18
Eternal Inflation

Inflation enlarges the size of the universe by an enormous factor, so we can observe only a tiny part of it. The theory explains very well what we see in this small domain, but it also makes predictions about the parts of the universe that we cannot see—beyond our cosmic horizon. This has led to a radical revision of our global view of the universe.

18.1 Volume Growth and Decay

In very general terms, the new worldview can be understood as follows. An inflating universe is governed by two competing processes: exponential growth of false vacuum volume and the decay of false vacuum. This is similar to the reproduction of bacteria which multiply by division and are destroyed by antibodies. The outcome depends on which process is more efficient. If the bacteria are destroyed faster than they reproduce, they will quickly die out. Alternatively, if the reproduction is faster, bacteria will rapidly proliferate. In most models of inflation, the rate of volume expansion is much higher than that of false vacuum decay. This means that expansion wins, and the total volume of inflating regions grows with time.

False vacuum decay is induced by probabilistic quantum processes, so it happens in random locations at random times. The result is a stochastic patchwork of true and false vacuum regions. In Fig. 18.1 we illustrate the dynamics schematically, using a simple 2D model. We start with a false vacuum region, shown as a white square in the first frame of the figure. The following three

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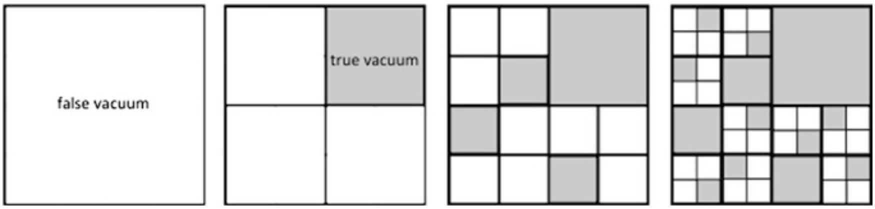

Fig. 18.1 The area of the false vacuum quadruples and one out of four newly created regions immediately decays to the true vacuum state at each time step (from *left* to *right*). True vacuum regions are indicated by *grey* shading. The smallest squares in each frame have the same physical size, but appear to decrease with time, because the expansion factor is taken out

frames show the same region after three consecutive doubling times. To avoid running out of space in the figure, we use "comoving coordinates", factoring out the expansion of the universe, so all four "snapshots" of the region have the same apparent size. In the second frame, the size of the region has doubled, and its area has quadrupled, so it now contains four squares of the same physical size as the original one. We assume that false vacuum has decayed into true vacuum in one of the squares, indicated by grey shading. In the third frame, the size of false vacuum regions has doubled again, and one quarter of the false vacuum regions have been converted into true vacuum. The same scenario plays out in the fourth frame.

This simple algorithm can be repeated any number of times. At each time step, the false vacuum area is quadrupled, and one quarter of it is lost to decay. The resulting change in the amount of false vacuum is by a factor of $4 \times \frac{3}{4} = 3$. After N steps this amount will grow by a factor of 3^N. Thus the expansion of false vacuum more than makes up for its loss due to vacuum decay.

If false vacuum regions multiply faster than they decay, inflation never ends in the entire universe. Even though it ended in our local region, it still continues in remote parts of the universe, producing new true vacuum regions like ours. This never ending process is called *eternal inflation*.

Fractals

The pattern of true and false vacuum regions obtained by repeated application of the algorithm in Fig. 18.1 is an example of what mathematicians call a self-similar fractal. "Self-similar" refers to the fact that the pattern is statistically the same on every distance scale. If, for example, we pick a small white square in the last frame, representing a false vacuum region, its subsequent evolution will be essentially the same as that of the initial white square in the first frame.

The evolution will not be exactly the same, because there is an element of randomness in the algorithm. But after many steps the statistical properties of the regions will be very similar.

The term "fractal" refers to the fact that the inflating part of space in this model has, in a certain sense, a fractional dimension. If you double the size of a one-dimensional line, its length will increase by a factor of 2. If you double the size of a 2D figure, its area will increase by a factor of $2^2 = 4$. And if you double the size of a 3D body, its volume will increase by a factor of $2^3 = 8$. In general, when the size of a *d*-dimensional object is doubled, the amount of "stuff" in the object is increased by a factor of 2^d. Now, in the model of Fig. 18.1, the area of the inflating part of space grows by a factor of 3 in one doubling time. This is between $2^1 = 2$ and $2^2 = 4$, suggesting that the fractal dimension of the inflating region is between 1 and 2. To find the exact dimension, we have to solve the equation $2^d = 3$. The solution is $d = \log_2 3 = 1.58$.

The eternal nature of inflation was first recognized by Vilenkin in 1983, soon after Guth proposed his theory of cosmic inflation, and was later investigated by a number of physicists, most notably by Linde. Inflation is eternal in nearly all models that have been studied so far. It is possible to construct non-eternal models, but they require rather contrived potential energy landscapes for the inflaton scalar field.

The simple model of Fig. 18.1 captures only rough features of an eternally inflating universe on very large distance scales; the details depend on the specific mechanism of false vacuum decay. There are two such mechanisms to consider: quantum random walk and bubble nucleation. We shall now discuss them in turn.

18.2 Random Walk of the Inflaton Field

As we discussed in Chap. 16, small density fluctuations are generated during inflation, because the inflaton scalar field is subjected to random quantum kicks as it rolls down the potential energy hill (see Fig. 18.2). While the field is rolling downwards, the quantum kicks are much weaker than the force due to the slope of the hill, and that is why the field reaches the bottom everywhere at about the same time, yielding only small density fluctuations.

