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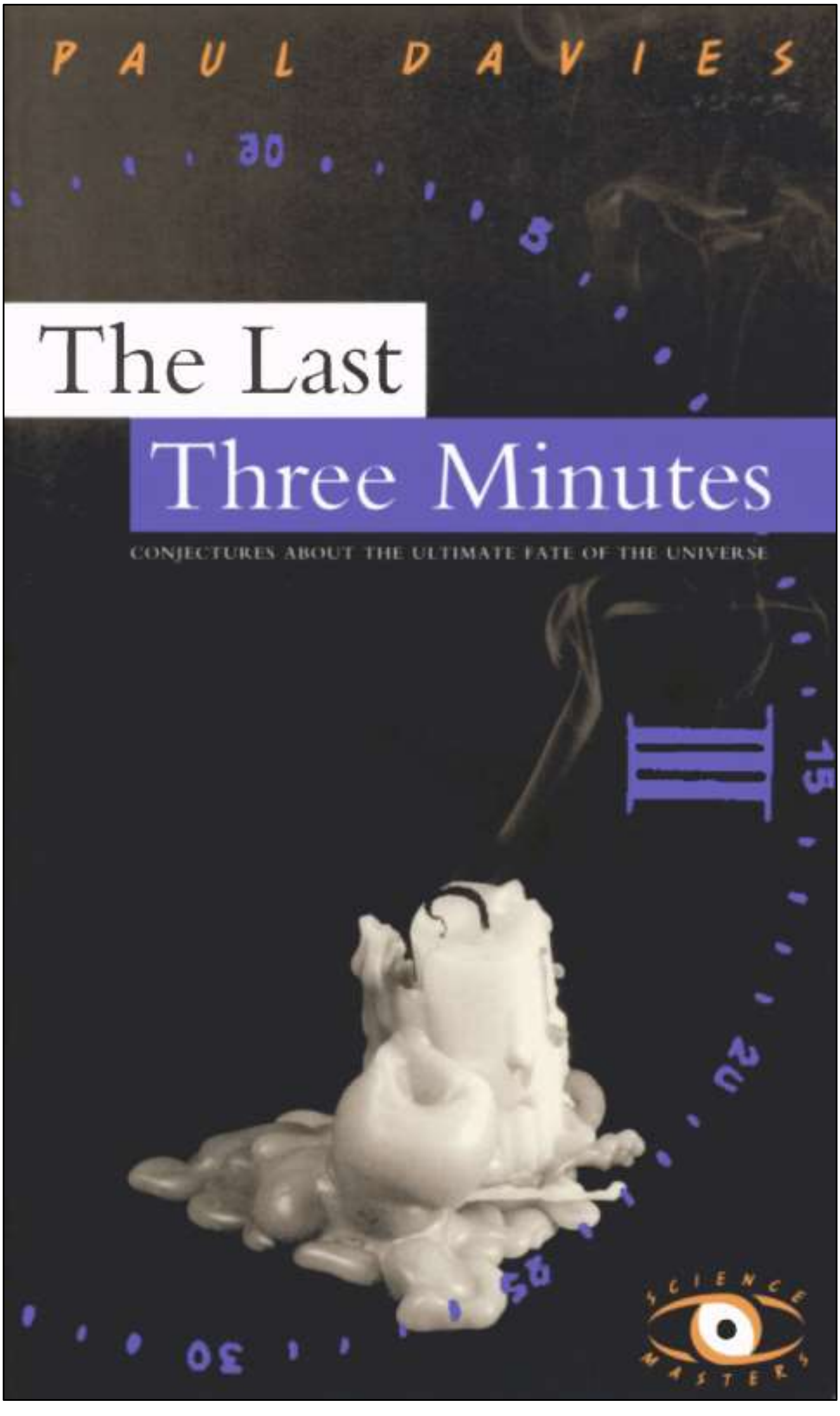
The Last Three Minutes

Conjectures About the Ultimate Fate of The Universe

By: Paul Davies



Chapter I: Doomsday

- The sun is a typical dwarf star, lying in a typical region of our galaxy, the Milky Way. The galaxy contains about a hundred billion stars, ranging in mass from a few percent to a hundred times the mass of the sun. These objects, together with a lot of gas clouds and dust and an uncertain number of comets, asteroids, planets, and black holes, slowly orbit the galactic center. Such a huge collection of bodies may give the impression that the galaxy is a very crowded system, until account is taken of the fact that the visible part of the Milky Way measures about a hundred thousand light-years across. It is shaped like a plate, with a central bulge; a few spiral arms made up of stars and gas are strung out around it. Our sun is located in one such spiral arm and is about thirty thousand light-years from the middle. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.4]
- All this space means that cosmic collisions are rare. The greatest threat to Earth is probably from our own backyard. Asteroids do not normally orbit close to Earth; they are largely confined to the belt between Mars and Jupiter. But the huge mass of Jupiter can disturb the asteroids' orbits, occasionally sending one of them plunging in toward the sun, and thus menacing Earth. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.5]
- Comets pose another threat. These spectacular bodies are believed to originate in an invisible cloud situated about a light year from the sun. Here the threat comes not from Jupiter but from passing stars. The galaxy is not static; it rotates slowly, as its stars orbit the galactic nucleus. The sun and its little retinue of planets take about two hundred million years to complete one circuit of the galaxy, and on the way they have many adventures. Nearby stars may brush the cloud of comets, displacing a few toward the sun. As the comets plunge through the inner solar system, the sun evaporates some of their volatile material, and the solar wind blows it out in a long streamer-the famous cometary tail. Very rarely, a comet will collide with the Earth during its sojourn in the inner solar system. The comet does the damage, but the passing star must bear the responsibility. Fortunately, the huge distances between the stars insulate us against too many such

encounters. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.5]

- Can humanity, in principle, survive forever? Possibly. But we shall see that immortality does not come easily and may yet prove to be impossible. The universe itself is subject to physical laws that impose upon it a life cycle of its own: birth, evolution, and-perhaps-death. Our own fate is entangled inextricably with the fate of the stars. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.7]

CHAPTER 2: THE DYING UNIVERSE

- In the year 1856, the German physicist Hermann von Helmholtz made what is probably the most depressing prediction in the history of science. The universe, Helmholtz claimed, is dying. The basis of this apocalyptic pronouncement was the so-called second law of thermodynamics. Originally formulated in the early nineteenth century as a rather technical statement about the efficiency of heat engines, the second law of thermodynamics (now often termed simply "the second law") was soon recognized as having universal significance-indeed, literallycosmic consequences. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.9]
- Overall, the entropy never goes down. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.11]
- If the universe as a whole can be considered as a closed system, on the basis that there is nothing "outside" it, then the second law of thermodynamics makes an important prediction: the total entropy of the universe never decreases. In fact, it goes on rising remorselessly. A good example lies right on our cosmic doorstep-the sun, which continuously pours heat into the cold depths of space. The heat goes off into the universe, never to return; this is a spectacularly irreversible process. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.11]
- An obvious question is, Can the entropy of the universe go on rising forever? Imagine a hot body and a cold body brought into contact inside a

thermally sealed container. Heat energy flows from hot to cold and the entropy rises, but eventually the cold body will warm up and the hot body will cool down so that they reach the same temperature. When that state is achieved, there will be no further heat transfer. The system inside the container will have reached a uniform temperature-a stable state of maximum entropy referred to as thermodynamic equilibrium. No further change is expected, as long as the system remains isolated; but if the bodies are disturbed in some way-say, by introducing more heat from outside the container-then further thermal activity will occur, and the entropy will rise to a higher maximum. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.11-12]

- Although Hermann von Helmholtz knew nothing of nuclear reactions (the source of the sun's immense energy was a mystery at that time), he understood the general principle that all physical activity in the universe tends toward a final state of thermodynamic equilibrium, or maximum entropy, following which nothing of value is likely to happen for all eternity. This one-way slide toward equilibrium became known to the early thermos-dynamicists as the "heat death" of the universe. Individual systems, it was conceded, might be revitalized by external disturbances, but the universe itself had no "outside" by definition, so nothing could prevent an all-encompassing heat death. It seemed inescapable.[Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.12]
- The discovery that the universe was dying as an inexorable consequence of the laws of thermodynamics had a profoundly depressing effect on generations of scientists and philosophers. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.12]
- Bertrand Russell, for example, was moved to write the following gloomy assessment in his book Why I Am Not a Christian: All the labours of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius, are destined to extinction in the vast death of the solar system, and. . . the whole temple of man's achievement must inevitably be buried beneath the debris of a universe in ruins-all these things, if not quite

beyond dispute, are yet so nearly certain that no philosophy which rejects them can hope to stand. Only within the scaffolding of these truths, only on the firm foundation of unyielding despair, can the soul's habitation henceforth be safely built. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.12-13]

