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Inflation

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Inflation

According to inflationary theory, there was a stage of exponentially rapid expansion of the early universe. The existence of this stage resolves many long-standing problems of the **BIG BANG THEORY** and changes our understanding of the origin of the universe and of its global structure.

Inflation and the big bang theory

Inflationary cosmology describes the very early stages of the evolution of the universe and its structure at extremely large distances from us. For many years, cosmologists believed that the universe from the very beginning looked like an expanding ball of fire. This explosive beginning of the universe was called the big bang. In the end of the 1970s a different scenario for the universe's evolution was proposed. According to this scenario, the universe at the very early stages of its evolution came through the stage of inflation, an exponentially rapid expansion in a kind of unstable vacuum-like state (a state with large energy density, but without elementary particles). This stage could be very short, but the universe within this time became exponentially large. At the end of inflation the vacuum-like state decayed, the universe became hot and its subsequent evolution could be described by the standard big bang theory (see also **UNIVERSE: SIMULATIONS OF STRUCTURE AND GALAXY FORMATION**, **UNIVERSE: THERMAL HISTORY**).

The existence of the inflationary stage is necessary to resolve many difficult problems which arise when one tries to unify the modern theory of elementary particles and the standard big bang theory. The standard big bang theory asserts that the universe was born at some moment $t = 0$ about 15 billion years ago, in a state of extremely high temperature T and density ρ (cosmological singularity). It is usually assumed that the standard description of the universe in terms of space and time becomes possible at the Planck time $t \sim 10^{-43}$ s after the singularity, when its density drops below the so-called Planck density $\rho_p \sim 10^{94}$ g cm⁻³ (see **UNIVERSE: DENSITY**). (At greater density, quantum fluctuations of space-time are so large that an alternative description of space-time is required.) The temperature of the expanding universe gradually decreased, as the reciprocal of its size, and finally the universe evolved into the relatively cold universe where we live now. Remnants of this primordial cosmic fire still surround us in the form of the microwave background radiation with a temperature of 2.7 K.

This theory was extremely successful in explaining various features of our world. However, in combination with the modern theory of elementary particles, it predicts the existence of a large amount of superheavy stable particles carrying magnetic charge: magnetic monopoles. These objects have a typical mass 10^{16} times that of the proton. According to the standard big bang theory, monopoles should appear at the very early stages of the evolution of the universe, and they should now be as abundant as protons. In that case the mean density

of matter in the universe would be about 15 orders of magnitude higher than its present value of about 10^{-29} g cm⁻³.

In addition to this problem, the standard big bang theory was unable to answer many other questions. For example, the universe is closed if $\Omega = \rho/\rho_c > 1$, it is flat if $\Omega = 1$ and it is open if $\Omega < 1$. Here ρ is the density of the universe, ρ_c is the critical density, which at the present epoch is of the order 10^{-29} g cm⁻³. The value of the parameter Ω changes in an expanding universe. Observational data suggest that now $0.3 < \Omega < 1.2$, which does not seem unnatural. However, according to the big bang theory, this requires that at the Planck time the value of Ω should coincide with 1 with an accuracy of 10^{-60} . A slightly higher value of Ω would lead to a closed universe which would immediately collapse; a slightly smaller value of Ω would lead to an open universe, which at present would be practically empty. The need for this incredible fine tuning of initial conditions in the standard big bang theory is the essence of the flatness problem.

One may also wonder, where did the universe come from? How could it happen that its different, causally disconnected parts could begin their expansion simultaneously? Why it is so big, homogeneous and isotropic? If it must be homogeneous for whatever reason, then what is the origin of galaxies? Why is our space three-dimensional? Is it possible that our universe could be created differently?

All these problems are extremely difficult, and some of them sound almost metaphysical. That is why it is so encouraging that most of the problems mentioned above can be resolved in the context of one simple scenario of the evolution of the universe—the inflationary universe scenario.

