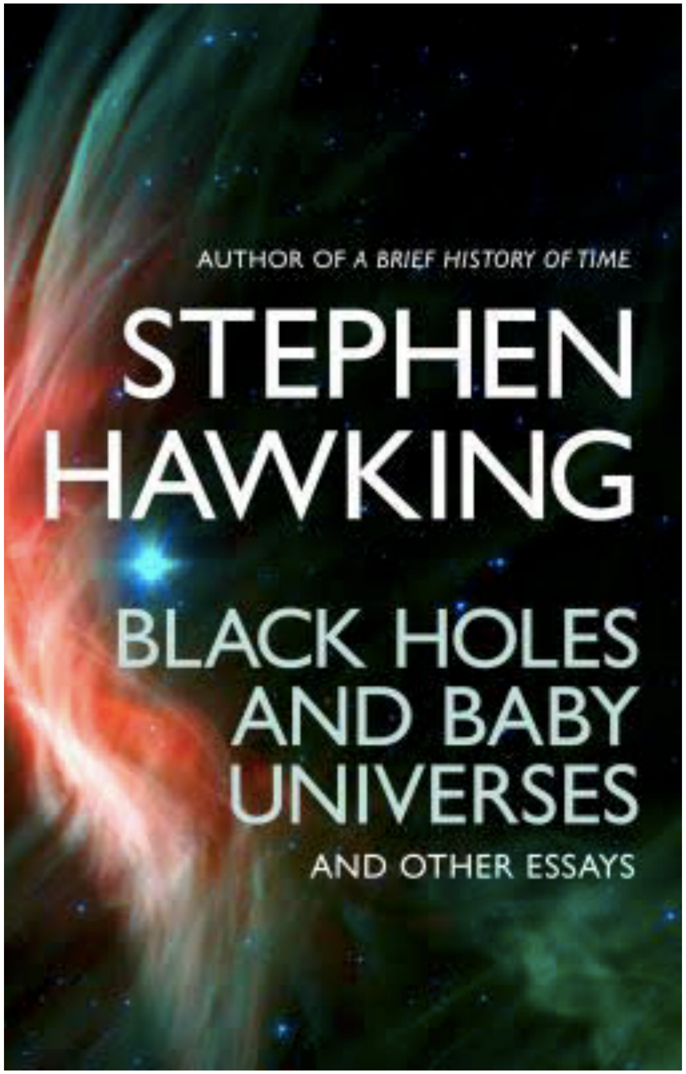

AUTHOR OF *A BRIEF HISTORY OF TIME*

STEPHEN HAWKING

BLACK HOLES AND BABY UNIVERSES

AND OTHER ESSAYS

Eleven

BLACK HOLES AND BABY UNIVERSES*

FALLING INTO A black hole has become one of the horrors of science fiction. In fact, black holes can now be said to be really matters of science fact rather than science fiction. As I shall describe, there are good reasons for predicting that black holes should exist, and the observational evidence points strongly to the presence of a number of black holes in our own galaxy and more in other galaxies.

Of course, where the science fiction writers really go to town is on what happens if you do fall in a black hole. A common suggestion is that if the black hole is rotating, you can fall

---

*Hitchcock lecture, given at the University of California, Berkeley, in April 1988.

through a little hole in space-time and out into another region of the universe. This obviously raises great possibilities for space travel. Indeed, we will need something like this if travel to other stars, let alone to other galaxies, is to be a practical proposition in the future. Otherwise, the fact that nothing can travel faster than light means that the round trip to the nearest star would take at least eight years. So much for a weekend break on Alpha Centauri! On the other hand, if one could pass through a black hole, one might reemerge anywhere in the universe. Quite how to choose your destination is not clear: You might set out for a holiday in Virgo and end up in the Crab Nebula.

I'm sorry to disappoint prospective galactic tourists, but this scenario doesn't work: If you jump into a black hole, you will get torn apart and crushed out of existence. However, there is a sense in which the particles that make up your body will carry on into another universe. I don't know if it would be much consolation to someone being made into spaghetti in a black hole to know that his particles might survive.