- Many other writers have concluded from the second law of thermodynamics and its implication of a dying universe that the universe is pointless and human existence ultimately futile. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.13]
- The prediction of a final cosmic heat death not only says something about the future of the universe but also implies something important about the past. It is clear that if the universe is irreversibly running down at a finite rate, then it cannot have existed forever. The reason is simple: if the universe were infinitely old, it would have died already. Something that runs down at a finite rate obviously cannot have existed for eternity. In other words, the universe must have come into existence a finite time ago. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.13]
- It is remarkable that this profound conclusion was not properly grasped by the scientists of the nineteenth century. The idea of the universe originating abruptly in a big bang had to await astronomical observations in the 1920s, but a definite genesis at some moment in the past seems to have been strongly suggested already, on purely thermo-dynamic grounds. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.13]
- Because this obvious inference was not made, however, nineteenth-century astronomers were baffled by a curious cosmological paradox. Known as Olbers' paradox, after the German astronomer who is credited with its formulation, it poses a simple yet deeply significant question: Why is the sky dark at night? At first, the problem seems trivial. The night sky is dark because the stars are situated at immense distancesfrom us and so appear dim. [Paul Davies, ***The Last Three Minutes: Conjectures About the***

Ultimate Fate of the Universe, BasicBooks, 1994, p.14-15]

- But suppose that space has no limit. In this case, there could well be an infinity of stars. An infinite number of dim stars would add up to a lot of light. It is easy to calculate the cumulative starlight from an infinity of unchanging stars distributed more or less uniformly throughout space. The brightness of a star diminishes with distance, according to an inverse-square law. This means that at twice the distance the star is one-quarter as bright, at three times the distance it is one-ninth as bright, and so on. On the other hand, the number of stars increases the farther away you look. In fact, simple geometry shows that the number of stars, say, two hundred light-years away is four times the number one hundred light-years away, while the number three hundred light-years away is nine times the latter. So the number of stars goes up as the square of the distance, while the brightness goes down as the square of the distance. The two effects cancel each other out, and the result is that the total light coming from all the stars at a given distance does not depend on the distance. The same total light comes from stars two hundred light-years away as from those one hundred light-years away. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.15]
- The problem comes when we add up the light from all the stars at all possible distances. If the universe has no boundary, there seems to be no limit to the total amount of light received on Earth. Far from being dark, the night sky ought to be infinitely bright! [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.15]
- The problem is ameliorated somewhat when account is taken of the finite size of stars. The farther away a star is from Earth, the smaller is its apparent size. A nearby star will obscure a more distant star if it lies along the same line of sight. In an infinite universe this will happen infinitely often, and taking it into account changes the conclusion of the previous calculation. Instead of an infinite flux of light arriving on Earth, the flux is merely very large-roughly equivalent to the sun's disk filling the sky, as would be the case if the Earth were located about a million miles from the solar surface. This would be a very uncomfortable location indeed; in fact,

the Earth would be rapidly vaporized by the intense heat. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.15-16]

- The conclusion that an infinite universe ought to be a cosmic furnace is actually a restatement of the thermodynamic problem I discussed earlier. The stars pour heat and light into space, and this radiation slowly accumulates in the void. If the stars have been burning forever, it seems at first sight that the radiation must have an infinite intensity. But some radiation, while traveling through space, will strike other stars and be reabsorbed. (This is equivalent to noticing that nearby stars obscure the light from more distant ones.) Therefore, the intensity of the radiation will rise until an equilibrium is established at which the rate of emission just balances the rate of absorption. This state of thermodynamic equilibrium will occur when the radiation in space reaches the same temperature as the surfaces of the stars-a few thousand degrees. Thus the universe should be full of heat radiation with a temperature of several thousand degrees, and the night sky, instead of being dark, should glow at this temperature. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.16]
- Heinrich Olbers proposed a resolution to his own paradox. Noting the existence of large amounts of dust in the universe, he suggested that this material would absorb most of the starlight and thus darken the sky. Unfortunately, his idea, though imaginative, was fundamentally flawed: the dust would eventually heat up and start to glow with the same intensity as the radiation it absorbed. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.16]
- Another possible resolution is to abandon the assumption that the universe is infinite in extent. Suppose the stars are many but finite in number, so that the universe consists of a huge assemblage of stars surrounded by an infinite dark void; then most of the starlight will flow away into the space beyond, and be lost. But this simple resolution, too, has a fatal flaw-one that was, in fact, already familiar to Isaac Newton in the seventeenth century. The flaw concerns the nature of gravitation: Every star attracts

every other star with a force of gravity, therefore all the stars in the assemblage would tend to fall together, congregating at the center of gravity. If the universe has a definite center and edge, it seems that it must collapse in on itself. An unsupported, finite, static universe is unstable, and subject to gravitational collapse. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.16-17]

- Here we need simply note the ingenious way in which Newton attempted to sidestep it. The universe can collapse to its center of gravity, Newton reasoned, only if it has a center of gravity. If the universe is both infinite in extent and (on average) uniformly populated with stars, then there will be no center and no edge. A given star will be pulled every which way by its many neighbors, like a gigantic tug-of-war in which ropes bristle in all directions. On average, all these tugs will cancel one another, and the star won't move. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.17]
- So if we accept Newton's resolution of the collapsing- cosmos paradox, we are back with an infinite universe again, and the problem of Olbers' paradox. It seems that we must face either one or the other. But with the benefit of hindsight we can find a way between the horns of the dilemma. It is not the assumption that the universe is infinite in space that is wrong but the assumption that it is infinite in time. The paradox of the flaming sky arose because astronomers assumed that the universe was unchanging, that the stars were static and had been burning with undiminished intensity for all eternity. But we now know that both these assumptions were wrong. First, as I shall shortly explain, the universe is not static but expanding. Second, the stars cannot have been burning forever, because they would have long since run out of fuel. The fact that they are burning now implies that the universe must have come into existence at a finite time in the past. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.17-18]
- If the universe has a finite age, Olbers' paradox goes away immediately. To see why, consider the case of a very distant star. Because light travels at a finite speed (300,000 kilometers a second, in a vacuum) we do not see the

star as it is today but as it was when the light left it. For example, the bright star Betelgeuse is about six hundred and fifty light-years away, so it appears to us now as it was six hundred and fifty years ago. If the universe came into existence, say, ten billion years ago, then we would not see any stars located more than ten billion light-years away from Earth. The universe may be infinite in spatial extent, but if it has a finite age we cannot in any case see beyond a certain finite distance. So the cumulative starlight from an infinite number of stars of finite age will be finite, and possibly insignificantly small. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.18]

- The same conclusion follows from thermodynamic considerations. The time taken for the stars to fill space with heat radiation and reach a common temperature is immense, because there is so much empty space in the universe. There has simply been insufficient time since the beginning for the universe to have reached thermodynamic equilibrium by now. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, Basic Books, 1994, p.18]
- All the evidence points, then, to a universe that has a limited life span. It came into existence at some finite time in the past, it is currently vibrant with activity, but it is inevitably degenerating toward a heat death at some stage in the future. A host of questions immediately arises. When will the end come? What form will it take? Will it be slow or sudden? And is it conceivable that the heat- death conclusion, as scientists currently understand it, might turn out to be wrong? [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, Basic Books, 1994, p.18]
- the laws of thermodynamics suggest a universe of limited longevity. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.19]
- The fact that space can stretch may seem surprising, but it is a concept that has been familiar to scientists since 1915, when Einstein published his general theory of relativity. This theory proposes that gravity is actually a manifestation of the curvature, or distortion, of space (strictly, spacetime). In a sense, space is elastic, and can bend or stretch in a manner that depends

on the gravitational properties of the material in it. This idea has been amply confirmed by observation. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.20]

