

MODERN COSMOLOGY *

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Introduction

Cosmology deals with the large-scale properties of the Universe, including its origin and evolution. As such it has occupied the human mind for thousands of years. Poets, philosophers and religious leaders had approached the subject in their own characteristic fashions. Science entered the fray relatively recently. We can say that cosmology as a science was launched on the theoretical front by Albert Einstein in 1917 and on the observational front by Edwin Hubble in 1929. In my talk today I want to give a glimpse of what the subject is like when viewed through the eyes of a scientist as he enters the last two decades of the 20th century.

The bread and butter of any science are the observations of nature which it is supposed to explain. The observations of modern cosmology are based on the data obtained about the distant parts of the universe with the help of various telescopes. I will therefore begin by describing some of the World's leading observing instruments.

Astronomical Instruments

The astronomical observations are made primarily with the help of electromagnetic radiation. This radiation manifests itself in different forms depending on its wavelength range. Table: 1 below gives an approximate classification of the radiation according to its wavelength ranges.

* Lecture delivered at Department of Physics, University of Bombay, Vidyanaigari Campus, Bombay 400 098 on September 4, 1981 under its Decennial Celebration Programme.

TABLE 1

<i>Type of Radiation</i>	<i>Approximate wavelength range in metres</i>
Radio	$> 10^{-1}$
Microwaves	$3 \times 10^{-4} - 10^{-1}$
Infrared	$8 \times 10^{-7} - 3 \times 10^{-4}$
Optical	$4 \times 10^{-7} - 8 \times 10^{-7}$
Ultraviolet	$3 \times 10^{-10} - 4 \times 10^{-7}$
X-ray	$3 \times 10^{-12} - 3 \times 10^{-10}$
γ -ray	$< 3 \times 10^{-12}$

The classical astronomer uses visual light and our popular notion is that of a roof top astronomer with his eye glued to the lens of his telescope. The professional astronomer, however, works in a completely different fashion. Figures 1 and 2 show two of the biggest optical telescopes in the world. Their apertures are 4 metres and 5 metres respectively. The telescope tubes are big enough to house a human being !

However, human beings hardly have a useful role to play within the telescope. The human eye is a poor collector of information and the human brain has an equally poor storehouse of memory for the data. Instead, modern electronic and solid state devices like the CCD (Charge Couple Device), SIT (Silicon Intensifier Target television camera), IPCS (Image Photon Counting System) play very useful role as accessories to modern telescopes. Similarly the electronic computer is extensively used not only for numerical work but also for 'constructing' astronomical images.

These devices have improved the astronomer's ability of probing the remote parts of the universe to a very great extent. The postwar growth of science and technology have therefore benefited astronomy also.

