

MODERN COSMOLOGY FROM A HISTORICAL PERSPECTIVE*

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This article presents a brief historical review of how paradigms about the universe changed with increasing inputs of factual evidence and described the current ideas on the origin and evolution of the universe, identifying their factual content and speculative framework.

Preamble

First of all let me convey my best wishes to Calcutta University as it enters its 150th year. I am indeed honoured by the invitation to deliver the prestigious Hasi Majumdar Memorial Lecture at Calcutta University. I am also pleased that a lecture series highlighting the historical development and the philosophical content of science has been instituted here. Very often students of science get their subject in a cut and dried form in their textbooks. They miss the historical development leading to that form or the thinking and motivations that led scientists to these concepts. I feel it is essential to learn the 'how' and 'why' behind science to appreciate its true nature.

Today cosmology has acquired considerable glamour and is considered the most interesting part of astronomy. Certainly, when one looks at the wonderful array of telescopes and detectors that modern technology have provided, one sees the reason for the boldness displayed by today's theoreticians. But boldness in formulating theories must rest on solid factual basis. To what extent is today's cosmology based on solid facts ? To what extent is it speculative ? Does it meet the scientific requirement of testability ? Is the criterion of repeatability of a scientific experiment satisfied in modern cosmology ? I will try to answer these questions against the historical backdrop of evolution of the subject.

Ancient cosmologies

The ancient Indian cosmology has the concept of the *Brahmanda* : the Cosmic Egg that contained the whole universe. All aspects of the living and the non-living matter was contained in the cosmic egg. The Nordic cultures had the concept of a Norse World Tree : the tree which carried the universe on its roots and branches. Concepts like these are today treated as highly imaginative speculations and no more : because they did not have any support in facts. Susceptibility to facts began to appear in theories more than two millennia ago, especially amongst the Greeks. Theories could be proposed and tested for their predictions. If the predictions of a theory failed to meet facts, the theory would have to be abandoned or modified. Symptoms of being on the wrong track for a theory therefore would be its need for frequent modification. An idea that failed when facts could not support it was the Pythagorean view of the Sun-Earth system. The followers of Pythagoras believed that the Earth does not go round the Sun, but rather it goes round a '*Central Fire*' with the Sun lying outside its orbit. This view is sometimes ascribed to Philolaus. The proponents of this theory were asked : why don't we see the Central Fire ? To explain the lack of visibility of the Central Fire, they proposed that there exists a *Counter-Earth* that came in between the fire and the Earth, thus blocking the view to the former. The Counter-Earth moved exactly in such a way as to block the Earth's view of the Central Fire.

This explanation worked for a while until some people asked : Why don't we see the Counter-Earth ? To this the reply given was that the Counter-Earth existed on the opposite side relative to Greece ! However, some travellers

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went to the 'opposite side' and still could not find it. Needless to say, the theory died a natural death.

The epicyclic theory of the Greek

A theory that required more and more additional assumptions to prop it up and had ultimately to be abandoned was of course, the epicyclic theory of the Greeks. This theory was based on the Aristotelian view that all natural motions are in circles. Aristotle preferred circles because they have a symmetry, namely any part (an arc) of it can be placed congruently on any other part of it. This is nothing but the translational symmetry. For similar reasons Aristotle also preferred the sphere amongst all other surfaces. The modern cosmologist also makes similar symmetry arguments (of homogeneity and isotropy) when modelling the universe.

However, the planetary orbits refused to fit into this pattern. So to make them fit, the Greeks invented epicycles, that is a sequence of circles whose centres moved on other circles, whose centres in turn moved on still other circles, drawn around a fixed Earth. By a suitable choice of parameters this construction could fit the motion of a planet over limited duration. It had to be redone for another period after the first one broke down. It was a rather elaborate but clumsy exercise but it was sustained for 16-17 centuries, because the intelligentsia believed in a geocentric framework controlled by Aristotelian views of the universe. Ultimately the correct solution was given by Kepler in terms of elliptical orbits of planets. (A mathematician will tell you that you can approximate elliptical motion by a series of epicycles over limited periods.) Thus the insistence on circles had to go in face of facts.

