COSMOLOGICAL INFLATION

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by

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Cosmological Inflation

Inflation is a radical modification of the "Big Bang" theory regarding the origin and evolution of the universe. In view of this, I will begin with a brief review of what may be reasonably thought of as the "standard" theory of the Big Bang.

Edwin Hubble in 1929 published data that suggested that the universe is expanding. Actually, what he discovered was that the spectra from distant galaxies is reduced in frequency ("red-shifted"), and that the amount of reduction increases in proportion to the distance of the galaxy. One way to interpret Hubble's observations is to assume that the red shift is caused by the motion of the galaxies away from the observer. This effect, a well-established and well-understood phenomenon, is called the Doppler Effect. If one considers the explosion of, say, a hand grenade, it is obvious that after the explosion each fragment would be located at a distance proportional to the initial velocity that was imparted to it. Since the same relationship between the distance and velocity holds for the distant galaxies, the Doppler interpretation of the red shift would suggest that the universe had its origin in a stupendous explosion.

This idea, however obvious and seemingly unavoidable, was nevertheless avoided for many years. Early on, some astronomers investigated the idea of "tired light" to explain the data, while avoiding the outrageous idea that the universe exploded into existence from an unimaginably dense and hot fireball. Later, Sir Fred Hoyle and J V Narlikar championed a seemingly crazy scenario initiated by Hermann Bondi, Thomas Gold and Hoyle himself, in which the universe maintained a constant density even though it was expanding. This seeming impossibility was made possible, according to Hoyle, by a continuous creation of matter out of space itself Hoyle was very critical of the "explosion" scenario, and it was Hoyle, in fact, who coined the phrase "Big Bang" as a term of derision for that scenario. The tired light idea would not fly for simple thermodynamic reasons, and Hoyle's "Steady State" theory failed to explain the cosmic background radiation discovered in 1965 by Penzias and Wilson. By that time the "Big Bang" interpretation was widely accepted.
It is notable that the red shift of the galaxies is very uniform as regards to direction. At first glance this would seem to suggest that we occupy a privileged position at the center of the explosion. That this is not the case was proved by E A Milne, who in 1935 showed that under reasonable assumptions, every observer, regardless of his distance *from* the center of such an explosion, would see the same linear relation between red-shift and distance regardless of what direction in space he might look.

As we shall see, this picture of the big bang as an explosion of a finite amount of material into the surrounding empty space is quite incorrect. For, if such were the case, the universe would not appear to be homogeneous, since all bodies would be attracted towards the center of mass. Also, observers not located at or near the center would see a non-uniform distribution of galaxies. Unfortunately, many commentators, including even professional astronomers, still commonly endorse this "explosion" picture. The explosion picture follows naturally *from* the interpretation of the red shift as a simple Doppler effect caused by the velocity of recession of the emitting body at the instant of emission. We now understand that this interpretation is also incorrect. This error also appears constantly, due in part to the fact that the magnitude of the red shift is usually given in terms of the Hubble constant, which, in turn, is almost always expressed in terms of the "velocity of recession" per unit distance, e.g., "73 kilometers per second per megaparsec." (A parsec equals 3.2615 light years.)

What is now generally thought to be the correct interpretation of the red shift was found by the application of Einstein's General Theory of Relativity to the cosmological problem. Already in 1922, Alexandre Friedmann had produced elegant, closed-form solutions to Einstein's equations for the gravitational field in a matter-filled, homogeneous and isotropic universe. All of these solutions predicted a red shift, and could be interpreted as describing an expanding universe. But ironically, as often happens in science, no one paid any attention to Friedmann's paper, and the "explosion" interpretation continued to hold sway.
Ironically, Einstein himself in 1917 had done approximate calculations leading to the same general results, but he rejected these out of hand because he was prejudiced to believe that the universe must be static, that is, does not change with time. To fulfill this presumption, he altered his original equations, incorporating a new term, which, though logically legitimate, was most peculiar in that it attributed a gravitational effect to empty space itself. This term is proportional to a new constant, A, (lambda) about which more will be said later. In rejecting the dynamic solutions, Einstein missed the opportunity to predict the red shift and the expansion of the universe. He later referred to this as the greatest blunder of his life.