New theories of elementary particles and the notion of a scalar field

Inflationary theory became possible owing to the rapid progress of the theory of elementary particles during the last two decades, after physicists have found a way to unify weak, strong and electromagnetic interactions (see **STANDARD MODEL OF PARTICLE PHYSICS**).

It is well known that electrically charged particles interact with each other by creating an electromagnetic field around them. Small excitations of this field are called photons. Photons do not have any mass, which is the main reason why electrically charged particles can easily interact with each other at a very large distance. Weak and strong interactions are mediated by similar particles. For example, weak interactions are mediated by particles called W and Z. However, whereas photons are massless particles, the particles W and Z are extremely heavy; it is very difficult to produce them. That is why weak interactions are so weak. In order to obtain a unified description of weak and electromagnetic interactions despite the obvious difference in properties of photons and the W and Z particles, physicists introduced scalar fields ϕ , which will play the central role in our discussion.

The closest analog of a scalar field is the electrostatic potential Φ . Electric and magnetic fields appear only if this potential is inhomogeneous or if it changes in time. If the whole universe were to have the same electrostatic potential, then nobody would notice it; it would be just another vacuum state. Similarly, a constant scalar field ϕ looks like a vacuum state; we do not see it even if we are surrounded by it.

The main difference is that the constant electrostatic potential Φ does not have its own energy, whereas the scalar field ϕ may have potential energy density $V(\phi)$. If $V(\phi)$ has one minimum at $\phi = \phi_0$, then the whole universe eventually becomes filled by the field ϕ_0 . This field is invisible, but, if it interacts with the W and Z particles, they become heavy. Meanwhile, if photons do not interact with the scalar field, they remain light. Therefore we may begin with a theory in which all particles initially are light and there is no fundamental difference between weak and electromagnetic interactions. This difference appears later, when the universe becomes filled by the scalar field ϕ . At this moment the symmetry between different types of fundamental interactions becomes broken. This is the basic idea of all unified theories of weak, strong and electromagnetic interactions. A scalar field ϕ of a similar type is the main ingredient of inflationary theory.

Development of inflationary theory

According to the big bang theory, the rate of expansion of the universe given by the HUBBLE 'CONSTANT' $H(t)$ is (approximately) proportional to the square root of its density. If the universe is filled by ordinary matter, then its density rapidly decreases as the universe expands. Therefore expansion of the universe rapidly slows down as its density decreases. This rapid decrease of the rate of the universe's expansion is the main reason for all our problems with the standard big bang theory. However, because of the equivalence of mass and energy established by Einstein ($E = mc^2$), the potential energy density $V(\phi)$ of the scalar field ϕ also contributes to the rate of expansion of the universe. In certain cases the energy density $V(\phi)$ decreases much more slowly than the density of ordinary matter. This may lead to the existence of a stage of extremely rapid expansion (inflation) of the universe.

The first version of inflationary theory was proposed in 1979 by Alexei Starobinsky of the Landau Institute, Moscow. Starobinsky's model created a sensation among Russian astrophysicists, and for two years it remained the main topic of discussion at all conferences on cosmology in the Soviet Union. However, his model was rather complicated, being based on the theory of anomalies in QUANTUM GRAVITY; it was not well known outside of Russia.

The crucial step in the development of inflationary theory was made in 1981 by Alan Guth of MIT. He suggested that the hot universe at some intermediate stage could expand exponentially, being in an unstable supercooled state called the 'false vacuum'. He called this stage of exponential expansion 'inflation'. The main idea of his model was based on the theory of cosmological

phase transitions with supercooling, which was developed in the mid-1970s by David Kirzhnits and Andrei Linde at the Lebedev Institute, Moscow. This scenario was so attractive that even now many people associate inflation with expansion in a false vacuum. Unfortunately, as Guth has found himself, the universe after inflation in his scenario becomes extremely inhomogeneous. After a year of investigation, Guth, in his paper with Eric Weinberg of Columbia University, concluded that his model could not be improved.