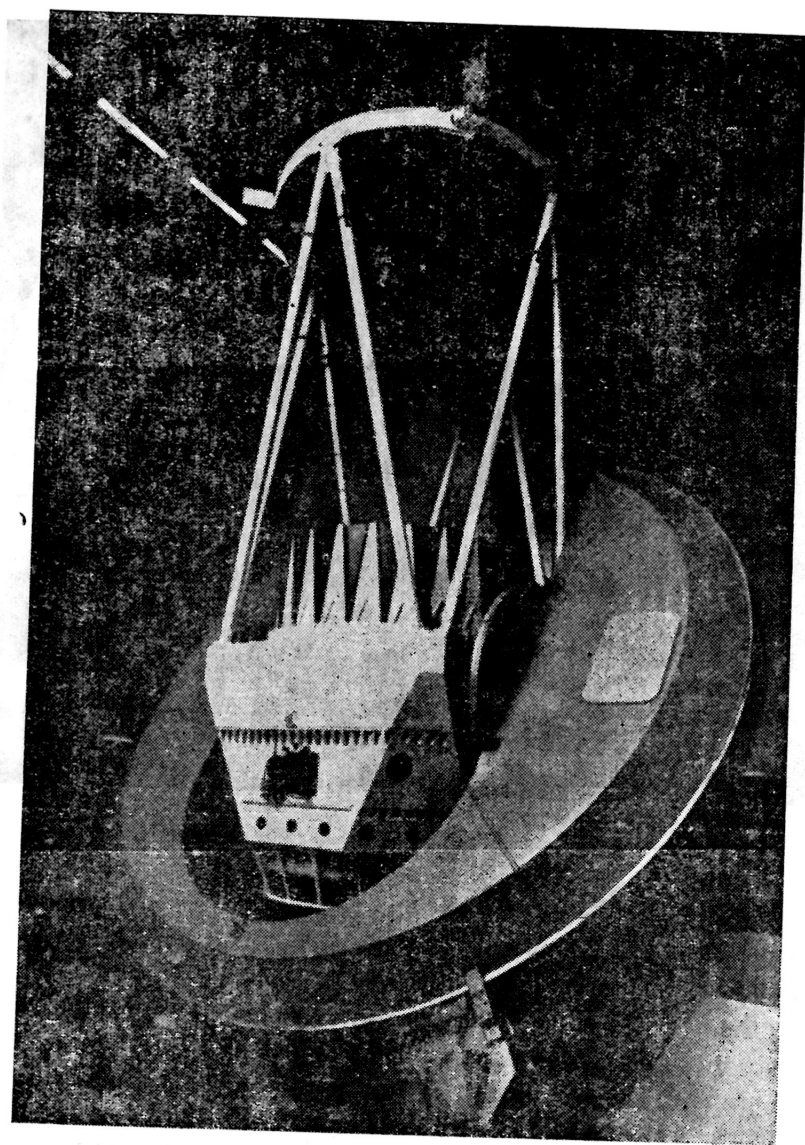


Fig. 1

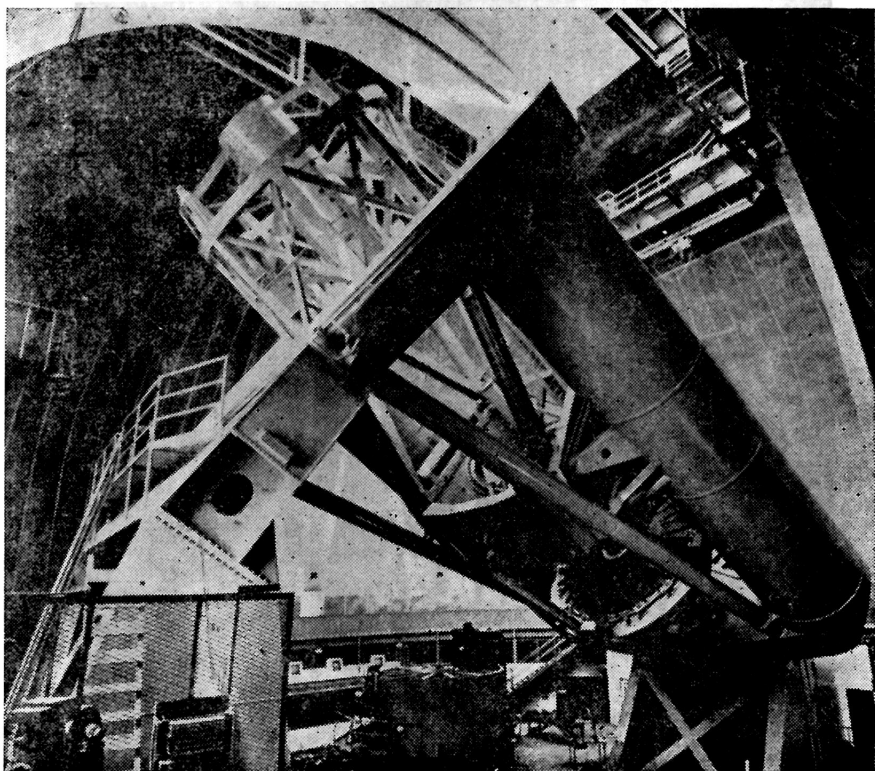


Fig. 2

Turning to another branch of astronomy, we see in Figures 3 and 4 two examples of large radio telescopes. Because they are collecting information through waves of longer wavelength (*cf* Table 1) the radio telescopes must have larger collecting area than their optical counterparts. This explains why the telescopes shown in Figures 3 and 4 are so much larger than those of Figures 1 and 2. The largest single system of radio receivers is the Very Large Array (VLA) in New Mexico, U.S.A. which was constructed in 1979. For a long time to come the VLA will dominate the field of observational radio astronomy.

