THE FIRST MOMENTS OF THE UNIVERSE

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Does the Universe have a begining? If so, When? and How did this happen? - are the questions that have engaged the consideration of mankind for thousands of years. The concept of the Universe itself has undergone radical changes with the passage of time, especially after discovery of the telescope and the applications of spectroscopy for the analysis of the light received from different celestial objects. Developments in the field of Astronomy since the begining of this century especially after the commissioning of the large telescopes, and the advent of radio and space astronomies, have made us realise the vast dimensions of the Universe and the existence of totally new environments very different from our experiences on the earth.
The recent astronomical observations together with advances in the field of High Energy and Elementary Particle Physics, have led to plausible theories on the origin of the Universe and its probable evolutionary course. The two most important astronomical discoveries of relavance in this context are :

(1) the discovery of the general expansion of the Universe, and
(2) the discovery of the Universal Microwave Radiation.

While the first led to the postulation of the Big Bang theory of origin, the second provided the strongest support for this theory. When we talk of the "the first moments of the Universe", it is with reference to the Big Bang.

2. The Structure and Composition of the Universe.

The Figure-1 summarises in a way our current knowledge regarding the composition, the distance scale, and the relation between the size and mass of the different constituents of the Universe.

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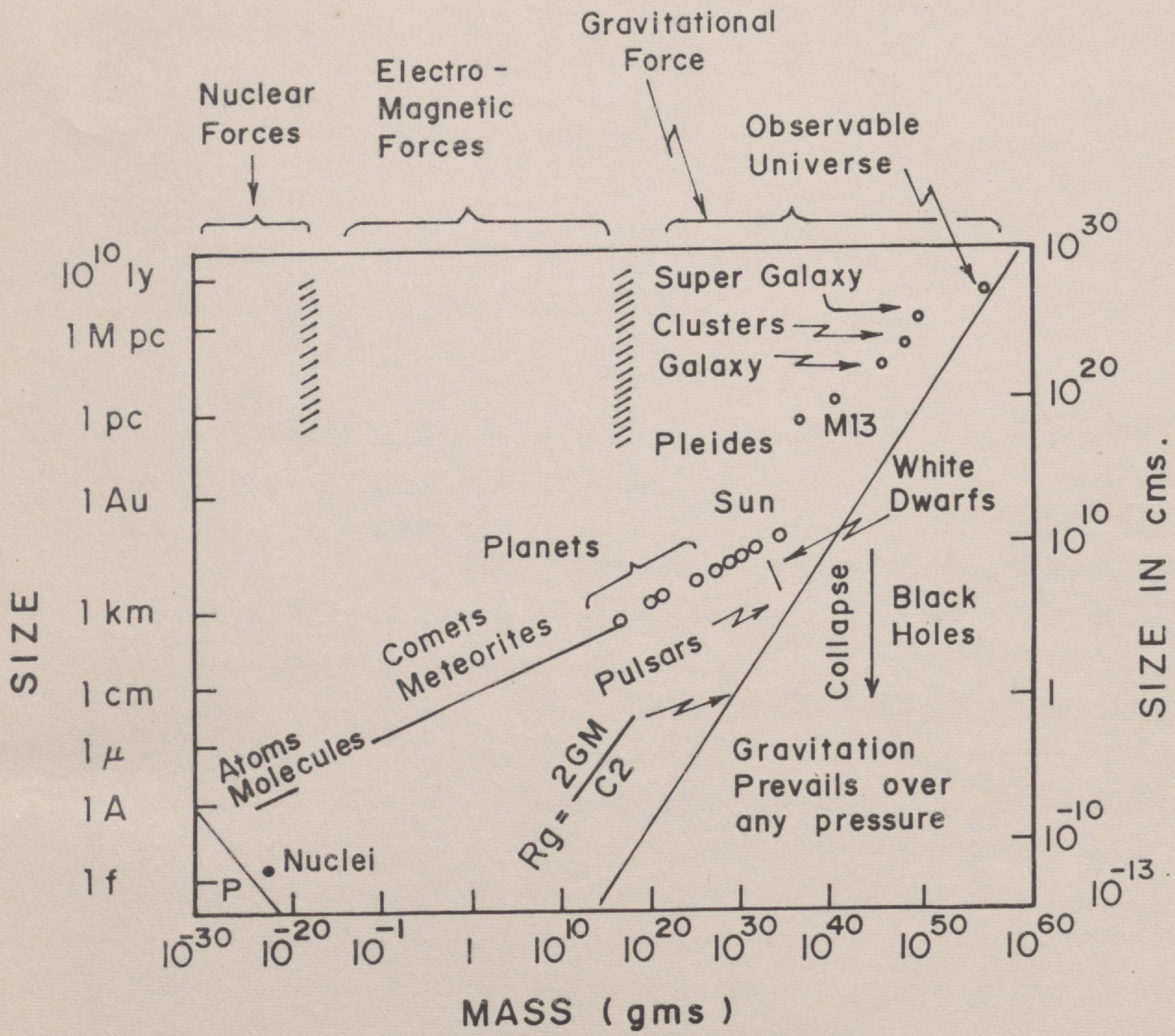

Fig.1 MASS AND SIZE OF THE STRUCTURAL UNITS OF THE UNIVERSE

[From Kleczek THE UNIVERSE]

The mass range of the structural units extends from 10^{-24} gms (mass of the nucleon) to 10^{56} gms, which is the total mass of the observable Universe. The corresponding size range is 10^{-13} to 10^{30} cms, with the heirarchy of celestial objects like Comets, Metreorites, Planets, Stars, Cluster of Stars, Galaxies and Clusters of Galaxies falling in between in terms of size and mass. It is also to be noted from the figure that majority of the objects populating the Universe satisfy the relation $Rg > \frac{2G.M}{C^2}$. It is only in the recent years that evidence has started accumulating on collapsed objects like Neutron Stars and Black Holes which fall in the category $Rg \leq \frac{2G.M}{C^2}$ The Universe in addition is also filled with photons, neutrinos, antineutrinos, electrons and positrons, which also play a major role in the history of the Universe.

3. The Expanding Universe.

Our current ideas on the origin of the Universe have arisen essentially out of parallel developments and the confluence of theoretical ideas stemming from the general theory of relativity and the astronomical observations made with the giant optical telescopes during the period 1917 - 1930.

Einstein had realised the implications of his general theory of relativity to the Cosmological problem and since at that time, the Universe was believed to be unchanging and static, had introduced the idea of a Cosmological repulsive force effective at very large distances, to overcome the attractive forces of gravity - Einstein had exchanged his ideas on this subject with de Sitter who came to the conclusion that Einstein's equations lead to an unstable exponentially expanding Universe. The Soviet Scientist Alexander Friedman found a flaw in Einstein's solution (which Einstein conceded later) and was the first to emphasise that the Universe is expanding and is associated with a hyperbolic velocity space. In 1925, Lemaitre traced this expansion back in time to the explosion of a "superdense atom" - the first germ of an idea of the Big Bang creation. In 1928 Robertson drew attention to the Cosmological Red Shift that would result from such an Universal expansion.

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Around the same period, the 60" and 100" telescopes in California were being used by Slipher and Hubble to explore and understand the structure of the bright patches in the sky - the Nebulae. They arrived at the unexpected and fascinating result that these are discrete galaxies composed of large number of Stars, similar to our own galaxy. Their observations led to another fundamental aspect of the Universe that these galaxies are receeding from us - the greater the distance of a galaxy from us, the greater is its velocity of recession as revealed by the red shift of the spectral lines — $\Delta\lambda/\lambda = z = k.r$ Assuming that the observed red shift is due to Doppler effect, Hubble deduced the famous relation $v = Hr$ where H is the Hubble's constant and v is the velocity of recession.

The Figure-2 shows the current status of this relation between the red shift and the distance of the galaxy expressed in terms of brightness magnitude. Hubble's original data corresponded to a very small range of distances. The validity of Hubble's relations is now established over a wide range of distances by Sandage.

It is most important to realise that this general expansion of the Universe is discernible only over distance scales of 100 to 300 megaparsecs (1 megaparsec $\sim 10^{24}$ cms). On this scale the number of Stars, and Galaxies is the same, in any region of space and on these scales we can talk about an average density of the Universe and also of homogeneity of the Universe.

The implications of such a universal expansion for Cosmology were first realised by Abbe Georges Lemaitre. Such a picture meant that as we go back in time any region of the Universe would have been in a highly squeezed state with much higher density, and this density would continuously go up as the Universe contracts more and more and will ultimately result in infinite density and therefore in a singularity.

