Origin(?) of the Universe

6. Present Challenges in Cosmology

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This six-part series will cover: 1. Historical Background. 2. The Expanding Universe. 3. The Big Bang. 4. The First Three Minutes. 5. Observational Cosmology. 6. Present Challenges in Cosmology.

The final article in the series reviews the strengths and weaknesses of the big bang cosmology, conceptual as well as observational. It is argued that despite its many successes there are enough question marks against this cosmology to keep the issue open. In particular, an alternative view-point developed by the author and his colleagues is described. In this the universe has always been in existence. Known as the Quasi-Steady State Cosmology it combines some good features of the big bang cosmology with new ideas which may help resolve some of the outstanding questions of today.

Strengths and Conceptual Weaknesses of the Big Bang Cosmology

In this concluding part of the series on cosmology we shall take a critical look at the big bang models and then make some projections for the future. To begin with, we consider the strengths of these models. Recall from Part 3 of the series that Einstein's general theory of relativity led Alexander Friedmann to expanding world models in 1922, and seven years later Hubble's law that received a simple interpretation within the Friedmann models was discovered.

Then in the 1940s, extrapolation of these models to epochs very close to the Big Bang led George Gamow and his students Ralph Alpher and Robert Hermann to the concept of primordial nucleosynthesis. And from their considerations of the early universe emerged the idea of a present day background of isotropic radiation. Both these concepts of relic nuclei and relic radiation received observational backing in the 1960s and 1970s through the measured abundances of light nuclei (^{4}He, ^{2}H, etc.) and the microwave background (see Part 4 of the series).

These are then the plus points of the big bang picture entitling it to a prima-facie position of trust. In any emerging branch of science such a theory is needed at the beginning. But after the early stages are completed and the subject progresses, one must take a more critical look at the theory, to see how far it fits the more detailed experiments / observations that inevitably follow. When we carry out such an exercise for the standard hot big bang cosmology, several disquieting features begin to show up.

Singularity : The concept of big bang origin itself marks a departure from standard physics. The event cannot be described by standard techniques of theoretical physics : all the equations break down. Mathematicians would call this a *singular* event, i.e., one where no standard mathematical techniques work. To the physicist, the appearance of *all* the matter in the universe at $t > 0$ with no discussion of what went on at $t = 0$, violates its conservation laws.

There are many plus points of the big bang picture entitling it to a prima-facie position of trust. But, a critical look reveals several disquieting features.

Some big bang cosmologists regard this as the signature of the profundity of the *Big Bang*. They argue that this event marks the origin of the universe including the origin of science and its laws; as such it lies beyond the scope of science. Other cosmologists regard this as a sign of incompleteness of our present understanding of science : perhaps the singularity would 'go away' when we learn more mature physical laws than we now know (e.g., quantum gravity).

Inflation : Approach of the latter kind led in the 1980s to the now well known idea of the *inflationary universe*. D Kazanas, K Sato and A Guth during 1980-81 independently suggested this idea. It takes into consideration the so-called grand unified

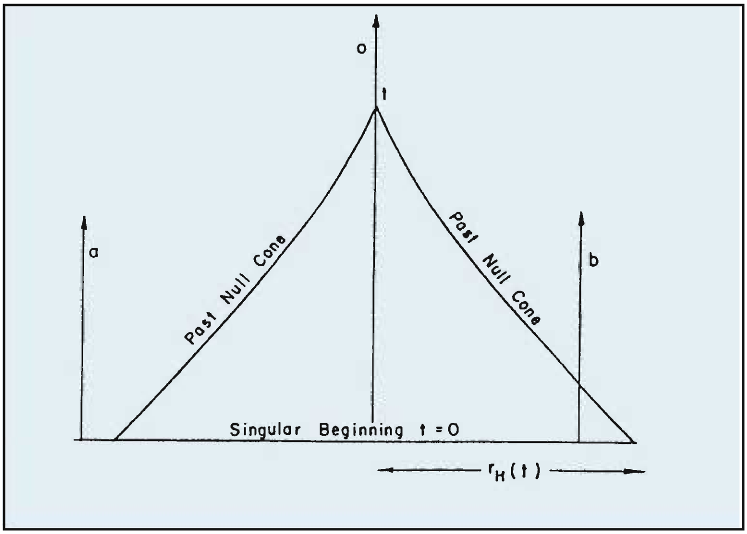

Figure 1 The Horizon Effect. The past light cone of observer O at r = 0, epoch t, terminates at the big bang epoch t = 0. There it has a radial coordinate extent of r_H (say). Particles like a lying beyond this distance don't causally affect the observer at O while particles like b lying within this cone do. The limited value of r_H for small t places a severe limit on the extent to which the universe can be homogeneous.

