years after the Big Bang. But there was a time before stars existed, and if we could see far enough into the red shifted past we might be able to resolve the earliest galactic condensations and their massive bright stars. But whereas people in the day of Columbus were afraid that distant travelers might drop off the edge of the world, today we are up against the event horizon. As our instruments approach it by gazing at progressively dimmer sources we start to drop off the edge of the spectrum. Beyond a certain distance space and whatever was in it is receding faster than the speed of light, or is sufficiently far off that its light has not yet reached us. This maximum distance from which we can retrieve signals is called the event horizon. Actually it is OUR event horizon since each far flung astronomer in the universe has his own. The cosmological principle claims that the structure of the universe, averaged over small details like planets, stars, galaxies, galactic clusters, and super clusters, is the same everywhere. In other words it is claimed to be NOT the case that, say one hundred event horizons away, the creatures there are seeing a whole different animal. This is an article of faith not inconsistent with the largest structure we can see.

Before stars and galaxies formed there were no objects to see, but there is detectable radiation coming to us, day and night, from all over the sky. This is relic radiation which dethermalized from its local electron temperature of 3,000 K, at t = 350,000 years after the Big Bang. After red shifting a factor of 1,000 its energy distribution is now a

Planckian in the microwave band. So, we seem to have a huge time gap in our observations: from the formation of the cosmic background radiation (CBR) at 350,000 years to our present observations of early galaxies at 500 million years. As our abilities progress other time windows may open up, especially prior to the CBR.

From detectable radiation together with the discovered facts of the present universe we can extrapolate back to conditions that do not remotely resemble those we live in today. But there are two important limitations to our knowledge: 1) We cannot detect any signal emitted beyond our event horizon, and 2) we cannot extrapolate back in time before the regime in which general relativity (GR) and quantum mechanics(QM), are simultaneously dominant (see below).

As described above, the earliest age from which light travels to us unhindered by scattering is that of the formation of atoms from hydrogen plasma at 350,000 years, when the temperature was 3,000 K. All previous eras must be theoretically constructed through the application of physical law and the known attributes of the present far-flung physical cosmos. In the future we may learn how to detect background neutrinos analogous to the above radiation, except streaming with information from an even earlier epoch. We may also succeed at the detection of gravitational waves, some of which may be primordial. Science will go on. The game isn't over.

As we move through the phases of the universe we must resist the temptation to visualize it as if from the outside, despite common 2-D models like the dotted skin of an expanding balloon. There is no outside, and if we are on the skin of an expanding balloon we are looking along the curved skin itself and getting signals form the receding dots around the curvature of the skin. It is hard to visualize the whole of a space from which we cannot escape, but that's what we must try to do because we are it.

In the headers below, time is in seconds, temperature is in degrees Kelvin (K), and energy, kT is in whatever units are presented. For reference, the mass-energy of the electron is about 512 KeV, and that of the proton is about 1 GeV.

TIME $5.4\ 10^{-44}$ TEMP $1.4\ 10^{32}$ kT $1.2\ 10^{19}$ GeV

The above time unit, sqrt($\hbar G/c^5$), is called the Planck time. It is the unique time scale derivable from the physical constants of quantum mechanics (h) and general relativity (c, G). It is the minimum meaningful time interval for any quantum gravity system. What significance does this fact have for cosmology? First, backward time extrapolation of the conditions of the early universe can be done through its various phases and physical regimes with their associated time intervals. As time ticks backward toward the Big Bang (or forward toward a hypothetical futuristic Big Crunch) densities and temperatures rise higher and higher. In a GR but NON- QM theory the backward tracking of time always leads to a singularity (infinite density and temperature) despite whatever asymmetries might be in the medium. This was proven by Penrose and Hawking, who employed a power branch of math rarely used in applied physics: algebraic topology. If we define the time of the singularity as t=0, what quantum gravity tells us, even though we understand very little about it, is that times shorter than 5.4 10^{-44} seconds from the singularity are not meaningful. In this regime time and space are quantized and highly chaotic. Therefore before this time there is no previous time, and there were no previous events. And, of course, in the beginning, there was no singularity, and maybe no beginning. An interesting discussion of these meta-problems is given at the end of a new book, Many Worlds in One, by Alex Valenkin.