In 1982 Linde introduced the so-called new inflationary universe scenario, which later was also discovered by Andreas Albrecht and Paul Steinhardt at the University of Pennsylvania. Inflation in this scenario occurs not only in the false vacuum $\phi = 0$ but also when the scalar field ϕ begins slowly moving towards the minimum of $V(\phi)$. This scenario was free of the main problems of the model suggested by Guth, but it was rather complicated. It assumed that the universe from the very beginning was extremely large and hot, that it was in a state of thermal equilibrium although the field ϕ was practically decoupled from all other particles. It also required the potential $V(\phi)$ to have a very specific, fine-tuned form. No realistic versions of this scenario have been proposed so far.

Finally, in 1983 Linde has found that inflation can naturally occur in many theories of elementary particles. There is no need for quantum gravity effects, phase transitions and supercooling. There is no need to assume that the whole universe was created at the same moment, that it was in a state of thermal equilibrium and that the scalar field from the very beginning was at the minimum of its potential energy density. One should consider all possible chaotic distributions of the scalar field in the early universe, and then check whether some of them lead to inflation. Those places where inflation does not occur remain small, whereas those domains where inflation takes place become exponentially large and give the main contribution to the total volume of the universe. This scenario was called 'chaotic inflation'. Its simplest version was described in the previous section. In the context of this scenario inflation is not an exotic phenomenon invoked by theorists for solving their problems. It is a very general regime which occurs in a wide class of theories including many models with polynomial and exponential potentials $V(\phi)$.

Chaotic inflation

To explain the basic idea of chaotic inflation, let us consider the simplest model of a scalar field ϕ with a mass m and with the potential energy density $V(\phi) = (m^2/2)\phi^2$ (figure 1). Since this function has a minimum at $\phi = 0$, one may expect that the scalar field ϕ should oscillate near this minimum. This is indeed the case if the universe does not expand. However, one can show that in a rapidly expanding universe the scalar field moves down very slowly, as a ball in a viscous liquid, viscosity being proportional to the speed of expansion.

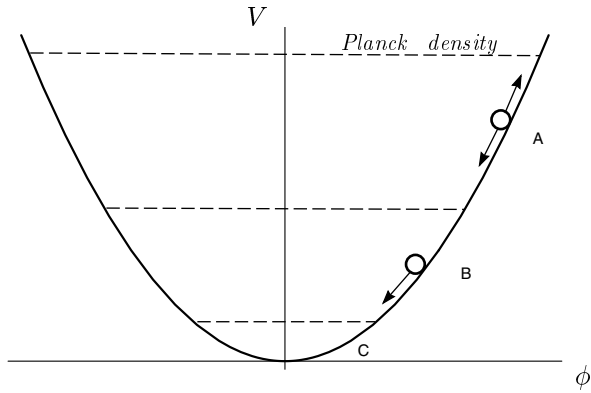


Figure 1. Motion of the scalar field in the theory with $V(\phi) = (m^2/2)\phi^2$. Several different regimes are possible, depending on the value of the field ϕ . If the potential energy density of the field is greater than the Planck density $10^{94} \text{ g cm}^{-3}$, quantum fluctuations of space–time are so strong that one cannot describe it in usual terms. Such a state is often called space-time foam. At a somewhat smaller energy density (region A) quantum fluctuations of space–time are small, but quantum fluctuations of the scalar field ϕ may be large. Jumps of the scalar field due to quantum fluctuations lead to a process of eternal self-reproduction of inflationary universe which we are going to discuss later. At even smaller values of $V(\phi)$ (region B) fluctuations of the field ϕ are small; it slowly moves down as a ball in a viscous liquid. Inflation occurs in both the region A and region B. Finally, near the minimum of $V(\phi)$ (region C) the scalar field rapidly oscillates, creates pairs of elementary particles, and the universe becomes hot.

