The State of the Universe

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There has been tremendous growth in our understanding about the universe in the last few decades mainly due to deep space observations in multi wavelength and better understanding of sub-nuclear or particle physics. The assumption that the same physics operates in distant parts of the universe as on our planet still has been providing the foundation of all our explanations about the varieties of phenomena observed in the universe. Although we know that classical mechanics which works at the scale of $1\ cm$ does not remain applicable at the scale of $10^{-8}\ cm$ and we need quantum mechanics, we still expect that the physics tested at scale of $10^{14}\ cm$ (solar system) will hold at scales of $10^{18}\ cm$ to $10^{28}\ cm$ also. This is a huge extrapolation. The relativity principle of Einstein which says that all inertial frames of reference are equivalent as far as physics is concerned, and the Copernican principle (cosmological principle) which says that all places and directions in the universe are equivalent can be interpreted as a proof of impartiality of nature. On the other hand the fine-tuning of more than two dozen physical parameters of the universe compatible with our existence forces us to believe that our universe is "special". Of course the anthropic principle is there to confuse us which says that we exist in that part of the universe, or in that universe, where physical parameters are suitable for our existence. This simply means that there is nothing special about the selection of the physical parameters for our universe: there may be parts of the universe or other universe (multiverse) where physical parameters are different from what they are here. In the present article I will try to draw a rough picture of our understanding of the universe to date and discuss what are the things that we know and what are things we do not know apart from many things we do not know we do not know.

The physical processes in the universe are explained at very large distances by Einstein's general theory of relativity since gravity dominates at these scales and at small scales (subatomic scales) by quantum mechanics. It is still not clear why macroscopic objects which are made of fundamental quantum particles behave classically. Neither is it clear why the universe operated by physical laws which are perfectly symmetric in time, is time-asymmetric. Anyway we have got a set of sometime overlapping and most of the time complimenting physical theories which help us to explain the things which we observe in the universe and make predictions for future. On the basis of three main fundamental constants named Newton gravitation constant (G), speed of light (c) and the Planck constant (h) we can decide which theory of physics will be applicable in which case (see Figure 1).

In most of cases either we need classical mechanics or quantum mechanics to explain a physical process. For example, motions of terrestrial bodies and planets can be explained on the basis of Newtonian mechanics, special theory of relativity is needed to explain the motion of relativistic particles, and General theory of relativity is needed for studying the motion of objects as well as of photons in strong gravitational fields. The atomic and nuclear processes can be explained on the basis of quantum theory. Once we incorporate special theory of relativity in quantum mechanics (quantum field theory), then, apart from black holes and the big bang, almost all physical processes in the universe can be explained without a quantum theory of gravity which we still do not have.

When the size of a system becomes of the order of h/mc quantum nature of the system is manifested and when it becomes of the order of Gm/c^2 curvature of space-time due to gravity cannot be ignored. On the basis of these two different scales related to quantum mechanics and gravity, we can form a system of units called the natural or Planck system. The Planck length (l_{pl}), Planck mass (m_{pl}) and the Planck time (t_{pl}) are given by $\sqrt{\hbar G/c^3}$, $\sqrt{\hbar c/G}$ and $\sqrt{\hbar G/c^5}$ respectively. When we substitute the presently known values of the fundamental constants then we get $l_{pl} = 1.61 \times 10^{-35}\ mt,\ m_{pl} = 2.17 \times 10^{-8}\ kg$ and $t_{pl} = 5.39 \times 10^{-44}\ sec$ respectively. So far we do not have any consistent theory of the Planck scale physics which may play a crucial role in the explanation of the origin of the universe or close to the big bang.

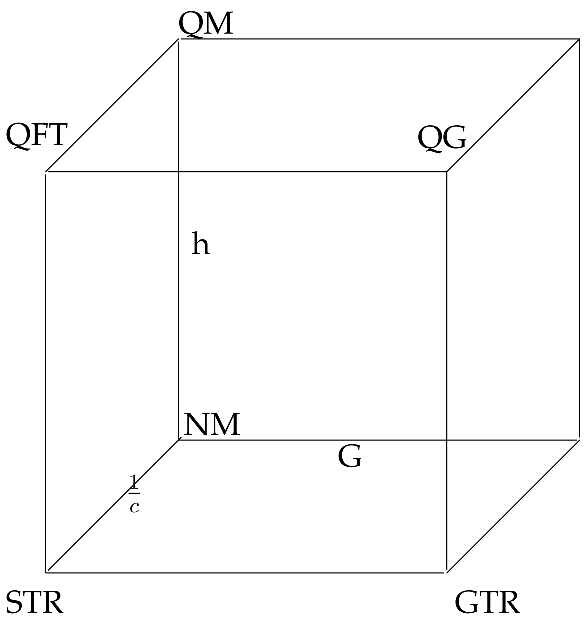

Figure 1: The motion of an object is described by Newtonian mechanics (NM) as long it moves with non-relativistic velocity ($v < c$) and its size is larger then h/mc. Special theory or relativity (STR) becomes important for objects moving with relativistic velocities. At subatomic scale gravitational effects can be ignored and the system is described by purely quantum mechanics (QM). Very high energetic processes at subatomic level are described by Quantum filed theory (QFT) which incorporates STR with QM. We need general theory of relativity (GTR) when the size of a system becomes comparable to Gm/c^2. Close to the big bang gravity becomes as strong as any other force described by quantum mechanics, so we need a quantum theory of gravity (QG) there.

