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Did the universe have an origin ?*

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1. Introduction

I consider it a great honour to give the S. N. Bose Memorial Lecture of the Indian Physical Society. My topic for today's talk lies in what is currently the most exciting frontier area between particle physics and cosmology. S. N. Bose made outstanding contributions to fundamental physics : to particle physics, unified theory as well as gravitation. In his days these areas stood apart and were considered as separate compartments of physics. Not so today : and my main theme will be concerned with this point.

Before I proceed I would like to state the answer to the question posed by the title. According to the majority view (which I don't share) the answer is 'yes'. The favoured scenario is that the universe exploded into existence about ten billion years ago and that everything we see around us, formed after that epoch. Even space and time did not have any meaning prior to the big bang.

How did this scenario come into cosmology ? What are the reasons that make it so appealing to scientists in general ? Why do I feel reservations about its validity ? These are the questions I will try to answer in this talk.

2. From Aristotle to Hubble

To appreciate the present cosmological beliefs we have to take a brief look at the evolution of ideas since the ancient times. A relevant epoch to start is that of Aristotle (384-322 B.C.), a disciple of Plato and the mentor of Alexander the Great.

Aristotle's ideas dominated the thinking of Greek scientists and astronomers, they gained currency in Arabia and farther east in India and by the middle ages they had acquired the status of religious tenets in the Christian Europe. Eventually they were dethroned by Copernicus and Galileo who laid the foundations on which modern physics stands.

Wrong though he proved to be, Aristotle must be given credit for believing that natural phenomena are subject to *some* definite laws. In this belief he

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is definitely backed by the modern theoretical physicist. There would be no physics, indeed no science at all, if nature chose to behave in whimsical or unpredictable ways.

Another of Aristotle's views which finds an echo in modern physics was his penchant for *symmetry.* This was reflected in his assumption (now known to be incorrect) that natural motion has to be in circular trajectories. Why circular ? Because a circle has the symmetry that any arc of it can be congruently placed on any other arc of it of the same length. This property is the modern concept of homogeneity and can of course be extended to higher dimensions. I will refer to this point again later.

Aristotle distinguished between natural motion and violent motion, the latter arising from the interference of other agencies. The circular trajectories of the Sun and the stars across the sky seemed to confirm that they were following natural motion. What about planets ? The word planet means 'wanderer' in the Greek language and suggests the apparent breakdown of the 'circular motion' rule for planetary motion. The planets indeed did not move on exact circular arcs, especially when observed over long periods of decades and centuries.

To fit the planets into the geocentric view (with fixed Earth and all heavenly bodies moving in circles) the Greeks had to invent *epicycles.* These are circular trajectories for planets whose centres move on other circles whose centres move on still other circles and so on. In this way the Greek astronomers like Ptolemy and Hipparchus obtained reasonable agreement between the predicted and observed positions of planets and so convinced themselves that the Aristotelian view of circular motions was working for planets too.

It often happens in science that initially the observed data support a simple hypothesis. But further experiments and observations do not bear out the hypothesis unless it is patched up with additional parameters. Eventually the original hypothesis loses its charm and simplicity under this patchwork superstructure. The epicycles did exactly that to the Aristotelian notion of circular symmetry.

One important epicycle from this picture was eliminated by Copernicus who correctly identified the Sun as the central fixed object around which the planets including the Earth move. But even Copernicus still thought in terms of circular trajectories. It was not until Kepler's careful analysis of the planetary data that it became clear that planets move in *elliptical* orbits with the Sun as a focus. In principle such a motion as per Kepler's laws can be simulated accurately by introducing arbitrarily large numbers of epicycles. But the need to include a large number of adjustible parameters should warn the theorist that he is on the worng track.

Transition from the geocentric to the heliocentric theory was undoubtedly 'progress' so far as man's understanding of the universe was concerned. But this transition was not enough. How did the Sun stand in relation to the stars in the night sky ? That it outshines them all is not because of its intrinsic power : it is because the stars lie much farther from us compared to the Sun. Nevertheless astronomers like Sir John Herschel who measured stellar distances in the eighteenth and the nineteenth centuries accorded the Sun the central position in the Milky Way, the Galaxy which (we now know) contains more than two hundred billion stars. This honourable position, however, proved to be transitory under the onslaught of progress.