There are two equations which describe the evolution of a homogeneous scalar field in our model:

$$H^2 + \frac{k}{a^2} = \frac{4\pi G}{3}(\dot{\phi}^2 + m^2\phi^2)$$

$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi.$$

Here $H = \dot{a}/a$ is the Hubble parameter in the universe with a scale factor $a(t)$, $k = -1, 0, 1$ for an open, flat or closed universe respectively, G is the gravitational constant. The first of these two equations is the Einstein equation for a homogeneous universe containing a scalar field ϕ with energy density $\rho = \dot{\phi}^2/2 + m^2\phi^2/2$. The second equation is the standard Klein–Gordon equation for a homogeneous scalar field. The only difference (but a very important one) is the presence of the term $3H\dot{\phi}$, which appears owing to the expansion of the universe. This equation is similar to the equation of motion for a harmonic oscillator, where instead of $x(t)$ we have $\phi(t)$, with a friction term $3H\dot{\phi}$.

If the scalar field ϕ initially was large, the Hubble parameter H was large too, according to the first equation. This means that the friction term $3H\dot{\phi}$ in the second equation was very large, and therefore the scalar field was moving very slowly, as a ball in a viscous liquid. Therefore at this stage the energy density of the scalar field, unlike the density of ordinary matter, remained almost constant, and expansion of the universe continued with a much greater

speed than in the old cosmological theory. Because of the rapid growth of the scale of the universe and the slow motion of the field ϕ , soon after the beginning of this regime one has $\dot{\phi} \ll 3H\dot{\phi}$, $H^2 \gg k/a^2$, $\dot{\phi}^2 \ll m^2\phi^2$, so the system of equations can be simplified:

$$\frac{\dot{a}}{a} = 2m\phi \left(\frac{\pi G}{3}\right)^{1/2} \quad 3\frac{\dot{a}}{a}\dot{\phi} = -m^2\phi. \quad (1)$$

The first equation shows that if the field ϕ changes very slowly, then the size of the universe grows approximately as e^{Ht} , where $H = (8\pi G V(\phi)/3)^{1/2} = 2m\phi(\pi G/3)^{1/2}$.

This stage of exponentially rapid expansion of the universe is called inflation. In realistic versions of inflationary theory its duration could be as short as 10^{-35} s. When the field ϕ becomes sufficiently small, viscosity becomes small, inflation ends and the scalar field ϕ begins to oscillate near the minimum of $V(\phi)$. As any rapidly oscillating classical field, it loses its energy by creating pairs of elementary particles. These particles interact with each other and come to a state of thermal equilibrium with some temperature T . From this time on, the corresponding part of the universe can be described by the standard hot universe theory.

The main difference between inflationary theory and the old cosmology becomes clear when one calculates the size of a typical inflationary domain at the end of inflation. Investigation of this question shows that even if the size of inflationary universe at the beginning of inflation in our model was as small as the Planck size $l_p \sim 10^{-33}$ cm, after 10^{-35} s of inflation the universe acquires a huge size of $l \sim 10^{10^{12}}$ cm. These numbers are model dependent, but in all realistic models this size appears to be many orders of magnitude greater than the size of the part of the universe which we can see now, $l \sim 10^{28}$ cm. This immediately solves most of the problems of the old cosmological theory.

Our universe is so homogeneous because all inhomogeneities were stretched $10^{10^{12}}$ times. The density of primordial monopoles and other undesirable ‘defects’ becomes exponentially diluted by inflation. The universe becomes enormously large. Even if it was a closed universe of a size $\sim 10^{-33}$ cm, after inflation the distance between its ‘south’ and ‘north’ poles becomes many orders of magnitude greater than 10^{28} cm. We see only a tiny part of the huge cosmic balloon. That is why the universe looks so flat. That is why we do not need expansion of the universe to begin simultaneously in many different causally disconnected domains of a Planck size.