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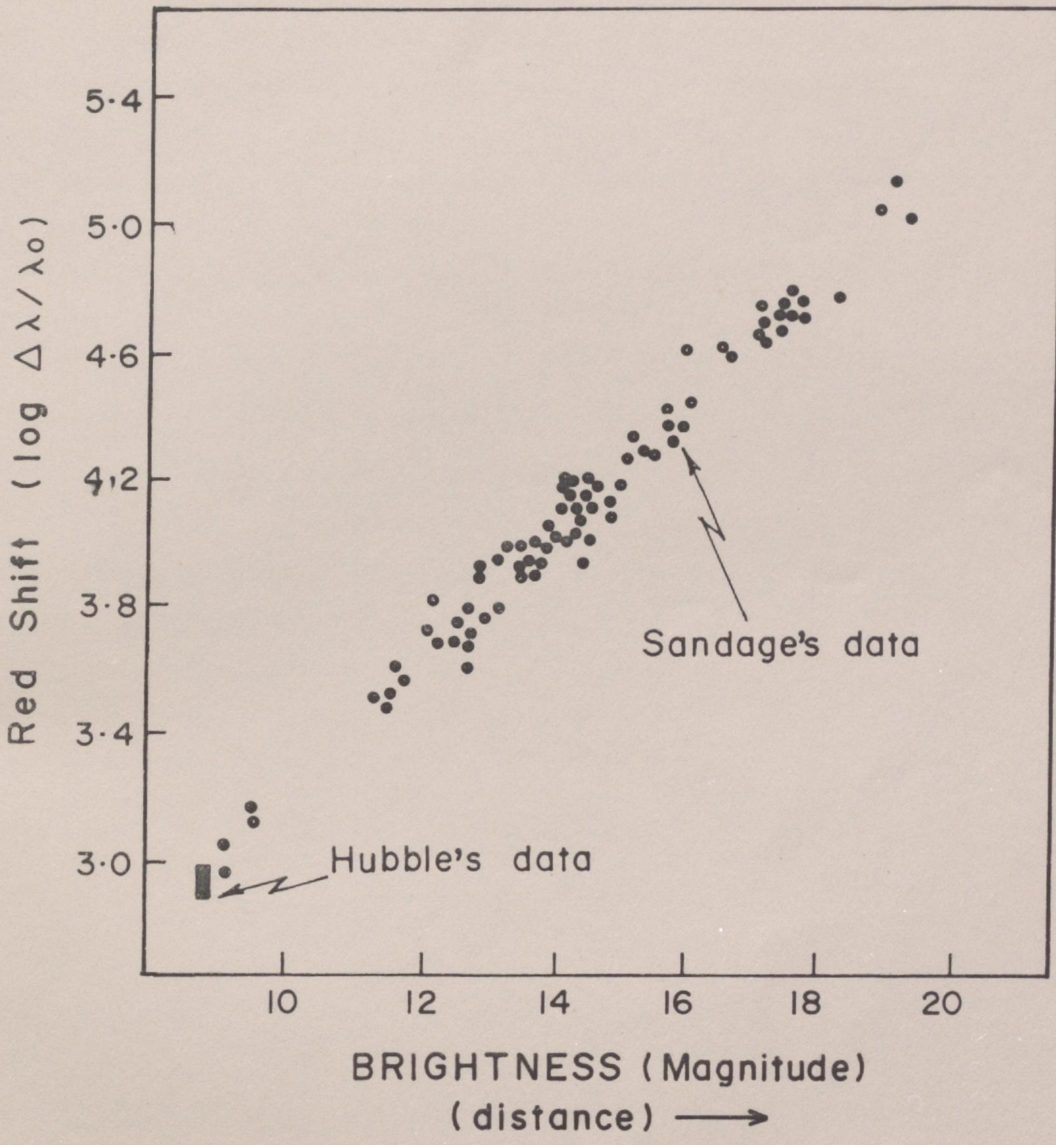

Fig. 2 EXPANSION OF THE UNIVERSE

Thus the Universe starts with the Big Bang singularity, and as some Scientists believe, "time" also started with this Big Bang explosion. The laws of Physics as are familiar to us, will not determine the initial state of this singularity. We can only use the physical laws to work out the evolution after the lapse of some finite time. The crucial question is how close in "time", can we get to the Big Bang Singularity ? Surprisingly as close as 10^{-43} seconds.

4. Radiation in the Universe.

The Universe consists not only of matter but also of radiation. In fact we learn about the state of the matter in the Universe only from the radiation that we receive in the different bands of the electromagnetic spectrum. The Figure-3 shows the spectrum of radiation that is encountered typically in a location far away from any single source as deduced from observations in the terrestrial neighbourhood. Eventhough there are several gaps in the observation, the information available is good enough to give us a general idea of the status of radiation in the Universe. The most dominant component in terms of "energy density" is in the Microwave radiation from milimetre to centimetre range.

The Microwave radiation was discovered accidentally by Penzias and Wilson in 1965. The spectral characteristic of this Microwave radiation as is known now is shown in the Figure-4. The spectrum corresponds to that of a black body of temperature $2.96^{\circ}K$. It is well established that the radiation is isotropic at the level of one part in 10^{4}. This very high degree of isotropy provides the best evidence for the assumption of homogeneity of the Universe. The energy density of microwave radiation is ~ 0.27 ev/cms^{3} and the Photon density is 400/cm^{3}. George Gamow, on the hypothesis of the Big Bang Universe, had predicted the possible existence of such a universal radiation as a relic of the initial hot phase and had estimated that its temperature now, would be about $5^{\circ}K$, rather close to the observed value.

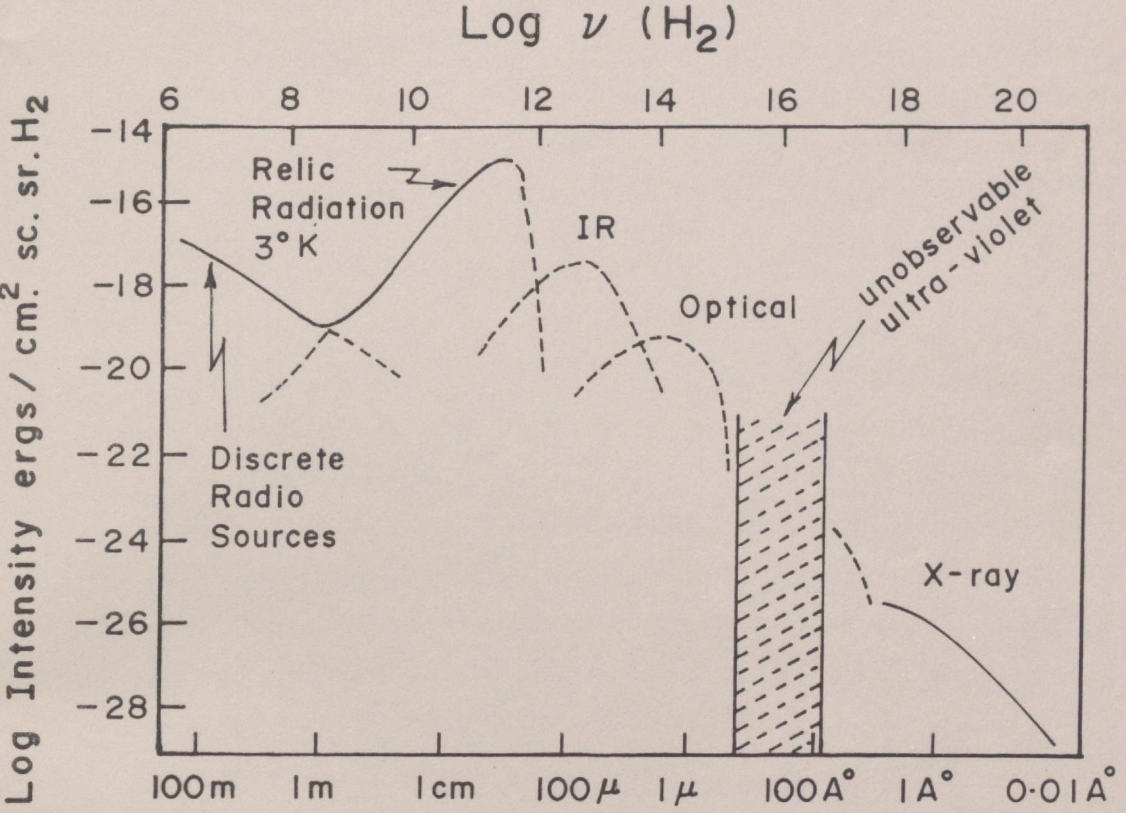

Fig.3 Spectrum of the Isotropic Background Radiation

Full lines - observation

Dashed lines - theoretical estimates

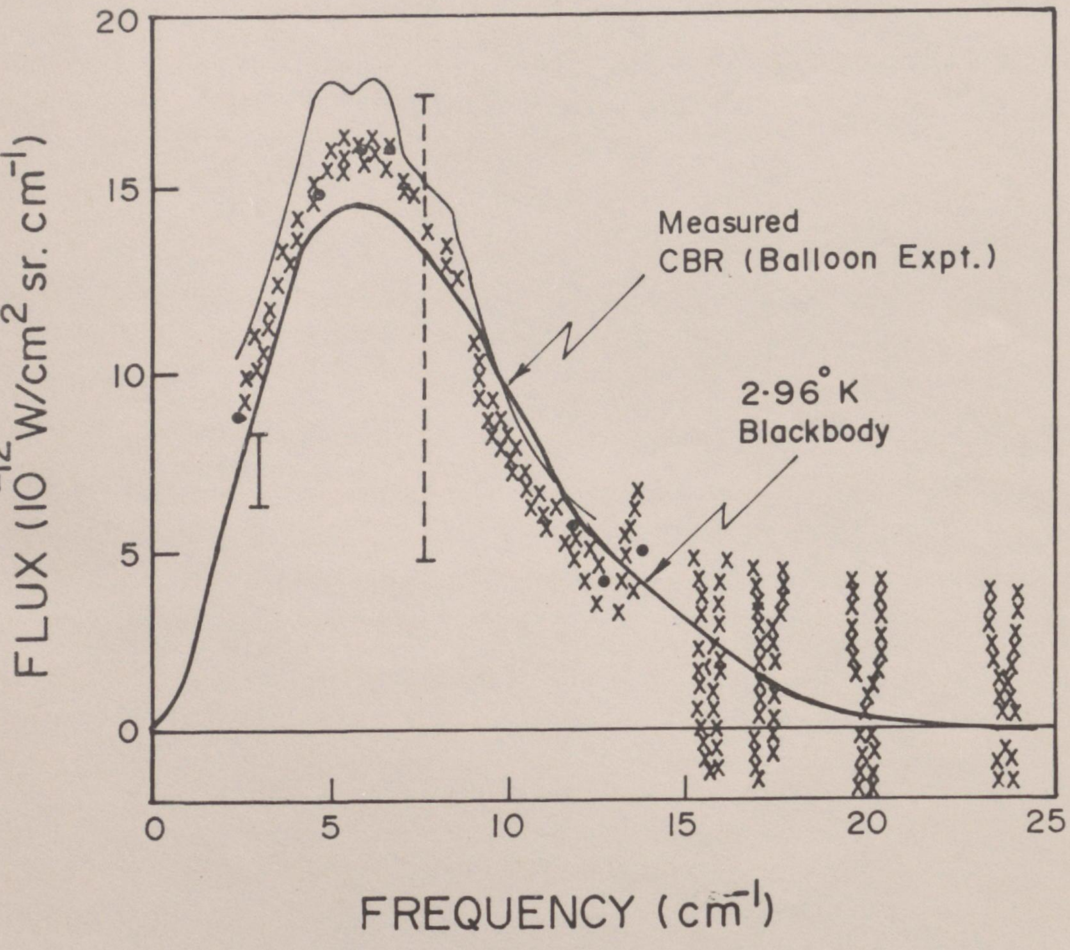

Fig. 4 SPECTRUM OF MICROWAVE RADIATION

The radiation density of 0.27 ev/cm^3 at the present epoch compared to the mass density of about $10^{-34} gms/cm^3$ is a thousand time less. The density of other components like the neutrinos are several orders of magnitude lower.

