Chapter 6

SOMETHING ALMOST OUT OF NOTHING

1. THE HORIZON PROBLEM AND THE FLATNESS PROBLEM

An interesting, frequently overlooked point is the fact that some of the ideas associated with the steady-state cosmology turned out to be longer lived than the theory that produced them. The steady-state theory disappeared from the scientific scene as a serious rival of relativistic cosmology, but years later certain ideas associated with it revived in another form and as it were on a different level, sometimes with the application of different, more sophisticated concepts. The ideas concerned are both the "generation of matter", as well as the steady state, though not within our own universe but in an infinite set of universes. As we recall, the notion of a multiplicity of universes was put forward by Hoyle in his attempt to salvage the steady-state theory. The new cosmology in which these ideas re-emerged was inflationary cosmology, which appeared in an effort to deal with certain theoretical problems encountered by relativistic cosmology, which was otherwise making dynamic progress.

From the very outset measurements of the microwave background radiation had been indicating that at the time when this radiation ceased to interact with other forms of matter – and according to the most recent data collected by the WMAP satellite that meant 380 thousand years after the Big Bang – the universe was extremely homogeneous: any disturbance in its density would have given rise to a deviation from the mean temperature of the background radiation. Subsequent measurements narrowed down the constraints determining the homogeneity of the young universe. Today we know that the temperature of the microwave background radiation is constant over the entire expanse of the sky to an

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accuracy of 10^{-5}, in other words that was the level of accuracy to which the young universe was homogeneous. The question arises why this was so. "Not very special" initial conditions will do to produce a chaotic universe; but to produce a universe with that degree of homogeneity a set of highly specific initial conditions is required. Our "sense of what is realistic" suggests the following solution: perhaps the initial conditions might have been "not very special," but presumably there must have been some kind of physical interaction to smooth out the originally chaotic universe. This line of reasoning seems appealing, but again there is a snag in the measurements for background radiation. As we remember, its temperature is virtually constant across the whole of the sky. Consider two points at opposite ends of this range. It may be easily calculated that the history of the universe was too short for the fastest physical signal, light, to join these points together. We say that the two points are separated from one another by a horizon. Therefore there is no physical interaction capable of evening out temperatures in regions separated from each other by a horizon. The standard cosmological models were not able to cope with the horizon problem.[1]

A second analogous problem is the flatness problem. According to the equations of standard relativistic cosmology, the curvature of space is constant, but it may be zero, or take any positive or negative value between plus and minus infinity. The determination of the curvature by estimating the mean density of matter had for a long time been indicating that the space of our universe is almost completely flat, viz. that it has a curvature very near to zero. This has been confirmed to a high degree of accuracy by the latest measurements carried out by the WMAP satellite. Now the line of reasoning is similar to the one for the homogeneity of the universe. The only distinguished value for curvature between plus and minus infinity is zero. It is distinguished because it separates the negative curvatures from the positive ones. Why did the initial conditions "select" a value for curvature so close to the distinguished value? The standard models cannot answer this question.[2]

Both the horizon problem as well as the flatness problem[3] disappear if we assume that at an appropriately early stage of its evolution the universe underwent a rapid process of expansion, referred to as inflation. Up to that point the entire universe as observable today might have occupied a very small volume with no horizons splitting it, such that any physical processes occurring within that volume would have smoothed out all the "bumps." Only later was space inflated to the size of the universe as observed today. Before its inflation the universe might have had any arbitrary curvature, but following its inflation what we observe is only a "small," approximately flat sub-region of space which has an arbitrary curvature (on the principle that as long as it is smooth, any arbitrary surface, e.g. a sphere, is locally flat).

The inflationary scenario was first proposed by Alan Guth in 1981,[4] to resolve the two above-described difficulties in standard cosmology, but soon it rose to the status of a new research programme. In this chapter we shall be concerned with those aspects of inflationary cosmology which are connected with the main subject of this book – the search for ultimate explanations.