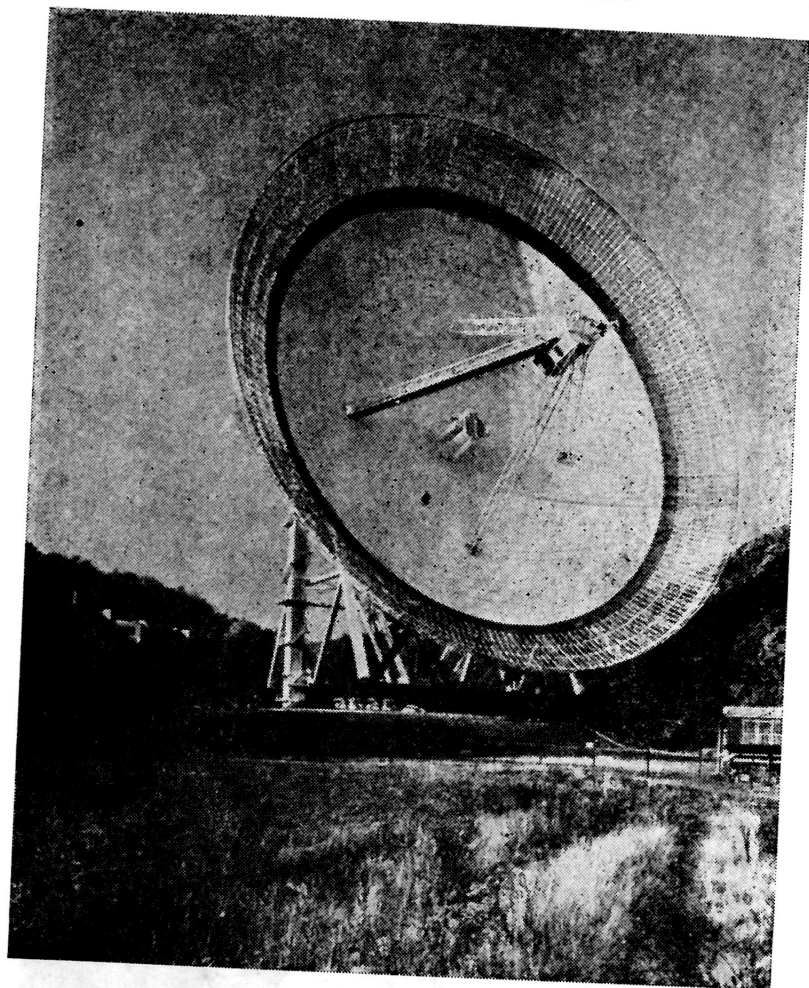


Fig. 3

Since the advent of the space age in the late 1950s, X-ray, γ -ray, ultraviolet and infrared astronomies have also blossomed. Balloons, rockets and satellites are playing useful roles in space astronomy.*

* See the talk given by Professor B. V. Sreekantan in this series.