5. The Evolution of the Hot Universe.

We shall now go back in time and trace the physical conditions of the Universe when it was smaller and smaller and correspondingly hotter and hotter. The Figure-5 shows the rise of radiation and matter density as we go to earlier times. It is seen that the radiation energy density increases faster than matter density and overtakes the latter around a million years from the Big Bang. If we take the present scale of the Universe at say 2×10^{10} yrs from the Big Bang as 1, then the scale factor becomes 1/1500 around 10^7 yrs when the temperature shoots upto 4000^oK and the density to $10^{-20} gms/cm^3$. Around a million years from the Big Bang, the scale factor would be 1/20,000 and the temperature close to $60,000^oK$. As we get to still earlier times, around a few minutes, the temperature would exceed the billion mark.

Since we are concerned in this paper with "the first moments of the universe", we will not consider the Stellar and Radiation, and Plasma eras which represent the periods of the build up of large scale structures as we see them today - the ionized clouds, molecular clouds, the stars, the galaxies, clusters of galaxies, etc.. We shall proceed straight to a consideration of the happenings earlier than a few minutes from the Big Bang.

6. Happenings in the Universe earlier than a few minutes.

As the temperature of the Universe goes beyond $10^{9}\ ^oK$ and the density higher than $10^9 gms/cm^3$, the application of our knowledge from the field of high energy physics on elementary particle

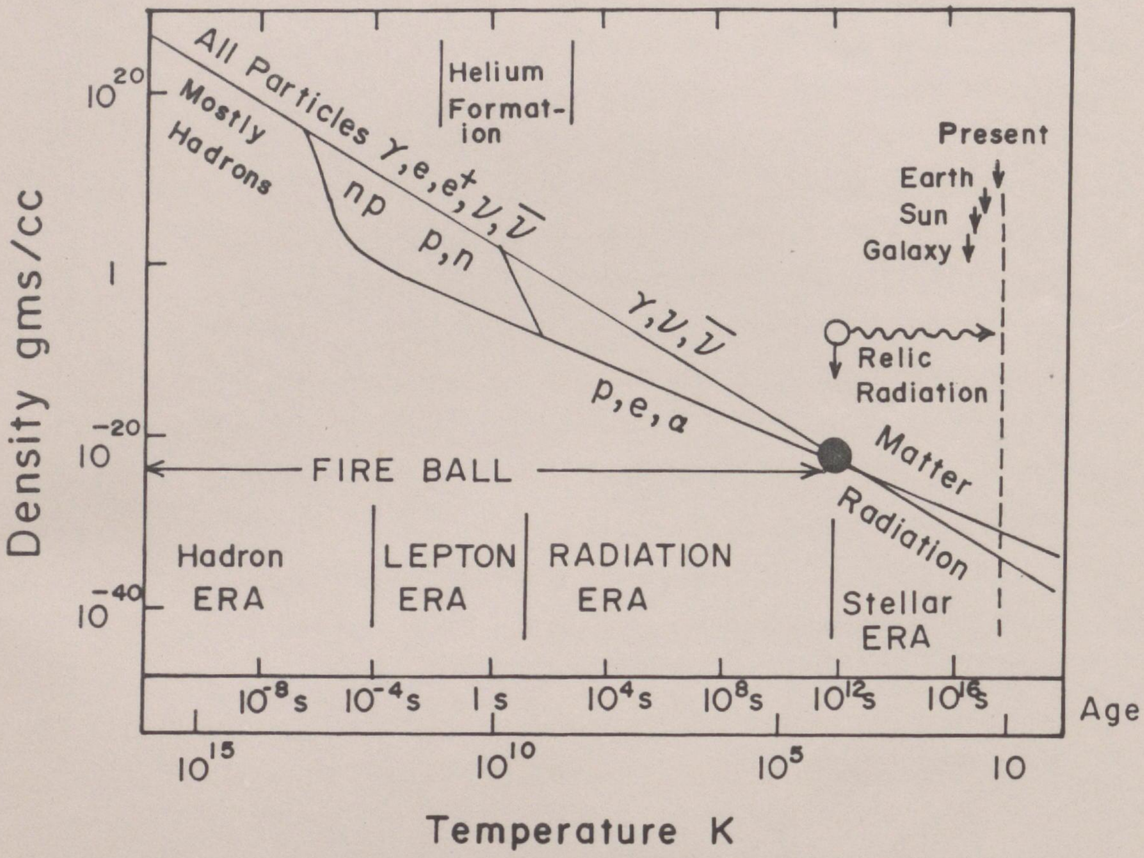

Fig. 5 Plausible Scenario of Evolution of the universe (10^{-8}-10^{16}s)

[From KLECZEK - The universe]

production becomes necessary and relavant. The threshold for the production of electron - positron pairs is 5.93×10^{9} ^{o}K, for the production of Pi-mesons 1.56×10^{12} ^{o}K and for Nucleon - Antinucleon production 1.1×10^{13} ^{o}K. The table I, shows the processes that take place from a microsecond when the temperature of the Universe was 10^{13} ^{o}K, to a few minutes, when the temperature dropped to 10^{9} ^{o}K. An important feature of this period is the production of Helium-4, which carries almost 25% of the mass of the Universe today and was all produced during this very early phase of the Universe. This is also the phase when all the fundamental particles produced (see table II) earlier than a microsecond disappear due to annihilations except protons, neutrons, electrons and neutrinos and antineutrinos which form the constituents of the present Universe. By this time the dominance in the number of photons over nucleons by a factor of 10^{9} - a feature that persists upto the present time was also decided. This radiation dominance is one of the very challenging aspects of the Universe for which an answer has been found in the happenings earlier than a microsecond.

7. The very early Universe : 10^{-6} to 10^{-43} seconds.

As we move to a time less than a microsecond from the Big Bang, the temperature rises from 10^{13} ^{o}K to 10^{28} ^{o}K at 10^{-36} second. Here the crucial question comes up - Can the temperature rise very much beyond the thermodynamical Hagedorn limit of 2×10^{12} ^{o}K, that was set on the basis of production of large numbers of mesons at these temperatures ? We also move to a distance scale very much less than the nuclear size of $\sim 10^{-13}$cm. How is this possible ? These questions find answers from comparatively recent developments in physics, in particular the discovery that the elementary particles, - the hadrons like the protons, neutrons, pi-mesons, etc., are themselves composite particles. They are made of more fundamental units - "the quarks" which have rather strange properties like fractional charge, fractional Baryon number, but are fermions and have spin 1/2.

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They are point particles whose dimensions are deduced to be less than 10^{-18}cm. Though free quarks with their characteristic properties have not been seen in the accelerator experiments, or in cosmic rays, there are good reasons to beleive in their existence. The new theory of Quantum Chromodynamics (QCD) is concerned with the question of "quark confinement" and "quark-quark" forces mediated by the mass-less bosons called 'gluons'. A large number of experimental features discovered at the accelerators are beautifully explained by the quark theory. From the point of view of the very early Universe the most important consequences of the quark theory are that the temperature limit of few times 10^{12} °K can be exceeded by orders of magnitude and one can proceed to dimensions much smaller than 10^{-13}cms.

Another important development in high energy physics that is particularly relavant to this very early phase of the Universe is the "trend" that has been discerned towards the "unification" of the four fundamental forces - Strong, Weak, Electromagnetic and Gravitational. The discovery of the intermediate Vector Bosons $W^{\pm}$ and Z^{o}, has put the final stamp on the success of the Electro-Weak theory - the unification of the electromagnetic and weak forces. Further extension of the Gauge Theories which brought about this electro-weak unification in the framework of Quantum Chromodynamics, lead to possibilities of the unification of the Strong and Electro-Weak interactions, to the so called Grand Unification (GUT). This predicts the existence of particles, the lepto-quarks (X, $\bar{X}$), in the mass range of 10^{15}Gev/C^2 - which mediate quark-quark interactions at extremely close range, and also lead to their production. It is clear that the production of such particles which requires energies greater than 10^{24}ev, in any terrestrial accelerator is beyond the realm of feasibility. However, the same GUT theories lead to the possibility that the Protons, the stablest of all particles in the Universe, undergo spontaneous decay - ofcourse with a life time in excess of 10^{29} years. The three quarks that compose the proton, because of the fact that they are confined to a volume less than 10^{-39}cm^3, move around with very high velocities; If two of them come very close to each other then they will exchánge a massive lepto-quark and lead to the

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production of a lepton and an antiquark which immediately interacts with the remaining quark to give a meson. Thus the proton will decay into a lepton and a meson. There are many other decay modes possible. There are quite a few experiments in the world including the one at the Kolar Gold Fields in India, which are specifically designed to look for this very very rare phenomenon of Proton Decay.