- If the universe is expanding, it must have been more compressed in the past. Hubble's observations, and the much improved ones made since, provide a measure of the rate of expansion. If we could run the cosmic movie backward, we would find all the galaxies merging together in the remote past. From a knowledge of the present rate of expansion, we can deduce that this merged state must have occurred many billions of years ago. However, it is hard to be exact, for two reasons. First, the measurements are difficult to perform precisely and are subject to a variety of errors. Even though modern telescopes have greatly increased the number of galaxies investigated, the expansion rate is still uncertain to within a factor of two, and is the subject of lively controversy. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.22]
- In other words, the material that makes up all the galaxies we can see today emerged from a single point, explosively fast! This is an idealized description of the so-called big bang. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.22-23]
- But are we justified in extrapolating the curve all the way back to the beginning? Many cosmologists believe so. Given that we expect the universe to have had a beginning (for the reasons I discussed in the previous chapter), it certainly looks as though the big bang is it. If so, then the beginning of the curve marks more than merely an explosion. Remember that the expansion being graphed here is that of space itself, so zero volume doesn't mean merely that matter is squashed to an infinite density. It means that space is compressed to nothing. In other words, the big bang is the origin of space as well as of matter and energy. It is most important to realize that according to this picture there was no preexisting void in which the big bang happened.
- If the big-bang theory, with its strange implications for the cosmic origin,

rested only upon the evidence for the expansion of the universe, many cosmologists would probably reject it. However, important additional evidence in support of the theory came in 1965, with the discovery that the universe is bathed in heat radiation. This radiation comes at us from space with the same intensity in all directions of the sky and has been traveling more or less undisturbed since shortly after the big bang. It thus provides a snapshot of the state of the primeval universe. The spectrum of the heat radiation matches exactly the glow that exists inside a furnace that has reached a state of thermodynamic equilibrium-a form of radiation known to physicists as blackbody radiation. We are thus led to conclude that the early universe was in such a state of equilibrium, with all regions at a common temperature. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.24]

- False vacuums, it should be emphasized, remain a purely theoretical idea, and their properties depend a great deal on the particular theory that is being invoked. They emerge naturally, however, in most recent theories that aim to unify the four fundamental forces of nature: gravitation and electromagnetism, familiar from daily life, and two short-range nuclear forces called the weak force and the strong force.[Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.34]
- In the case of the false vacuum, there is both a colossal energy and a comparably colossal pressure, so that they vie for gravitational dominance. The crucial property, however, is that the pressure is negative. The false vacuum doesn't push: it sucks. A negative pressure produces a negative gravitational effect-which is to say, it antigravitates. So the gravitational action of the false vacuum involves a competition between the huge attractive effect of its energy and the huge repulsive effect of its negative pressure. It turns out that the pressure wins, and the net effect is to create a repulsive force so large that it can blow the universe apart in a split second. It is this gargantuan inflationary push that causes the universe to double in size as rapidly as every 10^{-34} seconds. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.34]

- The false vacuum is inherently unstable. Like all excited quantum states, it wants to decay back to the ground state-the true vacuum. It probably does this after a few dozen ticks. Being a quantum process, it is subject to the inevitable indeterminism and random fluctuations discussed above in connection with the Heisenberg uncertainty principle. This means that the decay will not occur uniformly throughout space: there will be fluctuations. Some theorists suggest that these fluctuations may be the source of the COBE ripples. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.34-35]
- If the inflationary scenario is on the right track-and many leading cosmologists believe that it is-then the basic structure and physical contents of the universe were determined by processes that were complete after a mere 10^{-32} seconds had elapsed. The postinflationary universe underwent many additional changes at the subatomic level, as the primeval material developed into the particles and atoms that constitute the cosmic stuff of our epoch, but most of the additional processing of matter was complete after only three minutes or so. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.35]
- How do the first three minutes relate to the last? Just as the fate of a bullet fired toward a target depends critically on the aim of the gun, so the fate of the universe depends sensitively on its initial conditions. We shall see how the way in which the universe expanded from its primeval origins, and the nature of the material that emerged from the big bang, serve to determine its ultimate future. The beginning and the end of the universe are deeply inter-twined.[Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.35-36]

CHAPTER 4: STAR DOOM

- There is a simple relation between the pressure of a gas and its temperature. When a gas of fixed volume is heated, the pressure normally rises in proportion to the temperature. Conversely, when the temperature falls, so does the pressure. The interior of a star has an enormous pressure because it is so hot-many millions of degrees. The heat is produced by nuclear reactions. For most of its lifetime, the principal reaction that powers a star is the conversion of hydrogen into helium by fusion. This reaction requires a very high temperature to overcome the electric repulsion that acts between nuclei. Fusion energy can sustain a star for billions of years, but sooner or later the fuel runs low, and the reactor starts to falter. When this happens, the pressure support is threatened and the star begins to lose its long battle with gravity. A star essentially lives on bor- rowed time, staving off gravitational collapse by marshaling its reserves of fuel. But every kilowatt that flows away from the stellar surface into the depths of space serves to hasten the end. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.42]

- The end of the nuclear-burning chain is marked by the element iron, which has a particularly stable nuclear structure. The synthesis of elements heavier than iron by nuclear fusion actually costs energy rather than liberates it, so that by the time a star has synthesized a core of iron, it is doomed. Once the central regions of the star can no longer produce heat energy, the odds tip fatally in favor of the force of gravity. The star teeters on the edge of catastrophic instability, eventually toppling into its own gravitational pit. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.43]
- If the mass of the core is somewhat larger-say, several solar masses-it cannot settle down as a neutron star. The force of gravity is so strong that even neutronic matter- the stiffest-known substance-cannot resist further compression. The stage is then set for an event more awesome and more catastrophic than the supernova. The core of the star continues to collapse, and in less than a millisecond it creates a black hole and disappears into it. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.43]
- Our very existence in the universe is a consequence of the extraordinary stability of stars like the sun, which can burn steadily with little change for billions of years, long enough to allow life to evolve and flourish. But in the red-giant phase this stability will come to an end. The succeeding stages in the career of a star like the sun are complicated, erratic, and violent, with relatively sudden changes of behavior and appearance. Aging stars may

spend millions of years pulsating, or sloughing off shells of gas. The helium in the star's core may ignite to form carbon, nitrogen, and oxygen-thereby providing vital energy that will sustain the star a while longer. By blowing off its outer envelope into space, a star can end up stripped down to its carbon-oxygen core. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.47-48]

CHAPTER 5: NIGHTFALL

- The Milky Way blazes with the light of a hundred billion stars, and everyone of them is doomed. In ten billion years, most that we see now will have faded from sight, snuffed out from lack of fuel, victims of the second law of thermodynamics.[Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.49]
- The end of the universe will not come when the cosmic lights go out, however, for there is another source of energy even more powerful than nuclear reactions. Gravity, the weakest of nature's forces at the atomic level, becomes dominant on the astronomical scale. It may be relatively gentle in its effects, yet it is utterly persistent. For billions of years, stars shore themselves up against their own weight by nuclear burning. But all the while gravity is waiting to claim them. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.50]
- The gravitational force between two protons in an atomic nucleus is a mere ten-trillion-trillion-trillionth (10^{-37}) of the strong nuclear force. But gravity is cumulative. Every additional proton in a star adds to the total weight. Eventually, the gravitational force is overwhelming. And this overwhelming force is the key that unlocks immense power. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.50]
- If the black hole has a mass of ten million suns-similar to the hole that may lie at the center of the Milky Way-and is nonrotating, then the duration experienced by the astronaut in falling from the event horizon to the annihilating singularity will be about three minutes. Those last three minutes will be very uncomfortable; in practice, spaghettification will kill the hapless individual long before the singularity is reached. During this

final phase, the astronaut will in any case be unable to see the fatal singularity, because light cannot escape from it. If the black hole in question is of just one solar mass, its radius is about three kilometers, and the journey from event horizon to singularity will occupy just a few microseconds. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.64]

