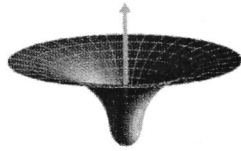


*Fig. 8.7 In the hot big bang model the rate of expansion is always decreasing with time, but in the inflationary model the rate of expansion increases rapidly in the early stages.*



picture in which the earth is a medium-sized planet orbiting around an average star in the outer suburbs of an ordinary spiral galaxy, which is itself only one of about a million million galaxies in the observable universe (Fig. 8.6). Yet the strong anthropic principle would claim that this whole vast construction exists simply for our sake. This is very hard to believe. Our Solar System is certainly a prerequisite for our existence, and one might extend this to the whole of our galaxy to allow for an earlier generation of stars that created the heavier elements. But there does not seem to be any need for all those other galaxies, nor for the universe to be so uniform and similar in every direction on the large scale.

One would feel happier about the anthropic principle, at least in its weak version, if one could show that quite a number of different initial configurations for the universe would have evolved to produce a universe like the one we observe. If this is the case, a universe that developed from some sort of random initial conditions should contain a number of regions that are smooth and uniform and are suitable for the evolution of intelligent life. On the other hand, if the initial state of the universe had to be chosen extremely carefully to lead to something like what we see around us, the universe would be

unlikely to contain any region in which life would appear. In the hot big bang model described above, there was not enough time in the early universe for heat to have flowed from one region to another. This means that the initial state of the universe would have to have had exactly the same temperature everywhere in order to account for the fact that the microwave background has the same temperature in every direction we look. The initial rate of expansion also would have had to be chosen very precisely for the rate of expansion still to be so close to the critical rate needed to avoid recollapse. This means that the initial state of the universe must have been very carefully chosen indeed if the hot big bang model was correct right back to the beginning of time. It would be very difficult to explain why the universe should have begun in just this way, except as the act of a God who intended to create beings like us.

In an attempt to find a model of the universe in which many different initial configurations could have evolved to something like the present universe, a scientist at the Massachusetts Institute of Technology, Alan Guth, suggested that the early universe might have gone through a period of very rapid expansion. This expansion is said to be "inflationary," meaning that the universe at one time expanded at an increas-

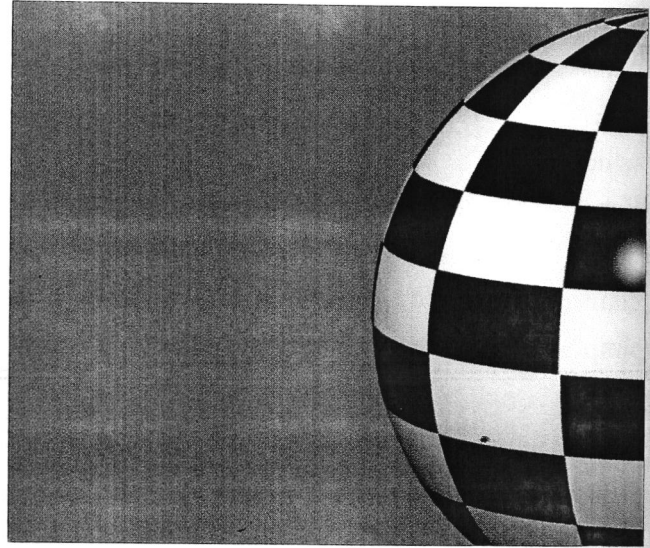
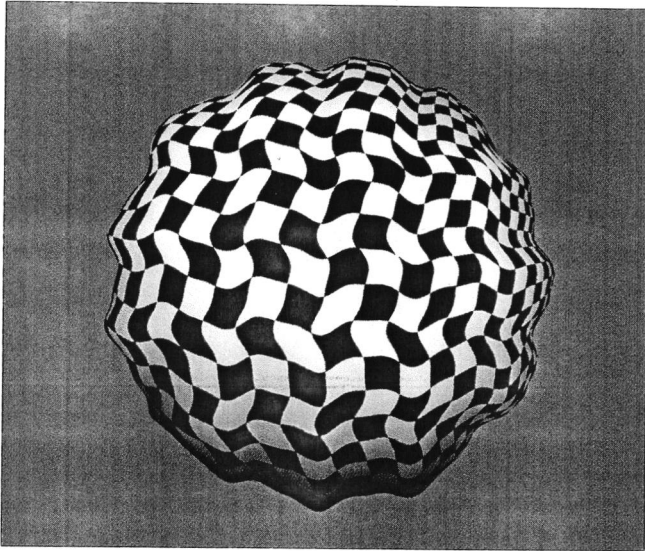
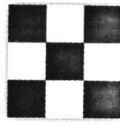


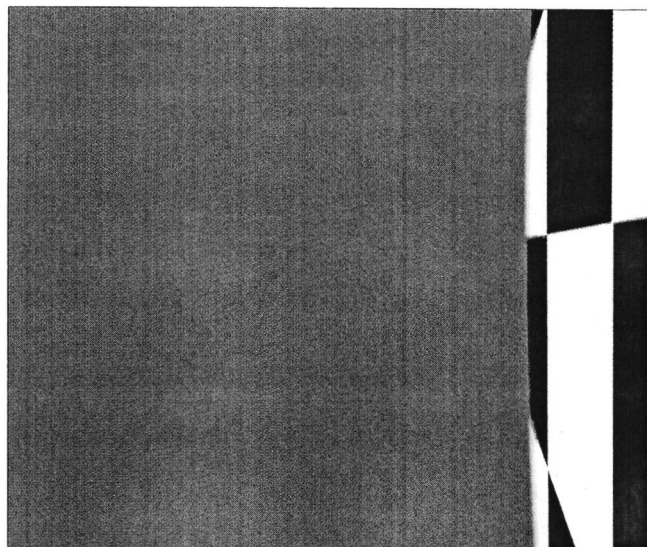
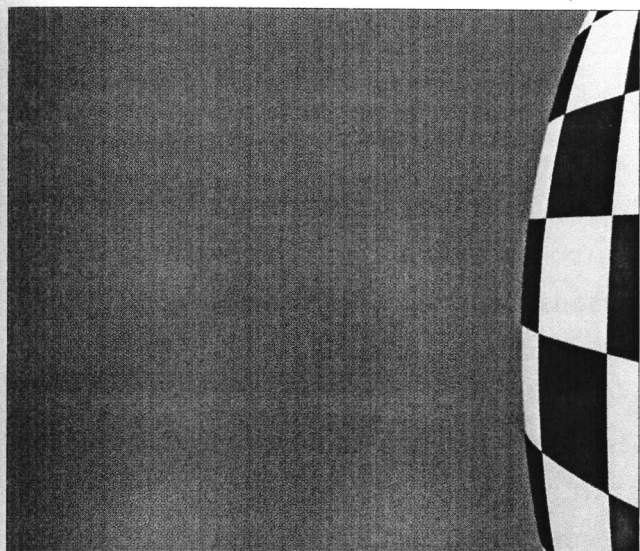
Fig. 8.8 *The rapid expansion of the universe in the first fraction of a second would flatten the universe and make the expansion almost the critical value.*