These grand unification ideas have important implications to the very early Universe. The Figure-6, shows the variation of the coupling strengths of the electro-weak and strong interactions as a function of energy. The corresponding temperatures of the Universe at the respective times are also shown in the figure. What this trend means is that before 10^{-36}s, all the three forces were one and the same, and the temperature high enough to produce the lepto-quarks $(X, \bar{X})$ - which are the very first species of particles to be produced in this heirarchy of particle production. The lepto-quarks give rise to leptons and quarks as the Universe cools. It is important to point out that at the limiting time of 10^{-43}seconds, the size of the Universe is around 10^{-33}cms and the density 10^{94}gms/cm^3. During this phase of the Universe, massive magnetic monopoles of mass $\sim 10^{16}$Gev/C^2 could be produced, in addition to $X, \bar{X}$.

8. The Planckian Era.

Why do we stop our considerations at 10^{-43}seconds ? Why not go to still smaller interval of time ?

It turns out that the smallest time interval that can be constructed out of the three familiar constants G, $\hbar$, and C is the Planck time = $\left[\frac{G\hbar}{C^5}\right]^{1/2} \backsimeq 1.3 \times 10^{-43}$seconds, and the smallest space interval, the Planck Length = $\left[\frac{G\hbar}{C^3}\right]^{1/2} \backsimeq 1.6 \times 10^{-33}$cm.

At these lengths, it is surmised that "quantum gravity" effects will start dominating. There is no good quantum gravity theory yet which can help us to proceed further. There are theoretical efforts based on Super Symmetry, Super Gravity and String Theories to explore this domain. These are still in their early stages.

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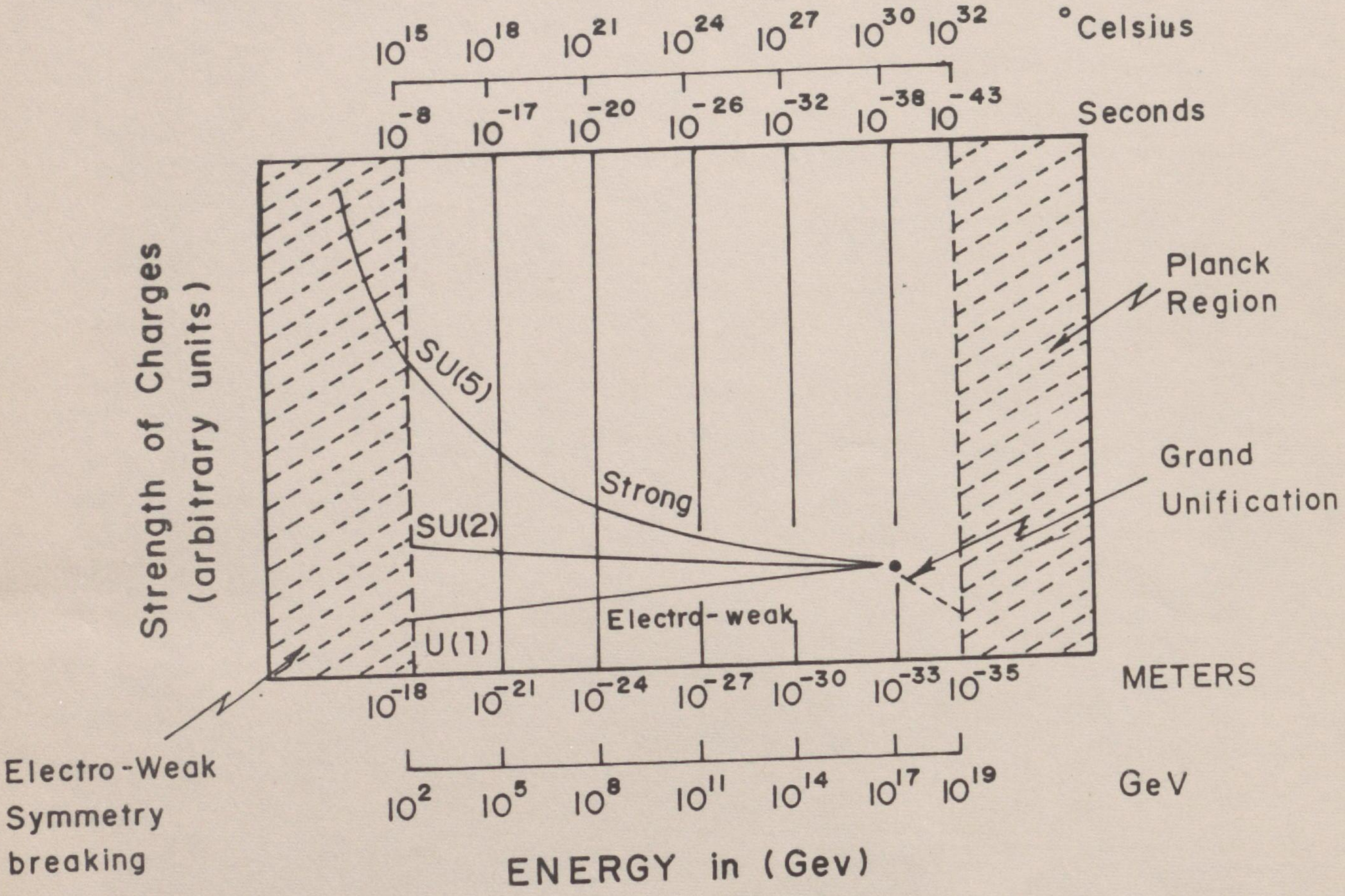

Fig. 6 The very early universe and Grand unification.

[From M. Green SUPERSTRINGS]

Time from Big Bang	Temperature	Status of the Universe
180 Seconds	10^9 °K	Nucleo Synthesis - Deuterium and Helium.
14 Sc	3×10^9 °K	$e^+ e^-$ annihilation disappearance of Positrons.
1 Sc	10^{10} °K	Neutron/Proton ratio freezes out of Thermal Equilibrium.
10^{-3} Sc	3×10^{10} °K	Disappearance of all Muons and Hadrons except Neutrons and Protons.
10^{-6} Sc	10^{13} °K	Quark-Gluon plasma in thermal equilibrium with Photons and Leptons.

TABLE I : The Big Bang Scenario : 3 mins. to a microsecond.

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Time from Big Bang	Temperature	Status of the Universe
10^{-6} Seconds	10^{13} ^{o}K $(10^{9}ev)$	pronounced changes in the non-gravitational properties of matter. Weak interactions and electromagnetic interactions have the same strength.
10^{-12} Sc	10^{16} ^{o}K $(10^{12}ev)$	Spontaneous Symmetry breaking Higgs mechanism operates to generate masses of $W^{\pm}$, Z^{o} from mass-less boson state.
10^{-36} Sc	10^{28} ^{o}K $(10^{24}ev)$	Unification of Strong and Electro-Weak forces Production of the lepto-quarks $(X,\bar{X})$, Massive Magnetic Monopoles $(\backsim 10^{16}Gev/C^{2})$
10^{-43} Sc (PLANCK TIME)	10^{32} ^{o}K $(10^{28}ev)$	Barrier quantum gravity becomes important. No good theories yet to make any predictions.

TABLE II : The Big Bang Scenario: 10^{-6} to 10^{-43}Seconds.

9. The Big Bang Scenario:

We cannot say anything from 0 to 10^{-43} seconds. Immediately after the Planck Era ($\sim 10^{-43}$ seconds) the Universe was at a temperature of $\sim 10^{32}$ °K, density $\sim 10^{94}$ gms/cm^3 and dimension $\sim 10^{-33}$ cms. At this temperature the Super heavy particles, the lepto-quarks were produced as also the magnetic monopoles. As the Universe cools the lepto-quarks lead to the formation of the quark-lepton soup. By about a microsecond the Universe consisted of nucleons, antinucleons, electrons, muons, pions, neutrinos, photons and gravitons. By about a millisecond, many of these annihilated leaving only the protons, neutrons, photons, electrons and neutrinos and antineutrinos. The Deuterium and Helium formed as the Universe cooled further. This was followed by the formation of ionized gases, Stars, Galaxies, etc.. The dominance of matter over antimatter, and of radiation over matter can be adequately accounted for on the basis of this scenario.

What is amazing is, that we are able to extrapolate over almost 60 decades of time from 5×10^{17} seconds (Now) to 10^{-43} seconds, over 128 decades of density from 10^{-34} gms/cm^3 to 10^{94} gms/cm^3 and over a temperature scale of 3^{o}K to 10^{32} °K, and come to some quantitative understanding of the early Universe; and its evolutionary course. This has been the combined achievement of astronomy, astrophysics and high energy physics and a synthesis of our knowledge of the micro and macrocosms based on a unification of the forces of nature.

10. The Inflationary Universe:

Some outstanding problems remain, for understanding which further ramifications of the very early phase of the Big Bang expanding Universe are necessary. The outstanding problems are:

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(a) The Horizon Problem:

The experimentally well established isotrophy of the microwave radiation at a level better than 1 in 10^4, implies that very distant parts of the Universe, which are beyond each other's horizon (defined as the distance Ct, where C is the velocity of light and t is the time from Big Bang) are at the same temperature. Since no physical process that can bring about **such** an equilisation of temperature can progress faster than light, this feature is one of the unsolved riddle's of Cosmology. The same situation would have persisted at earlier and earlier epoch's in the kind of picture that we have presented above. The 3^o radiation that we receive from the horizon today decoupled from the hot plasma around 10^5years after the Big Bang. If we consider two locations on opposite sides of us in the horizon today, they would be 10^7years apart when this decoupling took place and could not have had a causal connection at that time. How then do we understand the situation that the temperature is identical at these locations now ?