All physical processes in the universe are governed by the four fundamental interactions named gravitation, electromagnetic, weak and strong, which act between two sets of fundamental particles named quarks & leptons. Quarks and leptons are characterized by their quantum numbers (mass, charge, spin etc) and the strength of the four fundamental interactions is given by their coupling constants. The mass & size of many of the objects in the universe like atoms, mountains, planets, stars etc., can be explained on the basis of the values of the fundamental physical constants, masses of fundamental particles & strength of fundamental interactions. We know that if planets have to overcome their gravitational collapse then their size and mass should be of the order of $10^{10}\ cm$ and $10^{30}\ gm$ respectively so that electromagnetic repulsion between protons can keep them apart. Taking other considerations into account, we find that the mass of a typical star should be around $10^{32}\ gm$ (if its gravitational collapse has to be supported by the pressure of the photons produced in nuclear reactions), and mass of a typical galaxy around 10^{11} solar mass.

The plan of the present article is as follows. In the next section, I will describe the expansion of the universe in some detail and throw some light on its consequences. In the second section, I will discuss what the universe is made of. Here my discussion will be mainly centered on the two mysteries of the universe named the dark matter & the dark energy. In the final sections I will describe some theoretical ideas which are not much well established but have great power to predict. Finally, I will end the article by discussing some of the unresolved issues in physics & cosmology and some big experimental and observational projects.

1. Expansion of the universe

Some of the most interesting questions about the universe are regarding its origin, shape (geometrical & topological structure), dynamics & composition. Of course we do not know how the universe originated but now it has become widely accepted that around 14 billion years ago the universe was extremely small in size and very dense and hot, and then it started to expand from that state (called the big bang). The universe close to the big bang was so hot ($T > T_{Planck} = 10^{32}\ K$) that no theory of physics can help us there.

The universe at very large scale is expanding in the sense that the spectra of the distant galaxies appear to be shifted towards the lower frequencies as happens in Doppler effect. It has been found that the expansion of the universe is given by a linear relationship (Hubble law) between the relative velocities and distances of galaxies i.e., $v = Hr$. Here the proportionality constant H is called the Hubble parameter (see below). One of the interesting things about the expansion of the universe is that it can be characterized by a single time dependent function $a(t)$, called the scale factor, because physical distances between galaxies increase in its proportion when the universe expands. We can use the scale factor as a scale of time also and can choose the reference point either at the big bang ($t = a = 0$), or at the present ($t = t_0, a = a_0 = 1$). Note that in an expanding universe not all objects move away from each other or expand. For example, there is no effect of the expansion of the universe on solar systems, galaxies or even on clusters of galaxies because these are all gravitationally bound systems.

In general, the expansion of the universe is quantified by two parameters named the Hubble parameter $H = \dot{a}/a$, and the deceleration parameter $q = -a\ddot{a}/\dot{a}^2$. Note that these two parameters have to be measured observationally. It is interesting to note that they turn out be dependent on the material content of the universe as a consequence of Einstein's general theory of relativity. For convenience the value of H is expressed in the units of $100\ km\ sec^{-1}\ Mpc^{-1} = (1/9.78)\ Gyr^{-1}$ where $1\ Mpc = 3.08 \times 10^{24}\ cm$ and $1\ Gyr = 3.156 \times 10^{16}\ sec$. In these units the present value of the hubble constant (written as h) is 0.74, i.e. a galaxy at a distance of $1\ Mpc$ moves away with respect to us with speed $74\ km\ sec^{-1}$.

Now we have got one more physical constant (parameter) H, the hubble constant, apart from other fundamental physical constants G, h, c etc. Including this parameter, we can construct a very useful system of units to express the age, size and density of the universe. For example $d_h = c/H = (3000/h)\ Mpc$, called the hubble distance, can be used to express the size as well as very large distances in the universe. In the same way the hubble time $t_h = 1/H = (9.78/h)\ Gyr$, can be used to express the age of the universe. Cosmological densities of the various species of matter (energy) in the universe are expressed in the units of a critical density ρ_c [1].

When we throw an object upward from the surface of the earth then on the basis of whether the velocity of the object is less than, equal to or greater than the escape velocity on earth, the object will come down after going to some maximum height, may stop at the maximum height or escape to infinity respectively. This analogy can be used in the case of the universe also. When the density of the universe is greater than the critical density, then due to gravitational attraction of matter, universe will keep expanding for some time and then stop, turn around, and start collapsing towards the big crunch. However, in the other two cases the universe will keep expanding indefinitely. Here it is interesting to

[1] $\rho_c = (3H^2/8\pi) = 18.79 \times 10^{-30}\ h^2\ gm\ cm^{-3} = 2.76 \times 10^{11}\ M_\odot\ Mpc^{-3}$. This roughly corresponds to one galaxy per Mpc^3

note that it is very unlikely that we throw an object upward from the ground exactly with a velocity equal to the escape velocity and the object stuck at some height forever. In the same way it is very unlikely for the universe to have its density exactly equal to the critical density. In the observations it was found that the density of the universe is very close to the critical density which was difficult to explain in the big bang theory and so a new idea called inflation was introduced by Alan Guth in 1981. In order to explore this idea in some detail, it is relevant to introduce the concept of curvature.