Majority view is not necessarily correct

The fate of the epicyclic theory tells us that there is no guarantee that a speculation is correct just because a majority believe in it. This dictum has been demonstrated in science time and again. A striking example of this in cosmology about a century ago is seen in the way astronomers viewed bright nebulae.

A nebula is a cloudlike object which is visible and has different colours so that it can be contrasted with the point-like appearance of stars. Our Milky Way Galaxy has several such nebulae. However, the question was : Are all such cloudlike objects part of our Milky Way ? A small minority believed that quite a few of these were galaxies in their own right, and they looked tiny because they were very far away. The majority view was, however, quite firmly otherwise and can be summed up in the following extract

from a popular book on astronomy written about a century ago :

"The question whether nebulae are external galaxies hardly any longer needs discussion. No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of co-ordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebula of the sphere belong to one mighty aggregation, and stand in ordered mutual relations within the limits of one all embracing scheme."

Agnes Clerke,

The System of the Stars, 1905

The firmness of the tone in this extract reflects the firmness of confidence in the view held by the majority of astronomers who worked on stars and the Milky Way. However, with the advent of better telescopes and spectroscopy, this view was falsified within a couple of decades. Most of the nebulae were shown to be extragalactic, being galaxies in their own right. Edwin Hubble who made the discovery that the universe is expanding was mainly responsible for this change of perception.

Where speculations were backed by facts

Let me now describe briefly a case where a speculation was backed by facts. Newton's Law of Gravitation may be considered such a speculation, if we take the falling apple episode to indicate Newton's speculation that a universal force exists which attracts the Moon towards the Earth just as it attracts the apple towards the Earth. However, Newton did not stop at this speculation. He worked out from Kepler's laws what force attracts the planets to the Sun so that they move around it in Keplerian ellipses. To work out this problem based on his own laws of motion, Newton invented the calculus, a new branch of mathematics. He deduced that the force would have to be governed by the inverse-square law. Using calculus he solved the reverse problem too : What orbits would planets have if they were attracted by a force as per the inverse square law ? Again he got bound orbits to be ellipses.

How did this hypothesis fare vis-à-vis *new* observations ? For, a good scientific theory not only explains what has been found, but also explains new observations. Two separate events verified Newton's law : (i) the arrival of Halley's comet and (ii) the discovery of Neptune. Let us briefly look at these events.

Comets come near the Earth every year. Some of them are quite bright and can be seen with naked eye. It was

Edmund Halley, a friend of Newton's who had noticed that comets had been sighted in the years 1066, 1456, 1531, 1607 and 1682. Taking the last four sightings it was clear that there was a period of 75-76 years between appearances. Even the sighting in 1066 fits in the sequence $[(1456-1066)/5 = 78]$. Taking cue from planetary periods, Halley conjectured that this was the same comet orbiting the Sun in a highly elliptical orbit with a period of this order, under Newton's law of gravitation. He predicted the next arrival of the comet in 1758. Although he was not alive to see this prediction come true, others were impressed by this outcome and the comet was named after Halley.

The second example relates to the observed discrepancies in the motion of planet Uranus that had been discovered by William Herschel in 1781. As a planet it was expected to follow a Keplerian orbit, now well explained by Newton's law of gravitation. However, by the 1830s, the departure from the predicted trajectory was causing concern. In the 1840s J.C. Adams in Cambridge, England and U.J. J. Leverrier in Paris had independently concluded that the discrepancy was not due to any breakdown of Newton's law, but because of the existence of an as yet undiscovered planet nearby whose gravitational influence was causing the observed perturbations. This prediction, ignored at first, was subsequently verified by Galle in the Berlin Observatory who succeeded in locating the new planet. It was named *Neptune*.

Perhaps it is worth contrasting the above example with the "Counter-Earth" hypothesis. Both Neptune and Counter-Earth were not known before they were predicted. Neptune's existence was confirmed by observations whereas Counter-Earth's was not and additional hypothesis had to be framed as to why it could not be seen. This contrast illustrates the difference between a successful speculation and an unsuccessful one.