But now let us ask ourselves: What happens when the field is close to the top of the hill, where the slope is very small? There, the inflaton is at the mercy of quantum kicks, which shove it randomly one way and then the other. The typical time interval between the kicks is the doubling time of inflation, $t_D \sim 1/H$ (recall H is the Hubble parameter); hence the field will undergo a "random walk", making random steps forward and backwards,

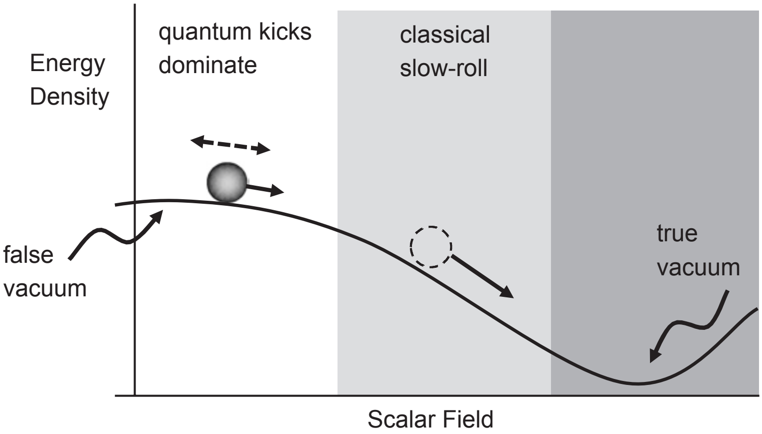

Fig. 18.2 At the *top* of the hill quantum kicks (*long dashed arrows*) are stronger than classical motion (*small solid arrow*), so the field undergoes a random walk. Once the slope is steep enough, the classical motion dominates (see *long solid arrow*), and the field slow-rolls to the end of inflation. This classical slow-roll regime is highlighted in *light grey*

separated by time intervals $\sim 1/H$. Eventually, after a number of steps, the field will get to a steeper part of the hill and then roll down towards the end of inflation.[1]

To see how the inflaton field values are distributed in space, let us recall that quantum kicks occur in small patches of Hubble size $d_H = c/H$. This is the maximum distance over which communication is possible in the inflating universe, so the directions of the kicks in different "Hubble patches" are random and independent of one another. If two points in space are separated by less than a Hubble distance, they experience the same quantum kicks. But the points are rapidly driven apart by the inflationary expansion, and once their separation exceeds d_H, their histories begin to diverge. As time goes on, the distance between the points gets larger and larger, and the field values become more and more divergent.

The smallness of density fluctuations in our observable region tells us that all points within our region were still within a Hubble distance of one

[1]In a "topless" model, having a potential energy landscape like the one shown in Fig. 17.8, the hill gets steeper at higher altitudes, so the classical force pushing the inflaton field downwards gets stronger. But Andrei Linde has shown that the strength of quantum kicks increases with altitude even faster. Thus, if the inflaton field starts out at high enough elevation, quantum kicks become the dominant force, and the field undergoes a quantum random walk, until it gets to a sufficiently low level and rolls classically downhill.

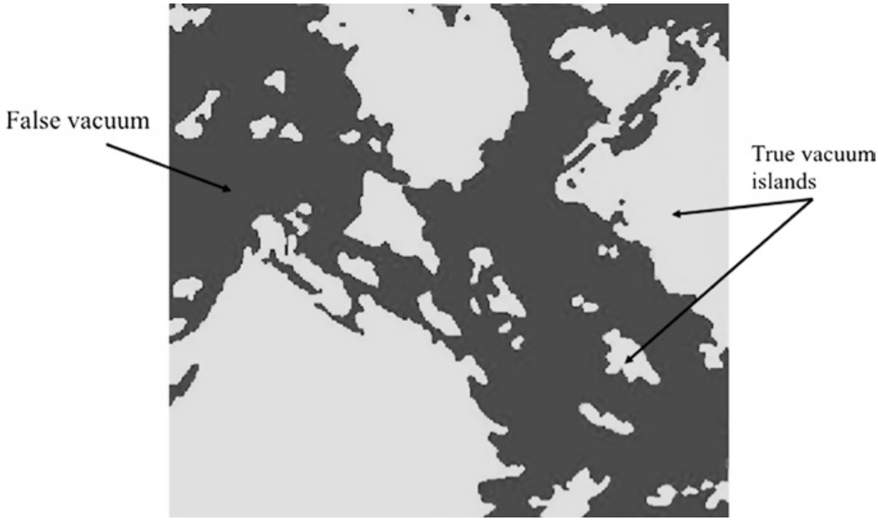

Fig. 18.3 2D simulation of an eternally inflating spacetime (performed by V. Vanchurin, A. Vilenkin and S. Winitzki). It shows true vacuum islands (*light*) in the inflating background (*dark*). The larger islands are the older ones: they have had more time to grow (*Note* that the color coding is different here than in Fig. 18.1)

another when the inflaton field was well on its way down the hill. That is why the effect of quantum kicks was very minor, and the field reached the bottom everywhere at about the same time. But if we could go to very large distances, far beyond our horizon, we would see regions that parted our company when the field was still wandering near the hilltop. Such regions have very different scalar field histories, and some of them may still be in the process of inflationary expansion.

Eternally inflating spacetimes produced via a quantum random walk have been studied in various computer simulations. Figure 18.3 is a snapshot of a 2D simulation which shows that true vacuum regions form as islands in the inflating background of false vacuum. The islands grow rapidly in size, as their boundaries advance into the inflating sea, but the inflating regions that separate them expand even faster, making room for more islands to form. The resulting pattern resembles an aerial view of an archipelago, with large islands surrounded by smaller ones, which are surrounded by still smaller ones, and so on. This fractal pattern is somewhat similar to that in our simple model of Fig. 18.1; the main difference is that the islands do not have orderly square shapes and are distributed in a more irregular manner.