(b) The Flatness Problem:

Will the Universe expand for ever ? This depends on whether the average density of the Universe is higher or lower than a critical density which is calculated as 10^{-29}gms/cm^3 in the Friedman Universe models. We have already seen that the estimated matter density is close to this critical value - around 10^{-29} to 5,10^{-30}gms/cm^3. The radiation density at the present time is however much lower. But there are reasons to believe that there could be considerable amount of 'hidden mass' in the Universe which is so cold that it is not perceived through the electromagnetic radiation. Also if the neutrinos which are abundant in terms of numbers, do have even a small mass, say of the order of $\sim$10 ev, their contribution to mass density may even exceed the ordinary matter density.

In the Friedman theory, the average density varies as $t^{-3/2}$ in the matter dominated era and as t^{-2} in the radiation dominated era (earlier than a million years from cosmic explosion) where 't' is the Cosmological time. But the "critical density" in the same theoretical model varies only as t^{-1}. This means that near to the Planck time (10^{-43}s) the energy density is "fine tuned" to an accuracy of the order of 10^{-59}. If this was not so the Universe would recollapse immediately after the Planck era. You can imagine how very exceptional our Universe **is**.

(c) The Monopole Problem:

In the era before 10^{-36} seconds, the possibility exists of profuse Super massive ($\sim 10^{16}$ Gev/C^2) monopole production. Their numbers could be as large as that of Nucleons. The monopoles cannot be easily destroyed. There is no evidence for such high intensity of monopoles (Also they would upset completely the mass densities. The Universe would have collapsed within 10,000 years of Big Bang). How did the Universe get rid of these monopoles or were they not produced at all ?

(d) Fluctuations+

The large scale structures in the Universe arose out of fluctuations in density. How did these fluctuations take place in an otherwise highly homogeneous, isotropic Universe expanding uniformly.

All these questions find an answer in a new scenario first proposed by Alan Guth, which has similarity to de Sitter's solutions of Einstein's equation, without the Cosmological constant term. According to Guth, the Universe, begining in a hot highly symmetric state with all the forces united (GUT), undergoes a phase transition and expands exponentially by a large factor in a short time ($\sim 10^{-30}$s).

During this phase transition the temperature falls. The conditions that prevail after this transition provide answers to the questions raised above. There is ofcourse a further complication - How to stop this exponential expansion ?

There are many Cosmological theories. In fact there are many solutions even to the Cosmological Equations of Einstein, and each one of them leads to a different Cosmology. The Big Bang Cosmology is perhaps the one that explains most of the astronomical observations, especially with the modifications of 'inflation' introduced into it.

I wish to thank the organisers of the D.M. Bose Centenary Celebrations for inviting me to participate in this Symposium.
In preparing this talk and the manuscript, I have made use of several books and articles which deal with this subject at a popular level.
I have listed these below. I recommend them for further reading by those who would like to get a deeper insight into this most fascinating problem of the origin of the Universe.

For Further Reading:

The Universe	- Josip Kleczek (Reidel Publishing Co.) Dordrecht-Holland/Boston.
The Left Hand of Creation	- John Barrow and Joseph Silk (Counterpoint, London)
The First Three Minutes	- Steven Weinberg (Bantam, London)
The Magic of Galaxies & Stars	- L.E. Gurevich and A.D. Chernin (Mir Publishing, Moscow)
The Early Universe and High Energy Physics.	- David N Schramm, Physics Today - April 1983.
The Accidental Universe	- P.C.W. Davies (Cambridge University Press)
Superstrings	- Michael Green (Scientific American - September 1986)

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The Figure-1 summaries in a way our current knowledge regarding the composition, the distance scale, and the relation between the size and mass of the different constituents of the Universe.

The mass range of the structural units extends from 10^{-24} gms (mass of the nucleon) to 10^{56} gms, which is the total mass of the observable Universe. The corresponding size range is 10^{-13} to 10^{28} cms, with the hierarchy of celestial objects like Comets, Meteorites, Planets, Stars, Cluster of Stars, Galaxies and Cluster of Galaxies falling in between in terms of size and mass. It is also to be noted from the figure that majority of the objects populating the Universe satisfy the relation $Rg > \frac{2G.M}{C^2}$. It is only in the recent years tha evidence has started accumulating on collapsed objects like Neutron Stars and Black Holes which fall in the category $Rg \leqslant \frac{2G.M}{C^2}$. The Universe in addition is also filled with photons, neutrinos, antineutrinos, electrons and positrons, which also play a major role in the history of the Universe.

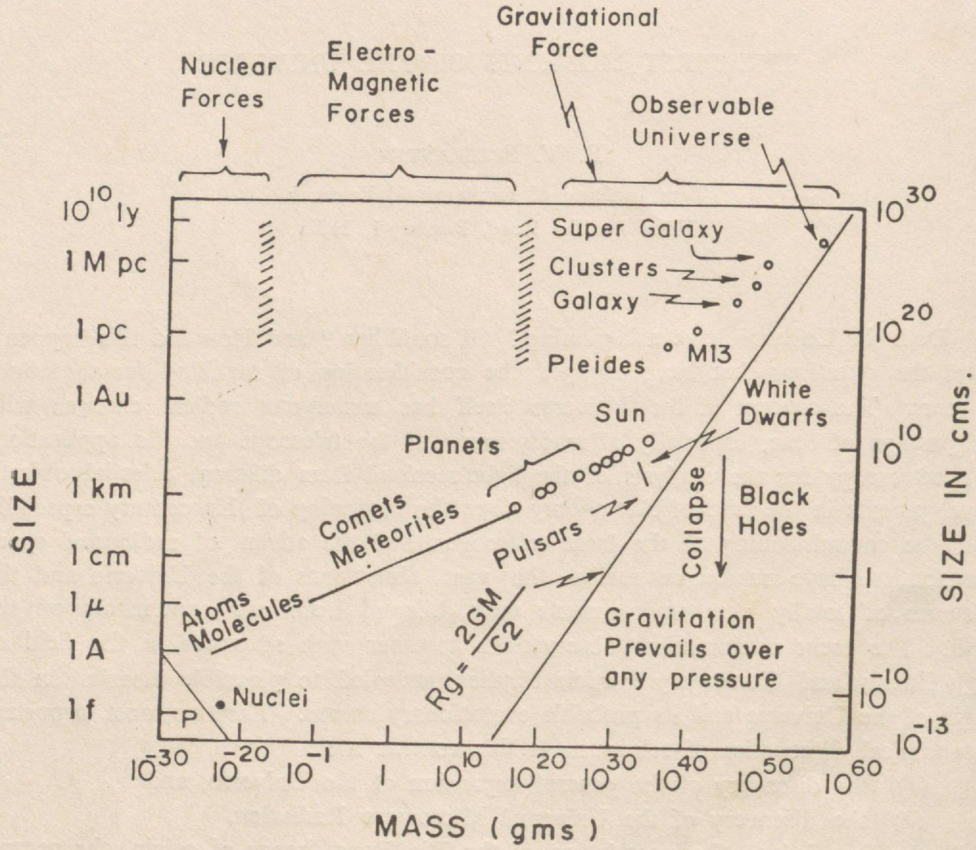

Fig. 1. Mass and size of the structural units of the universe
[From Kleczek THE UNIVERSE]

3. *The Expanding Universe.*

Our current ideas on the origin of the Universe have arisen essentially out of parallel developments and the confluence of theoretical ideas stemming from the general theory of relativity and the astronomical observations made with the giant optical telescopes during the period 1917—1930.

Einstein had realised the implications of his general theory of relativity to the Cosmological problem and since at that time, the Universe was believed to be unchanging and static, had introduced the idea of a Cosmological repulsive force effective at very large distances, to overcome the attractive forces of gravity—Einstein had exchanged his ideas on this subject with de Sitter who came to the conclusion that Einstein's equations lead to an unstable exponentially expanding Universe. The Soviet scientist Alexander Friedman found a flaw in Einstein's solution (which Einstein conceded later) and was the first to emphasise that the Universe is expanding and is associated with a hyperbolic velocity space. In 1925, Lemaitre traced this