theories (GUTs : see Part 4 of the series) which seek to unify all laws of physics into one single comprehensive framework. Particle physicists believe that GUTs will be significantly effective for very high energy particles, such as those found shortly after the big bang. Typically, GUT-energies are of the order of 10^{16} GeV per particle (1 GeV approximately equals the energy store of a proton) and such energies per particle may arise about 10^{-36} second after the big bang.

Just as a temperature of 100 Celsius marks a change of state for water to steam or vice versa, so does this energy mark a phase transition for the universe in the inflationary theory. As the universe expands it 'cools' with the particle energies dropping continuously. At $\sim 10^{15}$- 10^{16} GeV, the GUTs suggest a change of the lowest energy state of matter, normally designated as 'vacuum' in quantum theory. The universe discovers that extra energy is suddenly available for it to expand very rapidly. This same extra energy of steam condensing to water appears as latent heat.

This rapid expansion is called *inflation*. Just as compound interest grows much faster than simple interest, an inflationary universe expands very rapidly. This rapid

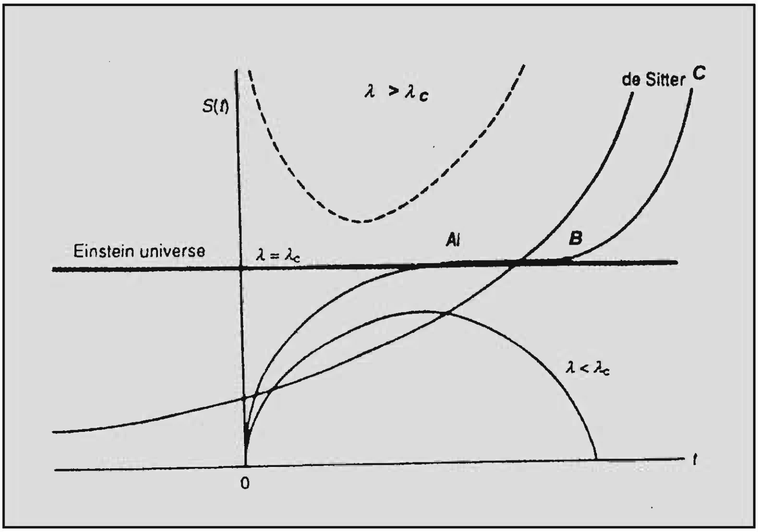

Figure 2 The scale factors of some of the different types of models with a non-zero cosmological constant are shown. In a typical model, by choosing λ close to the critical value λ_c, we can have a universe which expands from O to A, stays nearly static over an arbitrarily long stretch from A to B and then expands from B to the present C. Note that over the stretch BC the Universal expansion tends to accelerate. The figure also shows the 1917 models of Einstein and deSitter.

expansion lasts a very short time but is enough to make the initial size larger by a factor as high as 10^{50}.

Rapid expansion of this kind produces some lasting effects in the universe. One is that it helps to make it more homogeneous. Imagine a typical region 10^{-36} second after the big bang. Any physical effect will travel in it at most with the speed of light, $c = 3 \times 10^{10}$ cm/s and so will not cover a distance of more than 3×10^{-26} cm. Normally therefore we would expect regions of this size to be 'homogenized' at 10^{-36}s. Had there been no inflation, the normal slower expansion would have further increased their size at most to ~ 10 cm to 1 metre at the present epoch.

Known as the *horizon effect*, this had been a ticklish problem for the standard Friedmann models. Why do we find the universe homogeneous on scales of ~ 10^{26} metres when it should have been so only on scales of at the most 1 metre? The problem disappears if we assume the inflationary phase in between.