CHAPTER 6: WEIGHING THE UNIVERSE

- In fact, it turns out that the expanding universe behaves in a manner closely analogous to a body projected from Earth, even if there is no well-defined edge. If the rate of expansion is fast enough, the retreating galaxies will escape from the cumulative gravity of all the other material in the universe, and the expansion will continue forever. On the other hand, if the rate is too slow, the expansion will eventually be brought to a halt and the universe will start to contract. The galaxies will then "come down" again, and the ultimate cosmic catastrophe will ensue, as the universe collapses. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.68]
- Which of these scenarios will come to pass? The answer depends on a comparison of two numbers. On the one hand, there is the rate of expansion; on the other, there is the total gravitational pull of the universe- in effect, the weight of the universe. The bigger the pull, the faster the universe must expand to overcome it. Astronomers can measure the rate of expansion directly by observing the redshift effect; however, there is still some controversy over the answer. The second quantity- the weight of the universe-is even more problematical. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.68]
- How do you weigh the universe? It seems a daunting task; clearly we cannot do it directly. Nevertheless, we might be able to deduce its weight using the theory of gravitation. A lower limit is straightforward to attain. It is possible to weigh the sun by measuring its gravitational pull on the planets. We know that the Milky Way contains about a hundred billion stars of roughly one solar mass on average, so this provides a crude lower limit to the mass of the galaxy. We can now tot up how many galaxies there are in

the universe. You can't add them individually- there are too many-but a good guesstimate is ten billion. This comes to 10 21 solar masses, or about 10 48 tons in all. Taking the radius of this assemblage of galaxies to be fifteen billion light-years, we can calculate a minimum value for the escape velocity from the universe: the answer turns out to be about 1 percent of the velocity of light. We can conclude that if the weight of the universe were due only to the stars the universe would escape its own gravitational pull and go on expanding indefinitely. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.68-69]

- Overall, estimates of the amount of dark matter in the universe vary from one astronomer to another. It is likely that dark matter outweighs luminous matter by at least ten to one, and figures of a hundred to one are sometimes quoted. It is an astonishing thought that astronomers don't know what most of the universe consists of. The stars that they had long supposed accounted for most of the universe turn out to make up a rather small portion of the total. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.78-79]
- Given our present state of knowledge, we cannot say whether the universe will expand forever or not. If it will eventually start to contract, the question arises of when this will happen. The answer depends on precisely by how much the weight of the universe exceeds the critical weight. If it is 1 percent more than the critical weight, the universe will start contracting in about a trillion years; if it is 10 percent more, contraction is hastened to one hundred billion years from now. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.79]
- One of the predictions of the inflationary theory concerns the amount of matter in the universe. Suppose the universe starts out with a mass density much greater or less than the critical value at which collapse just fails to occur. When the universe embarks on the inflationary phase, the density changes dramatically, and in fact the theory predicts that it rapidly approaches the critical density. The longer the universe inflates, the closer the density gets to criticality. In the standard version of the theory, inflation

lasts for only a very brief duration, so unless by a miracle the universe began with exactly the critical density, it will emerge from the inflationary phase with a density slightly greater or less than criticality. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.80]

- How long did inflation last? Nobody knows, but for the theory to successfully explain the numerous cosmological puzzles I have described, it must endure for a certain minimum number of ticks (roughly one hundred; the figure is rather elastic). However, there is no upper limit. If by some extraordinary coincidence the universe inflated by only the minumum needed to explain our current observations, then the density after inflation could still be significantly above (or below) the critical value-in which case forthcoming observations should be able to determine the epoch of contraction, or that there will be no contraction. Much more likely is that inflation continued for many more ticks than the minimum, resulting in a density very close indeed to the critical value. This means that if the universe is going to contract it won't do so for an enormous length of time yet-very many times the present age of the universe. If that is the case, human beings will never know the fate of the universe they inhabit. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.80-81]

CHAPTER 7: FOREVER IS A LONG TIME

- The important thing about infinity is that it is not just a very big number. Infinity is qualitatively different from something that is merely stupendously, unimaginably huge. Suppose the universe were to continue expanding forever so that is has no end. For it to endure for all eternity means that it would have an infinite lifetime. If this were the case, any physical process, however slow or improbable, would have to happen sometime, just as a monkey forever tinkering on a typewriter would eventually type the works of William Shakespeare. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.83]
- The Hawking effect can be properly understood only with the help of the quantum theory of fields, a difficult branch of physics that I have already

alluded to in connection with the inflationary-universe theory. Recall that a central tenet of the quantum theory is Heisenberg's uncertainty principle, according to which quantum particles do not possess sharply defined values for all their attributes. For example, a photon or an electron cannot have a definite value for its energy at a specific moment of time. In effect, a subatomic particle can "borrow" energy, as long as it is paid back promptly. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.86]

- As I noted in chapter 3, energy uncertainty leads to some curious effects, such as the fleeting presence in apparently empty space of short-lived, or virtual, particles. This leads to the strange concept of the "quantum vacuum"- a vacuum that, far from being vacuous and inert, seethes with restless virtual-particle activity. Although this activity usually goes unnoticed, it can produce physical effects. One such effect occurs when the vacuum activity is disturbed by the presence of a gravitational field. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.86]
- An extreme case concerns the virtual particles that appear near the event horizon of a black hole. Recall that virtual particles live on borrowed energy for a very short time, after which the energy must be "paid back" and the particles obliged to disappear. If for any reason the virtual particles receive a big enough energy boost from some external source during their brief allotted time, the loan can be cleared on their behalf. There is then no longer any obligation for the particles to disappear to pay it off. The effect of this benefaction is therefore to promote the virtual particles to real particles, which are able to enjoy a more or less permanent existence. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.87]
- The distance a virtual particle may traverse depends on how long it lives, which in turn is dictated-via the Heisenberg uncertainty principle-by the size of the energy loan. The bigger the loan, the shorter the life of the particle. A major component of the energy loan is the particle's rest-mass energy. In the case of an electron, the loan has to be at least equal to the electron's rest-mass energy. For a particle with a larger rest mass-for

example, a proton-the loan would be bigger and hence briefer, so the distance traveled would be less. Therefore the production of protons by the Hawking effect requires a black hole even smaller than one of nuclear dimensions. Conversely, particles with a lower rest mass than electrons-for example, neutrinos-would be created by a black hole of greater than nuclear dimensions. Photons, which have zero rest mass, will be created by a black hole of any size. Even a black hole of one solar mass will have a Hawking flux of photons, and possibly neutrinos too; however, in such cases the intensity of the flux is very feeble. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.88]

- We can now paint a picture of what the universe would be like after all these incredibly slow processes have been completed. First, there will be the stuff left over from the big bang, the cosmic background that has been there all along. This consists of photons and neutrinos, and maybe some other completely stable particles we don't yet know about. The energy of these particles will go on declining as the universe expands, until they form a totally negligible background. The ordinary matter of the universe will have disappeared. All the black holes will have evaporated. Most of the mass of the black holes will have gone into photons, though some will also be in the form of neutrinos, and a very tiny fraction, emitted during the final explosive burst of the holes, will be in the form of electrons, protons, neutrons, and heavier particles. The heavier particles all rapidly decay, and the neutrons and protons decay more slowly, leaving a few electrons and positrons to join those others that are the last remaining residue of the ordinary matter we see today. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.98]
- The universe of the very far future would thus be an inconceivably dilute soup of photons, neutrinos, and a dwindling number of electrons and positrons, all slowly moving farther and farther apart. As far as we know, no further basic physical processes would ever happen. No significant event would occur to interrupt the bleak sterility of a universe that has run its course yet still faces eternallife-perhaps eternal death would be a better description. [Paul Davies, ***The Last Three Minutes: Conjectures About the***

Ultimate Fate of the Universe, BasicBooks, 1994, p.98-99]

- This dismal image of cold, dark, featureless near-noth- ingness is the closest that modern cosmology comes to the "heat death" of nineteenth-century physics. The time taken for the universe to degenerate to this state is so long that it defies human imagination. Yet it is but an infinitesimal portion of the infinite time available. As remarked, forever is a long time. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.99]
- Although the decay of the universe occupies a duration so vastly in excess of human time scales that it is virtually meaningless to us, people are still eager to ask, "What will happen to our descendants? Are they inevitably doomed by a universe that will slowly but inexorably shut down around them?" Given the rather unpromising state that science predicts for the universe of the far future, it seems that any form of life must ultimately be doomed. But death is not that simple. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.99]