By the second decade of this century the modern picture of the Galaxy emerged. It is a disc-like distribution of stars with a central bulge. The Sun is *not* at the centre but well away from it, about two thirds of the way to the periphery. Its distance from the centre is about thirty thousand light years. Harlow Shapley was largely responsible for arriving at the above picture of the Galaxy.

However, Shapley was on the wrong side of another controversy that finally dethroned the Galaxy from a privileged position. As early as in the last century some astronomers like R. A. Proctor had asserted that, contrary to the then prevalent belief not all diffuse nebulae seen by astronomers in their telescopes were contained in our Milky Way system. According to them these nebulae were galaxies of stars in their own right, lying well outside the Milky Way. This minority view supported the 'island universe hypothesis' of Immanuel Kant (1724 – 1804) that galaxies like our own exist all over the universe, separated by empty space, like islands in vast ocean.

By the 1920s the minority view had prevailed, however, and during this decade the foundations of modern cosmology were laid. For, in 1929 Edwin Hubble announced the important result that the spectra of these other galaxies show systematic redshifts which, if interpreted as Doppler effect implied the following simple relation :

$$v = H_0 D. \qquad (1)$$

Here v=speed of radial recession of a galaxy, D=the distance of the galaxy from us and H_0=a universal constant now known as *Hubble's constant*.

Although Hubble's measurements of galactic redshifts were reasonably accurate, he grossly underestimated the galactic distances. The modern value of Hubble's constant is therefore much smaller than Hubble's original value ; it lies in the range (20 billion yrs)$^{-1}$ to (10 billion years)$^{-1}$.

3. The Big-bang Models

Seven years *before* Hubble's observations, Alexander Friedmann had constructed theoretical models of the universe based on Einstein's general theory of relativity. To simplify Einstein's complicated differential equations Friedmann made simplifying assumptions. He assumed that the universe is *homogeneous* and *isotropic* ; that is, it looks the same at all points and in all directions. Here we find the same kind of symmetry requirement that was mentioned earlier in the context of Aristotle. Aristotle's circles are one dimensional curves of *constant curvature.* Friedmann's three dimensional spaces are also of constant curvature. The curvature can of course be zero (like the Aristotelian straight lines) or positive or negative. These choices turn out to have important dynamical implications.

By obtaining exact solutions of Einstein's equations Friedmann discovered that the universe is not static but expanding. That is, the space in which galaxies are embedded is expanding so that to an observer on each galaxy the rest would appear to recede. This is exactly what Hubble found in 1929. Moreover, in Friedmann's picture the Hubble type observations do not imply any privileged position for our Galaxy ; all galaxies have the same status. Thus we have finally arrived at a transition from the geocentric view of the universe to a perfectly democratic view.

The expansion of the universe can be described through a time-dependent scale factor $S(t)$ that is increasing at the present epoch*, $t=t_0$. The dynamical behaviour of the universe is described by a simple differential equation (overhead dot $\equiv d/dt$) :

$$\dot{S}^2 = -kc^2 + \frac{A}{S}, \tag{2}$$

where A is a constant and k takes the values $+1, 0$ or -1 according as the three dimensional space has positive, zero or negative curvature. This interrelationship between the dynamical behaviour of space and its geometry is a consquence of Einstein's equations.

Setting $k=0$ we get a simple solution of eq. (2) :

$$S(t) \propto t^{2/3}. \tag{3}$$

In terms of the epoch t, the Hubble constant is given by $H(t) = \dot{S}/S = 2/3t$. The present value of H is thus equal to $H_0 = 2/3t_0$.

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*The time used in cosmology has an unambiguous status : the homogeneity postulate ensures that all observers on different galaxies can coordinate their watches to measure the same time.