ing rate rather than the decreasing rate that it does today (Fig. 8.7). According to Guth, the radius of the universe increased by a million million million million (1 with thirty zeros after it) times in only a tiny fraction of a second.

Guth suggested that the universe started out from the big bang in a very hot, but rather chaotic, state. These high temperatures would have meant that the particles in the universe would be moving very fast and would have high energies. As we discussed earlier, one would expect that at such high temperatures the strong

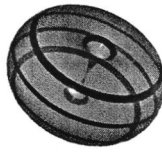
and weak nuclear forces and the electromagnetic force would all be unified into a single force. As the universe expanded, it would cool, and particle energies would go down. Eventually there would be what is called a phase transition and the symmetry between the forces would be broken: the strong force would become different from the weak and electromagnetic forces. One common example of a phase transition is the freezing of water when you cool it down. Liquid water is symmetrical, the same at every point and in every direction. However, when ice crystals form, they will have definite positions and will be lined up in some direction. This breaks water's symmetry.

In the case of water, if one is careful, one can



“supercool” it: that is, one can reduce the temperature below the freezing point ( $0^{\circ}\text{C}$ ) without ice forming. Guth suggested that the universe might behave in a similar way: the temperature might drop below the critical value without the symmetry between the forces being broken. If this happened, the universe would be in an unstable state, with more energy than if the symmetry had been broken. This special extra energy can be shown to have an antigravitational effect: it would have acted just like the cosmological constant that Einstein introduced into general relativity when he was trying to construct a static model of the universe. Since the universe would already be expanding just as in the hot big bang model, the repulsive effect of

this cosmological constant would therefore have made the universe expand at an ever-increasing rate. Even in regions where there were more matter particles than average, the gravitational attraction of the matter would have been outweighed by the repulsion of the effective cosmological constant. Thus these regions would also expand in an accelerating inflationary manner. As they expanded and the matter particles got farther apart, one would be left with an expanding universe that contained hardly any particles and was still in the supercooled state. Any irregularities in the universe would simply have been smoothed out by the expansion, as the wrinkles in a balloon are smoothed away when you blow it up (Fig. 8.8). Thus the present smooth and



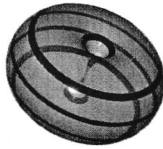
uniform state of the universe could have evolved from many different non-uniform initial states.

In such a universe, in which the expansion was accelerated by a cosmological constant rather than slowed down by the gravitational attraction of matter, there would be enough time for light to travel from one region to another in the early universe. This could provide a solution to the problem, raised earlier, of why different regions in the early universe have the same properties. Moreover, the rate of expansion of the universe would automatically become very close to the critical rate determined by the energy density of the universe. This could then explain why the rate of expansion is still so close to the critical rate, without having to assume that the initial rate of expansion of the universe was very carefully chosen.

The idea of inflation could also explain why there is so much matter in the universe. There are something like ten million million million million million million million million million million (1 with eighty zeros after it) particles in the region of the universe that we can observe. Where did they all come from? The answer is that, in quantum theory, particles can be created out of energy in the

form of particle/antiparticle pairs. But that just raises the question of where the energy came from. The answer is that the total energy of the universe is exactly zero. The matter in the universe is made out of positive energy. However, the matter is all attracting itself by gravity. Two pieces of matter that are close to each other have less energy than the same two pieces a long way apart, because you have to expend energy to separate them against the gravitational force that is pulling them together. Thus, in a sense, the gravitational field has negative energy. In the case of a universe that is approximately uniform in space, one can show that this negative gravitational energy exactly cancels the positive energy represented by the matter. So the total energy of the universe is zero.

Now twice zero is also zero. Thus the universe can double the amount of positive matter energy and also double the negative gravitational energy without violation of the conservation of energy. This does not happen in the normal expansion of the universe in which the matter energy density goes down as the universe gets bigger. It does happen, however, in the inflationary expansion because the energy density of the supercooled state remains constant while the



STATUS OF THE INFLATIONARY  
UNIVERSE SCENARIO SOME YEARS  
AGO (CAMBRIDGE 1982)



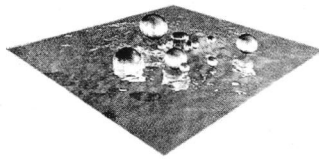
*Cartoon drawn by Andrei Linde showing the state of the inflationary model in the early 1980's.*

universe expands: when the universe doubles in size, the positive matter energy and the negative gravitational energy both double, so the total energy remains zero. During the inflationary phase, the universe increases its size by a very large amount. Thus the total amount of energy

available to make particles becomes very large. As Guth has remarked, "It is said that there's no such thing as a free lunch. But the universe is the ultimate free lunch."