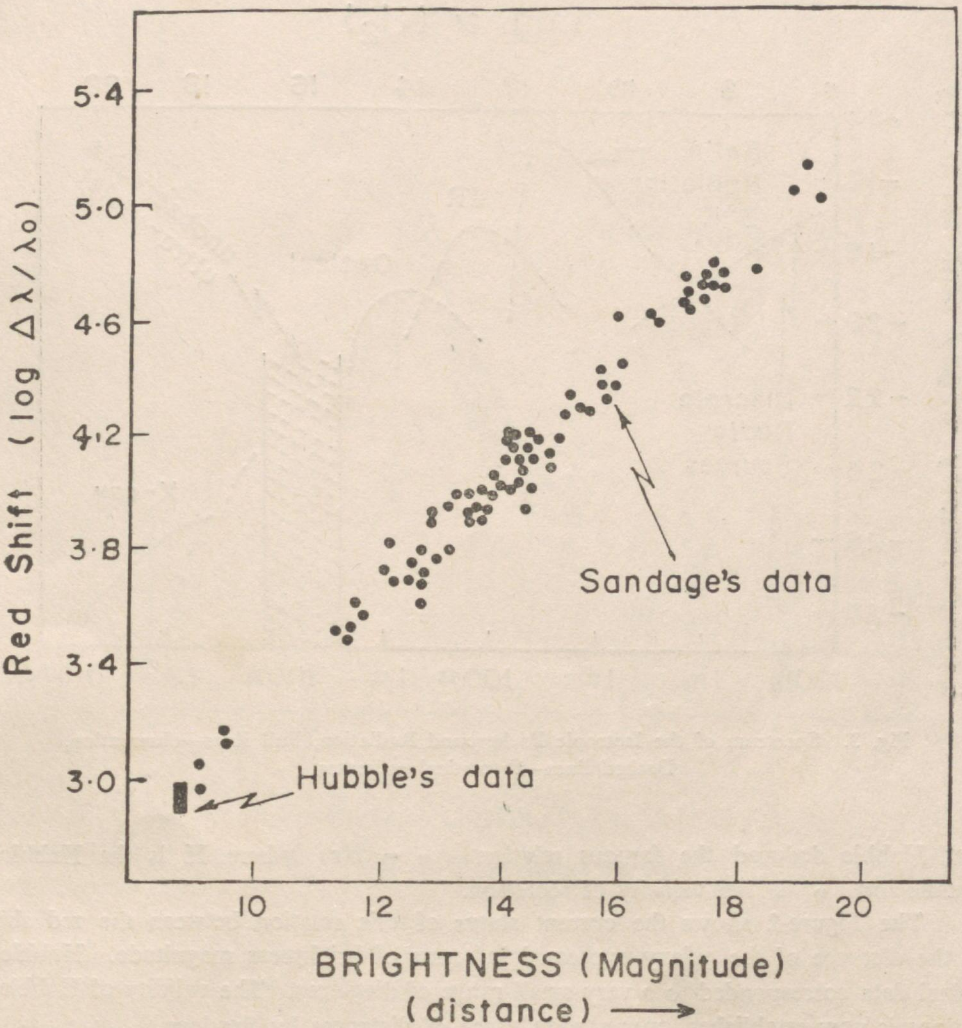

Fig. 2. Expansion of the universe

expansion back in time to the explosion of a "superdense atom"—the first germ of an idea of the Big Bang creation. In 1928 Robertson drew attention to the Cosmological Red Shift that would result from such an Universal expansion.

Around the same period, the 60″ and 100″ telescopes in California were being used by Slipher and Hubble to explore and understand the structure of the bright patches in the sky—the Nebulae. They arrived at the unexpected and fascinating result that these are discrete galaxies composed of large number of Stars, similar to our iwn galaxy. Their observations led to another fundamental aspect of the Universe that these galaxies are receeding from us—the greater the distance of a galaxy from us, the greater is its velocity of recession as revealed by the red shift of the spectral lines— $\Delta\lambda / \lambda = Z = kr$. Assuming that the observed red shift is due to Doppler

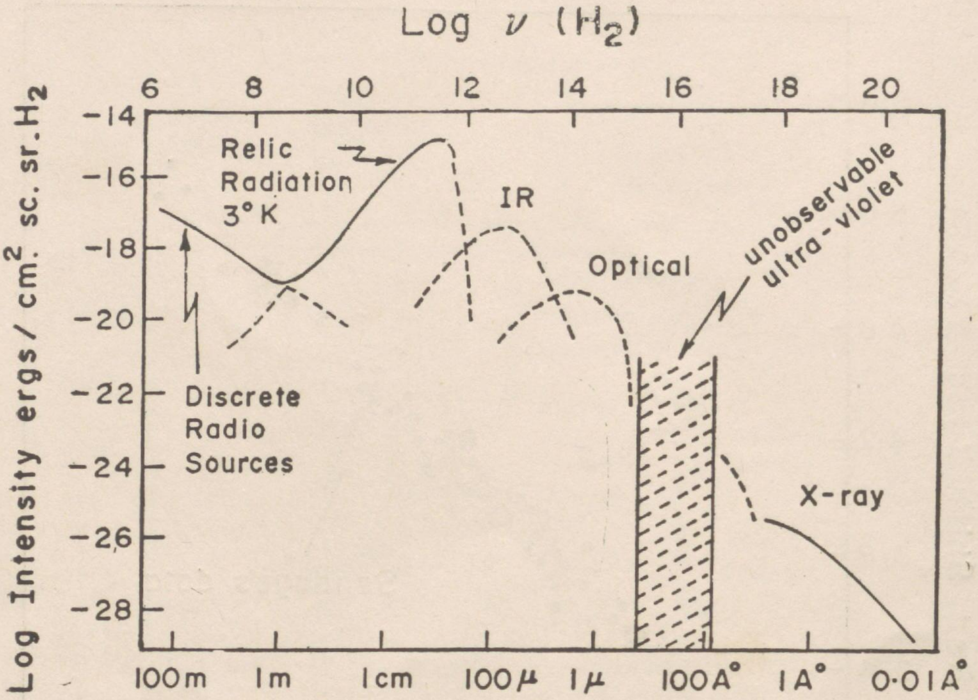

Fig. 3. Spectrum of the Isotropic Background Radiation, Full lines—observation, Dashed lines—theoretical estimates.

effect, Hubble deduced the famous relation $v = \mathbf{H}\mathbf{r}$ where H is the Hubble's constant and v is the velocity of recession.

The Figure-2 shows the current status of this relation between the red shift and the distance of the galaxy expressed in terms of brightness magnitude. Hubble's original data corresponded to a very small range of distances. The validity of Hubble's relations is now established over a wide range of distances by Sandage.

It is most important to realise that this general expansion of the Universe is discernible only over distance scales of 100 to 300 megaparsecs (1 megaparsec $\sim 10^{24}$ cms). On this scale the number of Stars, and Galaxies is the same, in any region of space and on these scales we can talk about an average density of the Universe and also of homogeneity of the Universe.

The implications of such a universal expansion for Cosmology were first realised by Abbe Georges Lemaire. Such a picture meant that as we go back in time any region of the Universe would have been in a highly squeezed state with much higher density, and this density would continuously go up as the Universe contracts more and more and will ultimately result in infinite density and therefore in a singularity. Thus the Universe starts with the Big Bang singularity, and as some Scientists believe, "time" also started with this Big Bang explosion. The laws of Physics as are familiar to us, will not determine the initial state of this singularity. We can only use the physical laws to work out the evolution after the lapse of some finite

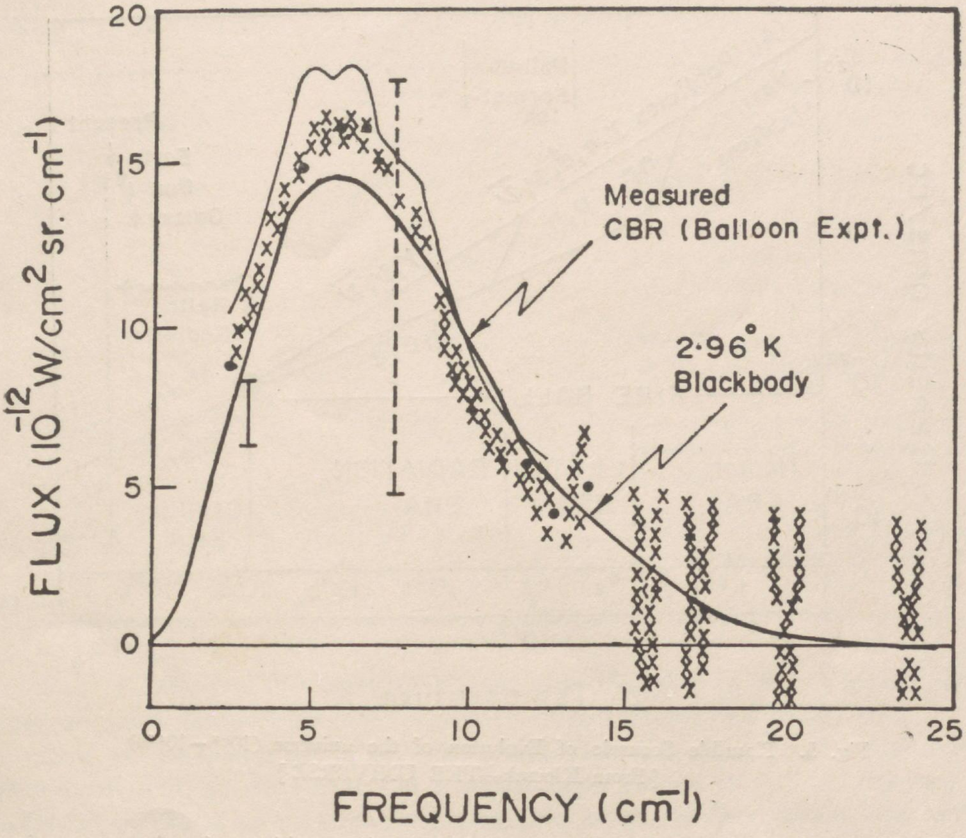

Fig. 4. Septrum of Microwave Radiation

time. The crucial question is how close in "time", can we get to the Big Bang Singularity? Surprisingly as close as 10^{-43} seconds.

4. *Radiation in the Universe.*

The Universe consists not only of matter but also of radiation. In fact we learn about the state of the matter in the Universe only from the radiation that we receive in the different bands of the electromagnetic spectrum. The Figure-3 shows the spectrum of radiation that is encountered typically in a location far away from any single source as deduced from observations in the terrestrial neighbourhood. Eventhough there are several gaps in the observation, the information available is good enough to give us a general idea of the status of radiation in the Universe. The most dominant component in terms of "energy density" is in the Microwave radiation from milimetre to centimetre range.