18.3 Eternal Inflation via Bubble Nucleation

Suppose now that the false vacuum is separated from the true vacuum by an energy barrier, as in Guth's model of inflation (see Fig. 16.6). Then the false vacuum decays through bubble nucleation. Bubbles of true vacuum pop out at random here and there and immediately start to expand. They expand faster and faster, approaching the speed of light, but they are driven apart by the expansion of intervening regions of false vacuum. Hence, in this scenario inflation never ends—it is eternal. This was bad news for Guth's original model because it was unclear how the false vacuum energy could ever be turned into a hot fireball. But later Paul Steinhardt realized that this could be achieved by modifying the shape of the inflaton energy landscape. Instead of a steep decline towards the true vacuum, he suggested that the barrier should be followed by a gentle slope, as in Fig. 18.4. Then the inflaton field in a newly formed bubble has a value on the right hand side of the barrier; this value is separated from the true vacuum by a long stretch of gentle slope.

While the bubble expands, inflation continues inside of it, as the field slowly rolls downhill. When the field gets to the bottom of the hill, it converts its energy into a hot fireball of particles. This model is thus a hybrid of Guth's original scenario and Linde's slow roll model. The false vacuum inflates eternally, producing an unlimited number of bubbles, and each of the bubbles undergoes a period of slow-roll inflation in its interior, followed by the production of a fireball and subsequent hot big bang evolution. If we could take a "bird's-eye view" of the eternally inflating false vacuum with bubbles, the picture would be the same as in Fig. 16.7, except now inflation continues within each bubble, as the field slowly rolls towards the true vacuum.

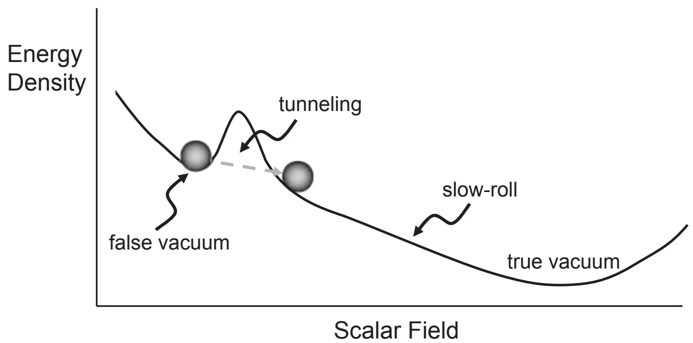

Fig. 18.4 Eternal inflation via bubble nucleation

According to this scenario, we live in one of the bubbles and can see only a small part of it. No matter how fast we travel, we cannot catch up with the expanding boundaries of our bubble. So, apart from rare bubble collisions, for all practical purposes, each bubble is a self-contained, isolated bubble universe.

18.4 Bubble Spacetimes

Bubble universes have a very interesting spacetime structure, which we shall now discuss in detail. Bubbles are microscopic when they materialize; then they expand without bound and become arbitrarily large. The central parts of large bubbles are very old. They evolved through all the phases of the hot big bang. Stars formed and died, intelligent life emerged and went extinct, so now these old regions are dark and barren. On the other hand, regions at the bubble periphery are young. This is where the false vacuum energy is being converted into a hot fireball and new stars are being formed.

The spacetime of a bubble universe is schematically illustrated in Fig. 18.5. Here, the vertical direction is time, the horizontal direction is space, and two of the three spatial dimensions are not shown. Each horizon-

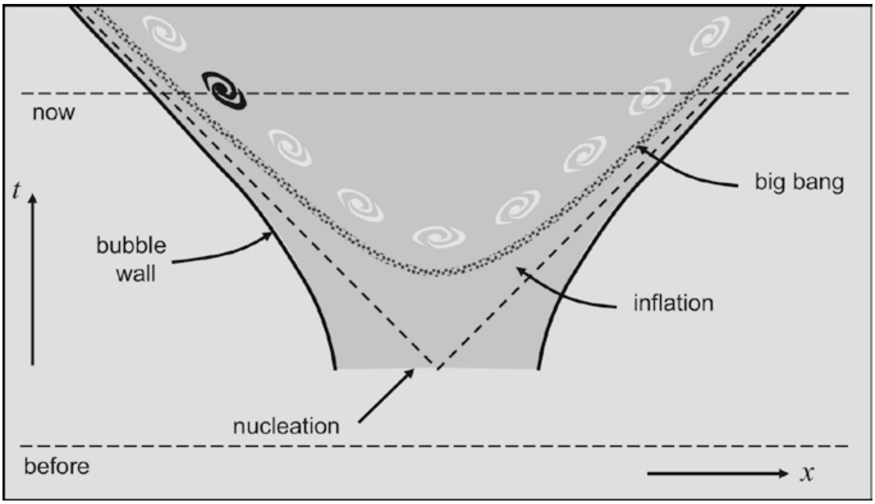

Fig. 18.5 Spacetime diagram of bubble universe (showing one spatial dimension only). The dashed lines at 45° angles are light signals sent outwards from the bubble center at the time of bubble formation. Note that these signals never catch up with the expanding boundaries of the bubble

tal slice through the diagram gives a snapshot of the universe at a moment of time. You can follow the history of the bubble by starting with the horizontal line marked "before" at the bottom of the figure and gradually moving it upward. The horizontal segment marked "nucleation" indicates the moment of bubble formation. The fuzzy grey line shows where the fireball is formed and hot big bang evolution begins. The location marked by a black galaxy is the here and now, and white galaxies indicate spacetime regions where the conditions are similar to what we have here today. The horizontal dashed line labeled "now" represents the present time. It shows the bubble universe with a barren central region and some hot evolving regions close to the boundaries.