Despite the slightly flippant tone I have adopted, this essay is based on hard science. Most of what I say here is now agreed upon by other scientists working in this field, though this acceptance has come only fairly recently. The last part of the essay, however, is based on very recent work on which there is, as yet, no general consensus. But this work is arousing great interest and excitement.

Although the concept of what we now call a black hole goes back more than two hundred years, the name *black hole* was introduced only in 1967 by the American physicist John Wheeler. It was a stroke of genius: The name ensured that black holes entered the mythology of science fiction. It also stimulated scientific research by providing a definite name for something that previously had not had a satisfactory title.

The importance in science of a good name should not be underestimated.

As far as I know, the first person to discuss black holes was a Cambridge man called John Michell, who wrote a paper about them in 1783. His idea was this: Suppose you fire a cannonball vertically upward from the surface of the earth. As it goes up, it will be slowed down by the effect of gravity. Eventually, it will stop going up and will fall back to earth. If it started with more than a certain critical speed, however, it would never stop rising and fall back but would continue to move away. This critical speed is called the escape velocity. It is about seven miles a second for the earth, and about one hundred miles a second for the sun. Both of these velocities are greater than the speed of a real cannonball, but they are much smaller than the velocity of light, which is 186,000 miles a second. This means that gravity doesn't have much effect on light; light can escape without difficulty from the earth or the sun. However, Michell reasoned that it would be possible to have a star that was sufficiently massive and sufficiently small in size that its escape velocity would be greater than the velocity of light. We would not be able to see such a star because light from its surface would not reach us; it would be dragged back by the star's gravitational field. However, we might be able to detect the presence of the star by the effect that its gravitational field would have on nearby matter.

It is not really consistent to treat light like cannonballs. According to an experiment carried out in 1897, light always travels at the same constant velocity. How then can gravity slow down light? A consistent theory of how gravity affects light did not come until 1915, when Einstein formulated the general theory of relativity. Even so, the implications of this theory for old stars and other massive bodies were not generally realized until the 1960s.

According to general relativity, space and time together can be regarded as forming a four-dimensional space called spacetime. This space is not flat; it is distorted, or curved, by the matter and energy in it. We observe this curvature in the bending of the light or radio waves that travel near the sun on their way to us. In the case of light passing near the sun, the bending is very small. However, if the sun were to shrink until it was only a few miles across, the bending would be so great that light leaving the sun would not get away but would be dragged back by the sun's gravitational field. According to the theory of relativity, nothing can travel faster than the speed of light, so there would be a region from which it would be impossible for anything to escape. This region is called a black hole. Its boundary is called the event horizon. It is formed by the light that just fails to get away from the black hole but stays hovering on the edge.

It might sound ridiculous to suggest that the sun could shrink to being only a few miles across. One might think that matter could not be compressed that far. But it turns out that it can.

The sun is the size it is because it is so hot. It is burning hydrogen into helium, like a controlled H-bomb. The heat released in this process generates a pressure that enables the sun to resist the attraction of its own gravity, which is trying to make it smaller.

Eventually, however, the sun will run out of nuclear fuel. This will not happen for about another five billion years, so there's no great rush to book your flight to another star. However, stars more massive than the sun will burn up their fuel much more rapidly. When they finish their fuel, they will start to lose heat and contract. If they are less than about twice the mass of the sun, they will eventually stop contracting and will settle down to a stable state. One such state is called a white dwarf. These have radii of a few thousand miles and densities

of hundreds of tons per cubic inch. Another such state is a neutron star. These have a radius of about ten miles and densities of millions of tons per cubic inch.

We observe large numbers of white dwarfs in our immediate neighborhood in the galaxy. Neutron stars, however, were not observed until 1967, when Jocelyn Bell and Antony Hewish at Cambridge discovered objects called pulsars that were emitting regular pulses of radio waves. At first, they wondered whether they had made contact with an alien civilization; indeed, I remember that the seminar room in which they announced their discovery was decorated with figures of "little green men." In the end, however, they and everyone else came to the less romantic conclusion that these objects were rotating neutron stars. This was bad news for writers of space Westerns but good news for the small number of us who believed in black holes at that time. If stars could shrink to as small as ten or twenty miles across to become neutron stars, one might expect that other stars could shrink even further to become black holes.