The universe is not expanding in an inflationary way today. Thus there has to be some mechanism that would eliminate the very large effective cosmological constant and so change the rate of expansion from an accelerated one to one that is slowed down by gravity, as we have today. In the inflationary expansion one might expect that eventually the symmetry between the forces would be broken, just as supercooled water always freezes in the end. The extra energy of the unbroken symmetry state would then be released and would reheat the universe to a temperature just below the critical temperature for symmetry between the forces. The universe would then go on to expand and cool just like the hot big bang model, but there would now be an explanation of why the universe was expanding at exactly the critical rate and why different regions had the same temperature.

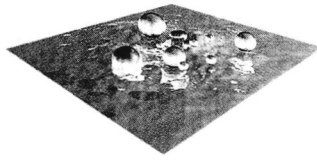
In Guth's original proposal the phase transition was supposed to occur suddenly, rather like the appearance of ice crystals in very cold water. The idea was that "bubbles" of the new phase



of broken symmetry would have formed in the old phase, like bubbles of steam surrounded by boiling water. The bubbles were supposed to expand and meet up with each other until the whole universe was in the new phase. The trouble was, as I and several other people pointed out, that the universe was expanding so fast that even if the bubbles grew at the speed of light, they would be moving away from each other and so could not join up. The universe would be left in a very non-uniform state, with some regions still having symmetry between the different forces. Such a model of the universe would not correspond to what we see.

In October 1981, I went to Moscow for a conference on quantum gravity. After the conference I gave a seminar on the inflationary model and its problems at the Sternberg Astronomical Institute. Before this, I had got someone else to give my lectures for me, because most people could not understand my voice. But there was not time to prepare this seminar, so I gave it myself, with one of my graduate students repeating my words. It worked well, and gave me much more contact with my audience. In the audience was a young Russian, Andrei Linde, from the Lebedev Institute in Moscow. He said

that the difficulty with the bubbles not joining up could be avoided if the bubbles were so big that our region of the universe is all contained inside a single bubble. In order for this to work, the change from symmetry to broken symmetry must have taken place very slowly inside the bubble, but this is quite possible according to grand unified theories. Linde's idea of a slow breaking of symmetry was very good, but I later realized that his bubbles would have to have been bigger than the size of the universe at the time! I showed that instead the symmetry would have broken everywhere at the same time, rather than just inside bubbles. This would lead to a uniform universe, as we observe. I was very excited by this idea and discussed it with one of my students, Ian Moss. As a friend of Linde's, I was rather embarrassed, however, when I was later sent his paper by a scientific journal and asked whether it was suitable for publication. I replied that there was this flaw about the bubbles being bigger than the universe, but that the basic idea of a slow breaking of symmetry was very good. I recommended that the paper be published as it was because it would take Linde several months to correct it, since anything he sent to the West would have to be passed by



Soviet censorship, which was neither very skillful nor very quick with scientific papers. Instead, I wrote a short paper with Ian Moss in the same journal in which we pointed out this problem with the bubble and showed how it could be resolved.

The day after I got back from Moscow I set out for Philadelphia, where I was due to receive a medal from the Franklin Institute. My secretary, Judy Fella, had used her not inconsiderable charm to persuade British Airways to give herself and me free seats on a Concorde as a publicity venture. However, I was held up on my way to the airport by heavy rain and I missed the plane. Nevertheless, I got to Philadelphia in the end and received my medal. I was then asked to give a seminar on the inflationary universe at Drexel University in Philadelphia. I gave the same seminar about the problems of the inflationary universe, just as in Moscow.

A very similar idea to Linde's was put forth independently a few months later by Paul Steinhardt and Andreas Albrecht of the University of Pennsylvania. They are now given joint credit with Linde for what is called "the new inflationary model," based on the idea of a slow breaking of symmetry. (The old inflationary

model was Guth's original suggestion of fast symmetry breaking with the formation of bubbles.)

The new inflationary model was a good attempt to explain why the universe is the way it is. However, I and several other people showed that, at least in its original form, it predicted much greater variations in the temperature of the microwave background radiation than are observed. Later work has also cast doubt on whether there could be a phase transition in the very early universe of the kind required. In my personal opinion, the new inflationary model is now dead as a scientific theory, although a lot of people do not seem to have heard of its demise and are still writing papers as if it were viable. A better model, called the chaotic inflationary model, was put forward by Linde in 1983. In this there is no phase transition or supercooling. Instead, there is a spin 0 field, which, because of quantum fluctuations, would have large values in some regions of the early universe. The energy of the field in those regions would behave like a cosmological constant. It would have a repulsive gravitational effect, and thus make those regions expand in an inflationary manner. As they expanded, the energy of the field in them would slowly