CHAPTER 8: LIFE IN THE SLOW LANE

- In chapter 2, I noted that Bertrand Russell, in a fit of depression over the consequences of the second law of thermodynamics, wrote in anguished terms about the futility of human existence given the fact that the solar system is doomed. Russell clearly felt that the apparently inevitable demise of our habitat somehow rendered human life pointless or even farcical. This belief certainly contributed to his atheism. Would Russell have felt better had he known that black-hole gravitational energy could outperform the sun many times and last for trillions of years after the solar system had disintegrated? Probably not. It is not the actual duration of time that counts but the idea that sooner or later the universe will become uninhabitable; this idea makes some people feel that our existence is pointless. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.102-103]
- A characteristic feature of information processing is that it dissipates energy. This is the reason the word processor on which I am typing this book must be connected to the main electricity supply. The amount of energy

expended per bit of information depends on thermodynamic considerations. Dissipation is least when the processor operates at a temperature close to that of its environment. The human brain and most computers operate very inefficiently, and dissipate copious uantities of excess energy in the form of heat. The brain, for example, produces a sizable fraction of the body's heat, and many computers need a special cooling system to prevent them from melting. The origin of this waste heat can be traced to the very logic on which the information processing operates, which necessitates discarding information. For example, if a computer carries out the computation 1 + 2 = 3, then two bits of input information (1 and 2) are replaced by one bit of output information (3). Once the computation has been performed, the computer may discard the input information, thus replacing two bits by one. Indeed, to prevent its memory banks from clogging up, the machine has to discard such extraneous information all the time. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.108-109]

- The process of erasure is by definition irreversible, and therefore involves an increase in entropy. So it seems that on very basic grounds information gathering and processing will inevitably irreversibly deplete the available energy and raise the entropy of the universe. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.109]
- Freeman Dyson has contemplated the limitations faced by a community of sentient beings-who are restricted by the need to dissipate energy at a certain rate, if only in order to think-as the universe cools toward a heat death. The first constraint is that the beings must have a temperature higher than that of their environment, otherwise the waste heat would not flow out of them. Secondly, the laws of physics limit the rate at which a physical system can radiate energy into its environment. Obviously, the beings cannot operate for long if they produce waste heat faster than they can get rid of it. These requirements place a lower limit on the rate at which the beings inevitably dissipate energy. An essential requirement is that there must exist a source of free energy to fuel this vital heat outflow. Dyson concludes that all such sources are destined to dwindle in the far cosmic future, so that all sentient beings eventually face an energy crisis. [Paul

Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.109]

- As far as we can tell, the universe started out in a more or less featureless state. With time, the richness and variety of physical systems we see today has emerged. The history of the universe is therefore the history of the growth of organized complexity. This seems like a paradox. I began my account by describing how the second law of thermodynamics tells us that the universe is dying, sliding inexorably from an initial state of low entropy to a final state of maximum entropy and zero prospects. So are things getting better or getting worse? [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.116]
- There is actually no paradox, because organized complexity is different from entropy. Entropy, or disorder, is the negative of information, or order: the more information you process-that is, the more order you generate the greater the entropic price paid: order here gives rise to disorder somewhere else. Such is the second law; entropy always wins. But organization and complexity are not merely order and information. They refer to certain types of order and information. We recognize an important distinction between say, a bacterium and a crystal. Both are ordered, but in a different way. A crystal lattice represents regimented uniformity-starkly beautiful but essentially boring. By contrast, the elaborately arranged organization of a bacterium is richly interesting. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.116-117]

CHAPTER 9: LIFE IN THE FAST LANE

- The early stages of cosmological contraction are not in the least threatening. Like a ball reaching the top of its trajectory, the universe will start its inward fall very slowly. Let us suppose for the moment that the high point is reached in a hundred billion years' time: there will still be plenty of stars burning then, and our descendants will be able to follow the motions of galaxies with optical telescopes-watching as the galactic clusters gradually slow in their retreat and then begin falling back toward each other. The galaxies we see today will be about four times farther away at that time.

Because of the greater age of the universe, astronomers will be able to see about ten times as far as we can, so their observable universe will encompass many more galaxies than are visible to us at our cosmic epoch. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.119-120]

- The "big crunch," as far as we understand it, is not just the end of matter. It is the end of everything. Because time itself ceases at the big crunch, it is meaningless to ask what happens next, just as it is meaningless to ask what happened before the big bang. There is no "next" for any-thing at all to happen-no time even for inactivity nor space for emptiness. A universe that came from nothing in the big bang will disappear into nothing at the big crunch, its glorious few zillion years of existence not even a memory. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.123]
- **CHAPTER 10: SUDDEN DEATH-AND REBIRTH**
- As I have explained, when astronomers peer at the heavens, they do not see the universe in its present state, displayed like an instantaneous snapshot. Because of the time that light takes to reach us from distant regions, we see any given object in space as it was when the light was emitted. The telescope is also a timescope. The farther away the object is situated, the farther back in time will be the image we see today. In effect, the astronomer's universe is a backward slice through space and time, known technically as the "past light cone," and epicted in figure 10.1. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.127]
- According to the theory of relativity, no information or physical influence can travel faster than light. Therefore, the past light cone marks the limit not only of all knowledge about the universe but of all events that can possibly affect us at this moment. It follows that any physical influence coming at us at the speed of light comes entirely without warning. If catastrophe is heading our way up the past light cone, there will be no harbinger of doom. The first we will know about it will be when it hits us. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.127-128]

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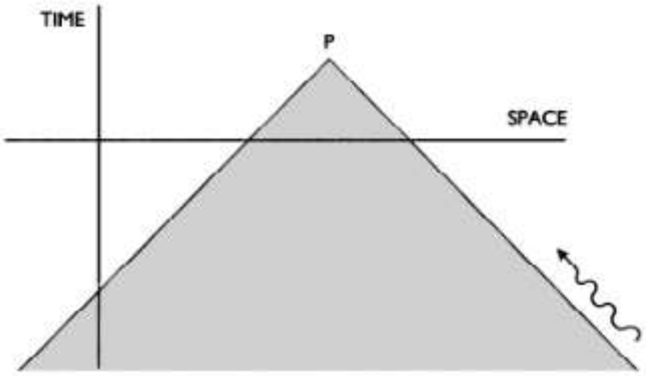

FIGURE 10.1

From a particular point *P* in space and time—which might be *here* and *now*, for example—an astronomer looking out into the universe actually sees the universe as it was in the past, not as it is now. The information arriving at *P* travels up along the "past light cone" through *P*, marked by the oblique lines. These are the paths of light signals converging on Earth from distant regions of the universe in the past. Because no information or physical influence can travel faster than light, the observer at the moment depicted can know only about influences or events happening in the shaded region. An apocalyptic event outside the past light cone might be sending disastrous influences (wavy line) racing toward Earth, but the observer would be blissfully unaware of this until the influences arrived.

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- To give a simple hypothetical example, if the sun were to blow up now, we would not be aware of the fact until about eight and a half minutes later,

this being the time it takes for light to reach us from the sun. Similarly, it is entirely possible that a nearby star has already blown up as a supernova-an event that might bathe Earth in deadly radiation-but that we shall remain in blissful ignorance of the fact for a few more years yet while the bad news - races across the galaxy at the speed of light. So although the universe may look quiet enough at the moment, we can't be sure that something really horrible hasn't already happened. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.128-129]

- But what about events of universe-wrecking proportions? Is it possible that a convulsion can occur that would destroy the entire cosmos at a stroke-in midlife, so to speak? Could a truly cosmic catastrophe already have been triggered, its unpleasant effects even now sweeping up our past light cone toward our fragile niche in space and time? [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.129]
- In 1980, the physicists Sidney Coleman and Frank De Luccia published a portentous paper with the innocuous title "Gravitational Effects on and of Vacuum Decay" in the journal Physical Review D. The vacuum to which they refer is not merely empty space but the vacuum state of quantum physics. In chapter 3, I explained that what appears to us as emptiness is in reality seething with ephemeral quantum activity, as ghostly virtual particles appear and disappear again in a random frolic. Recall that this vacuum state may not be unique; there could be several quantum states, all appearing empty but enjoying different levels of quantum activity and different associated energies. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.129]
- It is a well-established principle of quantum physics that higher-energy states tend to decay into lower-energy states. An atom, for example, may exist in a range of excited states, all of which are unstable, and will try to decay to the lowest energy, or "ground," state, which is stable. Similarly, an excited vacuum will try to decay to the lowest energy, or "true," vacuum. The inflationary-universe scenario is based on the theory that the very early

universe had an excited, or "false," vacuum state, during which time it inflated frenetically, but that in a very short time this state decayed to the true vacuum and inflation ceased. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.129-130]