There is, however, another way to think about this spacetime, which yields a very different view of the bubble universe. The key point is that "a moment of time" is not a uniquely defined concept in general relativity. When cosmologists talk about a moment of time, they picture a large number of observers, equipped with clocks and scattered through the universe. Each observer can see only a small region in her immediate vicinity, but the whole assembly of observers is needed to describe the entire spacetime. We can think of ourselves as one member in this assembly. Our clock now shows the time 13.8 billion years ABB. "The same time" in another part of the universe is when the clock of the observer located there shows the same reading. We have to decide, though, how observers, who are outside each other's horizons, are to synchronize their clocks.

In the case of a Friedmann universe, the answer is simple: the big bang is the natural origin of time, so each observer should count time starting from the big bang. But in an eternally inflating spacetime with multiple bubble universes, there is no such obvious choice. One possibility is to imagine observers who can exist in false vacuum and who synchronize their clocks in a small false vacuum region, while they are still within each other's Hubble distance. The observers are then driven apart by the inflationary expansion and encompass a large volume, including many bubble universes, at later times. The snapshots of the eternally inflating universe in Figs. 16.7 and 18.3 assume such a group of observers, and the moments "before" and "now" in Fig. 18.5 correspond to this choice as well.

But suppose now that we want to describe a specific bubble universe from the point of view of its inhabitants. Then the situation is similar to that of a Friedmann universe: there is now a natural choice for the origin of time. All observers inhabiting the bubble universe can count time from their local "big bang", that is, from the creation of the fireball at their respective locations. To distinguish between the large-region and single-bubble description

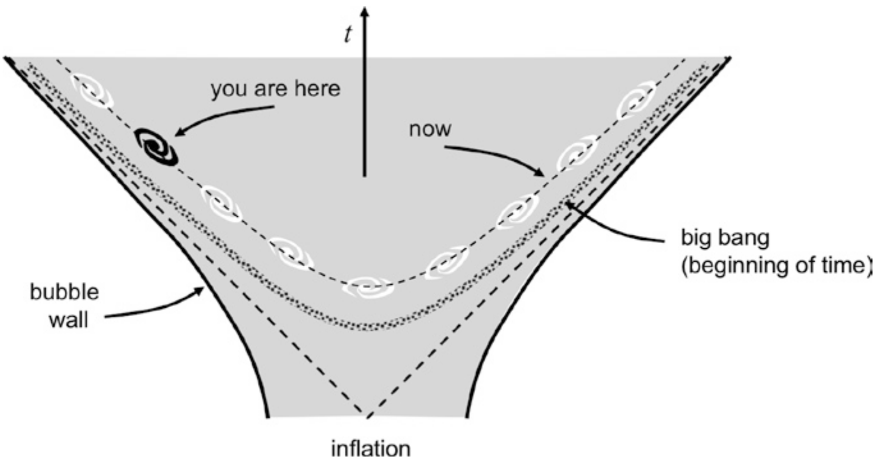

Fig. 18.6 Viewed from the inside (internal view), each bubble is an infinite universe. In the global view of Fig. 18.5, each bubble can grow for an infinite time, but is finite at any given moment of time. The difference is due to different definitions of time

we shall refer to them as "global" and "local" (or "internal") views, respectively.

The internal view of the bubble universe is illustrated in the spacetime diagram of Fig. 18.6. The spacetime structure is the same as in Fig. 18.5, but the lines representing moments of time are drawn differently. The fuzzy grey line representing the creation of the fireball now corresponds to the initial moment. The density of matter at this moment is very nearly uniform, and thus in the local view the bubble universe is nearly homogeneous (apart from small inhomogeneities due to quantum fluctuations). The present moment in this view is represented by the dotted line marked "now", which coincides with the line of galaxies in the figure. All points on this line are characterized by the same density of matter and the same average density of stars as observed in our local region. But most remarkably, from the local point of view the bubble universe is infinite.

In the global view, the bubble universe grows with time, as new hot fireball regions are created near its boundary, and becomes arbitrarily large if you wait long enough. But in the local view, the fireball is created all at once and the bubble universe is infinite from the very beginning. In Fig. 18.6 this infinity is evident from the fact that the fuzzy line representing the creation of the fireball never comes to an end. Analysis shows that the spatial geometry of a bubble universe in the local view is that of an open (negative

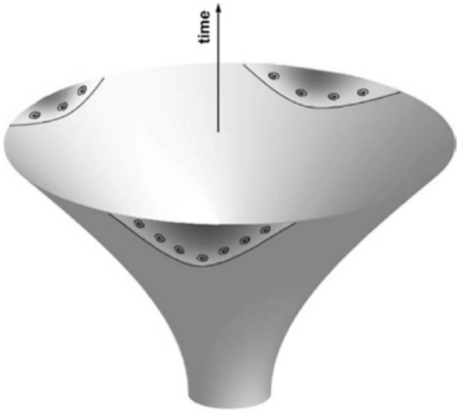

Fig. 18.7 The 2D surface represents the spacetime of a one-dimensional universe. This universe is closed and finite. It is filled with false vacuum at the initial moment (*bottom* of the figure) and contains three bubble universes at the time corresponding to the top of the figure. Each bubble universe appears to be infinite from the point of view of its inhabitants

curvature) Friedmann universe.[2] Thus, the picture of finite spatial sections which grow for an infinity of time in the global viewpoint is replaced by an infinity of spatial extent at each moment of time in the internal viewpoint.