Friedmann's solutions became well known after they were rediscovered and presented in a more accessible form by H P Robinson and A G Walker in the early thirties. These solutions are, strictly speaking, strictly mathematical. Nevertheless, it is reasonable to say that the best interpretation of these solutions can be summarized by saying that space itself seems to be expanding, and that each galaxy remains at rest with respect to the space in its immediate locale. The situation is often aptly described by an analogy to the way that raisins in a rising loaf of soda bread move away from one another while all the time remaining at rest in the dough. Now clearly this picture attributes to space the character of a thing, a substance, which, though wonderfully tenuous, is nevertheless something: something very like a gas, in that it can expand.

This picture is only now in the last few years finding acceptance. The reason, I think, for its long rejection is that almost everyone in science had developed an aversion to anything that came near to the concept of an aether. This because they were under the impression, still widely held, that Einstein had proved in 1905 that the idea of space-as-a-thing – an aether – is unnecessary, if not downright ridiculous. (Some of you will also know that I don't accept this rejection of the concept of the aether.)

Beginning in the late fifties, attitudes regarding what had previously been thought of as "empty space" began to change after Richard Feynman, Julian Schwinger, and Sin-Hiro Tomonaga developed the theory of Quantum Electrodynamics. In this theory, space is no longer considered to be empty. It is now called "the vacuum," and takes on the role of an active player, seething with somewhat ephemeral, but nevertheless consequential, "virtual particles.”

Regarding the red shift, Friedmann's solutions show that the ratio of the wavelength of an observed spectral line to that of the corresponding line as produced in the lab, is equal to the ratio of the size of the universe at the time of observation, to the size of the universe at the time of emission. That is to say, once a photon is emitted, its wavelength increases in direct proportion to the increase in the size of the universe.

$$\lambda(t_{obs}) / \lambda_{lab}) = A(t_{obs}) / A(t_{emit})$$

The main points that I want to make in this introductory part of the paper are these:

(1) The big bang is not to be thought of as an explosion of primordial matter into surrounding empty space. It is an expansion of space itself, and it occurs everywhere.

(2) The red shift is not to be interpreted as a Doppler effect associated with the velocity of recession of the distant galaxies. It is a simple consequence of the fact that light waves expand as space expands. Since the time required for light from a galaxy to reach us is proportional to its distance from us, its red shift is also proportional to its distance. (This is strictly true only so long as the rate of expansion can be considered to be constant, which is the case for nearby galaxies, but not for distant ones.)

Regarding the first point, it is important to note that if the universe is now infinite (which current data and the usual interpretation suggest to be the case), it was always infinite even at the very instant of the Big Bang.

One more preliminary is in order. As we look at objects that are more and more remote, they will be more and more red shifted, and at some distance, we may expect that the light will be red shifted to infinite wavelength (zero frequency). In the "explosion" terminology, one would say that the velocity of recession is equal to the speed of light. In the correct picture, it turns out that infinite red shift corresponds to light which originated at the very instant of the Big Bang. The distance corresponding to an infinite red shift is called the horizon distance, and the volume of the associated sphere is referred to as the visible universe. As the universe expands, our horizon broadens and new objects come into view. When people refer to the size of the universe, they are referring to the visible universe, not the Whole Shebang, which may well be infinite in extent.

Problems with the Standard Big Bang Theory.

Friedmann's solutions are of three types, or really, two types separated by a single, improbable, special case. The critical parameter determining the global character of space, and, indeed, the ultimate fate of the universe, is a number that compares the density of gravitating matter in the universe to the rate of expansion of the universe. This number is represented by the Greek upper case letter omega, Ω, and is the ratio of the observed density of mass in the universe to the critical mass density, ρ_c, which latter is equal to a constant, 3/(8πG), times the square of the Hubble constant, Ho^2.

Friedmann's solutions show that if the actual density of mass in the universe is greater than the critical density, i.e., $\Omega > 1$, the universe must have the topology of a three sphere - a space which is finite but which closes upon itself - and must also have a finite lifetime. This latter means that at some stage in the evolution of such a universe, the expansion will slow, stop, and then reverse, i.e., the universe will begin to contract at an ever increasing rate, culminating in what is called the "Big Crunch."