A star with a mass more than about twice that of the sun cannot settle down as a white dwarf or neutron star. In some cases, the star may explode and throw off enough matter to bring its mass below the limit. But this won't happen in all cases. Some stars will become so small that their gravitational fields will bend light to that point that it comes back toward the star. No further light, or anything else, will be able to escape. The stars will have become black holes.

The laws of physics are time-symmetric. So if there are objects called black holes into which things can fall but not get out, there ought to be other objects that things can come out of but not fall into. One could call these white holes. One might speculate that one could jump into a black hole in one place and come out of a white hole in another. This would be the ideal method of long-distance space travel mentioned earlier. All you would need would be to find a nearby black hole.

At first, this form of space travel seemed possible. There are solutions of Einstein's general theory of relativity in which it is possible to fall into a black hole and come out of a white hole. Later work, however, shows that these solutions are all very unstable: the slightest disturbance, such as the presence of a spaceship, would destroy the "wormhole," or passage, leading from the black hole to the white hole. The spaceship would be torn apart by infinitely strong forces. It would be like going over Niagara in a barrel.

After that, it seemed hopeless. Black holes might be useful for getting rid of garbage or even some of one's friends. But they were "a country from which no traveler returns." Everything I have been saying so far, however, has been based on calculations using Einstein's general theory of relativity. This theory is in excellent agreement with all the observations we have made. But we know it cannot be quite right because it doesn't incorporate the uncertainty principle of quantum mechanics. The uncertainty principle says that particles cannot have both a well-defined position and a well-defined velocity. The more precisely you measure the position of a particle, the less precisely you can measure its velocity, and vice versa.

In 1973 I started investigating what difference the uncertainty principle would make to black holes. To my great surprise and that of everyone else, I found that it meant that black holes are not completely black. They would be sending out radiation and particles at a steady rate. My results were received with general disbelief when I announced them at a conference near Oxford. The chairman of the session said they were nonsense, and he wrote a paper saying so. However, when other people repeated my calculation, they found the same effect. So in the end, even the chairman agreed I was right.

How can radiation escape from the gravitational field of a black hole? There are a number of ways one can understand how. Although they seem very different, they are really all equivalent. One way is to realize that the uncertainty principle allows particles to travel faster than light for a short distance. This enables particles and radiation to get out through the event horizon and escape from the black hole. Thus, it is possible for things to get out of a black hole. What comes out of a black hole, however, will be different from what fell in. Only the energy will be the same.

As a black hole gives off particles and radiation, it will lose mass. This will cause the black hole to get smaller and to send out particles more rapidly. Eventually, it will get down to zero mass and will disappear completely. What will happen then to the objects, including possible spaceships, that have fallen into the black hole? According to some recent work of mine, the answer is that they will go off into a little baby universe of their own. A small, self-contained universe branches off from our region of the universe. This baby universe may join on again to our region of space-time. If it does, it would appear to us to be another black hole that formed and then evaporated. Particles that fell into one black hole would appear as particles emitted by the other black hole, and vice versa.

This sounds like just what is required to allow space travel through black holes. You just steer your spaceship into a suitable black hole. It had better be a pretty big one, though, or the gravitational forces will tear you into spaghetti before you get inside. You would then hope to reappear out of some other hole, though you wouldn't be able to choose where.

However, there's a snag in this intergalactic transportation scheme. The baby universes that take the particles that fell into the hole occur in what is called imaginary time. In real time, an astronaut who fell into a black hole would come to a sticky end. He would be torn apart by the difference between the gravitational force on his head and his feet. Even the particles that made up his body would not survive. Their histories, in real time, would come to an end at a singularity. But the histories of the particles in imaginary time would continue. They would pass into the baby universe and would reemerge as the particles emitted by another black hole. Thus, in a sense, the astronaut would be transported to another region of the universe. However, the particles that emerged would not look much like the astronaut. Nor might it be much consolation to him, as he ran into the singularity in real time, to know that his particles will survive in imaginary time. The motto for anyone who falls into a black hole must be: "Think imaginary."