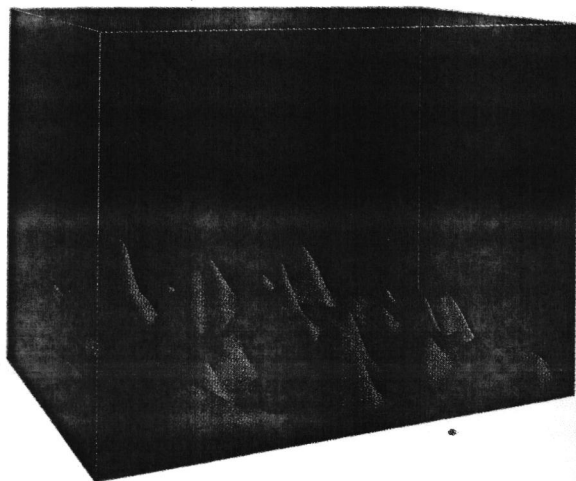
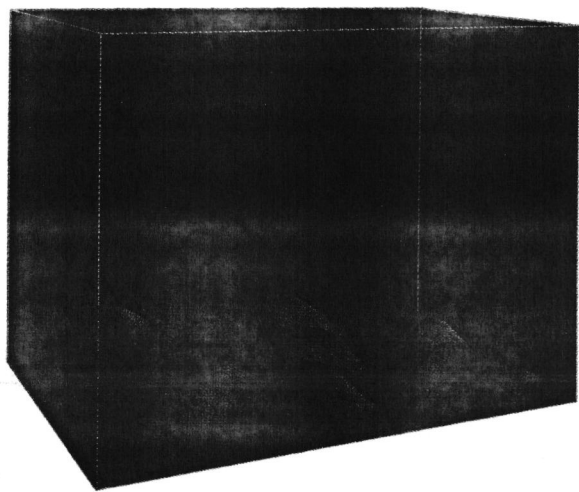
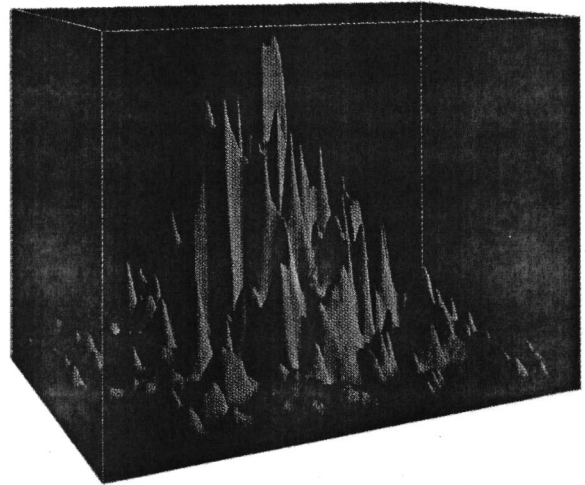
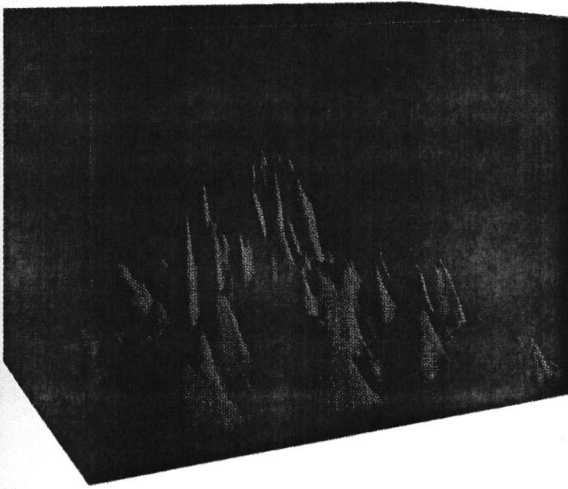


Fig. 8.9 *One inflationary model suggested by Andrei Linde is of a field in which quantum fluctuations occur, causing certain parts to expand rapidly as peaks while other domains such as our own, represented by the valleys, are no longer inflating.*

decrease until the inflationary expansion changed to an expansion like that in the hot big bang model. One of these regions would become what we now see as the observable universe. This model has all the advantages of the earlier inflationary models, but it does not depend on a dubious phase transition, and it can moreover give a reasonable size for the fluctuations in the temperature of the microwave background that agrees with observation.

This work on inflationary models showed that the present state of the universe could have

arisen from quite a large number of different initial configurations. This is important, because it shows that the initial state of the part of the universe that we inhabit did not have to be chosen with great care. So we may, if we wish, use the weak anthropic principle to explain why the universe looks the way it does now. It cannot be the case, however, that every initial configuration would have led to a universe like the one we observe. One can show this by considering a very different state for the universe at the present time, say, a very lumpy and irregular one. One could use the laws of science to evolve the universe back in time to determine its configuration at earlier times. According to the singularity theorems of classical general relativity, there would still have been a big bang singular-



ity. If you evolve such a universe forward in time according to the laws of science, you will end up with the lumpy and irregular state you started with. Thus there must have been initial configurations that would not have given rise to a universe like the one we see today. So even the inflationary model does not tell us why the initial configuration was not such as to produce something very different from what we observe. Must we turn to the anthropic principle for an explanation? Was it all just a lucky chance? That would seem a counsel of despair, a negation of all our hopes of understanding the underlying order of the universe.

In order to predict how the universe should have started off, one needs laws that hold at the beginning of time. If the classical theory of gen-

eral relativity was correct, the singularity theorems that Roger Penrose and I proved show that the beginning of time would have been a point of infinite density and infinite curvature of space-time. All the known laws of science would break down at such a point. One might suppose that there were new laws that held at singularities, but it would be very difficult even to formulate such laws at such badly behaved points, and we would have no guide from observations as to what those laws might be. However, what the singularity theorems really indicate is that the gravitational field becomes so strong that quantum gravitational effects become important: classical theory is no longer a good description of the universe. So one has to use a quantum theory of gravity to discuss the very early



stages of the universe. As we shall see, it is possible in the quantum theory for the ordinary laws of science to hold everywhere, including at the beginning of time: it is not necessary to postulate new laws for singularities, because there need not be any singularities in the quantum theory.

We don't yet have a complete and consistent theory that combines quantum mechanics and gravity. However, we are fairly certain of some features that such a unified theory should have. One is that it should incorporate Feynman's proposal to formulate quantum theory in terms of a sum over histories. In this approach, a particle does not have just a single history, as it would in a classical theory. Instead, it is supposed to follow every possible path in space-time, and with each of these histories there are associated a couple of numbers, one representing the size of a wave and the other representing its position in the cycle (its phase). The probability that the particle, say, passes through some particular point is found by adding up the waves associated with every possible history that passes through that point. When one actually tries to perform these sums, however, one runs into severe technical problems. The only way around

these is the following peculiar prescription: one must add up the waves for particle histories that are not in the "real" time that you and I experience but take place in what is called imaginary time. Imaginary time may sound like science fiction but it is in fact a well-defined mathematical concept. If we take any ordinary (or "real") number and multiply it by itself, the result is a positive number. (For example, 2 times 2 is 4, but so is -2 times -2.) There are, however, special numbers (called imaginary numbers) that give negative numbers when multiplied by themselves. (The one called  $i$ , when multiplied by itself, gives  $-1$ ,  $2i$  multiplied by itself gives  $-4$ , and so on.)