Later we will return to the Counter-Earth example and point out another aspect of an unsubstantiated speculation, namely to sustain it despite evidence to the contrary one is asked to believe additional speculation. Sometimes by postulating additional speculation the impression is created that the original speculation is vindicated. However, two unsubstantiated speculations together do not take the place of fact.

Repeatability of a scientific experiment

A scientific experiment should be repeatable and not a one-shot affair. Even in astronomy stellar evolution provides examples of 'repeated experiments', *vide* the stars in the Hertzsprung-Russell (H-R) Diagram. This diagram

plots the luminosity of a star against its surface temperature. The theory of stellar structure tells us how to compute the luminosity (L), radius (R) and surface temperature (T) of a star, given its mass (M). Thus the theoretician can predict the L, R, T values for the Sun, given its mass. The theory is right if these values check out OK. Indeed, the position of the Sun on the H-R diagram checks very well with the theory.

However, the matter does not end there. One can ask, how would these physical values change if the mass were different. The theory of course predicts the answer. Observers have to find stars of different masses and apply the theory to them. Such an exercise also checks out OK for a large number of stars. Thus we can think of each star as a separate experiment for checking the theory.

This is what the repeatability of an experiment is all about. Notice that unlike his laboratory counterpart who can vary the experimental parameters as needed, the astrophysicist does not enjoy that luxury of altering at will the parameters of his experiment. Rather he has to view the system from afar with no facility of controlling it. Nevertheless, as mentioned just now, he can still verify his theory by studying many stars. It is because he can do so and *has done so* that lends credibility to his theory of stellar structure. He could not have claimed such a credibility if he were able to test his theory for only one star, the Sun.

With these remarks I now turn to modern cosmology.

Standard cosmology

The brief history of the beginning of modern cosmology is as follows. In 1915 Albert Einstein formulated what he considered the *final* version of general relativity. He hoped it to be a comprehensive theory replacing Newton's law of 'universal' gravitation. In 1916 Karl Schwarzschild used Einstein's equations to work out the gravitational influence of a spherical mass M , in an otherwise empty universe. At the other extreme, Einstein attempted in 1917 the model of a static homogeneous and isotropic model of the universe. His attempts to get such a model from his 1915 equations, however, were unsuccessful and he needed to modify them still further by adding an extra term of particular relevance to cosmology.

This was the so-called 'lambda-term' which in Newtonian language implied an extra universal force of repulsion between any two particles : a force, that increased in proportion to their distance apart. Thus the force was small and negligible at the Solar System level, but became significant at cosmological distances. With this force Einstein could obtain a static model in which attractive gravitation was balanced by the λ -repulsion. The static

model held sway for about a decade since astronomers could not find evidence for any large scale motions in the universe. It should be mentioned that in 1917, using Einstein's modified equations W. de Sitter had found another model of the universe, that was expanding but empty ! This was not considered a realistic model.

During 1922-24, however, Alexander Friedmann produced mathematical models of the universe in which there was a systematic large scale motion. In fact a typical model described an *expanding universe*; that is any two points in the universe would be moving apart from each other. Unlike deSitter's model, the Friedmann models had non-zero density of matter. As the general belief those days was in a static universe, these models were, however, looked at by most cosmologists including Einstein as mathematical curiosities. In 1927 Abbe Lemaitre, for example rediscovered Friedmann models but his work also went unrecognized.

These 'mathematical curiosities' soon became representations of reality when after a decade-long series of observations of galaxies and their spectra, Edwin Hubble announced in 1929 the velocity distance relation that led to the acceptance of the idea of an expanding universe. This relation, now known as Hubble's law, tells us that any galaxy seen by us at distance R is moving radially away from us with a velocity $V = H \times R$, where H is a constant called the Hubble constant.