From this primordial, hot and compressed regime, the universe, infinite or finite, is thought to enter a very brief period of superluminal inflation and rapid cooling, followed by billions of years of normal gravitational dynamics, then more billions of years of gradual inflation. During this evolution it passes through a series of distinct eras and phase changes which we summarize below. We shall refer to the primordial quantum-gravity state as the Initial State (IS).

TIME: 10^{-36} -10^{-34} TEMP: 10^{24} ENERGY: 10^{10} GeV

This time interval is only one of many proposed for the era of inflation, the first event after the IS. The modern hypothesis is that in the inflation era the universe underwent violent expansion due to the presence of a " false vacuum" condition of great energy and negative pressure. Of course the super dense early universe is anything but a vacuum. The term is used to describe the state of space itself, that it contained a scalar field Φ which decayed into the "true vacuum", the condition of space we live in today. In this tiny speck of time the universe expanded by dozens of orders of magnitude and to great multiples of the event horizons of all reference locations. This ultra-fast expansion is thought to "freeze in" the uniformity and small deviations from uniformity of the preceding universe by inflating the distance and thereby creating event horizons between these features such that they cannot interact and equilibrate.

We introduce a few mathematical quantities. From a(t) one may construct the Hubble parameter, $H = (da/dt) / a$, the ratio of expansion speed to size. This is an important variable because it can be studied with telescopes, and it has been found to be a constant as we gaze out to greater and greater distances from our galaxy. The classical equation used by cosmologists, the Friedmann equation, is a statement of energy conservation in a fluid in which total energy density is assumed to be ρc^2. The left side is H^2 and the right side has a "curvature term" and a "pressure term" which fall off as the universe expands, forcing H to zero as a(t) grows asymptotically large. This equation was developed well before the concept of inflation was invented. To accommodate inflation the Friedmann equation is given an extra term on its right-hand-side, a "constant" term, Λ, called the "cosmological constant". If Λ is arbitrarily inserted into the right-hand-side of the Friedmann equation with a large value at, say, $t = 10^{-36}$ sec. then the equation predicts inflation, the exponential expansion of a(t). If Λ is removed at, say, 10^{-34} sec., then the inflation stops there, and other terms in the equation take over. If the value given to Λ is large enough then the universe will inflate through whatever number of doubling is necessary to fit the data.

Why do we think inflation occurred? What is this data we have to fit? There are three bothersome inconsistencies in the Big Bang theory that are resolved if inflation is postulated. Without it we cannot explain the observed lack of curvature in the known universe, nor the near isotropy of the cosmic background radiation. Without a huge expansion and dilution of material we also have a hard time explaining the apparent absence of certain relic, non-relativistic (i.e. massive) particles that, according to physical theory, should have been created at the earliest moments.

Secondly, it is not without physical basis in the standard theory of elementary particles, and thirdly, we observe that a very weak version of inflation has been going on for the last five billion years, meaning that this is something the universe does, and may have been doing shortly after the IS in a much more violent way.

The cosmological constant implies that empty space itself has negative pressure and a certain positive energy density, in addition to whatever energy density may exist in the form of matter, dark matter, or radiation. A mathematical implication is that the net energy of any initial cell of volume grows proportionate to the volume, appearing to violate conservation of energy. But conservation of energy is saved because, in the theory, the “false vacuum” energy turns into matter and radiation as the false vacuum decays into the “true” vacuum we live in today, and radiation and matter in space have a negative gravitational potential energy which cancels or tends to cancel the positive ρc^2 energy of the newly created material. So, the **cosmic frog** of Greene and Erenfest can have its cake (beautiful physical symmetries like energy conservation) and eat it too (swim around in a pond of locally positive energy).