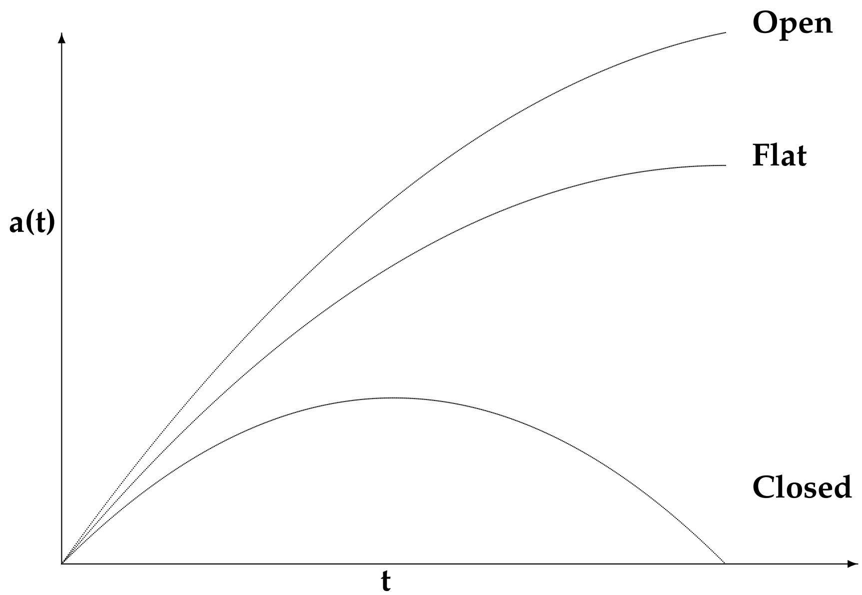

Figure 2: IN A CLOSED MODEL ($\Omega > 1$) THE UNIVERSE STARTS EXPANDING AT THE BIG BANG AND AFTER REACHING A MAXIMUM SIZE, STARTS COLLAPSING UNTIL THE BIG CRUNCH. IN A FLAT ($\Omega < 1$) AND OPEN MODEL ($\Omega = 1$) THE UNIVERSE KEEPS EXPANDING FOREVER.

The main idea of Einstein's general theory of relativity is that, gravity which is produced by all forms of energy in the universe, deforms the geometry of space-time. For example, in the presence of a gravitational field neither unaccelerated particles nor photons move along straight lines. The gravitational field of the matter in the universe can curve the space positively or negatively on the basis of whether the density parameter Ω, which is the ratio of the density of matter in the universe and critical density, is greater or smaller than unity. The universe is said to be flat when $\Omega = 1$. All the geometrical relations which we know, like the area of a circle is πr^2 or the sum of all angles of a triangle is 2π etc, are true only for Euclidean or flat space. In a positively curved space the distance between two free falling observers decreases with time and in negatively curved space it increases with time. On the basis of how the apparent size of the objects of standard size, and brightness of the objects of standard brightness (called standard candles) changes with distance, we can probe the curvature of space. Note that in a flat space they change as $1/r$ and $1/r^2$ respectively. It was found that for our universe $\Omega = 1$, which was a big surprise (called the flatness problem) and was explained by the inflationary theory which says that the enormous expansion of the universe ironed all the wrinkles on the fabric of space and made it flat.

The rate of expansion of the universe changes with time due to gravitational interaction of matter. This slowing down of the expansion is characterized by the deceleration parameter $q = -\ddot{a}a/\dot{a}^2 = (\rho + 3P)/2\rho_c$. Here ρ and P are the total energy density and pressure of the universe respectively.

Note that as long as $(\rho + 3P) > 0$, q is positive and the expansion of the universe slows down with time (deceleration). However, in the case when $(\rho+3P) < 0$, the expansion rate of the universe increases with time (accelerated expansion). For the usual kind of matter (called dust) $P = 0$, and ρ is always positive, so, deceleration is expected. However, for some exotic kind of matter (energy) called the dark energy or cosmological constant for which $(\rho + 3P) < 0$, the expansion of the universe is accelerated. Note that any species of matter (energy) in the universe is characterized by its equation of state parameter $w = P/\rho$ and so for $q = (\Omega/2)(1 + 3w) < 0$, we need $w < -1/3$.

For simplification, everything in the universe is considered as one of the following three types: non-relativistic matter or matter for which $w = 0$, relativistic matter or radiation for which $w = 1/3$, and the cosmological constant for which $w = -1$. Note that if $w \neq -1$ but $w < -1/3$, then in place of the term cosmological constant we use the term "dark energy". Both play the same role i.e., accelerate the expansion of the universe. If we consider that the expansion of the universe is adiabatic i.e., $dQ = dU + PdV = 0$, and substitute $dU = d(\rho a^3)$ and $PdV = w\rho d(a^3)$, then we find $\rho \propto a^{-3(1+w)}$. From this relation we can see that the density of matter and radiation fall as $1/a^3$ and $1/a^4$ respectively. However, that of the cosmological constant remains constant. When we extrapolate the present densities of matter, radiation and the cosmological constant back in time then we find that from the earliest epoch the energy density of the universe is dominated by radiation followed by matter and the cosmological constant. Note that in these three different regimes the universe expands differently: in matter era $a(t) \propto t^{2/3}$; in radiation era $a(t) \propto t^{1/2}$ and in the cosmological constant era $a(t) \propto e^{H_0 t}$.