The Microwave radiation was discovered accidentally by Penzias and Wilson in 1965. The spectral characteristic of this Microwave radiation as is known now is shown in the Figure-4. The spectrum corresponds to that of a black body of temperature 2.96°K. It is well established that the radiation is isotropic at the level of one part in

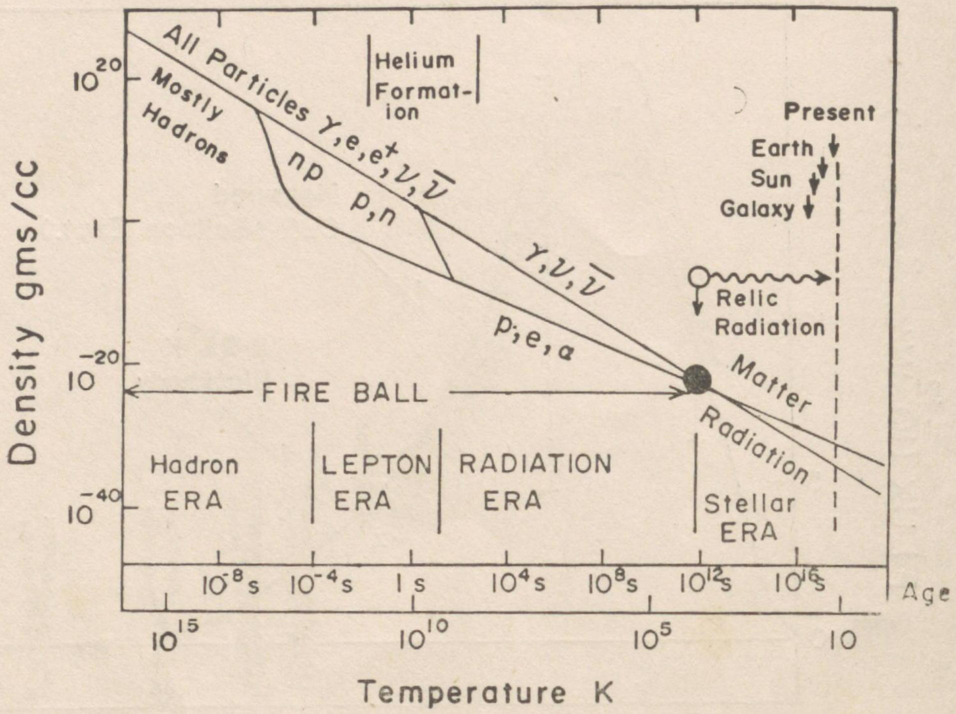

Fig. 5. Plansible Scenario of Evolution of the universe ($10^{-8}-10^{16}$s)
[From Kleczek—THE UNIVERSE]

10^4. This very high degree of isotropy provides the best evidence for the assumption of homogeneity of the Universe. The energy density of microwave radiation is ~ 0.27 ev/cms^3 and the Photon density is 400/cm^3. George Gamow, on the hypothesis of the Big Bang Universe, had predicted the possible existence of such a universal radiation as a relic of the initial hot phase and had estimated that its temperature now, would be about 5°K, rather close to the observed value.

The radiation density of 0.27 ev/cm^3 at the present epoch compared to the mass density of about 10^{-34} gms/cm^3 is a thousand time less. The density of other components like the neutrinos are several orders of magnitude lower.

5. *The Evolution of the Hot Universe.*

We shall now go back in time and trace the physical conditions of the Universe when it was smaller and smaller and correspondingly hotter and hotter. The Figure-5 shows the rise of radiation and matter density as we go to earlier times. It is seen that the radiation energy density increases faster than matter density and overtakes the latter around a million years from the Big Bang. If we take the present scale of the Universe at say 2×10^{10} yrs from the Big Bang as 1, then the scale factor becomes 1/1500 around 10^7 yrs when the temperature shoots upto 4000°K and the density to 10^{-20}gms/cm^3. Around a million years from the Big Bang, the scale factor

TABLE I : The Big Bang Scenario : 3 mins. to a microsecond.

Time from Big Bang	Temperature	Status of the Universe
180 Seconds	10^9 °K	Nucleo Synthesis—Deuterium and Helium.
14 Sc	3×10^9 °K	e^+ $e-$ annihilation, disappearance of Positrons.
1 Sc	10^{10} °K	Neutron/Proton ratio freezes out of Thermal Equilibrium.
10^{-3} Sc	3×10^{10} °K	Disappearance of all Muons and Hadrons except Neutrons and Protons.
10^{-6} Sc	10^{13} °K	Quark-Gluon plasma in thermal equilibrium with Photons and Leptons.

would be 1/20,000 and the temperature close to 60,000°K. As we get to still earlier times, around a few minutes, the temperature would exceed the billion mark.

Since we are concerned in this paper with "the first moments of the universe", we will not consider the Stellar and Radiation, and Plasma eras which represent the periods of the build up of large scale structures as we see them today—the ionized clouds, molecular clouds, the stars, the galaxies, clusters of galaxies, etc. We shall proceed straight to a consideration of the happenings earlier than a few minutes from the Big Bang.

6. *Happenings in the Universe earlier than a few minutes.*

As the temperature of the Universe goes beyond 10^9 °K and the density higher than 10^9 gms/cm^3, the application of our knowledge from the field of high energy physics on elementary particle production becomes necessary and relevant. The threshold for the production of electron-positron pairs is 5.93×10^9 °K, for the production of Pi-mesons 1.56×10^{12} °K. and for Nucleon-Antinucleon production 1.1×10^{13} °K. The table I, shows the processes that take place from a microsecond when the temperature of the Universe was 10^{13} °K, to a few minutes, when the temperature dropped to 10^9 °K. An important feature of this period is the production of Helium-4, which carries almost 25% of the mass of the Universe today and was all produced during this very early phase of the Universe. This is also the phase when all the fundamental particles produced (see table II) earlier than a microsecond disappear due to annihilations except protons, neutrons, electrons and neutrinos and antineutrinos which form the constituents of the present Universe. By this time the dominance in the number of photons over nucleons by a factor of 10^9—a feature that persists upto the present time was also decided. This radiation dominance is one

TABLE II : The Big Bang Scenario: 10^{-6} to 10^{-43} Seconds.

Time from Big Bang	Temperature	Status of the Universe
10^{-6} Seconds	10^{13} ^{0}K (10^{9}ev)	pronounced changes in the non-gravitational properties of matter. Weak interactions and electromagnetic interactions have the same strength.
10^{-12} Sc	10^{16} ^{0}K (10^{12}ev)	Spontaneous Symmetry breaking ; Higgs mechanism operates to generate masses of $W^{\pm}$, Z^{0} from massless boson state.
10^{-36} Sc	10^{28} ^{0}K (10^{24}ev)	Unification of Strong and Electro-Weak forces ; Production of the lepto-quarks (X, X), Massive Magnetic Monopoles ($\sim$ 10^{16} Gev/C^{2}) Barrier
10^{-43} Sc (PLANCK TIME)	10^{32} ^{0}K (10^{28}ev)	quantum gravity becomes important. No good theories yet to make any predictions.

of the very challenging aspects of the Universe for which an answer has been found in the happenings earlier than a microsecond.

7. *The very early Universe : 10^{-6} to 10^{-43} seconds.*

As we move to a time less than a microsecond from the Big Bang, the temperature rises from 10^{13} °K to 10^{28} °K at 10^{-36} second. Here the crucial question comes up—Can the temperature rise very much beyond the thermodynamical Hagedorn limit of 2×10^{12} °K, that was set on the basis of production of large numbers of mesons at these temperatures ? We also move to a distance scale very much less than the nuclear size of $\sim$ 10^{-13} cm. How is this possible ? These questions find answers from comparatively recent developments in physics, in particular the discovery that the elementary particles,—the handrons like the protons, neutrons, pi-mesons, etc., are themselves composite particles. They are made of more fundamental units—"the quarks" which have rather strange properties like fractional charge, fractional Baryon number, but are fermions and have spin 1/2. They are point particles whose dimensions are deduced to be less than 10^{-18} cm. Though free quarks with their characteristic properties have not been seen in the accelerator experiments, or in cosmic rays, there are good reasons to believe in their existence. The new theory of Quantum Chromodynamics (QCD) is concerned with the question of "quark confinement" and "quark-quark" forces mediated by the mass-less bosons called 'gluons". A large number of experimental features discovered at the accelerators are beautifully explained by the quark theory. From the point of view of the very early Universe the most important consequences of the quark theory are that the temperature limit of few times 10^{12} °K can be exceeded by orders of magnitude and one can proceed to dimensions much smaller than 10^{-13} cms.

Another important development in high energy physics that is particularly relevant to this very early phase of the Universe is the "trend" that has been discerned towards the "unification" of the four fundamental forces—Strong, Weak, Electro-magnetic and Gravitational. The discovery of the intermediate Vector Bosons $W^{\pm}$ and Z°, has put the final stamp on the success of the Electro-Weak theory—the unification of the electromagnetic and weak forces. Further extension of the Gauge Theories which brought about this electro-weak unification in the framework of Quantum Chromodynamics, lead to possibilities of the unification of the Strong and Electro-Weak interactions, to the so called Grand Unification (GUT). This predicts the existence of particles, the lepto-quarks $(X, \overline{X})$, in the mass range of 10^{15} Gev/C^2—which mediate quark-quark interactions at extremely close range, and also lead to their production. It is clear that the production of such particles which requires energies greater than 10^{24} ev, in any terrestrial accelerator is beyond the realm of feasibility. However, the same GUT theories lead to the possibility that the Protons, the stablest of all particles in the Universe, undergo spontaneous decay—of course with a life time in excess of 10^{29} years. The three quarks that compose the proton, because of the fact that they are confined to a volume less than 10^{-39} cm^3, move around with very high velocities ; If two of them come very close to each other then they will exchange a massive lepto-quark and lead to the production of a lepton and an anti-quark which immediately interacts with the remaining quark to give a meson. Thus the proton will decay into a lepton and a meson. There are many other decay modes possible. There are quite a few experiments in the world including the one at the Kolar Gold Fields in India, which are specifically designed to look for this very very rare phenomenon of Proton Decay.