It did not take theoreticians long to realize that this was precisely the relation to be expected from the Friedmann-Lemaitre models. If one associates a scale factor $S(t)$ with the expanding universe, so that the distance between any two points at epoch t increases in proportion to the scale factor, then these models tell us that $HS = dS/dt$. The velocity of recession V of a galaxy is estimated by the fractional increase (denoted by z) of wavelengths of light emitted by it and measured spectroscopically. Friedmann-Lemaitre models tell us that $(1 + z)$ is the *ratio* of the present scale factor to the scale factor at the time of emission which was necessarily smaller in an expanding universe. Thus we can say that these theoretical models had anticipated the expansion of the universe. This was therefore confirmation of a speculation by facts, a speculation that was initially not believed, even by Einstein.

After this discovery Einstein realized that expanding universe models exist even when the lambda-term is absent from his equations. He therefore reverted to those original equations, acknowledging his misjudgement in introducing it to get a static model that was no longer factually relevant. The sentence ascribed to him that the introduction of this term was 'the greatest blunder of his

life' is not found in any of his writings or lectures : it is in fact ascribed by George Gamow as a remark allegedly made by Einstein in a personal conversation to him !

Einstein indeed swung over to the other extreme when it was discovered that the universe is not static : he felt that the λ -term was an unnecessary baggage for general relativity to carry. In a paper written with de Sitter in 1932, Einstein opted for the simplest of the Friedmann models, one in which both the λ -term and the curvature of spatial sections ($t = \text{constant}$) were zero, and matter was pressure-free dust. This model came to be known as the Einstein-de Sitter model. Following Einstein most cosmologists took $\lambda = 0$ and preferred to work with essentially three kinds of models in which the space sections are (i) flat or (ii) with positive curvature or (iii) with negative curvature.

If the λ -term is not present, the Friedmann models predict a *deceleration expansion*. Indeed, the scale factor $S(t)$ can be related to the Hubble constant H , and a deceleration parameter q by $qSH^2 = -d^2S/dt^2$. For the Einstein de Sitter model, we have $q = 1/2$. The big bang models in favour during the period 1960-1980 had $q > 0$, and attempts were made to measure its value by extending the Hubble velocity-distance relation to larger and larger distances. The astronomer measures the velocity spectroscopically by measuring the spectral shift (the proportionate increase in the wavelength of a line) normally denoted by the symbol z . Likewise distance is estimated by measuring the apparent brightness on the magnitude scale and denoted by m . Most observations of the m - z relation unequivocally claimed to have established this result. The odd one out those days was the steady state model, which had $S = \exp Ht$, and so, $q = -1$. However, it was ruled inconsistent with observations because it described an *accelerating* universe. I will return to this test later.

The early hot universe

While observers were trying to determine which Friedmann model fitted observations of galaxies best, theoreticians were examining the physical properties of the Friedmann models. All models seemed to lead to the conclusion that the scale factor was zero at some epoch in the past. At this epoch the Hubble constant became infinite. Known as the *big bang* epoch this signified the creation of the universe in a singular and explosive event, when the density and temperature of matter as well as radiation were infinite. Mathematically speaking this instant defined any attempts at applying quantitative physics, which is why one uses the adjective 'singular'. Conditions soon after the big bang were so different from the present universe, that the extrapolation of present physical laws to those epochs was considered highly speculative.

Nevertheless, in the 1940s George Gamow made a daring extrapolation of known physics to the early epochs when the universe was 1-200 seconds old ! [For comparison, the present epoch is believed to be around 10-15 billion years from the big bang.] He used thermodynamics and nuclear physics to study the physical behaviour of the universe, which he assumed at that stage to be mainly containing neutrons and protons, light particles like electrons, positrons, neutrinos, etc., and of course photons. Using this brew he hoped to demonstrate that *all* chemical elements were made in that early epoch.

Gamow's speculations on primordial nucleosynthesis achieved partial success : they worked for light nuclei but failed for nuclei like carbon, oxygen or heavier nuclei than these. Gamow's calculation redone with improved nuclear data shows that of the 200-plus isotopes known, the calculated abundances of light nuclei like D, He, Li, Be, B are generally of the right order when compared to the observed abundances. For the production of heavier nuclei one has to look for stellar environments.

However, Gamow's work had another positive fallout. The prediction was made by two of Gamow's younger colleagues, Ralph Alpher and Robert Herman that the universe today should have a relic *thermal* radiation background with a temperature of 5K. This prediction was verified and found right when in 1965 Arno Penzias and Robert Wilson detected isotropic microwave background radiation (MBR) at 3K.