The discussion of the expansion of the universe is incomplete without discussing the "edge" of the universe. It is not that easy to say how big the universe is; however, there have been defined three scales named hubble distance, particle horizon and event horizon, which give some idea about the edge of the universe. The expansion of the universe is such that the recession velocities of galaxies with respect to us increases linearly with their distance. So we can identify a distance named hubble distance beyond which galaxies move with superluminal velocities i.e. $v > c$ (note that it does not violate special theory of relativity). It is clear that if a galaxy moves away from us with $v > c$, then no photon from that galaxy can reach us, so in general, these superluminal galaxies are not visible to us. However, in a decelerating universe when the expansion of the universe slows down, these galaxies can enter the hubble volume and become visible. Here we can summarize that in a decelerating universe we see more & more galaxies with time and in an accelerating universe less and less number of galaxies will be observed with time. If the value of the cosmological constant is positive, no matter how small it is, in very distant future hardly any galaxy will be observable in the universe, and it is speculated that if there are any intelligent beings at that time then they will fail to notice the expansion of the universe.

The speed by which photons can reach us is constant so the farthest distance from which photons can reach us since the big bang gives the measure of a horizon for us, called the particle horizon. Since with time more and more photons from the distant parts of the universe get the time to reach us, the particle horizon increases with the expansion of the universe. There is defined one more horizon also, called the event horizon, which contains all the spatial points in the universe from which the photons can reach us no matter how long they take. This in some sense is the true horizon because we can never communicate with the regions outside of it and so they can be considered other universes. It is interesting to note that the distances between the objects in the universe increases at a rate different from the rate at which the particle horizon increases. So it may happen that two spatial points which are inside the particle horizon i.e., are in causal connection, may go outside or vice versa. Before 1980, it was a mystery to explain why two widely separated points in the sky have the same temperature although before today they were never causally connected if we follow the conventional big bang expansion. This problem was called the horizon problem and was resolved by inflation by saying that before the starting of the big bang expansion,there was an exponentially rapid expansion of the universe for a very short time. The interesting feature of exponential expansion is that in this case the size of the particle horizon remains constant. However, the distances between objects increase exponentially. So inflation shrinks the distances between spatial points in the universe in such a way that all points present in the sky go inside the particle horizon and so are causally connected.

General theory of relativity is used to find the local geometry of the universe. However, it does not say anything about the topology of the universe. There are many questions which can be answered only when we know the topology of the universe, e.g., whether the universe is finite or infinite. It has been mentioned that the geometry of the universe can be open, flat or closed on the basis of whether $\Omega < 1, > 1$ or 1 respectively. But we can have more than one topological space which have the same local geometry. For example. locally the surface of a cylinder is also flat but its topology is different from that of a plain sheet. In the simplest form, topological spaces are made of building blocks called the fundamental polyhedra. For example, we can consider that our universe is made of very large cubical regions which, on average, are identical to each other. In this case, if we identify the opposite faces of the cube with each other, then the topology of such a universe is called three torus or T^3. If the topology of our universe is T^3 then at very large distances we may be able to see multiple images of galaxies. Not only that, by matching the pattern in the anisotropies of the Cosmic Microwave Background Radiation we can infer the topology of the universe.

2. Content of the universe

Galaxies can be considered the fundamental building blocks of the universe, which are distributed in the form of a rich network of filaments, sheets, clusters and super-clusters. Galaxies cannot lead us very far back in time since they were assembled very late in the history of the universe. Nevertheless, by observing the distribution of galaxies in the sky we can know a lot about the history as well as the large scale structure of the universe. Two very ambitious galaxy surveys named 2df Galaxy Redshift Survey (2dfGRS) and the Sloan Digital Sky Survey (SDSS) have been obtaining the photographs and spectra of hundred of galaxies per night using very powerful telescopes and state of the art computers. So far they have mapped millions of galaxies and many other objects. The most surprising thing which has been found in these and many other observations of galaxies and clusters of galaxies is that, in these structures the visible matter makes a small fraction of the total or gravitating matter, responsible for dynamics. For example, stars in the outer parts of galaxies move faster than the orbital velocities which visible matter can provide. In simple words, there is far more gravitating matter in galaxies and clusters of galaxies than the visible matter. In order to correct for this deficiency there has been invoked an invisible (since it does not interact with photons) type of matter called the dark matter which helps to cure some other problems also like the problem of galaxy formation.