QM demands that random fluctuations in local energy density must occur during the decay of the false vacuum. The features of these random patterns superimposed on spatial energy density are decoupled from each other by inflationary expansion of space, and, later in cosmic time, transmitted into matter. Acting as gravitational perturbations, these energy patterns initiate runaway gravitational condensations which become the clusters of galaxies we observe today.

Linde, Valenkin, and others have argued that the expanding false vacuum will give rise not to one but to many expanding bubbles of true vacuum. Each will be a whole “universe” with its own initial perturbations and corresponding structural details. They will form and grow endlessly as the false vacuum expands forever. This raises the logical but un-testable possibility of an infinite number of universes, each expanding infinitely. For the remainder of this summary we will concentrate only on this universe since we have no observations into the others.

TIME :10^{-43} -10^{-10} TEMP: 10^{28} - 10^{15} ENERGY: 10^{15} – 100 GeV

In some modern theories of particle physics all the forces of nature are predicted to merge into one force field with one interaction strength as conditions approach those of the earliest instants. Gravitation would have been the first to peel away from this unified field, leaving the other forces unified over a certain predictable era called the era of Grand Unification. We know that this era ended at t= 10^{-10} sec.

One reads of “broken symmetry” and how the universe lost its symmetry. Are the interaction strengths different today than they were in the early universe? No. The difference is that in those super hot conditions photons, quarks, electrons, neutrinos, etc. were colliding with more kinetic energy and thereby sampling their force fields at distances closer to their bare point-like “charges. The strength and character of these fields near “bare” charges is quite different from what they are at larger distances.

In more detail, gravitation and electroweak forces get stronger as collision impact parameters decrease, but the strong force gets weaker. The shielding around an electroweak charge is due to opposite charges on a cloud of virtual anti-particles attracted to the central charge, thereby weakening its effect. In the case of the strong force the massless boson force carriers (gluons) carry the quantum chromodynamic (QCD) “color charges” back and forth between quarks. They thereby act as centers of force in themselves, which gives rise to a very complicated field around a quark which increases in strength as distance from the quark increases. This is why we cannot use a high energy particle at Fermilab to knock a quark out of a proton. The relative weakness of the color force near the bare color charges is known as “asymptotic freedom”. The color field is especially complicated because there are eight different types of gluons and anti-gluons, displaying the symmetries of group theory. In the close collisions of the early universe anti-shielding makes the strong force weaker, and shielding makes the electroweak and gravitational forces stronger. Supersymmetric theories of particle interactions predict that all four forces will approach the same strength, and act as parts of the same field, as collisional impact parameters approach zero. Thus, the earliest universe may have been acting under the unified field we desire to comprehend.

TIME :10^{-10} -10^{-4} TEMP : 10^{15} - 10^{12} ENERGY : 100GeV – 100 MeV

The Grand Unification symmetry breaks up when kT falls to the mass-energy (90 GeV) of the electroweak force carriers, the $W^{\pm}$ and Z bosons. As cooling continues the strengths of strong and electroweak interactions diverge for the reasons given above. All known quanta remain unbound in this era. Therefore all material constituents are elementary and there is no formation or decay of compound entities.

TIME :10^{-4} -1 TEMP: 10^{12} - 10^{10} ENERGY: 100 GeV – 1 GeV

The start of this era is the quark-hadron phase transition. Quarks start to compound into the two types of hadrons: mesons (2 quarks) and baryons (3 quarks). Each meson consists of a quark and an anti-quark. For example, charmonium, the J / PSI particle, consists of the charm quark together with its own anti-quark, the anti-charm quark. The baryons include the neutron and proton, and a large “zoo” of unstable particles made from trios of the six quarks and anti-quarks . The typical strong force decay time is about 10^{-23} sec., so these zoo particles do not last the duration of the era. Rather, they are in a state of equilibrium of creation and decay.