If, on the other hand, the actual mass density is less than the critical value, $\Omega < 1$, the universe will not suffer the Big Crunch. Until recently, most cosmologists believed that such a universe must also be infinite in spatial extent, but in the last few years physicists have become aware of some previously obscure mathematical developments in Riemannian geometry, which show that finite, homogeneous three spaces of negative curvature are possible. The possibility and implications of our living in such a universe are the subject of an article in the April 1999 Scientific American authored by Glen Starkman of Case Western Reserve and colleagues Jean-Pierre Luminet and Jeffrey Weeks.

Separating these two possibilities - the mortal, finite universe of positive curvature, on one hand, and the immortal, infinite (or maybe finite) universe of negative curvature on the other - is the infinitely improbable ($\Omega = 1$) "flat" universe of zero curvature, which is also immortal. Zero curvature means that Euclidean geometry is valid in such a universe: parallel lines never meet, the angles of a triangle sum to 180 degrees, etc., etc. It may be, like its negatively curved mathematical neighbors, either finite or infinite.

An important point to note is that, in general, the parameter Ω changes as the universe evolves. Only in the special case of the "flat" universe for which $\Omega = 1$, does Ω remain constant. But if Ω is ever so slightly greater or less than unity, its value will very swiftly (exponentially) increase or decrease. One can say that Ω behaves in a chaotic manner, being exquisitely sensitive to the initial conditions.

Let's go back and look more carefully at the expansion of the universe. Friedmann's solutions predict that the red shift will not be strictly proportional to distance. This can be "understood" in terms of a naive model that suggests that the force of gravity will slow the expansion. If such slowing occurs, one would expect that the red shift of very distant galaxies would be larger than one would calculate on the basis of a linear extrapolation based upon data from nearby galaxies. This slowing effect is characterized by a parameter called the <u>deceleration parameter</u>, q_0. It turns out that under the reasonable assumption that the universe is "cool," in the sense that it is dominated by non-relativistic matter, there is a simple relation between the deceleration parameter, q_0, and Ω, the parameter that determines the structure and fate of the universe, namely, $\Omega = 2q_0$

It is only in the last year that telescopes and techniques have been developed which are capable of making observations of supernovas in galaxies sufficiently distant to permit a meaningful estimate of q_0. But during the two decades of the development of inflation theories, nothing was known regarding the value of the deceleration parameter.

But there are many things that were known about the universe. In particular, it was known that Galaxies exist. Sometime around 1978, Robert Dicke, a truly great American physicist adept at experiment as well as theoretical analysis, looked carefully at the conditions in the early universe, one second after the Big Bang in fact, that would be consistent with the fact that Galaxies exist. Dicke found the density of matter at that time would have to be extremely close to the critical value in order that galaxies would form. If the density were too low, the universe would have expanded too rapidly to permit the galaxies to coalesce. If too high, the universe would have reached its maximum size and collapsed into the Big Crunch before the galaxies had had time to form.

Now even absent the knowledge of the deceleration parameter, we can, by directly observing the radiant matter in the universe, and by making logical inferences regarding the amount of Dark Matter which evidences itself by its effect upon the dynamics of galaxies and clusters of galaxies, make a "ball park" estimate for the present density of matter in the universe. It is reasonable to say that we are ninety percent sure that the actual density is in the range of one-tenth to two times the critical density. That is, $0.1 < \Omega < 2.0$, at the present time.

Assuming this to be the case, Dicke calculated how close to unity the value of Ω would have had to have been one second after the Big Bang. The amazing conclusion is that, at that critical time, would have had to be equal to unity to one part in one hundred trillion _10^{14}_ (recall the extreme sensitivity of Ω). To imagine that this occurred purely by chance is not reasonable. Dicke convinced everyone that there was a problem with the standard theory of the Big Bang. This came to be called the Flatness Problem.