One can picture real and imaginary numbers in the following way (Fig. 8.10). The real numbers can be represented by a line going from left to right, with zero in the middle, negative numbers like  $-1$ ,  $-2$ , etc. on the left, and positive numbers,  $1$ ,  $2$ , etc. on the right. Then imaginary numbers are represented by a line going up and down the page, with  $i$ ,  $2i$ , etc. above the middle, and  $-i$ ,  $-2i$ , etc. below. Thus imaginary numbers are in a sense numbers at right angles to ordinary real numbers.

To avoid the technical difficulties with

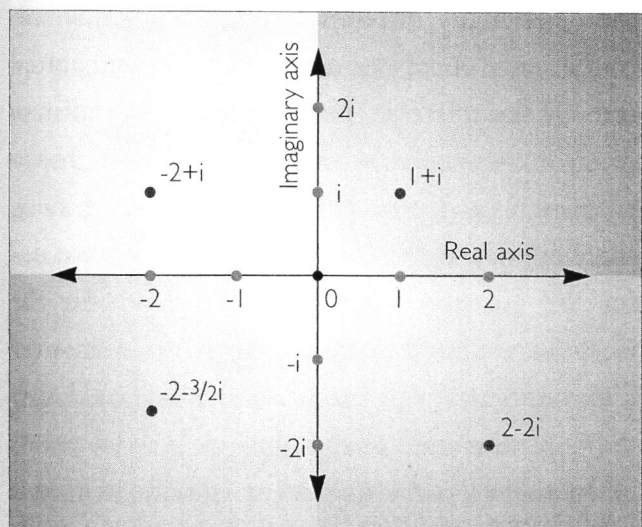
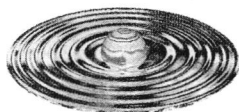
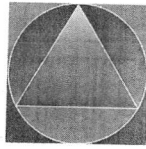


Fig. 8.10 Real numbers can be represented by a horizontal line running left to right. Imaginary numbers can be represented by a vertical line.

Feynman's sum over histories, one must use imaginary time. That is to say, for the purposes of the calculation one must measure time using imaginary numbers, rather than real ones. This has an interesting effect on space-time: the distinction between time and space disappears completely. A space-time in which events have imaginary values of the time coordinate is said to be Euclidean, after the ancient Greek Euclid, who founded the study of the geometry of two-dimensional surfaces. What we now call

Euclidean space-time is very similar except that it has four dimensions instead of two. In Euclidean space-time there is no difference between the time direction and directions in space. On the other hand, in real space-time, in which events are labeled by ordinary, real values of the time coordinate, it is easy to tell the difference — the time direction at all points lies within the light cone, and space directions lie outside. In any case, as far as everyday quantum mechanics is concerned, we may regard our use of imaginary time and Euclidean space-time as merely a mathematical device (or trick) to calculate answers about real space-time.

A second feature that we believe must be part of any ultimate theory is Einstein's idea that the gravitational field is represented by curved space-time: particles try to follow the nearest thing to a straight path in a curved space, but because space-time is not flat their paths appear to be bent, as if by a gravitational field. When we apply Feynman's sum over histories to Einstein's view of gravity, the analogue of the history of a particle is now a complete curved space-time that represents the history of the whole universe. To avoid the technical difficulties in actually performing the sum over histories, these



*See the Bold-Shadow of Virania's Glory,  
Immortal in His Race, no less in Story:  
An Artist without Error, from whose Lyne,  
Both Earth and Heav'ns, in sweet Proportions twine:  
Behold Great EUCLID! But behold Him well!  
For 'tis in Him Divinity doth dwell. /*

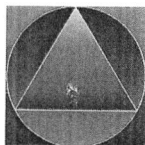
*G. Warton.*

*Euclid, 295 BC.*

curved space-times must be taken to be Euclidean. That is, time is imaginary and is indistinguishable from directions in space. To calculate the probability of finding a real space-time with some certain property, such as looking the same at every point and in every direction, one adds up the waves associated with all the histories that have that property.

In the classical theory of general relativity, there are many different possible curved space-times, each corresponding to a different initial state of the universe. If we knew the initial state of our universe, we would know its entire history. Similarly, in the quantum theory of gravity, there are many different possible quantum states for the universe. Again, if we knew how the Euclidean curved space-times in the sum over histories behaved at early times, we would know the quantum state of the universe.

In the classical theory of gravity, which is based on real space-time, there are only two possible ways the universe can behave: either it has existed for an infinite time, or else it had a beginning at a singularity at some finite time in the past. In the quantum theory of gravity, on the other hand, a third possibility arises. Because one is using Euclidean space-times, in which the time direction is on the same footing as directions in space, it is possible for space-time to be finite in extent and yet to have no singularities that formed a boundary or edge. Space-time would be like the surface of the earth, only with two more dimensions. The surface of the earth is finite in extent but it doesn't have a boundary or edge: if you sail off into the sunset, you don't fall off the edge or run into a



singularity. (I know, because I have been round the world!)

If Euclidean space-time stretches back to infinite imaginary time, or else starts at a singularity in imaginary time, we have the same problem as in the classical theory of specifying the initial state of the universe: God may know how the universe began, but we cannot give any particular reason for thinking it began one way rather than another. On the other hand, the quantum theory of gravity has opened up a new possibility, in which there would be no boundary to space-time and so there would be no need to specify the behavior at the boundary. There would be no singularities at which the laws of science broke down, and no edge of space-time at which one would have to appeal to God or some new law to set the boundary conditions for space-time. One could say: "The boundary condition of the universe is that it has no boundary." The universe would be completely self-contained and not affected by anything outside itself. It would neither be created nor destroyed. It would just BE.

It was at the conference in the Vatican mentioned earlier that I first put forward the suggestion that maybe time and space together formed a surface that was finite in size but did not have

any boundary or edge. My paper was rather mathematical, however, so its implications for the role of God in the creation of the universe were not generally recognized at the time (just as well for me). At the time of the Vatican conference, I did not know how to use the "no boundary" idea to make predictions about the universe. However I spent the following summer at the University of California, Santa Barbara. There a friend and colleague of mine, Jim Hartle, worked out with me what conditions the universe must satisfy if space-time had no boundary. When I returned to Cambridge, I continued this work with two of my research students, Julian Luttrell and Jonathan Halliwell.