When we go back in time the universe becomes smaller, denser and hotter and all matter in the universe starts to dissolve into its constituents above a certain temperature, firstly atoms into ions and then finally into a soup of fundamental particles, close to the big bang (see the table below). It is still speculative to explain how the matter in the universe came into being. It has been generally believed that at the time of the big bang there was equal amounts of matter and anti-matter, with a very small amount of asymmetry in favor of matter, which was amplified by some physical processes taking the advantage of extreme physical conditions of that time. Anyway we can start our universe with a plasma of quarks & gluons at some time after the big bang. When the universe cooled below some temperature ($1 GeV$) these quarks started to synthesize protons and neutrons which are the main constituents of the matter in the universe. As long as the temperature & density of the universe were high enough these protons and neutrons were in thermal equilibrium with the help of photons and neutrinos by weak interactions. Note that the expansion of the universe provides a time scale, and physical processes which take longer than this time become ineffective. For example, when the universe cools below some temperature called the electroweak scales, weak interactions become ineffective, protons & neutrons settle to some equilibrium densities and the neutrinos decouple. However, the photons keep interacting with the matter by quickly ionizing the atoms which form when protons & neutrons trap the electrons. Note that once neutrons & protons settle to their equilibrium values, they start to synthesize firstly Hydrogen and then Helium. On the basis of theoretical considerations it was predicted that the primordial matter should consist of 75% Hydrogen, almost 25% of Helium with trace amounts of other lighter elements like Lithium, which was later confirmed by observations. This again was a huge success for the big bang theory. Note that these light elements were synthesized in the first three minutes of the big bang and all other higher elements were synthesized in the thermonuclear reactions in the interior of stars or in supernova explosions.

Time	**Temperature (Energy)**	**Event**	**comment**
$0\ sec$	∞	The big bang	Not much is known
$10^{-43}\ sec$	$10^{32}\ K\ (10^{19}\ GeV)$	The Planck era	Quantum gravity is needed
$10^{-35}\ sec$	$10^{28}\ K\ (10^{15}\ GeV)$	Grand unification	Inflation
$10^{-11}\ sec$	$10^{16}\ K\ (10^{3}\ GeV)$	Electroweak transition	
$10^{-6}\ sec$	$10^{13}\ K\ (1\ GeV)$	Quark-hadron transition	
$1\ sec$	$10^{10}\ K\ (1\ MeV)$	Nucleosyntheis	Light elements synthesized
$3000\ yrs$	$16,500\ K\ (1.5\ eV)$	Matter domination	
$400,000\ yrs$	$3000\ K\ (0.4\ eV)$	Decoupling (Recombination)	CMBR produced
$0.1-1\ Gyr$		Galaxy formation	Re-ionization

A brief thermal history of the universe

As long as photons were hot enough to ionize Hydrogen they could not travel long distances due to frequent scattering with the free electrons in the medium, and so there was a dark age before an epoch, called recombination or decoupling. At this epoch, photons lost the capacity to ionize the matter due to stretching of their wavelength because of the expansion of the universe, and so electrons were recombined with protons and neutrons to form neutral Hydrogen. This event was more or less simultaneous everywhere in the universe and since then every observer in the universe finds himself at the center of a shell (called the surface of last scattering) formed by the photons which were scattered by electrons last time, outside which photons are coupled to matter. We observe these photons of last scattering in the form of a black-body radiation of around 3K which reach us almost uniformly from all directions, called the Cosmic Microwave Background Radiation or CMBR, which was observed by Wilson & Penzias in 1965 for the first time. Again this long sought radiation, first predicted in 1940s, was a big triumph for the big bang theory.

There are three main properties of CMBR: 1) It is a black-body radiation 2). Its temperature distribution in the sky is almost isotropic 3) There are small anisotropies of the order of one in 10^4. There has been decoded a great deal of information about the past of the universe using the above three features of CMBR, and so far CMBR physics has grabbed two Nobel prizes (Wilson & Penzias 1967; Marthr & Scot 2006). There has been tremendous growth in the number of people who care about CMBR including those who do not care about the rest of the three dimensional world (string theorists). It will be too much to describe what CMBR can tell us and what it cannot (I will not be surprise to hear from somebody who claims that he can prove the existence of God using CMBR !).

Now let us explain the properties of CMBR. The black-body nature of CMBR says that the universe was in thermal equilibrium in its past as is predicted in the hot big bang theory. The isotropy of CMBR says that in the early universe all parts of the universe which are separated by great distances today, were in contact with one another, which is exactly what is expected in the big bang theory. CMBR anisotropies show that the matter distribution at decoupling was slightly non-uniform i.e., there were density perturbations or over and under-dense regions. In the current models of structure formation, it is considered that these primordial density perturbations which are imprinted in the sky in the form of CMBR anisotropies were amplified by gravity and galaxies formed. It is interesting to find that the amount of CMBR anisotropy which we observe perfectly matches with the amount of perturbation which we need to form galaxies at present. If we plot the strength ($\Delta T/T$) of CMBR anisotropies against the patches of various angular sizes in the sky, we get a beautiful plot with peaks, valley and flat regions, called the CMBR angular power spectrum. On the basis of theoretical models and the angular power spectrum we can obtain some of the important parameters of the universe related to its geometry, composition and ionization history. So far all the results from CMBR observations (particularly from the COBE & WMAP experiments of NASA) have been compatible with other observations. In particular, CMBR studies reemphasize that the universe is dominated by dark energy and dark matter.

It was a common expectation up to 1998, that the expansion of the universe will slow down with time ($q > 0$). However, the observations of some distant supernovae by two independent groups showed that this is not the case. These supernovae were found to be fainter than what was expected in a decelerating universe. In order to explain these observations, the cosmological constant was reintroduced. This was first introduced by Einstein in the 1920s, to make the universe stationary, but was later abandoned after the discovery of the expansion of the universe. Once we consider that around 70% energy density of the universe is contributed by the cosmological constant, we can explain many other observations also including supernovae. For example, if we do not consider the cosmological constant then the age of the universe turned out to be smaller than the age of some of the oldest objects (globular clusters) in it.