What determines where the particles reemerge? The number of particles in the baby universe will be equal to the number of particles that have fallen into the black hole, plus the number of particles that the black hole emits during its evaporation. This means that the particles that fall into one black hole will come out of another hole of about the same mass. Thus, one might try to select where the particles would come out by creating a black hole of the same mass as that into which the particles went down. However, the black hole would be equally likely to give off any other set of particles with the same total energy. Even if the black hole did emit the right kinds of particles, one could not tell if they were actually the same particles that had gone down the other hole. Particles do not carry identity cards; all particles of a given kind look alike.

What all this means is that going through a black hole is unlikely to prove a popular and reliable method of space travel. First of all, you would have to get there by traveling in imaginary time and not care that your history in real time came to a sticky end. Second, you couldn't really choose your destination. It would be like traveling on some airlines I could name.

Although baby universes may not be of much use for space travel, they have important implications for our attempt to find a complete unified theory that will describe everything in the universe. Our present theories contain a number of quantities, like the size of the electric charge on a particle. The values of these quantities cannot be predicted by our theories. Instead, they have to be chosen to agree with observations. Most scientists believe, however, that there is some underlying unified theory that will predict the values of all these quantities.

There may well be such an underlying theory. The strongest candidate at the moment is called the heterotic superstring. The idea is that space-time is filled with little loops, like pieces of string. What we think of as elementary particles are really these little loops vibrating in different ways. This theory does not contain any numbers whose values can be adjusted. One would therefore expect that this unified theory should be able to predict all the values of quantities, like the electric charge on a particle, that are left undetermined by our present theories. Even though we have not yet been able to predict any of these quantities from superstring theory, many people believe that we will be able to do so eventually.

However, if this picture of baby universes is correct, our ability to predict these quantities will be reduced. This is because we cannot observe how many baby universes exist out there, waiting to join onto our region of the universe. There can be baby universes that contain only a few particles. These baby universes are so small that one would not notice them joining on or branching off. By joining on, however, they will alter the apparent values of quantities, such as the electric charge on a particle. Thus, we will not be able to predict what the apparent values of these quantities will be because we don't know how many baby universes are waiting out there. There could be a population explosion of baby universes. Unlike the human case, however, there seem to be no limiting factors such as food supply or standing room. Baby universes exist in a realm of their own. It is a bit like asking how many angels can dance on the head of a pin.

For most quantities, baby universes seem to introduce a definite, although fairly small, amount of uncertainty in the predicted values. However, they may provide an explanation of the observed value of one very important quantity: the so-called cosmological constant. This is a term in the equations of general relativity that gives space-time an inbuilt tendency to expand or contract. Einstein originally proposed a very small cosmological constant in the hope of balancing the tendency of matter to make the universe contract. That motivation disappeared when it was discovered that the universe is expanding. But it was not so easy to get rid of the cosmological constant. One might expect the fluctuations that are implied by quantum mechanics to give a cosmological constant that is very large. Yet we can observe how the expansion of the universe is varying with time and thus determine that the cosmological constant is very small. Up to now, there has been no good explanation for why the observed value should be so small. However, baby universes branching off and joining on will affect the apparent value of the cosmological constant. Because we don't know how many baby universes there are, there will be different possible values for the apparent cosmological constant. A nearly zero value, however, will be by far the most probable. This is fortunate because it is only if the value of the cosmological constant is very small that the universe would be suitable for beings like us.