I'd like to emphasize that this idea that time and space should be finite "without boundary" is just a *proposal*: it cannot be deduced from some other principle. Like any other scientific theory, it may initially be put forward for aesthetic or metaphysical reasons, but the real test is whether it makes predictions that agree with observation. This, however, is difficult to determine in the case of quantum gravity, for two reasons. First, as will be explained in chapter 11, we are not yet sure exactly which theory successfully combines general relativity and quantum mechanics, though we know quite a lot

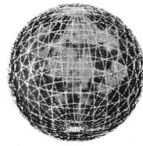
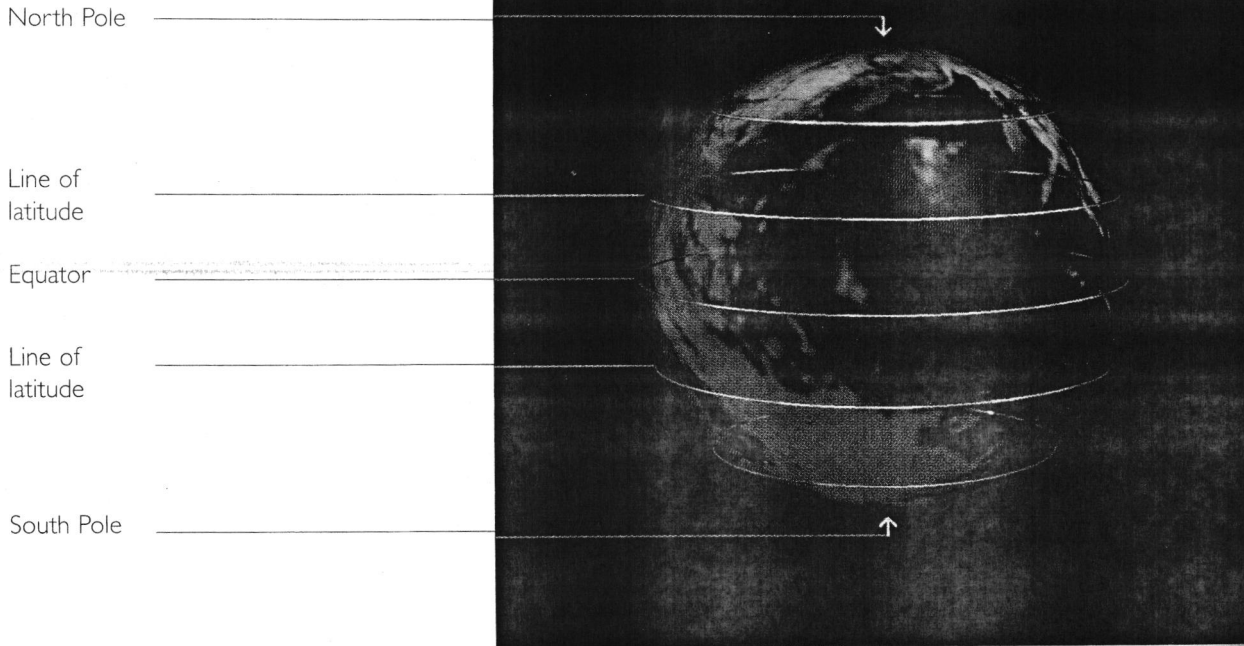


Fig. 8.11



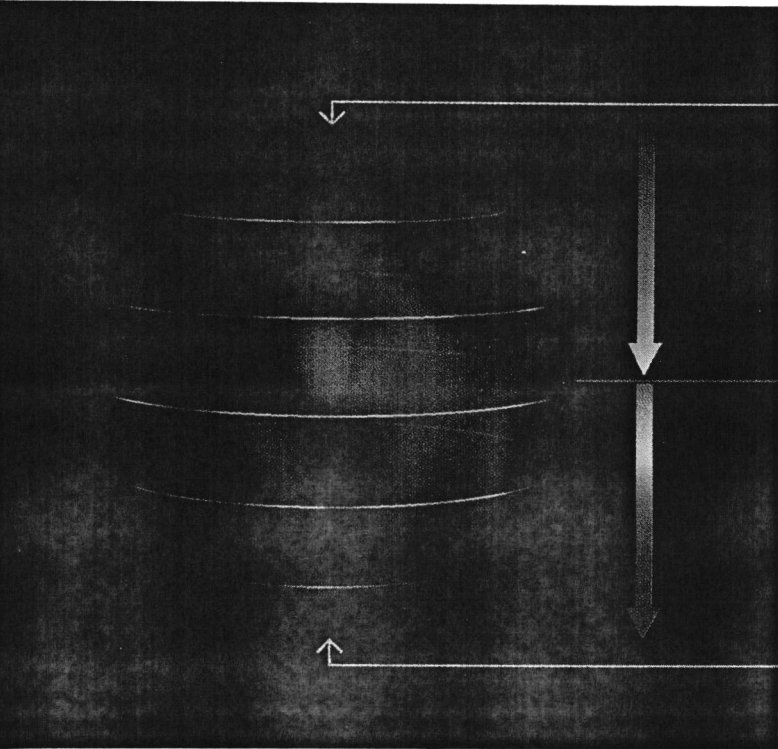
THE EARTH

about the form such a theory must have. Second, any model that described the whole universe in detail would be much too complicated mathematically for us to be able to calculate exact predictions. One therefore has to make simplifying assumptions and approximations — and even then, the problem of extracting predictions remains a formidable one.