From the current observations mainly related to galaxy surveys, CMBR & supernovae it has been concluded that 70% energy density of the universe consists of dark energy, 26% dark matter, and the rest 4% of normal matter. It is a great embarrassment for physicists to find out that whatever they know about the universe is only applicable to 4% normal matter.

3. Summary

Modern cosmology is based on a set of assumptions, observations and theoretical models. The assumptions are, for example, the cosmological principle and the extrapolation of the physical laws tested at terrestrial scales to the cosmological scales. The observations are mainly based on the receiving of photons, cosmic particles like neutrinos, and may be gravitational waves, from the distant parts of the universe by sophisticated ground, underground and space based telescopes & detectors. Theoretical models are build on quantum mechanics (particle physics) and theories of relativity. Apart from assumptions, a great deal of work has been done at observational and theoretical front. Observational capacity has been improved so greatly that now we can catch the faintest signals from the remotest parts of the universe. For example, gravitational wave detectors (like LIGO,LISA, VERGO etc) which are either under operation or planned have incredible sensitivity (one part in 10^{22}) and so they can probe the most powerful events in the universe like the merging of black holes and & the big bang. With very high degree of predictability and explanation power, quantum mechanics & general theory of relativity have remain the unchallenged theories of matter and space-time respectively, although these two theories still do not talk to each other i.e., we do not have a quantum theory of gravity.

The hot big bang theory has been quite successful in explaining a substantial portion of the history of the universe. Its main drawback still has been the non-trivial birth of the the universe or the big bang. In the framework of established theories of physics there is no way to answer how the universe originated or what was before the big bang. For the last few years there have been pouring a huge flux of weird ideas either to explain the initial singularity (big bang) or to get rid of it, but none of these ideas is better than others.

The credit of our ignorance about the earliest moments of the universe goes to our poor understating of the physics at very high energy scales. In the most successful theory of fundamental particles & interactions, called the standard model of particle physics, apart from gravitation all other interactions are explained by theories based on quantum mechanics & special theory of relativity, called the quantum field theories. In the framework of the standard model of particle physics, the fundamental interactions are operated by the exchange of mediating particles called gauge bosons. For example, photons are the gauge bosons of electromagnetic interactions, so two charged particles interact with each other by exchanging photons. In the same way the strong & weak interactions between particles are operated by the exchange of gluons and W and Z particles respectively.

At energies above 200 GeV weak & electromagnetic interactions lose their identities and unify in a single interaction, called the electroweak interaction, and at 10^{16} GeV strong interactions also join hand and there remains a single interaction named the grand unified interaction. It is quite difficult to incorporate gravitation in this unification program without invoking new ideas. One of these ideas, called the Supersymmetry (SUSY), says that corresponding to every fermion (leptons and groups of quarks like protons and neutrons) there exists a boson and vice versa. Once we invoke this idea then not only does gravity join the unification program at Planck scale (10^{19} GeV), we also get a zoo of new of particles (although none of these have been observed so far) in which some of the particles are considered strong candidates of dark matter.

Dark matter & Dark energies are the two great mysteries of modern cosmology & physics. Although there is almost perfect agreement between the physicists and cosmologists about their existence but there are some skeptics also who believe that there may be something seriously wrong with our understanding of gravity. For example, if we assume that Newton's law of gravity is modified at large distances (MOND or Modified Newtonian Dynamics) then we can explain the rotational curves of galaxies. But the problem is that now we do not need dark matter only for explaining the rotational curves, we need it for more than one dozen other observations also. So far most models of dark matter assume one species of dark matter for simplicity but that may not be the case. Apart from the Weakly Interacting Massive Particles (WIMP) which do not interact with photons and therefore are candidates of dark matter, there are some astrophysical candidates called Massive Astrophysical Compact Halo Objects (MACHO) also, which are astrophysical objects which do not emit light like large planets and dead stars.

We are completely in darkness as far as dark energy is concerned. Our best theoretical models over-predict the abundance of dark energy by at least 60 orders ! There are many ideas around mainly inspired by string theories which claim to fix these problems by going in an extra-dimensional space or by invoking some strange stuff like scalar or other kinds of fields whose existence is still doubtful. There is no doubt that all theoretical models make assumptions. Some models make a large number of sensible assumptions and others a small number of drastic assumptions. Now it depends on us which model we want to buy. My preference goes with the first type of models. I think one has to be brave enough before buying any such model which makes assumptions like we live in a more than three dimensional space. Max Tegmark, a theoretical cosmologist at MIT suggested that every model makes some predictions and we should rate the models on the basis of the number of predictions that have been confirmed by observations or experiments. If we follow this criteria, then a larger number of models which are flooding the scientific journals will go away.

As has been mentioned earlier also in unified theories of particle physics, it is considered that at very high energies the electromagnetic & weak interactions unify into a single interaction, named the electroweak interaction. Electromagnetic interaction is mediated by photons which are mass-less. However, the weak interaction is mediated by W and Z particles which are massive. In order to explain how the gauge bosons of weak interaction ($W\&Z$) got mass after the breaking of electroweak symmetry, a hypothetical entity called the scalar field (higgs field) has been proposed, which provides mass to the gauge bosons of weak interaction. Since the higgs field does not interact with photons, they are not affected by its presence. So far there is no experimental evidence for the existence of any scalar field. A billion dollar project named Large Hadron Collider (LHC) has been set up in the European laboratory for particle physics (CERN) in Geneva, which is expected to confirm the existence of the higgs field within a few years. Here my motivation in introducing the idea of scalar field was to explain the origin of the universe according to some popular models.