I mentioned before the observations of Penzias and Wilson of the cosmic microwave background radiation. Continuing studies, especially those implemented by NASA's COBE satellite, revealed a remarkable uniformity of this radiation, indicating that the universe was characterized by a correspondingly remarkably uniform temperature field at the time, about three hundred thousand years after the Big Bang, when the Universe became transparent. This occurred when the temperature decreased sufficiently to allow the previously ionized gas to recombine into uncharged atoms, which do not scatter and absorb photons. This radiation has the smooth continuous spectrum characteristic of a perfect emitter with an apparent temperature of 2.7^0 Kelvin. Since we know that a hydrogen plasma recombines to neutral hydrogen at about 4000^0 Kelvin, we know that the spectrum has been red shifted by the huge factor equal to 4000/2.7- 1500!

When we look at this radiation in one direction and then in the direction directly opposite, we are looking at opposite sides of a sphere that is now very nearly the size of the visible universe, which may be as much as 20 to 30 billion light years in diameter. From the standard (Friedmann) theory of the Big Bang one can calculate the distance between these points at the time, 300 thousand years after the Big Bang, when the radiation was emitted. The result is 900 million light-years, 1000 times the distance of 900 thousand light-years that light could travel in the three hundred thousand years since the big Bang. (Here it may seem to you that I have lost my marbles: How can light have traveled 900 thousand light-years in 300 thousand years? As I have said before, space itself is expanding, and in so doing, it carries the light along with it, at speeds which may, and in this case do, greatly exceed the speed of light itself.)

Anyway, this means that there was no possibility that heat could have been transferred between these points. Again, since the temperature inferred from the cosmic microwave radiation is uniform to one part in 100,000, we again appear to have a highly improbable coincidence. This seeming defect of the standard Big Bang theory is called the "Horizon Problem," referring to the fact that the realm of possible interaction, a sphere defined by the distance light has traveled since the Big Bang, is much smaller than the region of uniform temperature. These two problems, the flatness problem and the horizon problem, are not the only issues that the Standard Big Bang fails to adequately address. Most fundamentally, it fails to answer the Ur question: How did the universe come into existence?

Cosmic Inflation

We are now positioned to consider the theory of Cosmic Inflation. This theory in its various forms seemed to eliminate the flatness and horizon problems, and, amazingly, to actually describe a mechanism that could have triggered the Big Bang. In fact, according to its originator, Alan Guth, the question as to what caused the Big Bang was the beginning of the theory's development.

Remember my mentioning that modem field theory has found that the Vacuum is seething with virtual particles, constantly flashing into and out of existence. In 1973 Edward Tryon wrote a paper suggesting that the universe arose as a result of such a vacuum fluctuation. Tryon had first proposed the idea during a seminar in the late 1960s when he was an assistant professor at Columbia. Tyron was serious in making this suggestion, but his senior colleagues took it as a clever joke and broke into laughter. The theory of Cosmic Inflation, introduced by Alan Guth in December of 1979, supposes that Tryon was right.

I wish that I had the knowledge and writing skill to present to you a clear and detailed picture of inflation theory, but alas, I'm not up to the task. I fear that you will have to settle for the following rather vague and skimpy description. Before I get into that, however, let me describe what inflation is, and how it seems to solve the flatness problem and the horizon problem.

To say that Inflation begins very soon after the Big Bang is to push understatement to its limit. Inflation starts 10^{-37} seconds after the Big Bang, and lasts only about 2x 10^{-35} seconds. In that incredibly brief interval, nevertheless, the size of the universe increases by the mind-numbing factor of 10^{52}. You might think that such horrendous expansion would result in a huge universe, but remember that we are only able to discuss the visible universe, the part we have had time to see, so to speak, since the universe began. In the time between the Big Bang and the onset of inflation, the distance that light could have traveled is equal to twice (one only gets a factor of two in the early, radiation dominated epoch) the speed of light, 3×10^8 meters /second times 10^{-37} seconds, or 6×10^{-29} meters. During the inflationary period this would have ballooned by the factor of 10^{52} to a radius of 6×10^{23} meters = 6.6×10^7 light years. Remember that this refers to the situation at 10^{-35} second after the Big Bang. Thereafter, what might be called classical, or Friedmann, expansion would have followed. Now one can ask how big, or more appropriately, how small was our present visible universe at that time, at the beginning of the classical expansion. The answer is just about one meter! Thus it is clear that the precursor of our visible universe was a tiny thing compared with the volume of space which had had time before inflation to equalize temperature differences. This disposes of the horizon problem. Furthermore, assuming that space was only finitely curved prior to the inflationary epoch, any such curvature over the one-meter sphere from which our visible universe evolved would have been pulled to absolute flatness by the inflation. It can also be shown that inflation will drive Ω very strongly to unity, regardless of its initial value. Bingo, there goes the flatness problem. Inflation theory, by solving these vexing problems, had great appeal to cosmologists.