Each history in the sum over histories will describe not only the space-time but everything in it as well, including any complicated organ-

Fig. 8.11 *In the “no boundary” proposal, the history of the universe in imaginary time is like the surface of the earth: it is finite in size but doesn’t have a boundary.*

isms like human beings who can observe the history of the universe. This may provide another justification for the anthropic principle, for if all the histories are possible, then so long as we exist in one of the histories, we may use the anthropic principle to explain why the universe is found to be the way it is. Exactly what mean-



Beginning of the universe in imaginary time

Size of universe increasing with imaginary time

Maximum size

Size of universe decreasing with imaginary time

End of the universe in imaginary time

THE UNIVERSE

ing can be attached to the other histories, in which we do not exist, is not clear. This view of a quantum theory of gravity would be much more satisfactory, however, if one could show that, using the sum over histories, our universe is not just one of the possible histories but one of the most probable ones. To do this, we must perform the sum over histories for all possible Euclidean space-times that have no boundary.

Under the “no boundary” proposal one learns that the chance of the universe being

found to be following most of the possible histories is negligible, but there is a particular family of histories that are much more probable than the others. These histories may be pictured as being like the surface of the earth, with the distance from the North Pole representing imaginary time and the size of a circle of constant distance from the North Pole representing the spatial size of the universe. The universe starts at the North Pole as a single point. As one moves south, the circles of latitude at constant distance



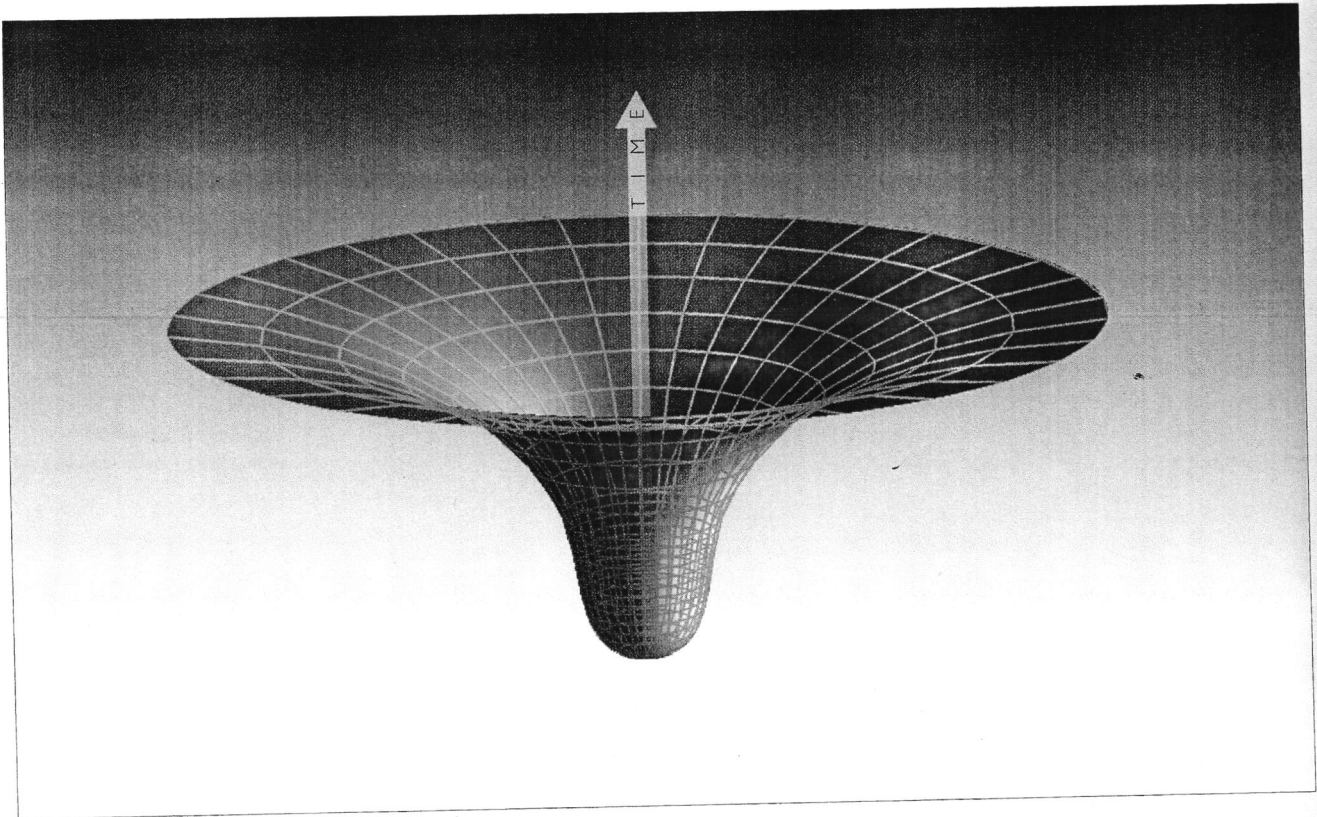
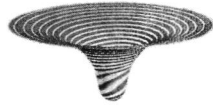


Fig. 8.12 *The universe expands in imaginary time like the surface of the earth from the North Pole to the equator, and then expands in real time at an increasing inflationary rate.*

from the North Pole get bigger, corresponding to the universe expanding with imaginary time (Fig. 8.11). The universe would reach a maximum size at the equator and would contract with increasing imaginary time to a single point at the South Pole. Even though the universe would have zero size at the North and South

Poles, these points would not be singularities, any more than the North and South Poles on the earth are singular. The laws of science will hold at them, just as they do at the North and South Poles on the earth.

The history of the universe in real time, however, would look very different. At about ten or



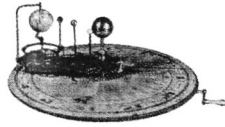
twenty thousand million years ago, it would have a minimum size, which was equal to the maximum radius of the history in imaginary time. At later real times, the universe would expand like the chaotic inflationary model proposed by Linde (but one would not now have to assume that the universe was created somehow in the right sort of state). The universe would expand to a very large size (Fig. 8.12) and eventually it would collapse again into what looks like a singularity in real time. Thus, in a sense, we are still all doomed, even if we keep away from black holes. Only if we could picture the universe in terms of imaginary time would there be no singularities.