- The usual assumption is that the present state of the universe corresponds to the true vacuum; that is, empty space at our epoch is the vacuum with the lowest possible energy. But can we be sure of that? Coleman and De Luccia consider the chilling possibility that the present vacuum may be not the true vacuum but merely a long-lived, metastable, false vacuum that has lulled us into a false sense of security because it has endured for a few billion years. We know of many quantum systems, such as uranium nuclei, that have half-lives of billions of years. Suppose the present vacuum falls into this category? The "decay" of the vacuum mentioned in the title of Coleman and De Luccia's paper refers to the catastrophic possibility that the present vacuum may suddenly fail and pitch the cosmos into an even lower energy state, with dire consequences for us (and all else besides). [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.130]
- The key to the Coleman and De Luccia hypothesis is the phenomenon of quantum tunneling. This can best be illustrated with the simple case of a quantum particle trapped by a barrier of force. Suppose the particle sits in a little valley bounded on either side by hills, as shown in figure 10.2. Of course, these don't have to be real hills; they could be electric or nuclear force fields, for example. In the absence of the energy needed to surmount the hills (or overcome the force barrier), the particle appears to be trapped forever. But recall that all quantum particles are subject to Heisenberg's uncertainty principle, which permits energy to be borrowed for small durations. This opens up an intriguing possibility. If the particle can borrow enough energy to reach the top of the hill and get across to the other side before having to pay the energy back, it can escape from the well. In effect, it will have "tunneled" through the barrier. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.130-131]

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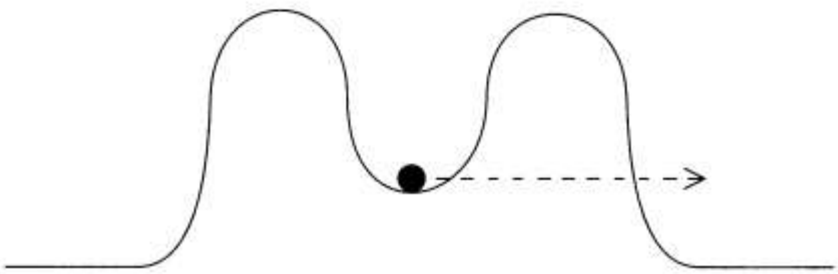

FIGURE 10.2

Tunnel effect. If a quantum particle is trapped in a valley between two hills, there is a small probability that it can escape by borrowing energy and hopping over the hill. In effect, it is observed to tunnel through the barrier. A familiar case occurs when alpha particles in the nuclei of certain elements tunnel through the nuclear force barrier and fly away, a phenomenon known as alpha radioactivity. In this example, the "hill" is due to nuclear and electric forces, and the picture drawn here is schematic only.

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- The probability for a quantum particle to tunnel out of a well like this depends very sensitively on both the height and the width of the barrier. The higher the barrier, the more energy the particle must borrow to reach the top, and so, according to the uncertainty principle, the shorter the duration of the loan must be. Hence high barriers can be tunneled through only if they are also thin, enabling the particle to traverse them quickly enough to repay the loan on time. For this reason, the tunnel effect is not noticed in daily life: macroscopic barriers are far too high and wide for significant tunneling to occur. In principle, a human being can walk

through a brick wall, but the quantum-tunneling probability for this miracle is exceedingly small. On an atomic scale, however, tunneling is very common; for example, it is the mechanism by which alpha radioactivity occurs. The tunnel effect is also exploited in semiconductors and other electronic devices, such as the scanning tunneling electron microscope. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.131-132]

- With regard to the problem of the possible decay of the present vacuum, Coleman and De Luccia speculate that the quantum fields making up the vacuum might be subject to a (metaphorical) landscape of forces like that shown in figure 10.3. The present vacuum state corresponds to the base of valley A. The true vacuum, however, corresponds to the base of valley B, which is lower than A. The vacuum would like to decay from the higher energy state A into the lower energy state B, but it is eterred from so doing by the "hill," or force field, that separates them. Although the hill impedes decay, it does not entirely prevent it, on account of the tunnel effect: the system can tunnel through from valley A to valley B. If this theory is correct, then the universe is living on orrowed time, hung up in valley A, but with an ever present chance that it will tunnel into valley B at some arbitrary moment. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.132-133]
- Coleman and De Luccia were able to model the decay of the vacuum mathematically-to trace the manner in which the phenomenon occurs. They found that decay will start at a random location in space, in the form of a tiny bubble of true vacuum surrounded by the unstable false vacuum. As soon as the bubble of true vacuum has formed, it will expand at a rate that rapidly approaches the speed of light, engulfing a larger and larger region of the false vacuum and instantaneously converting it into true vacuum. The energy difference between the two states-which might have the sort of enormous value I discussed in chapter 3-is concentrated in the bubble wall, which sweeps across the universe spelling destruction to everything in its path. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.133]
- The first we would know about the existence of a true-vacuum bubble would

be when the wall arrived and the quantum structure of our world suddenly changed. We wouldn't even have three minutes' warning. Instantaneously, the nature of all subatomic particles and their interactions would alter drastically; for example, protons might immediately decay, in which case all matter would abruptly evaporate. What was left would then find itself inside the bubble of true vacuum-a state of affairs very different from what we observe at the moment. The most significant difference concerns gravitation. Coleman and De Luccia found that the energy and pressure of the true vacuum would create a gravitational field so intense that the region embraced by the bubble would collapse, even as the bubble wall expands, in less than microseconds. No gentle fall toward a big crunch this time; instead, abrupt annihilation of everything, as the bubble interior implodes into a spacetime singularity. In short, instant crunch. "This is disheartening," remark the authors, in a masterful understatement, and they continue: The possibility that we are living in a false vacuum has never been a cheering one to contemplate. Vacuum decay is the ultimate ecological catastrophe; . . . after vacuum decay not only is life as we know it impossible, so is chemistry as we know it. However, one could always draw stoic comfort from the possibility that perhaps in the course of time the new vacuum would sustain, if not life as we know it, then at least some structures capable of knowing joy. This possibility has now been eliminated. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.133-134]

- The appalling consequences of vacuum decay became the subject of much discussion among physicists and astronomers following the publication of Coleman and De Luccia's paper. In a follow-up study published in the journal Nature, the cosmologist Michael Turner and the physicist Frank Wilczek arrived at an apocalyptic conclusion: "From the point of view of microphysics, then, it is quite conceivable that our vacuum is metastable. . . without warning a bubble of true vacuum could nucleate somewhere in the Universe and move outwards at the speed of light." [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.134]
- Shortly after the Turner and Wilczek paper appeared, Piet Hut and Martin Rees, also writing in Nature, raised the alarming specter that the formation

of a universe-destroying vacuum bubble might be inadvertently triggered by particle physicists themselves! The worry is that the very high-energy collision of subatomic particles might create conditions-just for an instant, in a very small region of space-which would encourage the vacuum to decay. Once the transition had occurred, even on a microscopic scale, there would be no stopping the newly formed bubble from rapidly ballooning to astronomical proportions. Should we place a ban on the next generation of particle accelerators? Hut and Rees gave welcome reassurance, pointing out that cosmic rays achieve higher energies than we can make inside our particle accelerators, and that these cosmic rays have been hitting nuclei in the Earth's atmosphere for billions of years without triggering vacuum decay. On the other hand, with an improvement by a factor of a few hundred or so in accelerator energies, we might be capable of creating collisions more energetic than any that have occurred from cosmicray impacts on Earth. The real issue, however, is not whether bubble formation could occur on Earth but whether it has occurred anywhere in the observable universe at any time since the big bang. Hut and Rees noted that on very rare occasions two cosmic rays will suffer a head-on collision, with energies a billion times higher than those possible in existing accelerators. So we don't need a regulatory authority yet. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.134-135]

- Paradoxically, vacuum-bubble formation-the same phenomenon that threatens the very existence of the cos-mos-could, in a slightly different context, prove to be its inhabitants' only feasible salvation. The one sure way to escape the death of the universe is to create a new one and escape into it. This may sound like the last word in fanciful speculation, but "baby universes" have been much discussed in recent years, and the argument for their existence has a serious side to it. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.135]
- The subject was originally raised by a group of Japanese physicists in 1981, who studied a simple mathematical model of the behavior of a small bubble of false vacuum surrounded by true vacuum-a situation the inverse of that just discussed. What was predicted is that the false vacuum would inflate in

the manner described in chapter 3, rapidly expanding into a large universe in a big bang. At first, it seems that the inflation of the false-vacuum bubble must cause the bubble wall to expand so that the region of false vacuum grows at the expense of the region of true vacuum. But this contradicts the expectation that it is the lower energy true vacuum that should displace the higher energy false vacuum and not the other way about. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.135-136]