Friedmann had assumed the universe to be made of pressure-free matter. The density $\rho(t)$ of such matter falls with $S(t)$ as

$$\rho \propto \frac{1}{S^3}. \tag{4}$$

In the $k=0$ model

$$\rho=\frac{3H^2}{8\pi G}\equiv\rho_c. \tag{5}$$

The denisity $\rho_c(t)$ is called the *closure density*, for the following reason. If for any Friedmann model we write

$$\rho(t)=\frac{\rho(t)}{\rho_c(t)}\cdot\rho_c(t)\equiv\Omega(t)\rho_c(t), \tag{6}$$

then from eqs. (2) and (4) we find that

$$\Omega(t)<1\Leftrightarrow k>0. \tag{7}$$

$k=+1$ implies a 'closed' universe of finite volume while k = −1 implies an 'open' universe of infinite volume. Thus $\Omega(t)$ decides whether the universe is open or closed.

A closed universe expands upto a certain finite epoch and then to $S=0$, while an open universe expands for ever to $S=\infty$.

Although the differences in spatial geometry imply different futures for the Friedmann models, all models share one common property. They all had a past epoch when S was zero. The geometrical properties of spacetime break down at $S=0$ since the so called curvature invariants become infinite. It is therefore meaningless to continue the geometrical description of the universe to the $S=0$ epoch which is called the 'singular epoch'.

This is the *big-bang* epoch, conventionally denoted by $t=0$. The Friedmann solution in general implies that $H(t)$ diverges at $t=0$, implying an infinite speed of ejection of matter—which explains the adjective 'big'.

The Hot Big-bang :

In the latter half the 1940s, George Gamow provided another input to the Friedmann models. As the Hubble constant was very large in the early stages it is natural to suppose that matter at that time was moving rapidly at near-light speed. Any random motions of galaxies today are small ; but they must have been large in the past. Indeed galaxies would not have existed as bound entities far back in the past. Matter in the early stages would have been in the form of simple sub-atomic particles moving relativistically. Gamow found that such motions imply high pressure and temperature, as if the predominant part of the universe was filled with radiation. Thus Friedmann's assumption of pressure-free matter got modified.

The Friedmann solution therefore gets modified too at such early times. Present observations suggest that the effect of the curvature term k would be negligible at those times and hence the expansion factor is given by

$$S(t) \propto t^{1/2}, \tag{8}$$

and the radiation temperature by

$$T \propto \frac{1}{S} \propto t^{-1/2}. \tag{9}$$

Gamow estimated that at $t = 1$ second the temperature of the universe would have been ten billion degrees absolute. He and his collaborators Ralph Alpher and Robert Herman argued that during the time from $t = 1$s to 200s the universe would cool to a few hundred million degrees and in this period protons and neutrons would combine to form helium and higher elements of the periodic table.

Gamow was only partially correct in this expectation. Nucleosynthesis *is* possible in the first three minutes or so, but only as far as the helium nucleus! For, beyond helium there is a gap at atomic weights 5 and 8 in the sense that no stable nuclei exist at these weights. The element building therefore cannot proceed beyond ^{4}He. Nucleosynthesis beyond helium can proceed, however, deep inside hot stellar cores.

Modern calculations and observations show that while stars can account for heavier nuclei like ^{12}C, ^{16}O etc., they apparently fail to generate the observed amount of helium (25 percent by mass) in their cores; while the primordial nucleosynthesis is able to deliver the requisite amount of helium during the first three minutes after the big bang. The traces of deuterium (^{2}H) found in the universe also could be produced primordially but not in stars.

Thus observations of light nuclei provide a good measure of support for Gamow's hot big bang. A more impressive relic of the hot era was, however, discovered in 1965 in the form of a radiation background in microwaves with a black body temperature currently estimated at 3 K. Gamow, as well as Alpher and Herman had predicted such a relic radiation, although not its exact temperature (which still remains a parameter in the big bang scenario).

It was the 1965 discovery by Arno Penzias and Robert Wilson that stirred up the big bang bandwagon. For, here was a direct evidence that pointed back to the early hot epoch. The support for big bang firmed up further with the demonstration that the radiation background has a Planckian spectrum. For the Planckian spectrum was expected on the relic radiation hypothesis.