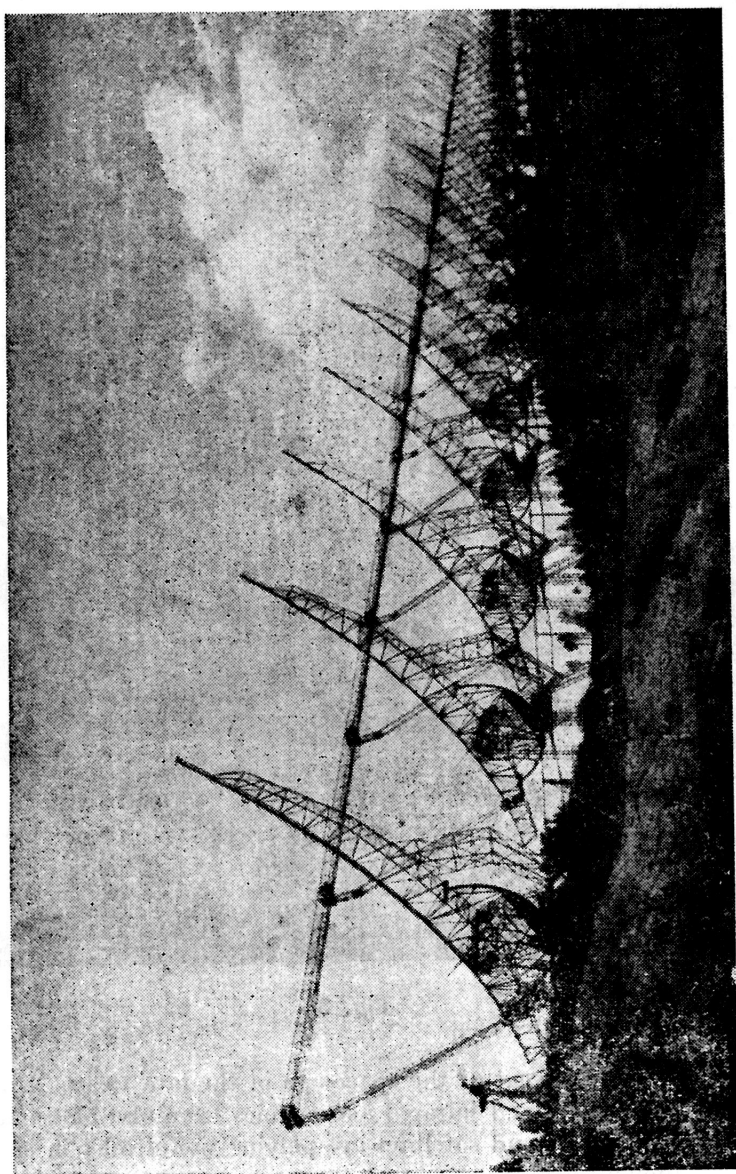


Fig. 4

The Structure of the Universe

What does the Universe look like as seen from these telescopes? The picture which has been put together from various bits and pieces looks like this.

Our Earth is part of a planetary system which has the Sun at its centre. The Sun is a typical star in the Milky Way System—or the Galaxy—which is a flattened bun shaped object of diameter— $\sim 100,000$ light years containing $\sim 10^{11}$ ($\equiv 100,000,000,000$) stars. The space between the stars is not empty but contains gas and dust. The former, especially when heated by star light, shines and gives rise to bright nebulae (cf. Figure 5) while the latter, through its absorption properties produces dark patches (cf. Figure 6). Before a proper realization of the contents and the extent of the Galaxy dawned on the astronomers, many misleading interpretations of observations were made. For example a dark patch was taken for a void. Also some bright nebulae which in fact were much more distant were erroneously thought to be within the Galaxy. At the beginning of this century the majority of astronomers assumed that the entire Universe was contained in our Galaxy floating like an island in infinite sea of space.

This 'island Universe' hypothesis was demolished by the better observations during the 1920s. It was during this decade that Edwin Hubble made the remarkable discovery that the Universe contains galaxies like our own, lying upto millions of light years and that these galaxies were moving away from our Galaxy with speeds increasing in proportion to their distances from us. Hubble's observations are illustrated schematically in Figure 7.

This observation did not necessarily imply that our Galaxy was at the centre of some exploding system. Rather the interpretation from Hubble's law relating recession velocities to distances was that the entire system of galaxies was expanding so that *each* galaxy would notice its neighbours rushing away.



Fig. 5



Fig. 6

The Expanding Universe

Why should this happen? This is where cosmological theory is needed. Indeed, as I mentioned before, this is where Einstein's pioneering work comes in. In 1917, Einstein constructed within the framework of his new theory of gravity—the general theory of relativity—a model of the Universe. Einstein's model

ascribed certain symmetry properties to the large scale structure of the Universe. Thus the Einstein Universe was homogeneous, isotropic and static. The first two properties of the Universe were borne out by the observations of the distribution of galaxies. However, the last property was shown to be incorrect by Hubble's observations. The Universe rather than be static, was expanding.