In general, all systems in the universe (particularly quantum systems & fields) stay in their ground state or in the lowest energy state, called the vacuum state. However, there exist some metastable states also (called false vacuum states) which are above the vacuum state in energy, and the systems can stay in these states for short periods of time. In inflationary models, it is postulated that in the very early universe (close to the big bang) there was a scalar field (called the inflaton field) in one of its metastable states (or there was a patch of false vacuum). Now the interesting thing is that false vacuum has negative pressure and Einstein's general theory of relativity says that negative pressure creates repulsive gravity. Due to repulsive gravity, the patch of false vacuum started to expand exponentially, called inflation. In some popular models of inflation, it is believed that inflation happened at around $10^{16}\ GeV$, which gives the duration of inflation to be $10^{-35}\ sec$. Note that the size of the universe during inflation increased from $10^{-24}\ cm$ to a macroscopic size.

Systems do not stay in metastable states for a longer time, they decay. So the inflation field also started to decay after inflation ended and the energy stored in it was used in the creation of particles. After the end of inflation, the universe started to expand according to the big bang theory. Note that, in inflationary models, the energy of the universe is very close to zero, since the positive energy of the particles is compensated by the negative energy of gravity. In conventional big bang theory we have to assume that all particles in the universe were present at the moment of big bang. It is interesting to note that, if we start the big bang at the Planck density and Planck time then according to the big bang theory in the present universe we should have hardly 10 particles ! But we know there are around 10^{80} particles in the universe. It seems that inflation gives a natural condition for the universe to begin with but there are still issues which have to be sorted out, including experimental and observational support, to raise the status of inflation from a paradigm to a theory.

Before ending the article, I would like to give a very short list of some of the unsolved problems in cosmology and physics and some of the biggest experiments and observations which have been set up to support our theoretical ideas.

In a conference named String 2000, some leading theoretical physicists sorted out the top ten unsolved problems of physics for the new millennium which are as follows.

1. Are all the (measurable) dimensionless parameters that characterize the physical universe calculable in principle or are some merely determined by historical or quantum mechanical accident and incalculable ?
   (David Gross, Institute for Theoretical Physics, University of California, Santa Barbara)

2. How can quantum gravity will help explain the origin of the universe ?
   (Edward Witten, California Institute of Technology and Institute for Advanced Study, Princeton)

3. What is the lifetime of the proton and how do we understand it ?

(Steve Gubser, Princeton University and California Institute of Technology)

4. Is Nature super-symmetric, and if so, how is Supersymmetry broken ?
   (Sergio Ferrara, CERN)

5. Why does the universe appear to have one time and three space dimensions ?
   (Shamit Kachru, University of California, Berkeley, Sunil Mukhi, Tata Institute of Fundamental Research, Hiroshi Ooguri, California Institute of Technology)

6. Why does the cosmological constant has the value that it has, is it zero and is it really constant ?
   (Andrew Chamblin, Massachusetts Institute of Technology, Renata Kallosh, Stanford University)

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature ?
   (Louise Dolan, University of North Carolina, Chapel Hill, Annamaria Sinkovics, Spinoza Institute, Billy & Linda Rose, San Antonio College)

8. What is the resolution of the black hole information paradox ?
   (Tibra Ali, Department of Applied Mathematics and Theoretical Physics, Cambridge, Samir Mathur, Ohio State University)

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?
   (Matt Strassler, Institute for Advanced Study, Princeton)

10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap ?
    (Igor Klebanov, Princeton University, Oyvind Tafjord, McGill University)

I am sorry for not touching upon some of the issues in the above list. I have put these also just for keeping the originality of the list.

Some other unsolved problems of cosmology and astrophysics which have been bothering people for a long time are as follows:

- Is there life elsewhere in the universe ?
- What is the fate of universe ? big crunch or big rip ?
- What is the topology of the universe ?
- What are dark matter and dark energy ?
- Will we be able to observe primordial gravitational waves ?

To find the answers of the above and many other such questions, there have been set up huge experimental & observational facilities around the world. Some of them are as follows.

1. **The Large Hadron Collider (LHC):** This is the biggest machine ever been made by human beings. According to quantum mechanics smaller a region we want to probe larger the energy we need. LHC want to see what is inside the protons which are the building blocks of matter in the universe, by colliding two beams of very high energy protons (7 TeV) moving in opposite directions in very precise orbits. LHC is built on the border of Switzerland & France in the form of a 27 km long circular tunnel of radius 3mt which is 100 mt underground. To keep the protons on their tracks the pipe inside which protons move are covered by superconducting magnets cooled at $-271^o\ C$. This multi-billion dollar project is a collaboration between 2000 physicists from 34 countries. The major scientific goals of LHC are to find the Higgs bosons and to confirm the hypothesis of Supersymmetry & extra dimensions. LHC will start doing its scientific experiments within one year or so.