This dual viewpoint leads to a very interesting situation: an eternally inflating spacetime can be closed and finite, and yet it can contain bubble universes that appear to be infinite to the observers who live inside (Fig. 18.7).

We note finally that analysis of random walk models of eternal inflation has shown that the properties of true vacuum islands predicted in these models (and illustrated in Fig. 18.3) are similar to those of bubble universes. An island also appears to be infinite to internal observers, and the observers cannot escape from their island, because its boundaries are expanding so fast.

[2]By the end of inflation the bubble universe becomes nearly flat, so its curvature is very difficult to observe.

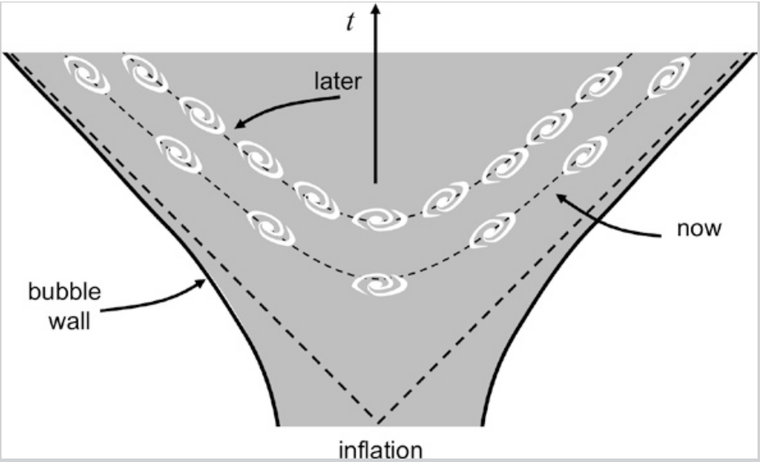

Fig. 18.8 A contracting bubble universe. The galaxies get closer together, even though the bubble radius grows with time

More on bubble spacetimes

Observers can find the expansion rate of their bubble universe by measuring how fast the distances between galaxies grow with time. But because of the complicated spacetime geometry, this rate is not simply related to, and is typically much slower than, the expansion rate of the false vacuum outside. It is even possible for the bubble interior to contract, while the bubble itself is expanding. An external observer would then see the bubble radius grow, while internal observers would see galaxies getting closer with time, as illustrated in Fig. 18.8. This situation could arise if the vacuum energy density (the cosmological constant) inside the bubble is negative. A negative cosmological constant produces an attractive gravitational force and causes the bubble universe to contract to a big crunch.

18.5 Cosmic Clones

At this point we would like to mention a remarkable and, to our minds, disturbing consequence of eternal inflation. Because the number of bubble universes is unlimited, and each of them expands without bound, they will contain an unbounded number of regions with the same size as our observable universe; let us call them *O*-regions. All these regions look the same at the end of inflation, except for the pattern of small density fluctuations. As fluctuations are amplified by gravity, the properties of the regions diverge, and they end up with different distributions of stars and galaxies. Random quantum events also influence the evolution of life, and this leads to further divergence of histories. So, should we expect the infinite number of *O*-regions to each have unique histories that result in their own unique present state?

In classical physics, the state of a physical system is described by specifying the precise positions and velocities of all its particles. Given a system of particles—say the contents of your refrigerator right now—you can always change its state by an arbitrarily small amount. Even if you barely changed the position or velocity of one single particle in the milk bottle, you would create a new distinct state. Classically, there is a continuum of states, which can be made arbitrarily close to one another, yet still maintain a unique identity. In quantum mechanics this is impossible because the uncertainty principle leads to an inherent fuzziness in the state of a system. Configurations which are too close to one another cannot be distinguished, even in principle. The upshot of the uncertainty principle is that the number of distinct quantum states in any finite volume is finite.

The number of possible histories of an *O*-region is finite as well. A history is described by a sequence of states at successive moments of time. The histories that are possible in quantum physics differ immensely from the ones possible in the classical world. In the quantum world the future is not uniquely determined by the past; the same initial state can lead to a multitude of different outcomes, and so only the probabilities of those outcomes can be determined. Consequently, the range of possible histories is greatly enlarged. Once again, though, the fuzziness imposed by quantum uncertainty makes it impossible to distinguish histories that are too close to each other. An estimate of the number of distinct histories that can unfold in an *O*-region between the big bang and the present gives $\sim 10^{10^{150}}$. This number is fantastically huge, but the important point is that the number is finite.

Let us now take stock of the situation. The theory of inflation tells us that the number of *O*-regions in an eternally inflating universe is infinite, and quantum uncertainty implies that only a finite number of histories can unfold in any *O*-region. The initial states of the *O*-regions at the big bang are set by random quantum processes during inflation, so all possible initial states are represented in the ensemble. Putting those statements together, it follows that every history which has a nonzero probability should be repeated an infinite number of times.

Among the infinitely replayed scripts are some very bizarre histories. For example, a huge quantum fluctuation could cause the Sun to suddenly collapse to a black hole. The probability of this happening is extremely small, but remember: in quantum mechanics all processes that are not strictly forbidden by conservation laws do occur with a nonzero probability.

A striking consequence of this picture of the world is that there should be an infinity of *O*-regions with histories absolutely identical to ours. That's right, scores of your duplicates are scattered throughout the eternally inflating spacetime. They live on planets exactly like Earth, with all its mountains, cities, trees, and butterflies. There should also be regions where histories are somewhat different from ours, with all possible variations. For example, some readers will be pleased to know that there are infinitely many *O*-regions where Hillary Clinton is the President of the United States.