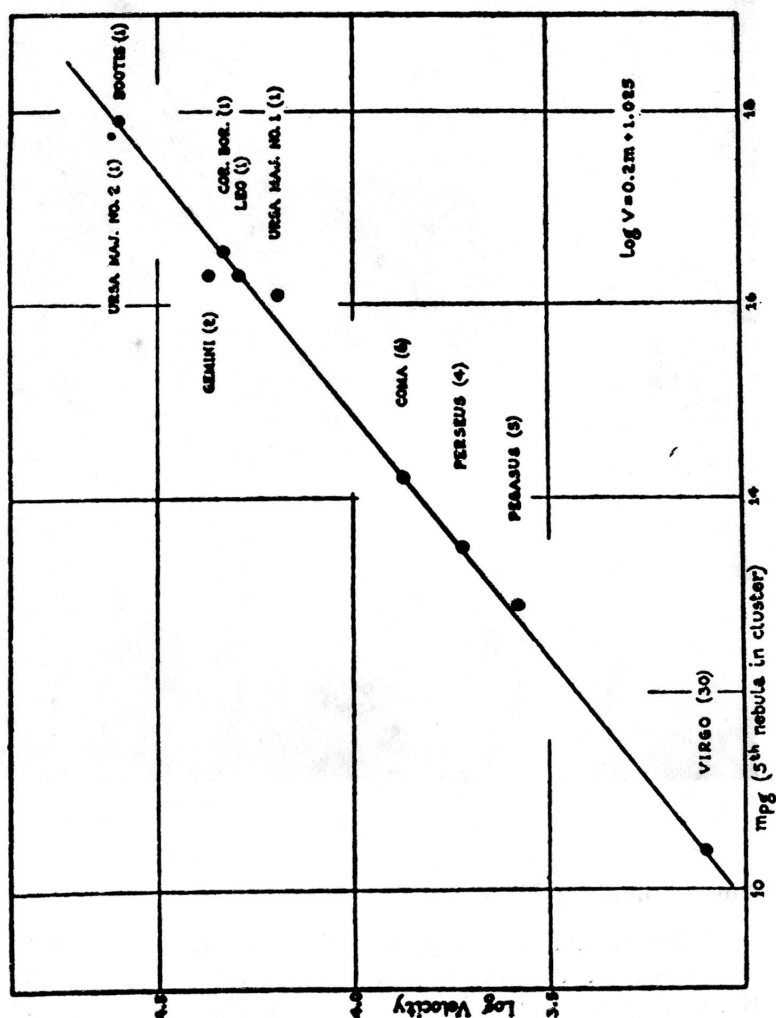


Fig. 7

In 1922, Alexander Friedmann had in fact constructed mathematical models of the Universe satisfying Einstein's equations and exhibiting the properties of homogeneity, isotropy and expansion. These Friedmann models therefore received confirmation from Hubble's observations. It is the same Friedmann models that the modern cosmologists take as their starting point for discussing and interpreting observations about the universe.

The Friedmann models tell us that the Universe exploded from an infinitely dense state about ten thousand million years ago. The initial explosion is known as the 'big-bang' and it is the limit to which we can apply Einstein's equations to cosmology. Why did the explosion occur? What, if anything existed prior to that? These questions cannot be answered by our present physics. Some cosmologists take the big-bang to represent the origin of the Universe.

Hubble's observations surveyed a relatively nearby region. As we look further and further away we see the Universe as it was earlier and earlier in time. This is because light takes a finite time to travel to us. Thus a galaxy a hundred million light years away is seen as it was hundred million years back in time. Have we any evidence which confirms the Friedmann models over larger distance scales and time spans than what Hubble's observations did?

Non-Euclidean Geometry

Einstein's general relativity tells us that the geometry of space-time is non-Euclidean over a cosmological scale. The Friedmann models tell us about a number of effects of non-Euclidean geometries and the astronomers have made several attempts to detect these effects. However, an unambiguous effect has not been detected so far. This is because any such cosmological effect is masked by the errors and uncertainties of observations.

One such effect is connected with the apparent angular size of an astronomical object. From our experience of Euclidean geometry we expect to see an object look smaller and smaller as we view it from further and further away. In a typical

Friedmann model, on the other hand, if objects of the same physical size are seen now at progressively increasing distances the angle subtended by them at us decreases to a minimum and then increases again. Thus a more remote object may look bigger than a nearby one! This remarkable effect is however not so easy to confirm because of the difficulties of ascertaining the distances of remote astronomical objects and also of ensuring that all the objects in a given survey are of the same physical size. (See Figure 8).