The inflationary phase also *flattens* the universe, that is, it severely diminishes the effect of the curvature term k / S^2 in the expansion of the universe (see Parts 3 and 4 of the series). Thus it strongly predicts that the present universe should be almost indistinguishable from the flat ($k = 0$) case.

An added advantage of the inflationary model is the way it allows any initial (primordial) inhomogeneities in the universe to grow. It predicts a spectrum of inhomogeneities which does not depend on scale. The present studies of large scale structure from galaxies to superclusters substantiate this prediction.

In spite of these attractive features the inflationary models also have their own conceptual problems. There have been several detailed inflationary models based on speculations in high energy particle physics, but they seem contrived and fine-tuned to get specific results.

The now well known idea of the *inflationary universe* was born in the 1980's to handle the *singularity problem*.

Some Practical Weaknesses of Big Bang Cosmology

Let us now look at a few of the problems that the big bang cosmology is currently facing.

The age problem : We referred to it in the last part of this series. If we accept the inflationary big bang model and the current estimates of Hubble's constant then the age of the universe is no greater than 8–10 billion years. This is far too short to accommodate galactic and stellar ages in the range of 12–18 billion years.

If we assume that all these values are correct, how does the big bang concept survive? Recall that in Part 3 of the series we had referred to the cosmological constant λ , first introduced by Einstein, then discarded as unnecessary but still available to the theoretician if needed as an extra parameter. Faced with the above problem, some theoreticians are once again taking refuge behind the cosmological constant.

In the inflationary model the cosmological constant is explained as the feedback of vacuum forces on spacetime. The inflationary expansion is caused by these forces. Conventionally these forces disappear when the GUTs phase transition is over and so today there is no λ – force around. But suppose that λ did not disappear entirely but a fraction, a few parts in 10^{108}, did survive. Then we would have a considerably reduced but nevertheless significant λ –term available today. And by a suitable choice of λ we may increase the theoretical age of the big bang model to around 15 billion years.

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Opinions differ amongst cosmologists as to whether this is the correct way out. At best the above explanation is contrived and may be termed as a "refuge for scoundrels!" At worst it still fails because it requires the expansion of the universe to accelerate at present and all observed indications are to the contrary.

The structure formation constraint : The inflationary cosmology provides a rationale for the scales of different structures. But detailed theories of structure formation must take into consideration the following questions :

- How do large scale structures grow by mutual gravitational interaction?
- How does the expansion of the universe control the growth?
- In what way do inhomogeneities arise in the form of long chains of galaxies with large voids in between ?
- What is their feedback on the observed inhomogeneities of the cosmic microwave background?
- How does non-baryonic dark matter affect structure formation?
- How and why do we find large scale streaming motions of galaxies as large as 1000 km/s over and above the Hubble expansion?

Alternatives to the standard big bang cosmology have been in the field from time to time. The most significant of them was the steady state cosmology proposed in 1948 by Hermann Bondi, Thomas Gold and Fred Hoyle.

Despite the euphoria of 1992 when COBE discovered, for the first time, tiny inhomogeneities of temperature (a few parts in a million) of the microwave background, and even after several different approaches to forming large scale structures, the gap between theories and observations remains wide. Maybe the gap will be eventually bridged but again only at the cost of elegance.

The Quasi-Steady State Cosmology

Over the last few years these inadequacies of big bang models are being increasingly noticed. Some cosmologists feel that one can play with available parameters (add a few more if needed) and make the models work. This attitude coupled with attempted scenarios is beginning to resemble epicyclic theories of the ancient Greeks trying to fit the observed planetary motions within the Aristotelian framework. While the majority of cosmologists have taken the neutral stance of waiting and watching as the situation develops, a few have taken the bold steps of suggesting alternatives.