The Theory of Inflation

The theory was and remains, however, highly speculative. The first thing one wants to know regarding Inflation is, "what caused this fantastic expansion?" The answer is to be found in that Pandora's Box, the Vacuum, as it is understood by modem quantum field theory. It is truly ironic that this discipline, developed to describe the behavior of the smallest things that exist, should be invoked in order to understand the largest thing we can have knowledge of, the Universe.

The electroweak theory, a unified description of electromagnetism and the so-called weak interactions, is one of the triumphs of modern physics. A typical weak interaction is the decay of a neutron into a proton plus an electron and an anti-neutrino. Fortunately there is no need here to go further into this complicated business. It is sufficient that you should know that it's an elegant theory, incredibly accurate in its predictions. What is not so well known is the fact that the theory has as an essential ingredient one or more ghostly quantum fields called <u>Higgs Fields</u>.

Higgs fields are in a sense the simplest type of field imaginable. Electromagnetism is described by a vector field, requiring a quartet of numbers at each point in spacetime; gravity by a tensor field, requiring ten numbers at each such point. Matter fields, such as those of electrons, quarks, and so forth, are described by various spinor fields represented by 4x4 matrix arrays of complex numbers. By comparison, a Higgs field is really simple - just a single complex number at each point in spacetime. But so far there is no <u>direct</u> evidence of any field of this type. But since Higgs fields are essential to the wonderfully successful electroweak theory, everyone is convinced that fields of this type must certainly exist. The theory of Cosmic Inflation is based upon the existence of one or more fields of the Higgs type. These fields are not, however, those that are involved in the electroweak theory.

It is perhaps natural to think that the non-existence of a field can be equated with the field having everywhere a zero value. In modern quantum physics, with its seething Vacuum, one has no such assurance. Rather, one must consider what would happen if the field took on a non-zero value. If the total energy in space is lower with the non-zero field, then the Vacuum will contrive to achieve that value of the field that will minimize its energy. Many versions of inflation theory have been put forward, but all of them assume that the Higgs fields responsible for inflation are characterized by a peculiar relationship between the field values and the energy density of space. All the models assume that the energy is extremely high when all of the Higgs fields have zero values, and that the energy achieves a minimum value over the surface of a spheroid in Higgs space. If there were just two Higgs fields, this would be a circle centered on the origin. In the original version of inflation proposed by Alan Guth in 1981, the Higgs fields were thought to be the same as those involved in what is known as Grand Unified Theories (GUTs) of particle physics. These theories seek to unify the theory of strong forces, (quantum chromodynamics), with the theory of electroweak interactions. The simplest such theory, developed by Howard Georgi and Sheldon Glashow in the 1974, requires 24 Higgs fields.

One seeming problem with GUTs is that they unavoidably involved the production of large numbers of magnetic monopoles, which should be very easy to detect but have never been seen. In fact, it was the monopole problem that led Guth to study the Higgs fields of GUTs. In particular, Guth was led to consider the gravitational effects associated with the Higgs fields. His analysis revealed two startling facts. First, that near zero values of the Higgs fields implied not only a high energy density in space, but also implied that space was characterized by equally high, but negative, pressure! Secondly, he found that Einstein's theory of gravity (general relativity) predicted that this negative pressure would produce a gravitational repulsion that was three times larger than the attraction caused by the positive energy density of the Higgs field. Space would thus be expected to expand. Also the nature of the Higgs field is such that the value of the Higgs field would be unaffected by the expansion of space. In these circumstances, space would expand as an exponential function of time, with the distance between objects at rest in space doubling every 10^{-37} seconds.