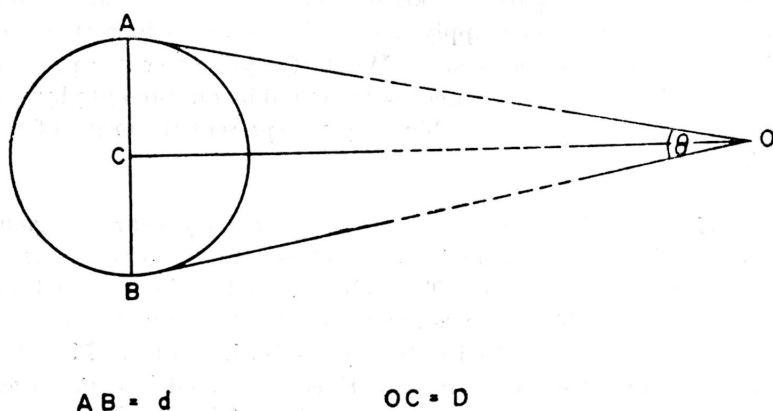


Fig. 8

The Relics of Big Bang

There is, however another observation which is believed to lend support to the big bang picture. If the Universe originated in a gigantic explosion we may have some relics of the early hot era. For example, we may expect to see a relic radiation from the early Universe. The microwave background radiation found first by A. A. Penzias and R. W. Wilson in 1965, does seem to be the radiation of this type. It is highly isotropic, thus ruling out the possibility that it could have originated in nearby sources. Its spectrum has a near black body shape which was expected from the relic radiation. Finally its temperature of ~ 3 K is in the right region for it to be a relic of an early hot era.

Although now-a-days the microwave background is naturally considered as a relic of big bang, its discoverers were first unaware of this interpretation, and they delayed publication of their result until they realized its significance. In fact the prediction of relic radiation was made by George Gamow and his colleagues R. Alphe and R. C. Hermann in the late 1940s. Gamow had made this prediction as a consequence of his 'hot big bang' theory in which the nuclei of the various elements seen today in the Universe were cooked in a gigantic fusion process lasting barely a few minutes after the creation of the Universe.

It was later realized that Gamow was right in so far as light nuclei are concerned. Nuclei like deuterium and helium can be manufactured in the early Universe but not the heavier nuclei like carbon, oxygen, iron etc. These elements have to be made inside stars.

But to return to cosmology. The evidence for relics of the big bang is not entirely consistent with the above picture, if examined closely enough. For example, the spectrum of the microwave background is not exactly in the black body form. The abundances of helium and deuterium are not entirely consistent with the big bang picture. More recently another difficulty has shown up in this picture.

Massive Neutrinos and the Age of the Universe

This difficulty comes from some experiments suggesting that neutrinos do have non-zero rest mass. If neutrinos have mass, then those neutrinos which have survived from the hot big bang must add substantially to the density of the Universe.

One consequence of the Friedmann models is that the density of matter in the Universe is directly related to the age of the Universe. The higher the density the lower is its age. A completely empty Universe is one with age H^{-1} where H is Hubble's constant (see Figure 7). The estimate of H^{-1} at present is not precisely known but is thought to be between 9 to 18 billion years. As we fill the empty Universe with more and more matter we

lower its age from 9 to 18 billion years to lower and lower values. If there are a substantial number of massive neutrinos in the Universe its age may be as low as half the above range of values. When we recall that the Earth is 4.6 billion years old and that our Galaxy may be 10 to 15 billion years old, we realize why too many massive relic neutrinos can be embarrassing to the standard big bang picture!

GUTs and Cosmology

Nevertheless, the agreement between the early Universe scenario and the observations today is considered good enough by many theoreticians for pursuing their speculations still further, and closer to the big bang epoch. Many particle physicists are at present engaged in constructing 'grand unified theories' (GUTs) which seek to unify the different interactions of physics (except gravity) in a single framework. The attempts at grand unification have been inspired by the success of the Salam-Weinberg-Glashow picture of unified gauge theory of electromagnetism and weak interaction.

Unlike the unified gauge theory which can be tested by high energy particle accelerators, the grand unified theories require particles at energies $\gtrsim 10^{15}$ GeV, more than 10^{12} times higher than those produced by the present man made accelerators. Thus direct verification of the predictions of GUTs is not possible. The early Universe, however, provides situations, very close to the big bang, when particles did have high enough energies to make GUTs relevant. Hence, the interest of particle physicists in GUTs and the early Universe. As is commonly said, 'the early Universe is the poor man's high energy accelerator!' The predictions of GUTs can be applied to the early Universe.