To sum up: It seems that particles can fall into black holes that then evaporate and disappear from our region of the universe. The particles go off into baby universes that branch off from our universe. These baby universes can then join back on

somewhere else. They may not be much good for space travel, but their presence means that we will be able to predict less than we expected, even if we do find a complete unified theory. On the other hand, we now may be able to provide explanations for the measured values of some quantities like the cosmological constant. In the last few years, a lot of people have begun working on baby universes. I don't think anyone will make a fortune by patenting them as a method of space travel, but they have become a very exciting area of research.

Thirteen

THE FUTURE OF THE UNIVERSE*

THE SUBJECT OF this essay is the future of the universe, or rather, what scientists think the future will be. Of course, predicting the future is very difficult. I once thought I should write a book called *Yesterday's Tomorrow: A History of the Future*. It would have been a history of predictions of the future, nearly all of which have fallen very wide of the mark. But despite these failures, scientists still think that they can predict the future.

In earlier times foretelling the future was the job of oracles or sibyls. These were often women, who would be put into a

---

*Darwin lecture given at the University of Cambridge in January 1991.

trance by some drug or by breathing the fumes from a volcanic vent. Their ravings would then be interpreted by the surrounding priests. The real skill lay in the interpretation. The famous oracle at Delphi, in ancient Greece, was notorious for hedging its bets or being ambiguous. When the Spartans asked what would happen when the Persians attacked Greece, the oracle replied: Either Sparta will be destroyed, or its king will be killed. I suppose the priests reckoned that if neither of these eventualities happened, the Spartans would be so grateful to Apollo that they would overlook the fact that his oracle had been wrong. In fact, the king was killed defending the pass at Thermopylae in an action that saved Sparta and led to the ultimate defeat of the Persians.

On another occasion, Croesus, King of Lydia, the richest man in the world, asked what would happen if he invaded Persia. The answer was: A great kingdom will fall. Croesus thought this meant the Persian Empire, but it was his own kingdom that fell, and he himself ended up on a pyre, about to be burned alive.

Recent prophets of doom have been more ready to stick their necks out by setting definite dates for the end of the world. These have even tended to depress the stock market, though it beats me why the end of the world should make one want to sell shares for money. Presumably, you can't take either with you.

Thus far, all of the dates set for the end of the world have passed without incident. But the prophets have often had an explanation for their apparent failures. For example, William Miller, the founder of the Seventh-Day Adventists, predicted that the Second Coming would occur between March 21, 1843, and March 21, 1844. When nothing happened, the date was revised to October 22, 1844. When that passed without incident, a new interpretation was put forward. According to this, 1844

was the start of the Second Coming—but first, the names in the Book of Life had to be counted. Only then would the Day of Judgment come for those not in the Book. Fortunately, the counting seems to be taking a long time.

Of course, scientific predictions may not be any more reliable than those of oracles or prophets. One has only to think of weather forecasts. But there are certain situations in which we think that we can make reliable predictions, and the future of the universe, on a very large scale, is one of them.

Over the last three hundred years, we have discovered the scientific laws that govern matter in all normal situations. We still don't know the exact laws that govern matter under very extreme conditions. Those laws are important for understanding how the universe began, but they do not affect the future evolution of the universe, unless and until the universe recollapses to a high-density state. In fact, it is a measure of how little these high-energy laws affect the universe now that we have to spend large amounts of money to build giant particle accelerators to test them.

Even though we may know the relevant laws that govern the universe, we may not be able to use them to predict far into the future. This is because the solutions to the equations of physics may exhibit a property known as chaos. What this means is that the equations may be unstable: Make a slight change to the way a system is by a small amount at one time, and the later behavior of the system may soon become completely different. For example, if you slightly change the way you spin a roulette wheel, you will change the number that comes up. It is practically impossible to predict the number that will come up; otherwise, physicists would be making a fortune at the casinos.

With unstable and chaotic systems, there is generally a time scale on which a small change in an initial state will grow into a change that is twice as big. In the case of the earth's atmosphere, this time scale is of the order of five days, about the time it takes for air to blow right around the world. One can make reasonably accurate weather forecasts for periods up to five days, but to predict the weather much further ahead would require both a very accurate knowledge of the present state of the atmosphere *and* an impossibly complicated calculation. There is no way that we can predict the weather six months ahead, beyond giving the seasonal average.