Curiously, the effect of the Einstein's regretted constant, Λ, is qualitatively, but certainly not quantitatively, identical to that of the Higgs fields. For positive values, it also represents a gravitational repulsion that would lead to an exponential expansion of space. One of the apparent failures of the attempts to apply quantum theory to cosmology has to do with attempts to calculate Λ. Recall that according to quantum mechanics the Vacuum is seething with virtual particles. The calculation of their gravitational effect predicts that they will give rise to a repulsive effect exactly of the Λ type. The only trouble is that the magnitude is a little off - the calculated value is too large by an astounding 120 orders of magnitude! At present no one has a clue as to how this paradox might be resolved.

The original inflation theory developed by Alan Guth proved to be unacceptable for the reason that there was no way to end the inflationary period in a manner that would be consistent with the observed uniformity of the universe. Late in 1981 Andrei Linde, and independently Paul Steinhart, proposed a new theory of inflation that allowed for what came to be called a graceful exit. The key was a change in the detailed structure of the function relating the magnitude of the Higgs field with the energy density of space. The function required had to be very different from that required for the Higgs fields of the GUTs. Guth had originally discovered inflation by considering the possible effects of gravitation upon the Higgs fields of the GUTs, but now inflation demanded a new type of Higgs field (or fields), and these are now referred to as inflaton fields.

Nevertheless, the truly weird features of the original theory are still present. Here again, rear-zero values of the inflaton fields are characterized by enormous energy densities, and here again these are accompanied by equally huge but negative pressures, and these produce, as before, gravitational repulsion, resulting in the exponential expansion of space. What is different is the much more gradual manner in which the inflaton fields decay. This permits a smooth phase transition in which the energy of the inflaton field is converted into a hot soup of energetic particles. Such phase transitions occur as a result of quantum fluctuations, and this means that some regions will begin the transition before others. Also, once a tiny region begins transition, it induces adjacent regions to do likewise. The phase change thus proceeds as a number of growing bubbles. Even though each bubble wall advances at the speed of light, the bubbles nevertheless move away from one another because the exponential expansion of space is still proceeding apace at speeds that dwarf the speed of light. In this picture, our whole visible universe was born of a single bubble, and if this new inflation theory is correct, there are undoubtedly a multitude of other separate universes in what is now sometimes referred to as the multiverse. Also, if, as one would expect, the Higgs fields of GUTs in different bubbles are not correlated, it would follow that the whole content of physics would be different in each bubble. Thus each universe would possess a unique set of coupling constants, field strengths, and particle masses measuring the Revolution in Cosmology

Just in the past year astronomers have finally succeeded in deceleration parameter, q_0, which supposedly determines the rate at which gravity is slowing the expansion of the universe. The technique depends upon the fact that a certain type of supernova, type Ia, has an intrinsic brightness that varies over a narrow range, and further, that this variation is correlated with rate at which the light from the supernova fades away with time. As you might guess, brighter supernovas fade more slowly than the dimmer ones. Astronomers are confident that they can determine the intrinsic brightness of these objects to within twelve percent. Such supernovas serve as ideal "standard candles," and so permit a measurement their distance. To everyone's amazement, the results revealed that these supernovas were much dimmer than one would expect on the basis of their red shift and the standard Friedmann theory of the expansion of the universe. They were even dimmer than the result one would get assuming an extreme open universe model, in which the area of a sphere increases faster than the square of the radius. There seems to be no alternative but to assume that the expansion of the universe is accelerating rather than decelerating. In response to this unforeseen development, theorists have been unusually prompt with newly minted explanations. The remarks that follow are based upon two articles in the January 1999 issue of *Scientific American*.

CWRU's Lawrence Krauss and others suggest that the answer is to be found in the once maligned cosmical constant, A. If it were to have just the right value it would solve two problems. First, recalling that A produces a repulsive effect, the right value for lambda could explain the acceleration of the expansion of the universe. Secondly, recall that observation strongly implies that there is not enough matter in the universe, counting dark as well as visible matter, to reach the critical value of energy density required to make a flat universe. But careful examination of the cosmic microwave background radiation strongly suggest that the universe is flat. The extra energy density required to flatten the universe could be provided by the cosmological constant. This may seem strange since a positive value of A implies a repulsive gravitational effect. But a positive A nevertheless represents a positive energy density, and thus it can help to flatten the universe. It happens that a single value for lambda seems to satisfy both requirements. This could be a coincidence, but if so, it's a happy one.