If one considers a universe which initially consisted of many domains with chaotically distributed scalar field ϕ (or if one considers different universes with different values of the field), then domains in which the scalar field was too small never inflated. The main contribution to the total volume of the universe will be given by those domains which originally contained a large scalar field ϕ . Inflation of such domains creates huge homogeneous islands out of initial chaos. Each inflationary domain in this scenario is much greater than the size of the observable

part of the universe. The properties of space inside each such domain after inflation practically do not depend on initial conditions at the beginning of inflation.

Quantum fluctuations as a source for galaxy formation

Solving many difficult cosmological problems simultaneously by a rapid stretching of the universe may seem too good to be true. Indeed, if all inhomogeneities were stretched away, there will be no inhomogeneities left, and these are necessary for the creation of galaxies (see GALAXY FORMATION). Fortunately, while removing previously existing inhomogeneities, inflation at the same time created new ones. The basic mechanism can be understood as follows.

According to quantum field theory, empty space is not entirely empty. It is filled with quantum fluctuations of all types of physical fields. These fluctuations can be regarded as waves of physical fields with all possible wavelengths. If the values of these fields, averaged over some macroscopically large time, vanish, then the space filled with these fields seems to us empty and can be called the vacuum.

In the inflationary universe the vacuum structure is more complicated. Those waves which have very short wavelength 'do not know' that the universe is curved; they move in all directions with a speed approaching the speed of light. However, inflation very rapidly stretches these waves. Once their wavelengths become sufficiently large, these waves begin feeling that the universe is curved. At this moment they stop moving because of the effective viscosity of the expanding universe with respect to the scalar field.

The first quantum fluctuations to freeze are those with large wavelengths. The amplitude of the frozen waves does not change later, whereas their wavelengths grow exponentially. In the course of expansion of the universe newer and newer fluctuations become stretched and freeze on the top of each other. At that stage one cannot call these waves 'quantum fluctuations' anymore. Most of them have exponentially large wavelengths. These waves do not move and do not disappear on being averaged over large periods of time. What we obtain is an inhomogeneous distribution of the classical scalar field ϕ which does not oscillate. Perturbations of the scalar field create Gaussian adiabatic perturbations of the metric (density perturbations). It is these perturbations that are responsible for the subsequent appearance of galaxies and formation of the large-scale structure of the universe.

Note that the amplitude of inflationary perturbations depends on the Hubble parameter H , which changes only very slowly during inflation. At the same time, the wavelength of the perturbations grows exponentially. As a result, the amplitude of the density perturbations is nearly scale independent; they have flat spectrum. The fact that inflation produces adiabatic Gaussian perturbations with a nearly flat spectrum practically does not depend on the choice of the inflationary potential $V(\phi)$, even though

the amplitude of the perturbations does depend on $V(\phi)$. In addition to adiabatic perturbations, inflation produces gravitational waves, which also have a flat spectrum.

Eternal inflation

The possibility that galaxies appear as a result of quantum fluctuations may seem very unusual. However, a further pursuit of this idea has led to an even less expected conclusion: quantum fluctuations may lead to an eternal process of self-reproduction of the universe. This effect is rather general, but it looks especially surprising and leads to most dramatic consequences in the context of the chaotic inflation scenario.

As we already mentioned, one can visualize quantum fluctuations of the scalar field in inflationary universe as waves, which move in all possible directions and then freeze on the top of each other. Each freezing wave slightly increased the value of the scalar field in some parts of the universe and slightly decreased this field in other parts of the universe.

Consider those rare parts of the universe where these freezing waves always increased the value of the scalar field ϕ , persistently pushing the scalar field uphill, to the larger values of its potential energy $V(\phi)$. This is an unusual and obviously improbable regime. Indeed, the probability that the field ϕ will make one jump up (instead of jump down) is equal to $1/2$ and the probability that the next time it also jumps up is also $1/2$, so that the probability that the field ϕ without any special reason will make N consecutive jumps in the same direction is extremely small; it will be proportional to $1/2^N$.