We also know the basic laws that govern chemistry and biology, so in principle we ought to be able to determine how the brain works. But the equations that govern the brain almost certainly have chaotic behavior, in that a very small change in the initial state can lead to a very different outcome. Thus, in practice we cannot predict human behavior, even though we know the equations that govern it. Science cannot predict the future of human society or even if it has any future. The danger is that our power to damage or destroy the environment or one another is increasing much more rapidly than our wisdom in using this power.

Whatever happens on earth, the rest of the universe will carry on regardless. It seems that the motion of the planets around the sun is ultimately chaotic, though with a long time scale. This means that the errors in any prediction get bigger as time goes on. After a certain time, it becomes impossible to predict the motion in detail. We can be fairly sure that the earth will not have a close encounter with Venus for quite a long time, but we cannot be certain that small perturbations in the orbits could not add up to cause such an encounter a billion years from now. The motion of the sun and other stars around the galaxy, and of the galaxy in the local group of galaxies, is also chaotic.

We observe that other galaxies are moving away from us, and the farther they are from us, the faster they are moving away. This means that the universe is expanding in our neighborhood: The distances between different galaxies are increasing with time.

Evidence that this expansion is smooth and not chaotic is given by a background of microwave radiation that we observe coming from outer space. You can actually observe this radiation yourself by tuning your television to an empty channel. A small percent of the flecks you see on the screen are due to microwaves from beyond the solar system. It is the same kind of radiation that you get in a microwave oven, but very much weaker. It would only raise food to 2.7 degrees above absolute zero, so it is not much good for warming up your take-away pizza. This radiation is thought to be left over from a hot early stage of the universe. But the most remarkable thing about it is that the amount of radiation seems to be very nearly the same from every direction. This radiation has been measured very accurately by the Cosmic Background Explorer satellite. A map of the sky made from these observations would show different temperatures of radiation. These temperatures are different in different directions, but the variations are very small, only one part in a hundred thousand. There have to be some differences in the microwaves from different directions because the universe is not completely smooth; there are local irregularities like stars, galaxies, and clusters of galaxies. But the variations in the microwave background are as small as they possibly can be, compatible with the local irregularities that we observe. To 99,999 parts out of 100,000, the microwave background is the same in every direction.

In ancient times, people believed that the earth was at the center of the universe. They would therefore not have been surprised that the background was the same in every direction.

Since the time of Copernicus, however, we have been demoted to a minor planet going around a very average star in the outer edge of a typical galaxy that is only one of a hundred billion galaxies we can see. We are now so modest that we cannot claim any special position in the universe. We must therefore assume that the background is also the same in any direction about any other galaxy. This is possible only if the average density of the universe and the rate of expansion are the same everywhere. Any variation in the average density, or the rate of expansion, over a large region would cause the microwave background to be different in different directions. This means that on a very large scale, the behavior of the universe is simple and is not chaotic. It can therefore be predicted far into the future.

Because the expansion of the universe is so uniform, one can describe it in terms of a single number, the distance between two galaxies. This is increasing at the present time, but one would expect the gravitational attraction between different galaxies to be slowing down the rate of expansion. If the density of the universe is greater than a certain critical value, gravitational attraction will eventually stop the expansion and make the universe start to contract again. The universe would collapse to a big crunch. This would be rather like the big bang that began the universe. The big crunch would be what is called a singularity, a state of infinite density at which the laws of physics would break down. This means that even if there were events after the big crunch, what happened at them could not be predicted. But without a causal connection between events, there is no meaningful way that one can say that one event happened after another. One might as well say that our universe came to an end at the big crunch and that any events that occurred "after" were part of another, separate

universe. It is a bit like reincarnation. What meaning can one give to the claim that a new baby is the same as someone who died if the baby doesn't inherit any characteristics or memories from its previous life? One might as well say that it is a different individual.

If the average density of the universe is less than the critical value, it will not recollapse but will continue to expand forever. After a certain time the density will become so low that gravitational attraction will not have any significant effect on slowing down the expansion. The galaxies will continue to move apart at a constant speed.