The big bang cosmology can therefore take credit for making two successful predictions, namely the creation of light nuclei and the presence of a relic background.

Although extrapolating well beyond the limits of observations, this approach of Gamow is securely based in known physics. The speculations about the early universe could be raised to the level of a sound physical theory because the physics used in the nucleosynthesis calculations was based on established applications of thermodynamics, statistical mechanics and nuclear physics.

The astronomical base of this approach is, however, not so secure for the following reason. Direct astronomical observations of distant galaxies and quasars go as far as $z \sim 6$, say. That is to the state when the scale factor was 1/7 of its present value. The big bang models show that even if we have much better telescopes, we still cannot observe the universe coherently beyond a redshift of a 1000, for the universe was opaque beyond $z \sim 1000$. *However, the hot universe calculations go back to redshifts as high as $z > 10^9$. In short cosmologists are talking about a phase in the history of the universe that is not observable. It is as if a thick curtain descended preventing our viewing what happened before that epoch.*

Further, the universe being a 'one and only' system, the above sequence of primordial nucleosynthesis followed by a relic radiation background is not a 'repeatable experiment'. It happened only once. By contrast, stellar nucleosynthesis is a repeatable experiment, since we can find many stars in which the process is taking place.

So, today's observations of light nuclear abundances and the origin of CMBR at best provide consistency checks on the early universe calculations. They do not guarantee that the scenario is unique. The one powerful tool of science, namely directly checking the consequences of a theory through repeated experiments is not available here.

Astroparticle physics

Nevertheless, the discovery of MBR and successes of primordial nucleosynthesis persuaded many cosmologists to be more daring and to push their investigations of the early universe even closer to the big bang epoch. These efforts are sometimes identified with the studies of the 'very early universe' whereas the Gamow-Alpher-Herman work was limited to the 'early universe'.

It is here that cosmologists were tempted to form a partnership with particle physicists to generate a new branch called 'astroparticle physics'. The idea here is that the physics to be used in the discussions of the very early epochs would be supplied by the particle physicists, whereas the cosmologists will supply the background scenario in which the particle physicists would test their theories. For example, theories and experiments in particle physics have shown that unification of the electromagnetic with the weak interaction will take place at particle energies of ~ 100 GeV. The Salam-Weinberg model works very well at this energy level. Using the extrapolations of these ideas, particle theorists are looking for a further unification of the above 'electro-weak' theory with the strong interaction. Calculations suggest that this 'grand unification' may be achievable at particle energies of $\sim 10^{16}$ GeV. These energies are beyond the range of particle accelerators by several orders of magnitude. So testing them in the laboratory like any other physical theory seems out of the question. How then can such a work be confirmed ? For, without any experimental check any physical theory remains a speculation. To get round this impasse particle physicists use the big bang models. These show that by going sufficiently close to the big bang epoch one gets a high enough temperature wherein particles have energies of the order 10^{16} GeV. So the hot universe provides them with a high energy particle accelerator. As already mentioned, the need for a physical theory to tell what the universe was like very early on, forced that cosmologists into the arms of the particle physicists. Thus both the cosmologist and the particle physicist stood to gain by this liaison.

The expectations on both sides may be summarized thus :

Particle physicists : Since the big bang is a well-established paradigm and secure as a theory of cosmology let me try my speculations of very high energy particle physics in this very early universe.

Cosmologists : Since particle physicists know what they are talking about, let me apply their well worked out theories to test my speculations of the very early universe.

Fact is that both sides are using speculations only !

The notion of inflation

However, nothing can better demonstrate the highly speculative turn cosmology has taken than the popularity enjoyed by the idea of inflation. This concept rests on the idea of phase transition at the break-down of the grand unification of the three fundamental forces. Since the phase transition signifies a change of state of matter from a unified theory to one in which the electroweak theory separates from the strong interaction, the physical change in the state of matter influences the way the universe expands. The phase transition does not occur instantly but over a short interval and during that interval the universe expands very rapidly (with $S(t) = \exp at$, $a \sim 10^{36} \text{ s}^{-1}$). This is known as the *inflationary* phase. It is claimed that the universe must have gone through such a phase, if some problems associated with the big bang models have to be resolved. I will not go into those problems except to mention that although these problems were known to exist for a long time, they were ignored and were highlighted only when the idea of inflation appeared on the scene to solve them !