2. THE MECHANISM OF INFLATION

The inflationary model makes the assumption that at a very early stage in its evolution the universe experienced a sudden (exponential) acceleration in its expansion, which was "superimposed" on the normal expansion of the standard model. The accelerated expansion was propelled by a scalar field φ with an equation of state rather exotic from the point of view of later evolution. In this equation it is assumed that the pressure p of the "cosmic matter" is equal in magnitude to its density ρ but takes the opposite sign, viz. $p = -\rho$ (in units for which the speed of light $c = 1$). The function for the potential energy $V(\varphi)$ of the scalar field φ also plays a significant role. The possible inflationary scenarios depend on the shape of this function. The equation of state and the shape of the function $V(\varphi)$ are selected such that the scalar field φ acquires the properties of a "repellent gravity". The region of space over which the scalar field has these properties, called the "false vacuum" region, undergoes a very rapid expansion. In a fraction of a second the dimensions of this region may increase 10^{30}-fold (or more, depending on the exact scenario). We say that this region is in a "false vacuum" state. After a time this state is transformed into particles and radiation, and the accelerated expansion reverts into the normal expansion of the standard cosmological model.

Guth's original inflationary model met with certain difficulties connected with the departure from the inflationary state. To avoid these problems, the nature of which we shall not go into here, the model was modified several times: by Linde,[5] then by Albrecht and Steinhardt,[6] and finally again by Linde,[7] who put forward the chaotic inflationary model.

Linde's last model made the most significant impact on the philosophical reflections which soon emerged in connection with the inflationary model. For technical reasons Linde proposed an idiosyncratic shape for the function of the potential $V(\varphi)$. It was appealing theoretically, but required special conditions indispensable to start the inflation. How could such special conditions be justified?

Linde put forward a hypothesis that before the onset of inflation the world was in a chaotic state, viz. the physical fields assumed various values at various points in a random, "chaotic" distribution. Most of these fields were in the most probable states, which did not lead to inflation, but here and there conditions with a low probability of occurrence were extant, initiating the inflationary phase in the given region. These regions were inflated to huge sizes, whereas regions with no inflation remained microscopically small in comparison. Soon the universe was dominated by the inflated regions.[8] Each of these regions may be regarded as a separate universe, evolving independently of other similar universes. Moreover, in each of these universes the production of new inflated domains and the generation of new universes may recur. Linde's scenario made a significant contribution to the specific philosophical vogue that was soon to come for the multiverse concept, viz. speculations as to the existence of "all possible universes."[9]

The initial versions of the inflationary scenario combined the phase of the universe's rapidly accelerated expansion with the Grand Unifying Theories (GUT). Before the period of inflation three of the fundamental physical forces, strong nuclear, weak nuclear, and electromagnetic, were believed to have made up one force (the gravitational force had split away earlier); usually this process is considered in reversed time, and that is why we speak of a unification of the interactions. The separating off of the strong nuclear force from the other two was referred to as the phase transition associated with GUT. It was said to have occurred 10^{-35} s after the singularity, when energies of the order of 10^{14} GeV prevailed in the universe. This phase transition was believed to have initiated the inflation. The scalar field φ required by the concept of inflation was regarded as identical with Higgs' field, an essential constituent in the mechanism of the Grand Unification. However, it turned out that inflation combined with GUT would have produced too large a perturbation in the microwave background radiation compared with the perturbation actually observed. That is why now the inflation is no longer associated with the GUT phase transition, but considered separately; while the scalar field φ is no longer thought of as identical with Higgs' field, but is simply called the inflaton field or abbreviated to the inflaton.

One of the essential properties of inflation is the fact that while it was in progress energy density remained constant and assumed a value characteristic for the false vacuum. At the beginning of the inflationary phase there was a gigantic energy density, but as volume increased, the only way in which the density could be kept constant was by the creation of new energy.[10] Since, according to the inflationary scenario, it was from this energy that the universe's current "material contents" emerged, it is sometimes claimed that in principle all that is now observable arose out of nothing in the inflationary era.[11]

3. THE INFLATIONARY SCENARIO

Let's try to apply the mechanism described above to the scenario of the processes that were going on. We shall limit ourselves to a consideration only of the simplest version, which was later modified and amended many times and in various ways.[12]