So the crucial question for the future of the universe is: What is the average density? If it is less than the critical value, the universe will expand forever. But if it is greater, the universe will recollapse and time itself will come to an end at the big crunch. I do, however, have certain advantages over other prophets of doom. Even if the universe is going to recollapse, I can confidently predict that it will not stop expanding for at least ten billion years. I don't expect to be around to be proved wrong.

We can try to estimate the average density of the universe from observations. If we count the stars that we can see and add up their masses, we get less than one percent of the critical density. Even if we add in the masses of the clouds of gas that we observe in the universe, it still brings the total up to only about one percent of the critical value. However, we know that the universe must also contain what is called dark matter, which we cannot observe directly. One piece of evidence for this dark matter comes from spiral galaxies. These are enormous pancake-shaped collections of stars and gas. We observe that they are rotating about their centers, but the rate of rotation is sufficiently high that they would fly apart if they contained only the stars and gas that we observe. There must be some unseen form of matter whose gravitational attraction is great enough to hold the galaxies together as they rotate.

Another piece of evidence for dark matter comes from clusters of galaxies. We observe that galaxies are not uniformly distributed throughout space; they are gathered together in clusters that range from a few galaxies to millions. Presumably, these clusters are formed because the galaxies attract each other into groups. However, we can measure the speeds at which individual galaxies are moving in these clusters. We find they are so high that the clusters would fly apart unless they were held together by gravitational attraction. The mass required is considerably greater than the masses of all the galaxies. This is the case even if we take the galaxies to have the masses required to hold themselves together as they rotate. It follows, therefore, that there must be extra dark matter present in clusters of galaxies outside the galaxies that we see.

One can make a fairly reliable estimate of the amount of dark matter in those galaxies and clusters for which we have definite evidence. But this estimate is still only about ten percent of the critical density needed to cause the universe to collapse again. Thus, if one just went by the observational evidence, one would predict that the universe would continue to expand forever. After another five billion years or so, the sun would reach the end of its nuclear fuel. It would swell up into what is called a red giant until it swallowed up the earth and the other nearer planets. It would then settle down to be a white dwarf star a few thousand miles across. So I am predicting the end of the world, but not just yet. I don't think this prediction will depress the stock market too much. There are one or two more immediate problems on the horizon. In any event, by the time the sun blows up, we should have mastered the art of interstellar travel, provided we have not already destroyed ourselves.

After ten billion years or so, most of the stars in the universe will have burned out. Stars with masses like that of the sun will become either white dwarfs or neutron stars, which are even smaller and denser than white dwarfs. More massive stars can become black holes, which are still smaller and have a strong gravitational field that no light can escape. However, these remnants will still continue to go around the center of our galaxy about once every hundred million years. Close encounters between the remnants will cause a few to be flung right out of the galaxy. The remainder will settle down to closer orbits about the center and will eventually collect together to form a giant black hole at the center of the galaxy. Whatever the dark matter in galaxies and clusters is, it might also be expected to fall into these very large black holes.

It could be assumed, therefore, that most of the matter in galaxies and clusters would eventually end up in black holes. However, some time ago I discovered that black holes aren't as black as they have been painted. The uncertainty principle of quantum mechanics says that particles cannot have both a well-defined position and a well-defined speed. The more accurately the position of the particle is defined, the less accurately its speed can be defined, and vice versa. If a particle is in a black hole, its position is well-defined to be within the black hole. This means that its speed cannot be exactly defined. It is therefore possible for the speed of the particle to be greater than the speed of light. This would enable it to escape from the black hole. Particles and radiation will thus slowly leak out of a black hole. A giant black hole at the center of a galaxy would be millions of miles across. Thus, there would be a large uncertainty in the position of a particle inside it. The uncertainty in the particle's speed would therefore be small, which means that it would take a very long time for a particle to escape from the black hole. But it would eventually. A large black hole at the center of a galaxy could take 10^{90} years to evaporate away and disappear completely; that is, a one followed by ninety zeroes. This is far longer than the present age of the universe, which is a mere 10^{10} years; a one followed by ten zeroes. Still, there will be plenty of time, if the universe is going to expand forever.