As a physical theory, let us ask if inflation follows the usual guidelines to which a scientific theory ought to be subjected. First, is the physics behind 'inflation' well and independently tested ? Secondly, has inflation been directly observed or is it directly observable in principle ? Lastly, does it describe a repeatable event that can be observed in other contexts ? The answer to all these questions is a resounding NO. We have seen that the particle / high energy physics at the energy 10^{16} GeV is not yet determined by physicists. Further, as mentioned earlier, inflation is believed to have taken place well before the epoch of redshift 1000, prior to which the universe was not observable by astronomical observations. That it is not a repeatable phenomenon is clear from the conditions that are supposed to give rise to it... they do not occur in the universe again. In short we are asked to accept a paradigm which is founded on insecure physics, is neither observable nor repeatable.

However, the earlier example of Pythagorean counter-Earth comes to mind when we see how this idea is marketed. First it was argued that if there were a grand unified theory, then it would necessarily lead to the existence of massive magnetic monopoles. Then it was estimated that their relic density today would be abnormally high, by some fifteen orders of magnitude. When cosmologists are reeling under this catastrophic conclusion they are reassured that the way this can be avoided, would be through inflation, for then these monopoles would be diluted away. Thus from a null observation (no monopoles seen today) one is apparently able to claim confirmation of two speculations, namely.

1. A grand unified theory operated in the very early epochs.
2. Inflation took place in the very early epochs.

Can two speculations together add up to a fact ? Apparently, they do if you are an astroparticle physicist !

Dark matter : Emperor's new clothes ?

From 1975 onwards astronomers have been receiving evidence indicating the presence of dark matter considerably in excess of visible matter in the universe. This evidence is in the form of flat rotation curves of neutral hydrogen clouds going round spiral galaxies and also arises from the dynamics of clusters of galaxies. If one follows the Newtonian laws of gravitation and dynamics, then the observations force one to have dark matter in addition to the visible matter. However, if one is willing to modify these laws, the presence of dark matter is not required. Following Occam's razor, cosmologists opt for dark matter.

What can dark matter be made of ? Prima facie, there are many possibilities, e.g., black holes, very old white dwarfs, brown dwarfs and planets of Jupiter size, etc. However, these alternatives are all of objects made with normal baryonic matter. If dark matter turned out to be wholly baryonic, it will pose problems for the big bang. First, if one assumes all the observed matter to be baryonic, the amount of deuterium produced in primordial nucleosynthesis would have been extremely low, too little to explain its observed abundance. Secondly, the process of making large scale structure would create fluctuations in the radiation background, far larger than observed today.

Now, the normal process of testing a scientific theory is to make predictions and check them with observations. By this standard, the presence of dark matter should have taken away the two major predictions of big bang cosmology, namely the production of light nuclei and the

existence of a relic microwave background. However, instead of following this paradigm, cosmologists have sought to modify the normal assumption that matter in the universe is baryonic. Instead they argue that dark matter may be made of esoteric particles generated by the grand unified, supersymmetric and other speculative particle theories : e.g. wimps, massive neutrinos, supersymmetric particles. In short, the assumption of what the majority of matter in the universe consists of is based on highly speculative particle theories rather than on the baryonic option that does not require any speculative assumption. This is done so that the big bang paradigm is propped up.

As yet there is no direct astronomical or laboratory evidence for non-baryonic dark matter. Yet the confidence with which it is asserted that such matter exists in far greater quantity than the normal baryonic matter reminds one of the story *Emperor's New Clothes* by Hans Christian Anderson.

Nevertheless, cosmologists soon realized that Emperor's new clothes need further additions, to keep their model intact !