If the universe really is in such a quantum state, there would be no singularities in the history of the universe in imaginary time. It might seem therefore that my more recent work had completely undone the results of my earlier work on singularities. But, as indicated above, the real importance of the singularity theorems was that they showed that the gravitational field must become so strong that quantum gravitational effects could not be ignored. This in turn led to the idea that the universe could be finite in imaginary time but without boundaries or singularities. When one goes back to the real

time in which we live, however, there will still appear to be singularities. The poor astronaut who falls into a black hole will still come to a sticky end; only if he lived in imaginary time would he encounter no singularities.

This might suggest that the so-called imaginary time is really the real time, and that what we call real time is just a figment of our imaginations. In real time, the universe has a beginning and an end at singularities that form a boundary to space-time and at which the laws of science break down. But in imaginary time, there are no singularities or boundaries. So maybe what we call imaginary time is really more basic, and what we call real is just an idea that we invent to help us describe what we think the universe is like. But according to the approach I described in Chapter 1, a scientific theory is just a mathematical model we make to describe our observations: it exists only in our minds. So it is meaningless to ask: which is real, "real" or "imaginary" time? It is simply a matter of which is the more useful description.

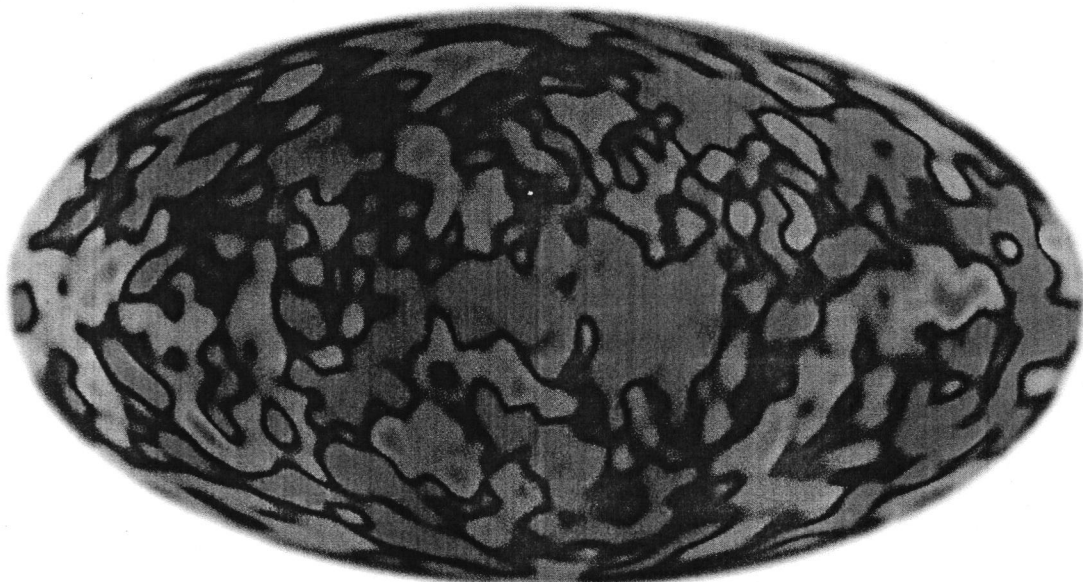
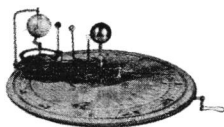
One can also use the sum over histories, along with the no boundary proposal, to find which properties of the universe are likely to occur together. For example, one can calculate the probability that the universe is expanding at



nearly the same rate in all different directions at a time when the density of the universe has its present value. In the simplified models that have been examined so far, this probability turns out to be high; that is, the proposed no boundary condition leads to the prediction that it is extremely probable that the present rate of expansion of the universe is almost the same in each direction. This is consistent with the observations of the microwave background radiation, which show that it has almost exactly the same intensity in any direction. If the universe were expanding faster in some directions than in others, the intensity of the radiation in those directions would be reduced by an additional red shift.

Further predictions of the no boundary condition are currently being worked out. A particularly interesting problem is the size of the small departures from uniform density in the early universe that caused the formation first of the galaxies, then of stars, and finally of us. The uncertainty principle implies that the early universe cannot have been completely uniform because there must have been some uncertainties or fluctuations in the positions and velocities of the particles. Using the no boundary condition, we find that the universe must in fact have started off with just the minimum possible

non-uniformity allowed by the uncertainty principle. The universe would have then undergone a period of rapid expansion, as in the inflationary models. During this period, the initial non-uniformities would have been amplified until they were big enough to explain the origin of the structures we observe around us. In 1992 the Cosmic Background Explorer satellite (COBE) first detected very slight variations in the intensity of the microwave background with direction. The way these non-uniformities depend on direction seems to agree with the predictions of the inflationary model and the no boundary proposal. Thus the no boundary proposal is a good scientific theory in the sense of Karl Popper: it could have been falsified by observations but instead its predictions have been confirmed. In an expanding universe in which the density of matter varied slightly from place to place, gravity would have caused the denser regions to slow down their expansion and start contracting. This would lead to the formation of galaxies, stars, and eventually even insignificant creatures like ourselves. Thus all the complicated structures that we see in the universe might be explained by the no boundary condition for the universe together with the uncertainty principle of quantum mechanics.



-0.27  +0.27

The idea that space and time may form a closed surface without boundary also has profound implications for the role of God in the affairs of the universe. With the success of scientific theories in describing events, most people have come to believe that God allows the universe to evolve according to a set of laws and does not intervene in the universe to break these laws. However, the laws do not tell us what the universe should have looked like when it started — it would still be up to God to wind up the clockwork and choose how to start it off. So

---

*Above: A map of the tiny temperature variations in the microwave background observed by the COBE satellite. The hot spots correspond to slightly more dense regions that later developed into clusters of galaxies.*

---

long as the universe had a beginning, we could suppose it had a creator. But if the universe is really completely self-contained, having no boundary or edge, it would have neither beginning nor end: it would simply be. What place, then, for a creator?