These grand unification ideas have important implications to the very early Universe. The Figure-6, shows the variation of the coupling strengths of the electro-weak and strong interactions as a function of energy. The corresponding temperatures of the Universe at the respective times are also shown in the figure. What this trend means is that before 10^{-36} s, all the three forces were one and the same, and the temperature high enough to produce the lepto-quarks $(X, \overline{X})$—which are the very first species of particles to be produced in this hierarchy of particle production. The lepto-quarks give rise to leptons and quarks as the Universe cools. It is important to point out that at the limiting time of 10^{-43} seconds, the size of the Universe is around 10^{-33} cms and the density 10^{94} gms/cm^3. During this phase of the Universe, massive magnetic monopoles of mass $\sim 10^{16}$ Gev/C^2 could be produced, in addition to $X, \overline{X}$.

8. *The Planckian Era.*

Why do we stop our considerations at 10^{-43} seconds ? Why not go to still smaller interval of time ?

It turns out that the smallest time interval that can be constructed out of

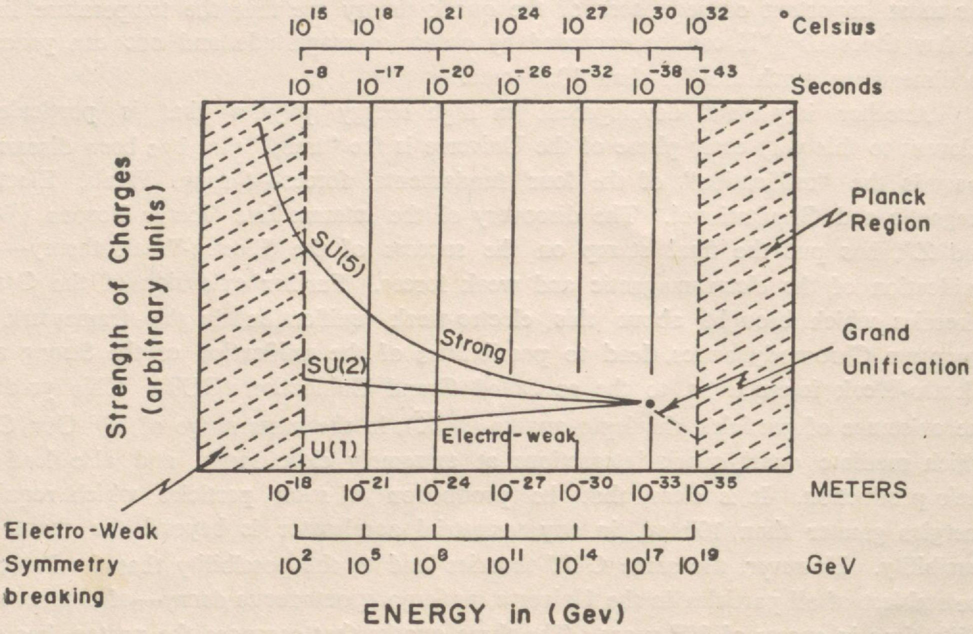

Fig. 6. The very early Universe and Grand Unification
[From M. Green SUPERSTRINGS]

the three familiar constants G, h and C is the **Planck time** $= \left[\frac{Gh}{C^5}\right]^{\frac{1}{2}} \simeq 1.3 \times 10^{-43}$ **seconds, and the smallest space interval, the Planck Length** $= \left[\frac{Gh}{C^3}\right]^{\frac{1}{2}} \simeq 1.6 \times 10^{-33}$ cm.

At these lengths, it is surmised that "quantum gravity" effects will start dominating. There is no good quantum gravity theory yet which can help us to proceed further. There are theoretical efforts based on Super Symmetry, Super Gravity and String-Theories to explore this domain. These are still in their early stages.

9. *The Big Bang Scenario* :

We cannot say anything from 0 to 10^{-43} seconds. Immediately after the Planck Era ($\sim 10^{-43}$ seconds) the Universe was at a temperature of $\sim 10^{32}$ °K, density $\sim 10^{94}$ gms/cm^3 and dimension $\sim 10^{-33}$ cms. At this temperature the Super heavy particles, the lepto-quarks were produced as also the magnetic monopoles. As the Universe cools the lepto-quarks lead to the formation of the quark-lepton soup. By about a microsecond the Universe consisted of nucleons, antinucleons, electrons, muons, pions, neutrions, photons and gravitons. By about a millisecond, many of these annihilated leaving the protons, neutrons, photons, electrons and neutrinos and antineutrinos. The Deuterium and Helium formed as the Universe cooled further. This was followed by the formation of ionized gases, Stars, Galaxies, etc. The dominance of matter over antimatter, and of radiation over matter can be adequately accounted for on the basis of this scenario.

What is amazing is, that we are able to extrapolate over almost 60 decades of time from 5×10^{17} seconds (Now) to 10^{-43} seconds, over 128 decades of density from 10^{-34} gms/cm^{3} to 10^{94} gms/cm^{3} and over a temperature scale of 3°K to 10^{32} °K, and come to some quantitative understanding of the early Universe; and its evolutionary course. This has been the combined achievement of astronomy, astrophysics and high energy physics and a synthesis of our knowledge of the micro and macrocosms based on a unification of the forces of nature.

10. *The Inflationary Universe* :

Some outstanding problems remain the understanding of refuire which further ramifications of the very early phase of the Big Bang expanding Universe. The outstanding problems are :

(a) *The Horizon Problem* :

The experimentally well established isotrophy of the microwave radiation at a level better than 1 in 10^{4}, implies that very distant parts of the Universe, which are beyond each other's horizon (defined as the distance Ct, where C is the velocity of light and t is the time from Big Bang) are at the same temperature. Since no physical process that can bring about such an equilisation of temperature can progress faster than light, this feature is one of the unsolved riddle's of Cosmology. The same situation would have persisted at earlier and earlier epochs in the kind of picture that we have presented above. The 3° radiation that we receive from the horizon today decoupled from the hot plasma around 10^{5} years after the Big Bang. If we consider two locations on opposite sides of us in the horizon today, they would be 10^{7} years apart when this decoupling took place and could not have had a causal connection at that time. How then do we understand the situation that the temperature is identical at these locations now ?

(b) *The Flatness Problem*:

Will the Universe expand for ever ? This depends on whether the average density of the Universe is higher or lower than a critical density which is calculated as 10^{-29} gms/cm^{3} in the Friendman Universe models. We have already seen that the estimated matter density is close to this critical value—around 10^{-29} to 5, 10^{-30} gms/cm^{3}. The radiation density at the present time is however much lower. But there are reasons to believe that there could be considerable amount of hidden mass' in the Universe which is so cold that it is not perceived through the electromagnetic radiation. Also if the neutrinos which are abundant in terms of numbers, do have even a small mass, say of the order of ~ 10 ev, their contribution to mass density may even exceed the ordinary matter density.

In the Friedman theory, the average density varies as $t^{-3/2}$ in the matter dominated era and as t^{-2} in the radiation dominated era (earlier than a million years from cosmic explosion) where 't' is the Cosmological time. But the "critical density" in the same theoretical model varies only as t^{-1}. This means that near to the Planck time (10^{-43} s) the energy density is "fine tuned" to an accuracy of the order of 10^{-59}. If this was not so the Universe would recollapse immediately after the Planck era. You can imagine how very exceptional our Universe is.

(d) *The Monopole Problem* :

In the era before 10^{-36} seconds, the possibility exists of profuse Super massive ($\sim 10^{16}$ Gev/C^2) monopole production. Their numbers could be as large as that of Nucleons. The monopoles cannot be easily destroyed. There is no evidence for such high intensity of monopoles (Also they would upset completely the mass densities. The Universe would have collapsed within 10,000 years of Big Bang). How did the Universe get rid of these monopoles or were they not produced at all ?

(d) *Fluctuations* :

The large scale structure in the Universe arose out of fluctuations in density. How did these fluctuations take place in an otherwise highly homogeneous, isotropic Universe expanding uniformly.

All these questions find an answer in a new scenario first proposed by Alan Guth, which has similarity to de Sitter's solutions of Einstein's equation, without the Cosmological constant term. According to Guth, the Universe, beginning in a hot highly symmetric state with all the forces united (GUT), undergoes a phase transition and expands exponentially by a large factor in a short time ($\sim 10^{-30}$ s).

During this phase transition the temperature falls. The conditions that prevail after this transition provide answers to the questions raised above. There is ofcourse a further complication—How to stop this exponential expansion ?

There are many Cosmological theories. In fact there are many solutions even to the Cosmological Equations of Einstein, and each one of them leads to a different Cosmology. The Big Bang Cosmology is perhaps the one that explains most of the astronomical observations, especially with the modifications of 'inflation' introduced into it.

In preparing this paper and the manuscript, I have made use of several books and articles which deal with this subject at a popular level. I have listed these below. I recommend them for further reading by those who would like to get a deeper insight into this most fascinating problem of the origin of the Universe.

For Further Reading :

The Universe	—	Josip Kleczek (Reidel Publishing Co.) Dordrecht-Holland/Boston.
The Left Hand of Creation	—	John Barrow and Joseph Silk (Counterpoint, London)
The First Three Minutes	—	Steven Weinberg (Bantam, London)
The Magic of Galaxies & Stars	—	L.E. Gurevich and A.D. Chernin (Mir Publishing, Moscow)
The Early Universe and High Energy Physics	—	David N Schramm, Physics Today— April 1983.
The Accidental Universe	—	P.C.W. Davies (Cambridge University Press)
Superstrings	—	Michael Green (Scientific American—September 1986)