Alternatives to the standard big bang cosmology have been in the field from time to time. The most significant of them was the steady state cosmology proposed in 1948 by Hermann Bondi, Thomas Gold and Fred Hoyle. This cosmology has the universe in perpetual existence with new matter being

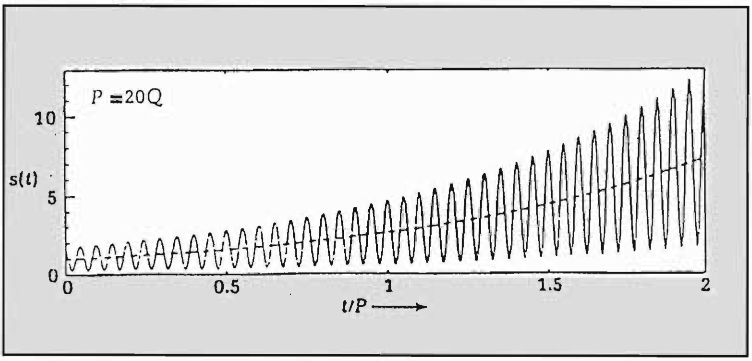

Figure 3 The Quasi-Steady State Cosmology shows expansion over a long time scale with cycles of expansion and contraction. This universe did not have any finite epoch of origin but has been in existence perpetually.

injected into it steadily. The stresses produced by the injection process keep the universe in steady expansion with a scale factor $S(t) = \exp(Ht)$. This model has a constant Hubble's constant. Indeed, as the adjective 'steady' implies, all its physical characteristics are epoch-independent.

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This alternative played a useful role for nearly two decades by prompting observers to find tests to distinguish between it and the big bang cosmologies. As discussed in Part 5 of the series most such tests turned out to be indecisive but they led to an improvement of extragalactic astronomy. Eventually however, the steady state model fell into disfavour because it could not offer a reasonable explanation for light nuclear abundances and the microwave background.

Since 1992, however, Fred Hoyle, Geoffrey Burbidge and this author have revived the steady state idea in a more realistic form. Called the *Quasi-Steady State Cosmology* (QSSC), this model has a scale factor given by

$$S(t) = \exp(t/P) \, . \, [1 + \alpha \cos\theta(t)].$$

Here the exponential function is the steady state part with a time scale P. The function $\cos\theta(t)$ is periodic but has a much shorter time period Q, while α is a parameter lying between 0 and 1. The periodic part is the reason for the adjective quasi-steady. The universe has no beginning and has a long term exponential trend of expansion superposed on short term oscillations.

What is the physical cause of such dynamical behaviour? The QSSC has a field theory for matter creation which allows for matter to be created near collapsed massive objects. The process conserves energy. Thus a negative energy field is produced along with matter and with its large negative stresses the field drives the matter out explosively.

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So, instead of a mythical primordial event of Big Bang, we have here minicreation events (MCEs) whose explosive character can be described by a respectable field theory. Also the Big Bang has not been observed (nor is it observable) but the MCEs are, in this picture familiar to us in the form of explosions in galactic nuclei. *Thus while every particle of matter has a finite beginning the universe as a whole has had no origin.*

A comparison with observations suggests that $P \sim 10^{12}$ years, $Q \sim$ 40–50 billion years while $\alpha \sim 0.8$. Thus these time scales are large compared to the big bang time scales. Although they are consistent with Hubble's constant as measured today, *there is no age problem*. But how does this cosmology explain the microwave background?

Recall that the time scale Q of a typical cycle of QSSC is long enough to burn out all but the very low mass stars. The light of stars from all previous cycles is left over in the universe. If it can somehow be thermalized we should get the *exact* microwave background of temperature 2.7 kelvin. Hoyle et al show that 0.5-1 mm long whiskers of iron could carry out this thermalization efficiently. Laboratory evidence shows that hot metallic vapours condense as whiskers just like these. Thus iron produced and ejected from supernovae can indeed condense as metallic whiskers. These whiskers are pushed out into intergalactic space where they efficiently thermalize the relic starlight.

In QSSC, the universe has no begining and has a long term exponential trend of expansion superposed on short term oscillations.

What happens to the burnt out stars? These appear as dark matter. The dark matter in the QSSC thus appears to be largely baryonic. Note that the baryonic option for dark matter is denied to the big bang cosmology as it severely cuts down the production of deuterium in primordial nucleosynthesis (see Part 5 of the series). The production of light nuclei in the QSSC follows an entirely different route