Inflation appeared on the evolutionary scene soon after the era of quantum cosmology ended on "Planck's threshold," gravitation separated off from the other unified forces and a space-time governed by the laws of the general theory of relativity emerged from the Big Bang. The universe expanded in accordance with one of the Friedman-Lemaître models. Its material contents comprised hot plasma ("ordinary matter") and the inflaton field. Immediately after Planck's threshold was crossed the density of the plasma was of the order of 10^{93} g/cm^3 (the Planck density) and dominated the inflaton field to such an extent that the influence of the latter on evolution may be ignored. However, as the universe expanded the density of the plasma decreased (as R^{-4}), while the density of the inflaton remained unchanged. At a certain point the density of the plasma was equal to the inflaton density (in Guth's original model this occurred when the universe was 10^{-35} s old); at this time the strong nuclear interaction split away from the electroweak interaction. Subsequently the density of the inflaton started to predominate and the universe entered the inflation era. Its linear dimensions increased at an exponential rate. The plasma was rapidly diluted and its density reduced at an exponential rate. After a short time there was hardly any plasma left in the universe. But, as we know, energy density remained constant, therefore, in view of the rapid inflation by volume, energy had to be created.

There are several scenarios for the end of the inflationary era (this is still the theory's most delicate point). In all cases the energy of the inflaton transformed into the energy of the elementary particles present now in the universe. It is estimated that in the whole of our galaxy there may be just one proton or electron at the most derived from the pre-inflation era. On leaving the inflation era the universe was thermalised (heated up), and the rest of its evolution followed the standard model. The initial conditions for this evolution were determined by the physical processes which brought the universe out of the inflationary phase. What had come before inflation did not influence what came after.

The various models for the inflation envisage different times of its duration. If we assume that inflation lasted 10^{-30} s, then by the end of inflation the linear dimensions of the universe would have increased by a factor of the order of 10^{28}. It may be readily calculated that if before the inflation the typical size of the universe was of the order of 10^{-30} cm (viz. about a thousand Planck units), then after the inflation its typical size was of the order of 10^{-2} cm. A macroscopic size, nonetheless we are shocked by its "smallness." The shock should help us realise that when we are talking about inflation we are really very close to a "beginning."

4. SOME CRITICAL REMARKS

The inflationary scenario has a very strong presence in the cosmological literature, but we have to bear in mind that it is highly hypothetical and prone to a number of objections. We shall enumerate a few of the most important ones, after Gordon McCabe:[13]

First, according to what is known today in cosmology, the observable evolution of the universe may be explained in two ways: either by simply assuming the appropriate initial conditions, or by invoking a variety of physical processes which acted causally to bring about the evolution of the universe as it is today. The inflationary scenarios imply the latter, which seems the more appealing of the two ways. However, until we get a fundamental theory of physics we cannot be sure that the initial conditions responsible for the current state of the universe, acting "at the beginning" of its evolution, were not the outcome of some still unknown necessities which had nothing at all to do with inflation.

Secondly, if there was an inflation, then not all the material "contents of the universe," but *almost* all of them grew out of nothing during the inflation, since at the start of the inflationary phase there was already a certain "extant" energy density, which merely "proliferated" to keep the density constant.

Thirdly, the inflationary scenario in itself does not provide a guarantee that almost all the "material contents" of the universe grew out of nothing during the inflation phase. An inflationary universe may be either spatially infinite (non-compact), or spatially finite (compact). Only in the latter case would the universe have a finite volume, and almost all of its (non-gravitational) energy could have been created in the inflationary era. But if the former instance had occurred, then inflation could not have affected all of the universe and the matter beyond the inflationary area must have come about in some other manner.

Fourthly, inflation does not explain the origin of either space-time or the initial amount of energy.

And fifthly, an inflaton field is necessary for inflation to come about. In the current inflation scenarios the inflaton field is "manually inserted" into the equations. The justification of its existence by reference to mechanisms known from other branches of physics which should have been active in the early phases of the universe's evolution is still an open question.

Despite these difficulties, the inflation idea has become well-established in cosmology. It does explain several problems in standard cosmology, but itself requires a better foundation, as regards both theory and (especially) observational data. The concept of inflation has certainly not provided an "ultimate explanation" of the universe, but, as the latest history of cosmology shows, it has staked out a new path in the search for such explanations. Quite paradoxically, this has happened not so much thanks to its basic idea, but rather to a "side product," that is thanks to the fact that some inflationary scenarios postulate the existence of "other universes," different from the one in which we live and which we can observe, or even completely disconnected from it. This idea would return later in a variety of forms, to become one of the approaches in the search for "ultimate explanations." But before that happened, cosmology would be enriched with a number of brave new ideas.