You may be wondering whether all these things in different regions are happening at the same time. This question does not have a definite answer, because time and simultaneity are not uniquely defined in general relativity (as we discussed in Sect. 18.4). If, for example, we use the local time definition in a bubble universe, then at each moment of time the bubble interior is an infinite hyperbolic space, and each of us has an infinite number of duplicates presently living in our bubble.[3]

Note that infinity of space (or time) is not by itself sufficient to warrant these conclusions. We could, for example, have the same galaxy endlessly repeated in an infinite space. So we need some "randomizer", a stochastic mechanism that picks initial states for different regions from the set of all possible states. Even then, the entire set may not be exhausted if the total number of states is infinite. So the finiteness of the number of states N is important for the argument. In the case of eternal inflation, the finiteness of N and the randomness of initial conditions are both guaranteed by quantum mechanics.

18.6 The Multiverse

So far we have assumed that all other bubble universes are similar to ours in terms of their physical properties, but this does not have to be so. Consider for example the energy landscape shown in Fig. 18.9. It has four vacuum states, labeled A, B, C and D, with A having the highest energy density. Vacuum D has the lowest energy density, which is negative in this example.

[3]If you want to meet some of your duplicates, there is a problem: your nearest cosmic clone lives about $10^{10^{90}}$ m away. Another issue is that clones who are identical at this time will not remain so, because their subsequent evolution is influenced by random quantum processes.

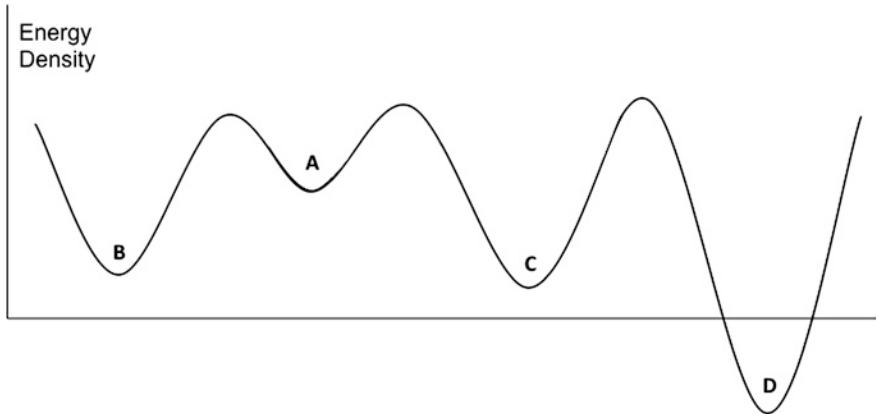

Fig. 18.9 A model energy landscape with four vacuum states, labeled A, B, C and D. Bubbles of B and C can form in vacuum A by quantum tunneling through energy barriers. Similarly, bubbles of D can nucleate in C

Suppose the universe is initially filled with vacuum A. The high energy density of A will then drive exponential inflationary expansion, and bubbles of vacuum B and vacuum C will nucleate and expand in the background of A.[4] Both B and C have positive energy densities, so the interiors of these bubbles will also be inflating (but at a slower rate than A). Bubbles of vacuum D will nucleate inside the inflating bubbles of C. Furthermore, tunneling "up" from low to high energy density is also possible, albeit with a very low probability—much less than the probability to tunnel "down". Hence, new bubbles of A will form inside the bubbles of B and C, but they will be very rare.[5] All of these tunneling processes populate the inflating universe with all four types of vacua (see Fig. 18.10). The number of bubbles of all types will grow without bound in the course of eternal inflation.

A more realistic energy landscape would include several scalar fields. The Higgs field of the Standard Model is an example of a scalar field that we know exists. Grand unified theories predict a number of other Higgs fields whose values determine the particle properties. A model with two scalar fields would have a two-dimensional energy landscape with mountains

[4]We assume here that tunneling from a given vacuum is possible only to a neighboring vacuum in the landscape; hence it is not possible to tunnel from A to D.

[5]Tunneling up from zero and negative energy vacuum states is impossible. We note, however, that such tunneling may occur from zero or negative energy bubbles, if they have inflation or matter dominated periods at the early stages of their evolution (which temporarily increases their overall energy density above the vacuum value of zero or less).