4. GUTs and Inflation in the very early universe

While the second half of the 1960s consolidated the evidence for relic radiation, particle physicists were given a new direction for research by the success of the Salam-Weinberg-Glashow picture of the unified electro-weak interaction. This picture pointed out a new way of unifying the basic interactions of physics—through the medium of gauge field theories. Just as the electromagnetic interaction and the weak interaction could be unified, could we not have a grand unified theory (GUT) that brings together the strong interaction as well as the above two interactions ?

Although there are several approaches to the ultimate goal of unification, all GUTs agree that the unification occurs at extremely high energies—above 10^{14}GeV. The symmetry between the three interactions breaks down *below* this energy spontaneously, separating the strong interaction from the electro-weak counterpart. The latter splits into its two components at the much lower energy of $\sim$ 100 GeV.

Manmade accelerators have verified the latter result but they fall short by too wide a margin to verify the former. The current limits on high energy particles produced in the biggest accelerators at Fermilab and CERN do not exceed $\sim$ 1000 GeV. No foreseeable human technology can take this limit to 10^{14} GeV or above.

The particle physicists were thus forced to the situation where their GUTs would remain unverifiable. Theories without the possibility of verification don't have much standing in science and GUTs would have suffered this fate but for the big bang cosmology.

For, recall formulae (8) and (9) and the fact that the temperature T of relativistic gas denotes an average particle energy kT. It is clearly possible to have arbitrarily high energies for t arbitrarily close to $t=0$. For particle energies of $\gtrsim 10^{14}$ GeV, we need $t \lesssim 10^{-35}$s. To distinguish it from the early universe of Gamow *et al* ($1s \lesssim t \lesssim 200s$) I will call the universe at $t \lesssim 10^{-35}$s the very early universe (VEU).

Except for the VEU there is *no* other scenario wherein GUTs could be seen in operation. It is not surprising therefore that particle physicists resorted to the applications of GUTs in the VEU. To make the VEU more respectable this argument is tacitly made : 'Since whatever is possible in physics must happen somewhere sometime, the existence of GUTs implies the VEU and hence the big bang'. A more honest statement is 'GUTs and VEU stand or fall together'. Without the VEU there is no way of verifying GUTs ; without GUTs there are no means of linking any present day relics to the VEU. (It is of course not ruled out that both GUTs and VEU are wrong concepts altogether !).

The present excitement in this frontier area of GUTs/VEU therefore derives from making theoretical calculations that affect the particle behaviour as well as the cosmological behaviour at energies $\gtrsim 10^{14}$ GeV, $t \lesssim 10^{-35}$s and to see if their consequences can be traced in the present universe.

One of the relics of VEU+GUTs is the baryon to photon number ratio which appears to be in the range 10^{-10} to 10^{-8}, assuming (a result that is far from secure) that the observable universe has no antimatter. This ratio has remained frozen since the time that the quarks united into baryons during VEU : its value in principle depends on the GUT parameters. Although a number of the order stated above is yet to emerge satisfactorily in this hot-cookery the believers are convinced that they are on the right track. (Good luck to them !). But they should occasionally compare their *modus operandi* with that of Hipparchus and Ptolemy two millenia ago.

An excellent example of the Greek experience is seen in the so called inflationary scenario. When first proposed in 1982 by A. Guth it had the merit of simplicity and elegance. It was proposed to eliminate certain problems of VEU. Two of these are outlined below.

The microwave background radiation is found to be extremely homogeneous on the small scale. The temperature fluctuations $\Delta T/T$ are less than 5×10^{-4}. Why ? The question assumes ominous significance when we pose it in the context of the particle horizons. Stated in simple terms, the particle horizon limits the distance of communication in the universe. Thus an observer looking at the universe at epoch t is able to see at most out to distance of $\sim$ ct. For, light from more remote places has not had time to reach him yet. The limit arises because the universe had a beginning a finite time ago.