As of the year 2007, the greatest collision energy created at CERN and Fermilab is 2 TeV. The most massive particles created in these collision have considerably less energy than 2 TeV because the energy of colliding quarks in two colliding protons is only a fraction of the total energy of the collision, and any one particle produced may have only a fraction of the quark-quark collision energy. Thus the largest accelerators have not created particles more massive than the weak force carriers, the $W^{\pm}$ and Z bosons, at about 90 GeV, and the top quark at 174 GeV.

In the middle of this era is the log mean time 10^{-2} seconds. At this age nearly all the protons have annihilated against the anti-protons, leaving a small but highly important trace abundance of protons, which are the basis of the universe of ordinary matter (as opposed to anti-matter) we live in today. It takes about 2 GeV to create a proton + anti-proton pair from a pair of gammas with 1 GeV each. When there are enough high energy gammas left in the tail of their energy distribution the pair production and pair annihilation processes are in equilibrium, but when the gammas with $h\nu > 1$ GeV become sufficiently sparse, due to the combination of redshifting and volume expansion, only annihilation continues to operate. As the scale size a(t) of the universe increases the photon number density drops off as $1/a^3$, and the mean photon energy drops off as 1/a, so the radiation energy density (mostly gamma) drops off as $1/a^4$. So, pair production ceases to compete with pair annihilation when kT has dropped somewhat below 1 GeV. At the end of this era there are about a billion photons, electrons, positrons, gammas, neutrinos, or anti-neutrinos for every proton. If physical law had perfect symmetry there would be no protons left over, and no universe as we know it. We owe our existence to a one-part-in-a-billion asymmetry.

TIME :1 - 10 TEMP: 10^{10} - 10^{9} ENERGY < 1 MeV

After temperatures fall through the 1 MeV point the decoupling of electron neutrinos, ν_e occurs. The electron neutrino scattering rate has cross-section $\sigma = G_f \rho^2$, where $\rho \sim 1/a^4$ for relativistic neutrinos. As the universe expands, the rate of scattering clearly drops steeply. When the mean time of scattering surpasses the doubling time of the universe, H^{-1}, the neutrinos are no longer coupled to their local conditions, and are mainly free-streaming. These cosmic background neutrinos, if detectable, would tell us about the conditions at their era of decoupling just as the CMB does for its era of decoupling (see below). But, if not in superdense media, neutrinos have a mean free path of about ten light years in solid steel. Detecting neutrinos is difficult even in a dense flux of them, and detecting the hypothesized cosmic neutrinos is at present way beyond our capability.

The mass of the electron neutrino may be important for total energy density with its implications for closure of curved space. This mass is small but unknown at the present time, and we do not even know if cosmic neutrinos are relativistic, or if, for example, one family of neutrinos is and two are not. In addition to the electron neutrino and its anti-neutrino, two more pairs exist which could have important cosmological implications if they are sufficiently massive. But they are rare, hard to detect, and little is known about them at present. It is futuristic but not out of the question that background fluxes of these neutrinos will some day be detected and quantified, and will give us vital information about the earlier universe.

When discussing neutrinos it is important to explain that if their mass is non-zero but sufficiently small then they will be "relativistic" at their moment of creation and for much of the life of the universe. By relativistic we mean that their kinetic energy exceeds their mass-energy. As the universe expands, the de Broglie wave of relativistic particles is stretched out with the expansion, as with light. A particles' total energy is the Pythagorean sum of mass-energy and kinetic energy: $E^2 = M^2c^4 + P^2c^2$. Momentum P is inversely proportional to this wavelength, so the kinetic energy component of such a particle falls off like the quantum energy of photons in the expanding universe, as the fourth power of the expansion scale, while mass-energy drops off as the third power. If a neutrino has very little mass energy to start with, then by the time its kinetic energy red shifts down to the level of its mass energy, it will be one tired neutrino, and maybe hard to detect. At present we don't know much about neutrinos; we can only speculate and work out scenarios from the various possible realities.