Figure 9 gives a time-temperature chart according to one particular scenario of GUTs and cosmology. These speculations rest on the assumption that our extrapolations are valid upto such small time scales as given there. Notice that at $t \sim 10^{-44}$ second even the classical picture of gravity is suspect and must be replaced by quantum gravity. Quantum gravity and cosmology are still in very elementary stages of development.

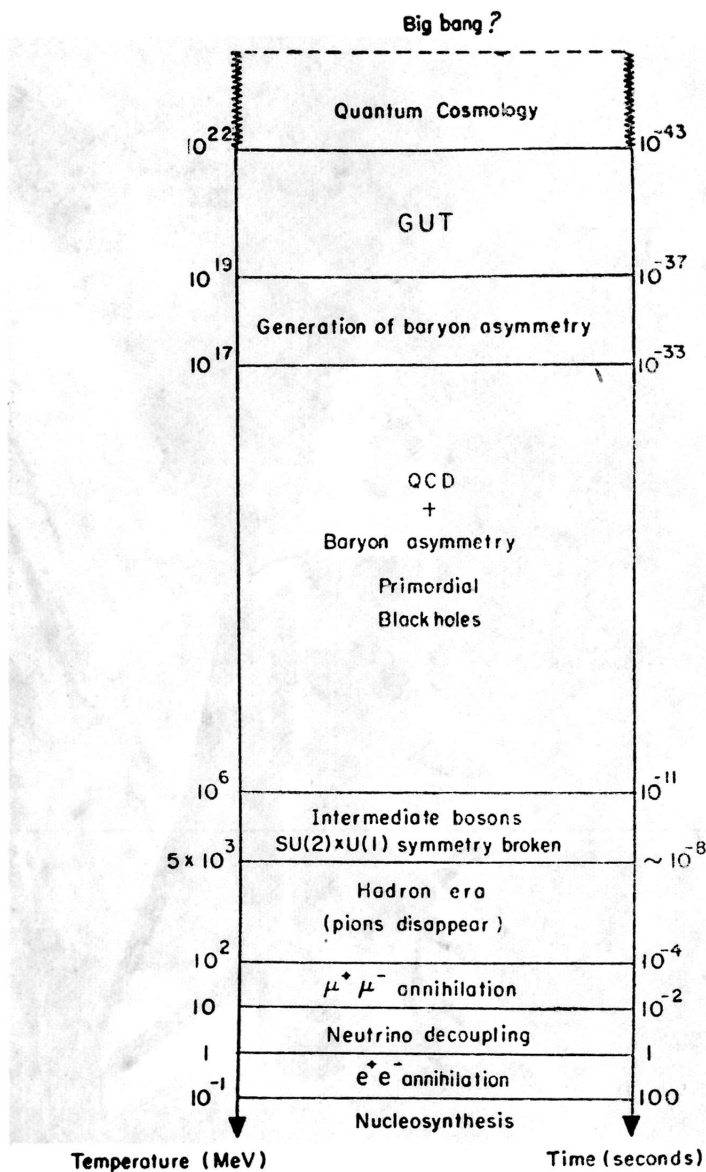


Fig. 9

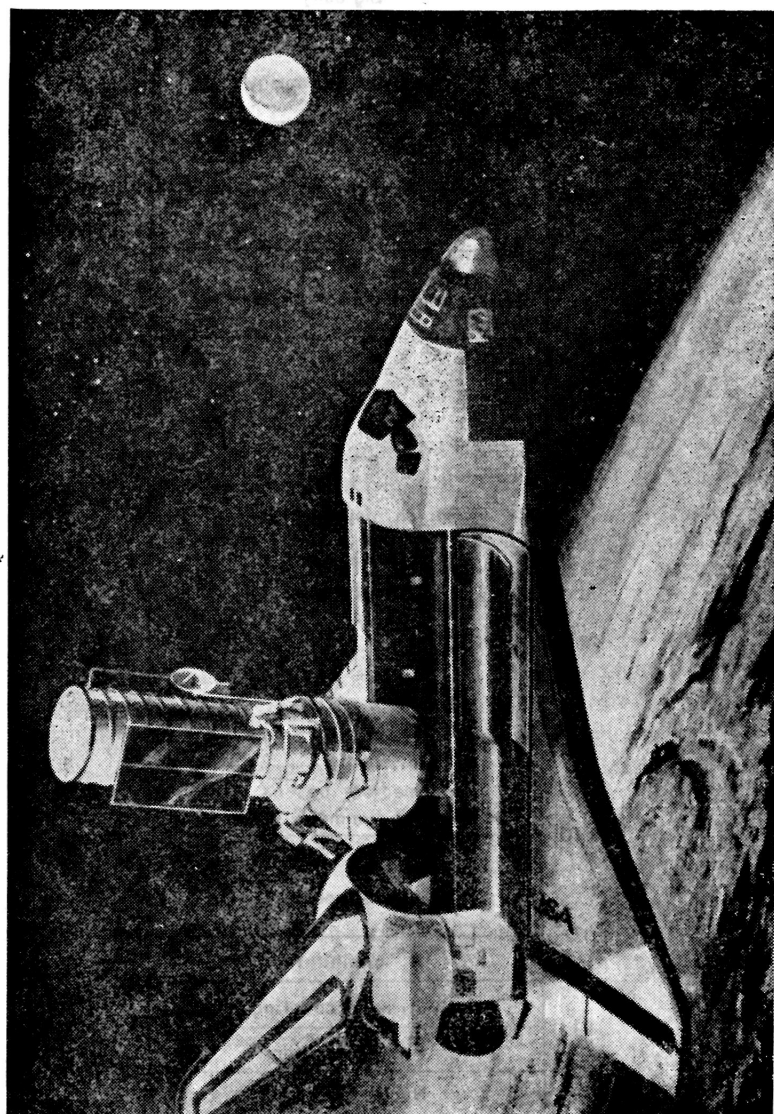


Fig. 10

Future Projection

Is the big bang picture necessarily the correct one? I have not had time to describe alternative theories of cosmology such as the steady state theory of Bondi, Gold and Hoyle, the cosmologies of Dirac, Brans and Dicke, Hoyle and Narlikar and so on. These alternatives have not been developed as much as the big bang picture mainly because most cosmologists think that the latter describes the Universe sufficiently accurately.

To me this situation is dangerously close to the state of affairs existing at the beginning of this century. At that time the island Universe theory was taken to be correct, and was proved wrong by better observations.

The Space Telescope shown in Figure 10 is due to be launched in 1984-85. It is expected to improve the angular resolution of optical images tenfold and extend the seeing condition to 50 times fainter objects than now possible by the best terrestrial telescopes. The wise cosmologist today should keep his options open until he sees the Universe through the Space Telescope. He may be in for a number of surprises.

Figure Captions

- Fig. 1 : The 4 metre telescope at the Kitt Peak National Observatory. The diameter of the main mirror is 4 metres. (Photograph from Kitt Peak National Observatory).
- Fig. 2 : The 5 metre Hale telescope at Mt. Palomar. (Photograph from Palomar Observatory, California Institute of Technology).