Normally one neglects such fluctuations. However, in inflationary cosmology they can be extremely important. Indeed, those rare domains of the universe where the field jumps high enough begin exponentially expanding with ever-increasing speed. Remember that the inflationary universe expands as e^{Ht} , where the Hubble constant is proportional to the square root of the energy density of the field ϕ . In the simple model with $V(\phi) = (m^2/2)\phi^2$ the Hubble constant H will be simply proportional to ϕ . Thus, the higher the field ϕ jumps, the faster the universe expands. Very soon those rare domains, where the field ϕ persistently climbs up the wall, will acquire a much greater volume than those domains which keep sliding to the minimum of $V(\phi)$ in accordance with the laws of classical physics.

This implies that, if the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing newer and new inflationary domains. Inflation at each particular point may stop very quickly, but there will be many other places which will continue expanding exponentially. The total volume of all inflationary domains will grow without end. This picture differs considerably from the standard big bang cosmology which assumed that our universe is similar to one huge homogeneous expanding ball. According to the new theory, our universe is not a ball but a fractal,

which looks like a tree consisting of an infinite number of inflationary balloons producing new balloons.

In this scenario the universe as a whole is immortal. Each particular part of the universe may appear from a singularity somewhere in the past, and it may end up in a singularity somewhere in the future. However, there is no end to the evolution of the whole universe. The situation with the beginning is less certain. It is most probable that each part of the inflationary universe has originated from some singularity in the past. However, at present we do not have any proof that all parts of the universe were created simultaneously in a general cosmological singularity, before which there was no space and time at all. Moreover, the total number of inflationary bubbles on our 'cosmic tree' exponentially grows in time. Therefore most of the bubbles (including our own part of the universe) grow indefinitely far away from the root of this tree. This does not necessarily eliminate the big bang, but it removes the possible beginning of the whole universe to the indefinite past.

Until now we have considered the simplest inflationary model with only one scalar field ϕ . However, in realistic models of elementary particles there are many different scalar fields. For example, in the unified theories of weak and electromagnetic interactions there exist at least two other scalar fields, Φ and H . In some versions of these theories the potential energy density of these fields has about a dozen different minima of the same depth. During inflation these fields, just as the field ϕ , jump in all possible directions owing to quantum fluctuations. After inflation they fall down to different minima of their energy density in different exponentially large parts of the universe. Scalar fields change properties of elementary particles and the laws of their interaction. This means that after inflation the universe becomes divided into exponentially large domains with different laws of low-energy physics.

Note that, if fluctuations are not too strong, scalar fields cannot jump from one minimum of their energy density to another. In this case the new parts of the inflationary universe remember the 'genetic code' of their parents. However, if fluctuations are sufficiently large, mutations occur. In some inflationary models quantum fluctuations become so strong that even the effective number of dimensions of space and time can change. According to these models, we find ourselves inside a four-dimensional domain with our kind of physical laws not because domains with different dimensionality and with different particle properties are impossible or improbable, but simply because our kind of life cannot exist in other domains.

Inflation, observational data and particle physics

In addition to explaining many features of our world, inflationary theory makes several important predictions. First of all, most of the inflationary models predict that the universe should be extremely flat, $\Omega = 1 \pm 10^{-4}$ ¹. It

¹ Note that, from the point of view of the geometry of the universe, the flatness condition $\Omega = 1$ takes into account the

is possible to have inflationary models with $\Omega < 1$ (open inflation). So far all models of this type are much more complicated than the models which lead to $\Omega = 1$.

Also, as we already mentioned, inflation generates Gaussian adiabatic perturbations of metric with a nearly scale-independent (flat) spectrum. This is one of the most important and robust predictions of inflationary cosmology that can be experimentally tested. We are unaware of any non-inflationary mechanism that would produce such perturbations.

Flatness of the universe can be experimentally verified, since the density of a flat universe is related in a very simple way to the speed of its expansion given by the Hubble constant. So far observational data are consistent with the simplest possibility $\Omega = 1$. If it happens that the total energy density is smaller than ρ_c , so that the universe is open, it will be necessary to make substantial adjustments to inflationary theory and consider models of open inflation.