TIME :1 – 100 TEMP: 10^{10} - 10^{9} ENERGY : 1 MeV – 0.1 MeV

The stage is now set for the formation of the lightest isotopes, but the universe must wait a little longer to cool to a temperature at which the reactions controlling the N/P ratio become slow relative to the reactions of nucleogenesis. When the equilibrium reactions dominate, the neutron-to-proton abundance ratio, N/P, is given by the Maxwell-Boltzmann equation, $N/P = \exp(-\Delta mc^2/kT)$. Near t=1 second, when the reaction rates which keep neutrons in equilibrium with protons starts to exceed the age of the universe, the M-B equation leaves the N/P ratio with a value of 1/5. At this point neutrons decouple from protons, but do not yet start to fuse with them to create deuterium, and neutron abundance is slowly eroded by beta decay, with half life $T_{1/2} = 614$ seconds. Formation of the light isotope nuclei starts at about 100 seconds, when the N/P ratio has fallen somewhat below its decoupling value of 1/5.

The value of N/P at t = 400 sec. is 1/8, which is the value taken as that at the start of nucleosynthesis, but the usual era for nucleosynthesis is quoted as 100 sec. – 300 sec. Ambiguity of sources must be resolved.

TIME < 14 TEMP < 3 10^{9} ENERGY < 500 KeV

Just before the formation of the light isotopes the expanding medium still has an important source of energy that it is about to dump into the thermal pool, namely the mass-energy of the overwhelming bulk of electrons and their anti-particles, the positrons. Like the proton anti-proton pairs these two species cannot co-exist unless the temperatures is high enough to form them as fast as they can annihilate. The mass-energy of the electron or positron is 511 KeV. At much below this temperature photon pairs with enough combined energy to create an electron-positron pair are becoming scarce, even in the high energy tail of the Planck distribution. So e^+e^- pair production slows and halts and only annihilation proceeds. As in the case of protons, after annihilation runs its course the anti-matter particles (e^+) are gone and a small residual of matter particles (e^-) remains. In both cases matter slightly dominates over anti-matter. This could be due to a small imbalance in the initial abundances, or in a small asymmetry in the physical processes of annihilation.

At the time of this annihilation event a free-streaming (non interacting) field of electron neutrinos has already come into existence. The unbalanced annihilation of the e^+e^- pairs releases energy into the radiation field, but fails to create neutrinos due to a low cross-section for that process. In the context of rapid expansion and cooling this effect is not big enough to actually raise the falling temperature of the universe, but it temporarily slows the cooling, flattening the T(t) curve. Injecting energy into the photons while leaving the neutrinos untouched effectively lowers the energy distribution of the neutrinos to about 1.9 K. If we ever detect these relic neutrinos we expect to detect them at this temperature and to find a distribution like the Planckian black body, but skewed downward in its soft wing.

TIME :100 - 300 TEMP: ~>10^8 ENERGY 0.2 - 0.1 MeV

This is the era of the formation of the light isotopes. The binding energy of the deuteron is 2.2 MeV, and detailed calculations show that the temperature of the medium must fall to 0.1 MeV before the hot tail of the thermal distribution is depleted enough for deuterium to be created without immediate dissociation. Only when some deuterium is present can the next few isotopes be formed. So, the neutron-proton ratio is now somewhat less than 1/5, thermal energy is now well under the deuteron binding energy, and deuterons can now be formed by the reaction P + N ----> D.

It is of interest that the half life of the neutron is somewhat longer than the span of this era. Otherwise we would not be here. It is also of interest that the factor $\Delta mc^2 = 1.3$ MeV in the exponential in the Maxwell-Boltzmann equation, $N / P = \exp(-\Delta mc^2/kT)$, is the energy differential between the neutron and proton, which is small compared to the energy (1 GeV) of either.