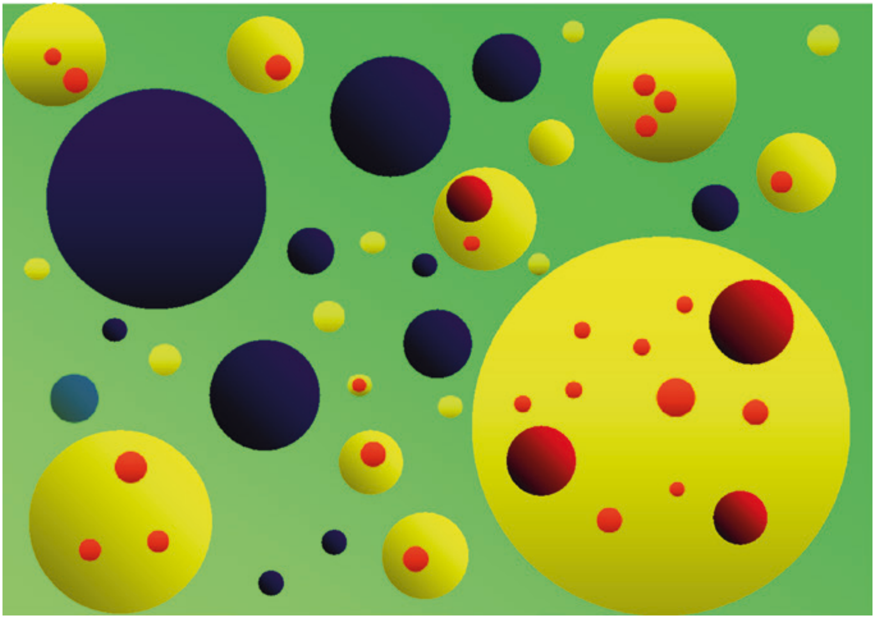

Fig. 18.10 The multiverse of the model with energy landscape shown in Fig. 18.9. *Green*, *blue*, *yellow* and *red* bubbles correspond to vacua A, B, C and D, respectively. Positive-energy vacua (A, B and C) are inflating, while bubbles of vacuum D do not inflate. Interiors of such negative-energy bubbles eventually collapse to a big crunch

and valleys, as depicted in Fig. 18.11. As before, each valley corresponds to a classically stable vacuum, and transitions between the vacua can occur through bubble nucleation.

With n scalar fields, the energy landscape is n-dimensional. For $n > 2$, we cannot draw such a landscape on a piece of paper, but it is not difficult to analyze mathematically and find all classically stable vacua. As long as inflation begins in one of the positive-energy vacua, all of the other vacua will be realized via the dynamics of eternal inflation. Bubbles of positive-energy vacua will inflate, allowing for more bubbles within bubbles to form, exactly like in the eternal inflation scenario with a single scalar field. Negative-energy bubbles will expand externally, but internally they will contract to a big crunch (see the box in Sect. 18.4).

The values of the Higgs fields vary from one vacuum to another, and as a result particle masses and interactions vary as well. One vacuum state in the energy landscape should correspond to our world, but others are likely to be very different. We thus arrive at the picture of an inflationary *multiverse*, populated by bubble universes with diverse properties.

Fig. 18.11 Energy landscape in a model with two scalar fields. The height represents the value of the potential energy density, and the two axes represent two different scalar fields. Each valley represents a vacuum state. We shall see in Chap. 19 that some modern particle theories predict a large number of such valleys

18.7 Testing the Multiverse

The theory of eternal inflation is mainly concerned with far-away regions, outside our cosmic horizon, and some physicists have raised doubts that the theory can ever be tested observationally. Surprisingly, such tests may in fact be possible.

18.7.1 Bubble Collisions

If a new bubble nucleates within a distance d_H from our expanding bubble, then it will crash into ours. The collision would produce a round spot of higher radiation intensity in the cosmic background radiation. Detection of such spots with the predicted intensity profile would provide direct evidence for the existence of other bubble universes (Fig. 18.12).

The expected number of collision spots in the CMB depends on the rate of bubble nucleation in the false vacuum, and their brightness depends on

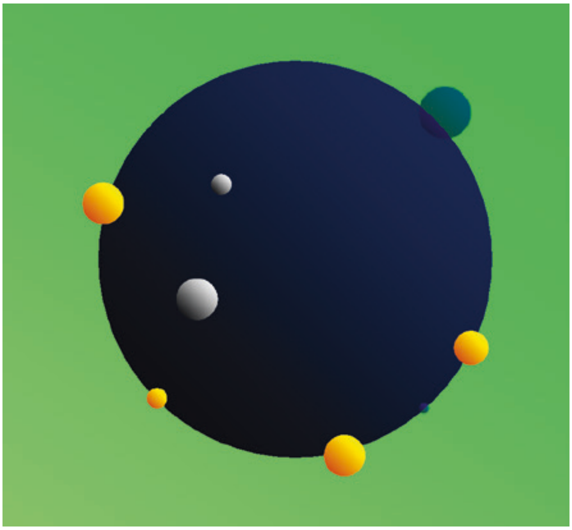

Fig. 18.12 Even though bubble collisions are rare, our expanding bubble will collide with an infinite number of other bubbles in the course of its history

the amount of inflation that took place in our bubble interior: the more inflation, the dimmer are the spots. Unfortunately there is no guarantee that detectable bubble collisions have occurred within our horizon.

18.7.2 Black Holes from the Multiverse

Another interesting possibility is that evidence for the multiverse may be found in our own neighborhood, in the form of black holes. During the slow roll inflation period within our bubble, bubbles of other kinds can nucleate and expand within it. When inflation ends, these bubbles suddenly find themselves surrounded by the very low-energy vacuum that we live in now. At this point they stop expanding and start contracting. (Bubbles expand when they are surrounded by a higher-energy vacuum and contract when the vacuum outside has lower energy.) There is nothing to stop this contraction, so the bubbles collapse to form black holes.[6]

[6]Even though bubbles collapse as viewed from outside, their interiors are filled with a high-energy vacuum and continue to inflate. In a two-dimensional analogy, the resulting geometry can be pictured as an inflating balloon, which is connected to a flat exterior region by a thin "throat". The throat is seen as a black hole from outside. Thus, black holes formed in this way contain inflating universes inside.

Bubbles that formed earlier have bigger sizes, and bubbles that formed near the end of inflation are very tiny. Bigger bubbles form larger black holes, so the result is a population of black holes with a wide distribution of masses, ranging from less than a gram to millions of Solar masses. These black holes are fossils of the multiverse. If black holes with the predicted mass distribution are discovered, this would provide evidence for the existence of a multiverse.

Apart from these direct methods, some indirect tests of the multiverse theory may also be possible. In fact, some indirect evidence for the multiverse has already been found, as we shall discuss in the following chapters.