- Oddly, viewed from the true vacuum, the region of space occupied by the bubble of false vacuum does not appear to inflate. In fact, it looks more like a black hole. (In this it resembles the Tardis, Dr. Who's time machine, which appears bigger on the inside than it does on the out-side.) A hypothetical observer situated inside the false-vacuum bubble would see the universe swell to enormous proportions, but, viewed from outside, the bubble remains compact. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.136]
- One way to envisage this peculiar state of affairs is by analogy with a rubber sheet that blisters up in one place and balloons out (see figure 10.4). The balloon forms a sort of baby universe connected to the mother universe by an umbilical cord, or "wormhole." The throat of the worm-hole appears, from the mother universe, as a black hole. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.136]
- This configuration is unstable; the black hole quickly evaporates by the Hawking effect, and disappears from the mother universe completely. As a result, the wormhole is pinched off, and the baby universe, now disconnected from the mother universe, becomes a new and independent universe in its own right. The development of the child universe following this budding-off from the mother is the same as it supposedly was for our universe: a brief period of inflation followed by the usual deceleration. The model carries the obvious implication that our own universe may have originated in this way-as the progeny of another universe. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the***

Universe, BasicBooks, 1994, p.136]

- None of these ideas amounts to much more than wild conjecture, but the subject of cosmology is still a very young science. The fanciful speculations considered above at least serve as an antidote to the gloomy prognoses developed in the earlier chapters. They hint at the possibility that even if our descendants must one day face the last three minutes, conscious beings of some sort may always exist somewhere. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.139]

CHAPTER II: WORLDS WITHOUT END?

- The appeal of the cyclic model is that it evades the specter of total annihilation, without replacing it by eternal degeneration and decay. To avoid the futility of endless repetition, the cycles should be somehow different from each other. In one popular version of the theory, each new cycle emerges phoenix like from the fiery death of its predecessor. From this pristine condition, it develops new systems and structures and explores its own rich novelty before the slate is wiped clean once more at the next big crunch. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.142]
- Attractive though the theory may seem, it unfortunately suffers from grave physical problems**.** One of these is identifying a plausible process that will allow the collapsing universe to bounce at some very high density rather than to annihilate itself in a big crunch. There has to be some sort of antigravitational force that becomes overwhelmingly large at the late stages of collapse in order to reverse the momentum of implosion and counter the formidable crushing power of gravity. No such force is known at present, and if it existed its properties would have to be very strange. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.142]
- Even supposing that such problems could be circumvented somehow, there remain serious difficulties with the cyclic-universe idea. One of these I discussed in chapter 2. Systems subject to irreversible processes that proceed at a finite rate will tend to approach their final state after a finite period of time. It was this principle that led to the prediction of universal

heat death in the nineteenth century. Introducing cosmic cycles does not circumvent the difficulty. The universe can be compared to a clock, slowly running down. Its activity will inevitably eventually cease unless it somehow gets rewound. But what mechanism could rewind the cosmic clock without itself being subject to irreversible change? [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.143]

- The upshot of all this is a net transfer of energy from matter to radiation. This has an important effect on the way the universe contracts, because the gravitational pull of radiation is quite different from that of matter of the same mass energy. Tolman showed that the extra radiation in the contracting phase causes the universe to collapse at a faster rate. If by some means a bounce were to occur, the universe would then emerge expanding at a faster rate too. In other words, each big bang would be bigger than the last. As a result, the universe would expand to a greater size with each new cycle, so the cycles would gradually get both bigger and longer. (See figure 11.2). [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.144-145]
- The irreversible growth of the cosmic cycles is no mystery. It is an example of the inescapable consequences of the second law of thermodynamics. The accumulating radiation represents a growth of entropy, which manifests itself gravitationally in the form of bigger and bigger cycles. It does, however, put an end to the idea of true cyclicity: the universe clearly evolves over time. Toward the past, the cycles cascade together into a complicated and messy beginning, while the future cycles expand without limit, until they become so long that any given cycle would be for the most part indistinguishable from the heat-death scenario of the ever-expanding models. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.145]
- Since the work of Tolman, cosmologists have been able to identify other physical processes that break the symmetry of the expanding and contracting phases of each cycle. One example is the formation of black holes. In the standard picture, the universe begins without any black holes, but as time goes on stars collapse and other processes FIGURE 11.2 -

Irreversible processes cause the cosmological cycles to grow and grow, thus destroying true cyclicity. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.145]

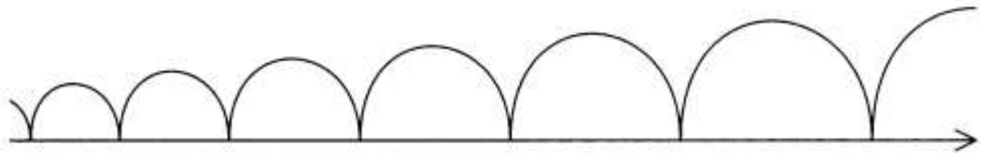

FIGURE 11.2

Irreversible processes cause the cosmological cycles to grow and grow, thus destroying true cyclicity.

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- cause black holes to form. As the galaxies evolve, more and more black holes appear. During the late stages of the collapse, the compression will encourage the formation of yet more holes. Some of the black holes may merge to form larger holes. The gravitational arrangement of the universe near the big crunch is therefore much more complicated-indeed, distinctly more holey-than it was near the big bang. If the universe were to bounce, the next cycle would begin with many more black holes than this one. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.146]
- The conclusion seems inescapable that any cyclic universe that allows physical structures and systems to propagate from one cycle to the next will not evade the degenerative influences of the second law of thermodynamics. There will still be a heat death. One way to sidestep this dismal conclusion is to suppose that the physical conditions at the bounce are so extreme that no information about earlier cycles can get through to the next. All preceding physical objects are destroyed, all influences annihilated. In effect, the universe is reborn entirely from scratch. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.146]
- It is hard to see, however, what attraction such a model holds. If each cycle is physically disconnected from the others, what meaning does it have to say that the cycles succeed each other, or represent the same universe somehow enduring? The cycles are effectively distinct separate universes,

and might just as well be said to exist in parallel rather than in sequence. The situation is reminiscent of the doctrine of reincarnation, whereby the reborn person has no memory of previous lives. In what sense can one say that the same person is reincarnated? [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.146]

- Another possibility is that the second law of thermodynamics is somehow violated, so that "the clock gets rewound" at the bounce. What does it mean for the damage caused by the second law to be undone? Let's take a simple example of the second law at work: the evaporation of perfume from a bottle, say. A reversal of fortunes for the perfume would entail a gigantic conspiracy of organization, in which every perfume molecule throughout the room was knocked back into the bottle. The "movie" would be played in reverse. It is from the second law of thermodynamics that we obtain the distinction between past and future-the arrow of time. A violation of the second law therefore amounts to a reversal of time. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.146-147]
- In the 1980s, Stephen Hawking also toyed with the idea of a time-reversing universe for a while, only to drop it with the admission that it was his "greatest mistake." Hawking at first believed that applying quantum mechanics to a cyclic universe required detailed time symmetry. It turns out, however, that this is not so-at least, in the standard formulation of quantum mechanics. Recently, the physicists Murray Gell-Mann and James Hartle have discussed a modification to the rules of quantum mechanics, in which the time symmetry is simply imposed, and then they have asked whether this state of affairs would have any observable consequences at our cosmic epoch. So far, it is not clear what the answer might be. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.147-148]
- A very different way of avoiding cosmic doom has been proposed by the Russian physicist Andrei Linde. It is based on an elaboration of the inflationary-universe theory discussed in chapter 3. In the original inflationary-universe scenario, it was supposed that the quantum state of the

very early universe corresponded to a particular excited vacuum that had the effect of temporarily driving runaway expansion. In 1983, Linde suggested that the quantum state of the early universe might instead vary from place to place in a chaotic manner: low energy here, moderately excited there, very excited in some regions. Where the state was excited, there inflation would occur. Furthermore, Linde's calculations of the behavior of the quantum state showed clearly that highly excited states inflate the fastest and decay the slowest, so that the more excited the state was in a particular region of space, the more the universe would inflate in that region. It is clear that after a very short time the regions of space where the energy was accidently greatest, and inflation fastest, would have swelled the most and would occupy the lion's share of the total space. Linde likens the situation to Darwinian evolution, or to economics. A successful quantum fluctuation to a very excited state, although it means borrowing a lot of energy, is immediately rewarded by a huge growth in the volume of that region. So the high-borrowing, superinflating regions soon come to predominate. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.148]