The proponents of inflation would at first thought seem to be in an untenable position, since up to now all versions of the theory have predicted that the universe must be extremely flat, with the density parameter Ω equal to unity within one part in 100,000. But these are crafty people, and as you might guess, the day can be saved by careful modification of the inflaton field. In the new scenario, called "open inflation," the universe begins to inflate as before but now the process is held up by the presence of a local minimum in the function that describes the relation between the energy and the value of the inflaton field. Most of space-time is trapped in this "false vacuum" but here and there, every now and then, a bubble will form by means of quantum tunneling. At the wall of the bubble the inflaton field decays producing again a hot soup of particles. But now the inflation does not proceed with the incredible speed that characterized the expansion in the (now old) "new inflation." Rather the value of Ω is zero at the wall of the bubble and increases toward the center of the bubble. For any observer inside the bubble, the value of Ω will increase with time and gradually approach the value of unity so long as the inflation continues. When the inflation stops, the value of Ω will begin to decrease, so that any value, including the value of 0.3 that seems to characterize our comer of our bubble, is possible. In this model the horizon problem - how is it that the observable universe is so uniform - is handled by the first stage of inflation, the one that precedes the epoch of the "false vacuum" and the production of bubbles.

I cannot resist remarking that the whole business regarding the origin of the universe admits an alternate interpretation. In this interpretation, the red shift can be understood to be the result of an on-going process that results in a continual increase in the rate at which all physical processes occur. Thus the light from distant galaxies is understood to be red shifted because that light originated in an epoch when the frequencies of all atomic transitions were much lower than they are today. Also, according to this interpretation, the universe is not really expanding, although it appears to be. This is because the same phenomenon that causes the speed-up of physical processes also has the effect of causing all material objects to shrink. A little thought will make it clear that, philosophically at least, there is no difference between the statement "the universe is expanding," on the one hand, and the statement, "our measuring rods are shrinking," on the other. Nevertheless this interpretation seems at least whimsical, if not downright outrageous. Why it is not unreasonable to adopt this strange interpretation this will require some explanation.

You may recall my brief remarks regarding the electroweak theory to the effect that the Higgs fields act to endow the various particle fields with rest mass. In the alternate interpretation of cosmology, fields of this type are thought to act so as to increase the rest mass of all particles as a function of time, and that function has precisely the same form as the function that is said to describe the supposed expansion of the universe.
It is trivial to show, using elementary quantum mechanics, that the period of a clock and the length of a measuring rod will be decreased in direct proportion to the increase in the rest mass of the elementary particles of which they are composed. To imagine that this is actually happening is not merely fanciful speculation. There is a very sound reason to believe that it must be so. All of the conservation laws (which may be said to constitute the foundation of physical theory) stem from the symmetries that physical systems exhibit. In the case of cosmology, a fundamental symmetry is the homogeneity of space. The corresponding conserved quantity is momentum, and its conservation demands that the rest mass of all objects must increase in direct proportion to the function that is identified in conventional theories as that describing the expansion of the universe. Thus we may say that the universe is not expanding, but rather we, along with our measuring rods, are contracting. These ideas were originally presented to the philosophical club of Cleveland in my first talk before the club just 21 years ago this spring. Time does not permit any further consideration of this interpretation, but I will be happy to provide those interested with a copy of the most recent version of that paper.

Summing up, it must be said that the picture that emerges regarding current theories in cosmology is very confused. It is clear that progress depends upon the development of an adequate quantum field theory of the inflaton field, and of scalar fields in general. These include the GUTs Higgs fields which are held to be responsible for the breaking of supersymmetry, by means of which breaking the elementary particles acquire their rest masses, as well as the Higgs fields of the electroweak theory. Experiments are now planned to detect the Higgs particle associated with this latter field. Theorists are hopeful that the detection of such particles and the measurement of their mass spectrum will guide them in the development of better theories. Likewise it will be very helpful if a resolution can be found to the mystery regarding the magnitude of the energy density of the vacuum and its relationship to Einstein's cosmical constant, Λ. Until these things come about, it is unlikely that any of the present theories describing the origin of the universe will gain widespread acceptance among physicists. And who can guess when ordinary men will feel comfortable with, if not understand, these profoundly strange and difficult ideas.