2. **Laser Interferometer Gravitational-Wave Observatory (LIGO):** According to the general theory of relativity when massive objects accelerate, they emit gravitational waves, exactly as Maxwell's theory of electromagnetism predicts that when charged objects accelerate they emit electromagnetic waves. Gravitational waves are incredibly weak in comparison to electro-magnetic waves so they can be noticed only in very violent processes in the universe like the merging of black holes or the big bang. When gravitational waves strike objects, they produce very small displacements which can be noticed only by shifting of the interference patterns produced by laser beams in a Michelson-Morley-like experiment. LIGO is a joint project of MIT, Caltech & NSF in the form of two laboratories located in USA at Hanford (Washington) and Livingston (Louisiana) which work together. Both of these laboratories house Michelson-Morley like interferometers of around 2 km arm length. The main scientific goals of LIGO are to confirm the existence of gravitational waves, to test if gravitional waves propagate with speed of light and to confirm the existence of black holes and may be of big bang. LIGO is one of the most sensitive instruments ever built by human beings.

3. **Laser Interferometer Space Antenna (LISA) :** This is also a gravitational wave detector, proposed by NASA and the European space agency (ESA) which will operate from space in the form of three satellites located at the corners of a triangle, moving around the Sun. These three satellites will also be in the form of a Michelson-Morley interferometer and will also use laser beams. Since in this case the baseline will be million kilometers long and the operation will be in space, LISA will have enormous sensitivity in comparison to any other ground based detector. The main scientific goals of LISA are mostly the same as of LIGO.

4. **Planck mission:** This instrument is designed by the European Space Agency (ESA) for observing CMBR anisotropies with great accuracy, which will help to find many important cosmological parameters. Planck will be put in space within few years in an orbit very close to the L2 point of the Earth-Sun system. Note that at this location, the telescope of the instrument can always be pointed away from the Sun, since the temperature of CMBR is $3K$, which is very small, so the instrument has to be well protected. According to the website of Planck, "PLANCK will not only yield CMBR anisotropies, but also near-all-sky maps of all the major sources of microwave emission, opening a broad expanse of astrophysical topics to scrutiny".

5. **James Webb Space Telescope (JWST):** This is an infrared-optimized 6.5 mt size telescope which will be jointly build by ESA & NASA, and will be put in an orbit around the Earth at 1.5 million km in 2013. This telescope is considered a successor of the Hubble Space Telescope which will be retiring very soon. The scientific goals of JWST are to observe the first galaxies formed in the early universe and observe the regions around the stars in which planetary systems are forming.

6. **The IceCube:** Neutrinos are the most unsocial particles with fluctuating personality. They exist in three different forms (ν_e, ν_μ, ν_τ) and hardly interact with any known form of matter (they just pass through anything) and keep changing their form. In order to trap these elusive particles which come from various sources (deep space, supernovae explosions, black holes, Sun, Earth's upper atmosphere etc), there have been devised many sensitive detectors at various places around the world. The IceCube is a neutrino detector constructed at the South pole in deep ice below 1,450 and 2,450 meters. Thousands of optical sensors are buried in the ice to record the feeble interactions of neutrinos. The main scientific goals of IceCube are to detect neutrinos of very high energy ($10^{11}\ eV - 10^{21}\ eV$).

7. **Cassini-Huygens Probe:** This is a spacecraft with an on-board probe named Huygens, which consist of a set of sophisticated instruments, which was launched in 1997 to probe the region around the Saturn. After a long journey of 1.5 billion kilometer in seven years, it reached the orbit of Saturn in 2004. Since then it has completed 70 orbits around Saturn and has sent a great deal of information about Saturn and its moons. The main scientific goals of this mission are to measure Saturn's huge magnetosphere, analyze rings and study Saturn's composition and atmosphere. The age of this NASA proposed mission is around four years. Apart from Saturn, Cassini-Huygens Probe is also observing its moon Titan in great detail.

8. **Search for Extra-Terrestrial Intelligence (SETI):** Started by Frank Drake in 1960, this is a project to find life elsewhere in the universe using the most powerful radio telescopes and state of the art computer technology. The main approach of SETI is to scan the sky at some selected frequencies of radio-band, at which extra-terrestrials are expected to communicate, using powerful radio-telescopes including 25-meter diameter radio telescope at Green Bank(West Virginia) and the 305 meter Arecibo Radio Telescope in Puerto Rico. Mostly funded by private agencies and supported by thousands of amateurs by providing their computers in spare time for analyzing data, so far this project has not given any signal of any form of extra-terrestrial life.

9. **The Virgo Consortium:** So far it has remained an unsolved problem to understand how galaxies in the universe formed. The most acceptable hypothesis has been that the primordial density perturbations which were there at the time of decoupling amplified by gravity, and later on normal matter started to fall in the over-dense regions in dark matter and galaxies formed. Since gravitational collapse is a non-linear process this problem can be solved only by simulating the actual system in place of analytic calculations. Not only that, in galaxy formation there are many complicated processes involved related to radiation & gas dynamics which can be handled only numerically. The Virgo Consortium is a joint effort of cosmologists from around a dozen research institutes in the UK, Germany, Canada the USA and Japan to provide a supercomputing facility for cosmological simulations. This project has recently finished a simulation of more than one billion particles (Millennium simulation) which was a cover story of Nature. The website says : "The simulation was carried out by the Virgo Consortium using a cluster of 512 processors located at the Max Planck Institute for Astrophysics in Garching, Germany. The simulations took a total of 28 days (600 hours) of wall clock time, and thus consumed around 343000 hours worth of cpu-time".

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