- As a result of chaotic inflation, the universe would become divided into a cluster of miniuniverses, or bubbles, some inflating like crazy, others not inflating at all. Because some regions-simply as a result of random fluctuations-will have a very large excitation energy, there will be much more inflation in those regions than was assumed in the original theory. But because these are precisely the regions to inflate the most, a point selected at random in the post-inflationary universe would be very likely located in such a highly inflated region. Thus our own location in space very probably lies deep within a superinflated region. Linde calculates that such "big bubbles" may have inflated by a factor of 10 to the power 10^8 which is 1 followed by a hundred million zeros! [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.148-149]
- Our own megadomain would be but one among an infinite number of highly inflated bubbles, so on an enormous scale of size the universe would still look extremely chaotic. Within our bubble-which extends beyond the currently observable universe by a stupendously large distance-matter and

energy are distributed approximately uniformly, but beyond our bubble lie other bubbles, as well as regions that are still in the process of inflating. In fact, inflation never ceases in Linde's model: there are always regions of space where inflation is taking place, where new bubbles are forming even as other bubbles pass through their life cycles and die. So this is a form of eternal universe, similar to the baby-universes theory discussed in the last chapter, where life, hope, and universes spring eternal. There is no end to the production of new bubble universes by inflation-and probably no beginning either, although there is currently some contention about that. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.149]

- Does the existence of other bubbles offer our descendants a lifeline? Can they avoid cosmic doom-or, more accurately, bubbledoom-by always transferring to another, younger bubble in the fullness of time? Linde addressed precisely this question in a heroic paper on "Life after Inflation," published in the journal Physics Letters in 1989. "These results imply that life in the inflationary universe will never disappear," he wrote. "Unfortunately, this conclusion does not automatically mean that one can be very optimistic about the future of mankind." Noting that any particular domain, or bubble, will slowly become uninhabitable, Linde concludes: "The only possible strategy of survival which we can see at the moment is to travel from old domains to the new ones." [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.149-150]
- The discouraging thing in Linde's version of the inflationary theory is that the size of a typical bubble is enormous. He computes that the nearest bubble beyond our own might be so far away that its distance in light-years must be expressed as 1 followed by several million zeros-a number so large it would need an entire encyclopedia of its own to be written out in full! Even at close to the speed of light, it would take a similar number of years to reach another bubble, unless by some extraordinarily good fortune we just happen to be situated near the edge of our bubble. And even this happy circumstance, Linde points out, would obtain only if our universe continues to expand in a predictable manner. The most minute physical effect-one that would be utterly inconspicuous at the pres ent epoch-could eventually

determine the way in which the universe expands once the matter and radiation that dominate it at present become infinitely diluted. For example, there could remain in the universe an exceedingly weak relic of the inflationary force that is at present completely'swamped by the gravitational effects of matter but which, given the oceans of time needed for beings to escape from our bubble, would eventually make itself felt. In that case, the universe would, after a long enough duration, begin to inflate once more-not in the frenetic manner of the big bang but exceedingly slowly, in a sort of pale imitation of the big bang. However, this feeble whimper, weak though it might be, would continue forever. Although the growth of the universe would accelerate only at a tiny rate, the fact that it accelerates at all has a crucial physical consequence. The effect is to create an event horizon within the bubble, which is rather like a black hole inside out and just as effective a trap. Any surviving beings would become helplessly entombed deep within our bubble, because as they sped toward the edge of the bubble the edge would recede even faster, as a result of the renewed inflation. Linde's calculation, although fanciful, nicely makes the point that the ultimate fate of humankind or our descendants may hinge on physical effects so small that we can have no real hope of detecting them before they start to manifest themselves cosmologically. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.150-151]

- Linde's cosmology is in some respects reminiscent of the old steady-state theory of the universe, which was popular in the fifties and early sixties and is still the simplest and most appealing proposal for avoiding the end of the universe. In its original version, expounded by Hermann Bondi and Thomas Gold, the steady-state theory assumed that the universe remains unchanged on a large scale for all time. It therefore has no beginning or end. As the universe expands, new matter is continuously created to fill the gaps and maintain an overall constant density. The fate of any given galaxy is similar to what I have described in the earlier chapters: birth, evolution, and death. But more galaxies are always forming, from the newly created material, which is supplied inexhaustibly. The general aspect of the universe as a whole therefore looks identical from one epoch to the next, with the same total number of galaxies in a given volume of space, consisting of a mixture of various ages. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.151]

- The concept of a steady-state universe does away with the need to explain how the universe came into existence from nothing in the first place, and it combines interesting variety through evolutionary change with cosmic immortality. In fact, it goes beyond this and provides eternal cosmic youth, because although individual galaxies slowly die, the universe as a whole never grows old. Our descendants never have to grub around scavenging for ever more elusive energy supplies, because the new matter provides it for free. The inhabitants just move on to a younger galaxy when the old one runs out of fuel. And this can continue ad infinitum, with the same level of vigor, diversity, and activity being maintained for all eternity. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.151-152]
- There are, however, some physical requirements needed to make the theory work. The universe doubles in volume every few billion years, due to the expansion. To maintain a constant density requires 10 50 tons or so of new matter to be created over that period. This seems a lot, but on average it amounts to the appearance of just one atom per century in a region of space the size of an aircraft hanger. It is unlikely that we would notice such a phenomenon. A more serious problem concerns the nature of the physical process responsible for creating matter in this theory. At the very least, we should want to know where the energy comes from that supplies the additional mass, and how this miraculous jar of energy manages to be inexhaustible. This problem was tackled by Fred Hoyle, who, with his collaborator Jayant Narlikar, developed the steady-state theory in great detail. They proposed a new type of field-a creation field-to supply the energy. The creation field itself was postulated to have negative energy. The appearance of each new particle of matter with mass m had the effect of contributing an energy -mc 2 to the creation field. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.152]
- Although the creation field provided a technical solution to the problem of creation, it left many questions unexplained. It also seemed rather ad hoc,

as no other manifestations of the mysterious field were apparent. More seriously, observational evidence began to mount against the steady-state theory in the 1960s, the most important of which was the discovery of the cosmic background heat radiation. This uniform background receives a ready interpretation as a relic of the big bang, but it is hard to explain convincingly in the steady-state model. In addition, deep-sky surveys of galaxies and radio galaxies showed unmistakable evidence that the universe is evolving on a large scale. When this became clear, Hoyle and his coworkers abandoned the simple version of the steadystate theory, although more complicated variants make fitful reappearances from time to time. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.152-153]

- Quite apart from physical and observational problems, the steady-state theory raises some curious philosophical difficulties. For example, if our descendants have truly infinite time and resources at their disposal, no obvious limits can be placed on their technological development. They would be free to spread across the universe, gaining control over ever greater volumes of space. Thus a large portion of the universe in the very far future would essentially be technologized. But by hypothesis the large-scale nature of the universe is supposed to be unchanging with time, so the steady-state assumption obliges us to conclude that the universe we see today is already technologized. Because the physical conditions in the steady-state universe are overall the same at all epochs, intelligent beings must arise at all epochs too. And because this state of affairs has existed for all eternity, there should be some communities of beings that have been around for an arbitrarily long time and will have expanded to occupy an arbitrarily large volume of space-including our region of the universe-technologizing it. This conclusion is not evaded by supposing that intelligent beings generally have no desire to colonize the universe. It takes only one such community to arise an arbitrarily long time ago for the conclusion to be valid. It is another case of the old conundrum that in an infinite universe anything that is even remotely possible must happen sometime, and happen infinitely often. Following the logic to its bitter conclusion, the steady-state theory predicts that the processes of the universe are identical to the technological activities of its inhabitants. What we call nature is, in fact, the activity of a superbeing, or a community of uperbeings. This seems like a version of Plato's demiurge (a deity who works within the bounds of physical laws already laid down), and it is interesting that Hoyle, in his later cosmological theories, explicitly advocates such a superbeing. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.153-154]

- If there is a purpose to the universe, and it achieves that purpose, then the universe must end, for its continued existence would be gratuitous and pointless. Conversely, if the universe endures forever, it is hard to imagine that there is any ultimate purpose to the universe at all. So cosmic death may be the price that has to be paid for cosmic success. Perhaps the most that we can hope for is that the purpose of the universe becomes known to our descendants before the end of the last three minutes. [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.155]
- [Paul Davies, ***The Last Three Minutes: Conjectures About the Ultimate Fate of the Universe***, BasicBooks, 1994, p.]

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