By the end of this era the isotopes formed with significant populatons were: H, D, ^{3}He, ^{4}He, and ^{7}Li. The stable helium isotope, ^{4}He, ended up at 22% by mass relative to hydrogen due to several factors, especially the number of neutrons available at the onset of nucleogenesis. The mass abundance of D, ^{3}He, and ^{7}Li ended up at 10^{-4}, 10^{-5}, and 10^{-10}, respectively. Theory and observation agree very closely on these numbers – a great coup for the general idea of Big Bang nucleogenesis. When the neutrons are all used up, the game is over, and the universe must await the formation of stars for the production of heavier isotopes up to iron, and massive stars for the formation of elements heavier than iron. These massive stars explode as type IIa supernovae, injecting all the elements of the periodic table into the interstellar medium. In addition, the first three rows of the periodic table are seeded into space by carbon dwarf stars in binary pairs with stellar winds. When the winds increase the dwarf masses to the Chandrasekhar limit they undergo carbon-flash thermonuclear detonation, exploding as type Ia supernovae. These are used as the “standard candles” by which the Hubble parameter at the greatest distances is measured.

The chemical enrichment of the interstellar medium allows the formation of not only of interstellar molecules and chemically enriched stars, but also planetary systems, including terrestrial planets like earth.

TIME 10^{12} (30,000 Yrs) TEMP 10^4 ENERGY 1eV

At this time radiation gives way to matter as the dominant form of energy. In the expanding universe radiation energy density falls off as the fourth power of the scaling parameter, $a(t)$, and matter falls as the third power. At 30,000 years the curves cross.

Radiation has pressure, which, contrary to intuition, acts like mass-energy and attracts radiation to itself. This slows the expansion rate relative to what it would be if the universe were dominated by a substance with zero pressure, like matter, or dark energy. When matter does assume dominance, the expansion can proceed with less deceleration. The scaling parameter’s time dependence goes from $a(t) =(t/t_0)^{1/2}$ to $a(t) = (t/t_0)^{2/3}$, where $t_0 = 4\ 10^{17}$ sec. , the present age of the universe. The Hubble parameter changes its dependence from $H(t) = 2/3t$ to $H(t) = 1/2t$. The energy density functions $\rho(t)c^2$ for radiation and matter can be worked out by the reader from $a(t)$ above.

TIME 10^{13} (350,000 Yrs) TEMP $3\ 10^3$ ENERGY 0.7 eV

We finally arrive at the creation date for the cosmic background radiation. Before this age radiation had been trapped by the scattering opacity of electrons, or other particles in the early universe. Like sunlight on a foggy day at the beach the radiation scatters randomly, but unlike sunshine, which is in equilibrium with the sun’s surface temperature of about 4,000 K, it stays in thermal equilibrium with the local conditions. At 350,000 years the temperature falls to about 3,000 K and the plasma of electrons and protons combines to form neutral H atoms. This takes the electrons, and therefore the scattering opacity, out of the picture. The 0.7 eV photons cannot interact with the H atoms because the first excited state of H is at about 10 eV above the ground state, and a similar statement is true of helium. So, the radiation field is set free to stream through space without interaction.

The CBR at 3,000K starts off as reddish and infrared radiation but red shifts as the universe expands, nonetheless continuing to follow a Planckian black body distribution, but at the decreasing temperature, $T = T_0/a(t)$, where $a(t)$ is the expansion scale and T_0 is the present day 3 K background temperature. So, the CBR gets thinner and “redder” as the universe expands, stretching out the wavelength of the photons. It eventually becomes the 3 K cosmic microwave background (CMB) of the present era, still bearing the spatial patterns from the earlier 3,000 K universe, which, it is theorized, bears the imprint of the earliest quantum fluctuations. Averaged over galaxies and intergalactic space, the CMB also represents the largest contribution to total radiation energy density.

Sophisticated space-borne instruments have determined that the CMB is isotropic to a few parts in a million. Both its isotropy and its small deviation from perfect isotropy give us important clues to understanding the early universe. The most modern of these detectors will measure the polarization of the CMB, which may tell us about gravitational waves in the earlier universe.

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Referenced from http://www.sackett.net/cosmologyAll.htm.