Summary

The end of inflation is triggered by quantum, probabilistic processes and does not occur everywhere at once. In our cosmic neighborhood, inflation ended 13.8 billion years ago, but it still continues in remote parts of the universe, where other "normal" regions like ours are constantly being formed.

In the "bubble nucleation" picture, the new regions appear as tiny, microscopic bubbles and immediately start to grow. The bubbles keep growing without bound; all the while they are driven apart by the inflationary expansion of the parent false vacuum, making room for more bubbles to form. We live in one of these bubbles and can observe only a small part of it. The "quantum random walk" picture is similar, giving rise to an infinite number of self-contained island universes separated by inflating false vacuum. Both of these pictures result in a never-ending process called e*ternal inflation*. All that is needed for cosmic inflation to be eternal is a false vacuum region that multiplies faster than it decays.

Modern particle physics suggests that a number of Higgs scalar fields should contribute to an energy landscape replete with mountains and valleys. Each valley corresponds to a classically stable vacuum, but transitions between the vacua can occur through bubble nucleation. Thus, if the universe starts in a positive energy vacuum state, then through a random series of transitions from one vacuum to another, all the other vacua in the landscape can be realized. One vacuum state should correspond to our world, but others are likely to be very different. We thus arrive at the picture of an inflationary *multiverse*, populated by bubble universes with diverse properties.

A collision of our expanding bubble with another bubble would produce a round spot of higher radiation intensity in the cosmic background radiation. A detection of such a spot with the predicted intensity profile would provide direct evidence for the existence of other bubble universes.

An unsettling consequence of eternal inflation is that anything that can possibly happen *will* happen, and it will happen an infinite number of times. In particular, there should be an infinite number of regions absolutely identical to ours. There should also be regions somewhat different from ours, with all possible variations.

Questions

1. What do we mean by the phrase "eternal inflation"? Does it mean that inflation never ends at any given place? Does it mean that inflation continues forever to the past, as well as to the future?
2. Imagine you are a comoving observer in the inflating region represented by one of the white squares in the simple model of Sect. 18.1. What is the probability that inflation will continue in your neighborhood for another doubling time? What is the probability for it to continue for 10 doubling times?
3. Suppose that in each doubling time of inflation the volume of false vacuum grows by a factor $2^3 = 8$ and a fraction f of this volume decays to true vacuum. By how much will the false vacuum volume change after N doubling times? How large should f be in order to prevent eternal inflation from happening?
4. Once a bubble nucleates in an inflating false vacuum, is it possible for inflation to continue inside the bubble?
5. During the course of eternal inflation, how many bubble universes will be formed?
6. Can we in principle travel across the inflating false vacuum and visit other bubble universes?
7. From the external viewpoint, are bubble universes infinite or finite in spatial extent? What about from an internal viewpoint?
8. How is it possible to have a closed and finite universe, which nevertheless contains bubble universes that are infinite from the viewpoint of their inhabitants?
9. Eternal inflation can also be achieved via a quantum random walk. Explain how this works.
10. How would you modify the shape of the potential energy hill in Fig. 18.2 to prevent eternal inflation from happening, while still keeping inflation in the slow-roll region?

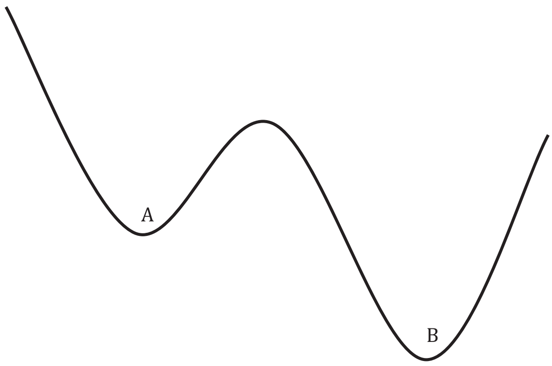

Fig. 18.13 Potential energy density curve with two minima

11. What do we mean by a "multiverse"?
12. Consider the potential shown in Fig. 18.13. Will this model give rise to a multiverse? Assuming that both vacua have positive energy density, sketch a 2–dimensional cartoon of the resulting pattern of bubbles (analogous to Fig. 18.10).
13. Is it possible to test the existence of other bubble universes observationally? If yes, how?
14. Consider the following statement: "In an infinite universe, anything that can possibly happen will happen an infinite number of times." Is this necessarily true? If not, what additional assumptions about the properties of the universe should we make in order for it to be true?
15. Is the number of distinct states in an infinite volume finite or infinite? Explain. *Hint:* consider an infinite sequence of regions, each of which can only be in one of two states, labeled by 1 and 2. Now consider how many different sequences (consisting of the numbers 1 and 2) are possible.
16. If an eternally inflating universe produces an infinite number of regions having the size of our observable region, and if each region can only have a finite number of histories, is it likely, unavoidable, or impossible to have other regions where someone has had the exact same past as you? If such a person does exist, will she or he have the same future as you?
17. Suppose a region can be in an infinite number of states, and the universe contains an infinite number of such regions. Can we conclude that all possible states will occur somewhere in the universe? (*Hint:* suppose we label the possible states by integers 1, 2, 3, ... Can you think of an infinite sequence of integers which does not include all possible integers?)

18. Is it possible for the Earth to heat up by suddenly ejecting a huge chunk of ice? Is it likely?
19. Suppose astronomers do not find any signatures of bubble collisions in the CMB. Would that mean that the theory of eternal inflation is wrong? If not, should we still believe that inflation is eternal?
20. How do you feel about the existence of identical Earths? Are you disappointed that our civilization may not be unique? If there is an infinity of other Earths, our civilization appears to be totally insignificant on the cosmic scale. Do you find this upsetting?