Properties of density perturbations produced during inflation can be tested not only by looking at the distribution of matter in the universe. These perturbations make their imprint on the COSMIC MICROWAVE BACKGROUND radiation. They make the temperature of this radiation slightly different in different places in the sky. This is exactly what was found by the Cosmic Background Explorer (COBE) and later confirmed by several other groups of observers.

A new generation of satellites measuring the anisotropy of the microwave background radiation will bring us much more detailed information about the spectrum of perturbations of the metric in the early universe. This information, combined with independent investigation of Ω by other methods, will make it possible to perform a thorough test of various versions of inflationary theory. It may rule out many particular versions of inflationary theory. However, even though each particular version of inflationary theory can be tested, it may be difficult or even impossible to rule out the main idea of inflationary cosmology. For example, as we already mentioned, if observations show that the universe is not flat but open, we will need to consider more complicated versions of inflationary theory. However, it is important that these versions do exist. Meanwhile, at present we do not have any non-inflationary theory of an open universe which would explain why the universe is so homogeneous and predict the small inhomogeneities ('ripples in space') discovered by COBE.

It is too early to claim that the recent observational data have confirmed inflationary theory, but it is certainly true that these results already at their level of accuracy could definitively disprove most of the inflationary models, and this did not happen. Recent observational data give certain evidence in favor of the simplest

contributions to ρ from all sources, including vacuum energy, or cosmological constant. However, astronomers often exclude the contribution to Ω from the vacuum energy, which sometimes leads to terminological misunderstandings.

versions of inflationary theory predicting a flat universe with a flat spectrum of Gaussian adiabatic perturbations. Meanwhile, during the last few years the observational data practically ruled out the only alternative mechanism of formation of the large-scale structure of the universe, based on the theory of topological defects. Note also that the theory of topological defects did not address any other problems of the standard big bang theory that have been solved by inflation. Thus, although we still do not know whether inflationary theory is true, perhaps it is fair to say that it is the only internally consistent cosmological theory that is at present available.

Inflationary theory is changing together with the rapid development of elementary particle theory. The greatest challenge is to obtain a natural realization of the inflationary universe scenario in the context of supergravity, string theory or M-theory. This appears to be a very difficult task. In order to accomplish it, many different inflationary models have been suggested, some of which are based on investigation of more complicated theories with several different scalar fields. The list of new models includes 'extended inflation', 'natural inflation', 'topological inflation,' 'hybrid inflation,' etc. Most of these models are based on the same physical principles as the simplest chaotic inflation model discussed above, but each of them has its own unique features which can be experimentally tested.

Conclusion

For many centuries scientists believed that the universe is static. Later, they learned that the universe expands. This was a psychological shock, which provoked many attempts to restore stationarity either by modifying the Einstein equations or by invoking permanent matter creation in a steady-state universe. Eventually all these attempts failed. Discovery of the cosmic microwave background radiation and successful prediction of abundances of hydrogen, helium and other elements in the universe confirmed the big bang theory. Finally, the inflationary scenario appeared, which solved many of the intrinsic problems of the big bang cosmology and apparently removed the last doubts concerning its validity.

However, the development of the inflationary theory is gradually giving rise to a completely new cosmological paradigm, which is considerably different from the old big bang theory and even from the first versions of inflationary cosmology. The universe appears to be both chaotic and homogeneous, expanding and stationary. It may consist of many exponentially large domains with different laws of low-energy physics and perhaps even with different dimensionality. Our cosmic home grows, fluctuates and eternally reproduces itself in all its possible forms, as if adjusting itself for all possible types of life which it can support. Some parts of the new theory, it is hoped, will stay with us for years to come, some others may be considerably modified in the nearby future. However, it seems that the last 20 yr of development of cosmology have already

changed in an irreversible way our understanding of the structure and the fate of our universe and of our own place in the world.

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