The horizon size at a time of 10^{-35} second was only $\sim 3 \times 10^{-25}$ cm. It is over this distance that the VEU could be expected to be uniform. At larger distances there was no physical communication possible to establish homogeneity. From 10^{-35}s to the persent the universe has expanded by a factor $\sim 10^{27}$ so that the homogeneous region of 3×10^{-25} cm has now been blown to a size of $\sim$ 30 cm. This is much too small compared to the size of $\sim 10^{28}$ cm over which the homogeneity of the microwave background is now seen.

The *inflationary universe* of Guth achieved a sudden and large expansion during the phase transition when the symmetry of GUT was broken into two district interactions—the strong interaction and the electroweak interaction. The expansion factor during this phase was

$$S \propto \exp\,(at) \qquad (10)$$

where a turns out to be a large number. Thus the present homogeneous observable universe was supposed to have come from an extremely tiny bubble through rapid inflation.

Inflation cures another evil of the big bang universe : the problem known as 'flatness'. To see its significance let us recall the density parameter $\Omega(t)$. Presently $\Omega(t_0)$ differs from 1 by a margin which is no greater than

$$0.1 \lesssim \Omega(t_0) \lesssim 5. \tag{11}$$

To some purists the above inequality may seem too broad to be of much use. But let us trace the history of a model with $\Omega(t_0)=2$, say. As we go back in time the difference $|\,\Omega(t)-1\,|$ decreases and at $t\sim 10^{-37}$s, it was extremely small ($\sim 10^{-50}$). In other words, the universe was extremely finely tuned near $\Omega=1$ when its initial parameters were determined. If this fine-tuning were disturbed the universe would have had a very different future. For example, if $\Omega(t)$ were 2 at $t=10^{-35}$s, the universe would have contracted back to $S\doteq 0$ in a time of $\sim 10^{-35}$s. Clearly some mechanism was at work which tuned the universe close to $\Omega=1$, to enable it to lie within the range given by eq. (11) at present.

The inflationary phase necessarily achieves this by making the curvature term kc^2 in eq. (2) extremely small compared to the expansion term $\dot{S}^2$. In fact it ensures that the fine tuning is so perfect that even at the present epoch we have $\Omega=1$ to a high degree of accuracy : $|\,\Omega(t_0)-1\,|\lesssim 10^{-4}$.

Inflation, however, brings in more problems than it solves. For example, the type of small scale inhomogeneities in the VEU that are expected to grow into galaxies are too large at the end of the inflationary scenario to explain galaxy formation. Further, the age of the universe for $\Omega=1$ is too small to accommodate old systems like globular clusters found in our Galaxy.

It will take me too long to describe these problems and the evolution of the original Guth idea into various models of inflationary universe of increasing complexity. Here again the temptation to build epicycles appears to have suppressed a rational assessment of cosmological theory.

Before I leave the topic of VEU, I will discuss another step which brings us even closer to the big bang.

5. Quantum cosmology

Given the three fundamental constants $\hbar$, c and G (the gravitational constant) we can construct a time scale from it ; called the 'Planck time scale' given by

$$t_p=\sqrt{\frac{G\hbar}{c^5}}\simeq 5\times 10^{-44}\text{s}. \tag{12}$$

What is the significance of this time scale ?

Obviously the presence of G and $\hbar$ together implies that we are discussing here the quantum effects of gravity. Like any other basic interaction of physics gravity is also subject to the laws of quantum theory and the above time scale indicates *when* such effects may be noticeable. The smallness of the time scale compared to macroscopic times is not surprising ; what is significant is that t_p is at least hundred million times smaller than the GUTs time scale.

So if we were to look for discrete quantum effects of spacetime structure we have to go to the state of the universe for $t \lesssim t_p$. In this very very early epoch the idea of a spacetime continuum with smooth geometrical properties implicit in Einstein's general relativity breaks down. The question therefore arises : 'To what extent can we trust the general relativistic solution of the big bang universe for $t \lesssim t_p$?' For, notice that the concepts of 'big bang' or 'origin' or 'singularity' etc. are all linked up with the classical notions of what happens to the spacetime geometry at $t=0$.