- Fig. 3 : The 100 metre dish of the radio telescope at the Max Planck Institute at Bonn.
- Fig. 4 : The array of antennas that make up the 550 metre long telescope at Ootacamund, run by the Tata Institute of Fundamental Research. (Photograph by Bharat Upadhyaya).
- Fig. 5 : The Ring Nebula (Photograph from Palomar Observatory, California Institute of Technology).
- Fig. 6 : The Horsehead Nebula. The dark patch shaped like a horse's head comes from absorption of starlight by interstellar dust. (Photograph from Palomar Observatory, California Institute of Technology).

- Fig. 7 :** Hubble's observations included a plot of the radial velocity of distant galaxies against their distance. The radial velocity V was estimated from the Doppler shift in the spectrum of the galaxy while the distance D was estimated from its faintness. Hubble found a simple law $V = HD$, H = constant known as Hubble's constant.
- Fig. : 8** The spherical object subtends a certain angle at the observer O . This angle decreases as the observer O moves further away from the object. In the non-Euclidean geometries of Friedmann's model universes the above decreasing trend is reversed beyond a certain distance.
- Fig. : 9** A time-temperature chart of the early Universe. The temperature falls as the Universe explodes and expands from the big bang. The initial stages are considered to belong to quantum gravity. Then GUTs operate, followed by formation of particles, baryons, pions etc. Then nucleosynthesis takes place leading to the deuterium, helium etc.
- Fig. 10 :** The Space Telescope is a 93 inch reflecting telescope which will be kept above the atmosphere and will make observations in the optical and the ultraviolet wavelengths (Photograph from NASA).
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