Claims for dark energy

Post-1999 there has been an upsurge in confidently made assertions by cosmologists on the presence of dark energy, quintessence, branes, etc. These are extensions of the cosmological constant first introduced by Einstein into general relativity (and later withdrawn as being unnecessary). What is the evidence for these ideas ?

The spurt in these speculations started with the claim in 1999 by several observational cosmologists that supernovae at high redshifts are significantly dimmer than expected in a decelerating universe. These observations can be explained by assuming that the universe is accelerating, which in turn leads the general relativist to the λ -term. However, such a claim should be moderated by at least three uncertain factors. Do we know that distant supernovae are of the same intrinsic brightness as the nearby ones ? This aspect has still not been properly sorted out. Do we know for certain that intergalactic dust is not making distant supernovae dimmer ? Again, counter-examples suggesting that dust may be playing a major role have been proposed. Finally, are we certain that gravitational lensing is not playing a role in amplifying brightness of distant supernovae and thus making all calculations subject to further uncertainty ?

Beyond this, it is also claimed that having a non-zero cosmological constant helps in fitting data on the

angular power spectrum of inhomogeneities of the microwave background. The most popular ideas on formation of large scale structure also rely increasingly on λ , besides on the esoteric (non-baryonic) dark matter. In fact it is argued that the MBR, structure formation and supernova measurements allow one to determine the cosmological parameters so accurately that one can now talk of 'precision cosmology'.

Before we get carried away by this new euphoria, let us assess dispassionately the role of the cosmological constant. A balance sheet for λ may be prepared as follows.

Previous studies (1960-80) using the m - z relation revealed several practical pitfalls in the claims to measure the deceleration or acceleration of the universe. Recall that in those years the claim that the universe is decelerating was made so firmly that the steady state theory, the only one to predict an accelerating universe was taken as disproved. These and other uncertainties persist in the present supernova m - z test also as just mentioned. But those have been largely ignored because current theoretical speculations in cosmology find it attractive to have a positive nonzero λ .

It has been the previous history of the λ -term that cosmologists have resurrected it whenever they felt the need to do so in order to explain all the observations. If the observations change or get discredited, then back it goes into mothballs ! So it remains to be seen how long it maintains its present popularity.

The present compulsions for λ are (a) It solves the age problem. The ages of models of the universe with a non-zero λ are large enough to accommodate the oldest known objects in the universe. (b) It explains some of the observations of fluctuations of the radiation background as well as dimming of distant supernovae. (c) Its origin can be linked to inflation. These are hopes of relating the present value of this constant to the inflationary phase.

However, this term comes with a bag of problems too : (a) Why and how did λ drop by 108 orders of magnitude from inflation to the present epoch ? For this is what must happen if the origin of this term lies in inflation. (b) How is 'dark energy' typified by λ related to the rest of the forces of nature ? This is not yet understood.

General comments

Let me summarize the discussion of modern cosmology in terms of four comments :

- A. The studies of the very early universe are highly speculative both in terms of astronomy and particle physics.

- B. They describe a scenario that is not expected to repeat. Although quantum mechanics also started with esoteric looking ideas, these gained credibility through *repeated experiments*. Take for example, Bose statistics. It seeks to apply an abstract mathematical concept to ensembles of microscopic indistinguishable particles. We may not be able to see these particles, yet the predictions about their collective behaviour are very clearly verified in the laboratory through several experiments.
- C. Time scales of the order of 10^{-36} second are used in inflation and related predictions. We have, however, no operational way of measuring a time scale of this order.
- D. Direct observations of the universe extend up to

densities of matter ~ 200 times the present value, whereas the extrapolations to the very early universe extend to $\sim 10^{87}$ times the present value. Nowhere in physics are theories extrapolated (that too without some verification) over such a range of parameters.

Today there are buoyant claims from cosmologists that they have everything worked out to explain our universe. Words describing the present day cosmology as 'precision cosmology' or 'concordance cosmology' are misleading when we consider the extent of speculative element in today's cosmology. I therefore feel that a fair assessment of the situation today should give rise to a more pragmatic attitude that permits other theoretical models of the universe.

I thank you for your patience !