The subject of quantum gravity is, however, very difficult and has not so far yielded a general answer to this question. Approaches seeking a general formal description of quantum gravity have become bogged down in mathematical formalisms without yielding any physical insights. Approaches seeking physical insights are open to the criticism of not being general or mathematically rigorous. I wish to describe briefly an example of the latter type.

We may argue in a somewhat pragmatic vein that the question of singularity of the universe is linked up with its overall volume, or *scale*. A scale transformation on space and time of a local nature ('local' in the sense of local gauge transformation) stretches or compresses the length and time intervals arbitrarility at different spacetime points, while preserving the angles. Such transformations are called 'conformal transformations'.

These transformations introduce an arbitrary scale factor Q in spacetime geometry. By varying Q arbitrarily from point to point we can get a wide range of geometries. In particular, starting with any spacetime geometry that satisfies Einstein's classical relativistic equations we can generate *nonclassical* geometries from it that do not satisfy Einstein's equations.

By *quantizing* Q we therefore achieve a partial insight into quantum gravity. This is analogous to quantizing the radial coordinate of the hydrogen atom while keeping the angular coordinates classical. Such an approach was adopted by T. Padmanbhan and myself and we find that it does lead to interesting results*. For example, the problems of singularity and horizon

*For details see *Physics Reports C*, **100**, 151-200 (1983).

disappear : the non-classical conformal solutions that are free from these defects overwhelmingly dominate in the quantum regime ($t \lesssim t_p$). Likewise, if the universe arose through quantum conformal of the empty Minkonski spacetime, it is overwhelmingly likely to go into the $k=0$ Friedmann solution. Thus the decision $\Omega=1$ was made not at the inflationary stage but much earlier, during the Planck time.

To what extent partial quantization is indicative of full quantization is debatable. Semiclassical approaches (e.g. an atom interacting with classical radiation) have proved useful in the past in understanding how quantum theory differs from the classical one. The case of partial radial quantization of the H-atom cited earlier does give us the important (and correct) notion of stationary states. So we feel that conformal quantization has a valuable role to play in the overall scheme of quantum gravity.

Another reason in defence of this approach comes from the fact that in a conformal transition the light cone structure of spacetime is globally unaltered. Thus all causal relations remain intact as geometries fluctuate. In other words, 'the rest of physics' remains unaffected. In a general quantization, spacetime geometry will so fluctuate as to alter the causal relationships of the contents of the universe. This messy situation is avoided in our approach.

6. The origin of the Universe

If we take this quantum cosmological view seriously then 'almost certainly' there was no big bang at $t=0$ nor was there a 'beginning'. The universe has existed (and will exist) indefinitely. It may occasionally pass through highly dense or compact phases when it makes quantum transitions of geometry, while outside such phases its description is adequately given by classical general relativity.

I end this discussion with two anti-views even more radical than the one I have just cited.

The less radical of the two questions the evidence of microwave background as being a relic of the big bang. Over the years I have been engaged with my colleagues in exploring the alternative in which this radiation is shown to be of much recent origin. It could very well be obtained by thermalizing the radiation available from starlight etc. by intergalactic dust. The energetics of this theory work out satisfactorily but it is not yet clear whether the theory can meet the stringent tests imposed by the finescale homogeneity of the observed radiation. If it does, then the strongest reason for believing in a big bang at the *classical level* disappears and the steady state theory may be revived.

Even more radical are the implications of certain recent evidence which questions the validity of Hubble's law for quasars and some galaxies. At present such evidence, presented mainly by H. C. Arp, is being debated*. If it holds out then the very basis of present cosmology : 'the expanding universe' would need to be modified.

I give these alternatives just to remind you that the cosmological question is far from settled. It is my conviction that it will never be settled : for as astronomical techniques make us better and better informed about the structure of the universe we will become wiser in the following sense : 'A wise man is one who knows how little he knows'.

*For details see *Introduction to Cosmology* by J. V. Narlikar (Jones and Bartlett, Boston, 1983)