The future of a universe that expanded forever would be rather boring. But it is by no means certain that the universe will expand forever. We have definite evidence only for about one-tenth of the density needed to cause the universe to recollapse. Still, there might be further kinds of dark matter that we have not detected that could raise the average density of the universe to the critical value or above it. This additional dark matter would have to be located outside galaxies and clusters of galaxies. Otherwise, we would have noticed its effect on the rotation of galaxies or the motions of galaxies in clusters.

Why should we think there might be enough dark matter to make the universe recollapse eventually? Why don't we just believe in the matter for which we have definite evidence? The reason is that having even a tenth of the critical density now requires an incredibly careful choice of the initial density and rate of expansion. If the density of the universe one second after the big bang had been greater by one part in a thousand billion, the universe would have recollapsed after ten years. On the other hand, if the density of the universe at that time had been less by the same amount, the universe would have been essentially empty since it was about ten years old.

How is it that the initial density of the universe was chosen so carefully? Maybe there is some reason that the universe should have precisely the critical density. There seem to be two

possible explanations. One is the so-called anthropic principle, which can be paraphrased as: The universe is as it is because if it were different, we wouldn't be here to observe it. The idea is that there could be many different universes with different densities. Only those that are very close to the critical density would last for long enough and contain enough matter for stars and planets to form. Only in those universes will there be intelligent beings to ask the question: Why is the density so close to the critical density? If this is the explanation of the present density of the universe, there is no reason to believe that the universe contains more matter than we have already detected. A tenth of the critical density would be enough matter for galaxies and stars to form.

Many people do not like the anthropic principle, however, because it seems to attach too much importance to our own existence. There thus has been a search for another possible explanation of why the density should be so close to the critical value. This search has led to the theory of inflation in the early universe. The idea is that the size of the universe may have kept doubling, in the same way that prices double every few months in countries undergoing extreme inflation. However, the inflation of the universe would have been much more rapid and more extreme: an increase by a factor of at least a billion billion billion, in a tiny inflation, would have caused the universe to have so nearly the exact critical density that it would still be very near the critical density now. Thus, if the theory of inflation is correct, the universe must contain enough dark matter to bring the density up to the critical density. This means that the universe would probably recollapse eventually but not for much longer than the fifteen billion years or so that it has already been expanding.

What could the extra dark matter be that must be there if the theory of inflation is correct? It seems that it is probably different from normal matter, the kind that makes up stars and planets. We can calculate the amounts of various light elements that would have been produced in the hot early stages of the universe in the first three minutes after the big bang. The amounts of these light elements depend on the amount of normal matter in the universe. One can draw a graph showing the amount of light elements vertically and the amount of normal matter in the universe along the horizontal axis. One gets good agreement with the observed abundances if the total amount of normal matter is only about one-tenth of the critical amount now. It could be that these calculations are wrong, but the fact that we get the observed abundances for several different elements is quite impressive.

If there is a critical density of dark matter, the main candidates for what it might be would be remnants left over from the early stages of the universe. One possibility is elementary particles. There are several hypothetical candidates, particles we think might exist but that we have not actually detected yet. But the most promising case is a particle for which we have good evidence, the neutrino. This was thought to have no mass of its own, but some recent observations have suggested that the neutrino may have a small mass. If this is confirmed and found to be of the right value, neutrinos would provide enough mass to bring the density of the universe up to the critical value.

Another possibility is black holes. It is possible that the early universe underwent what is called a phase transition. The boiling and freezing of water are examples of phase transitions. In a phase transition an initially uniform medium, like water, develops irregularities, which in the case of water can be lumps of ice or bubbles of steam. These irregularities might collapse to form black holes. If the black holes were very small, they would have evaporated by now because of the effects of the quantum mechanical uncertainty principle, as described earlier. But if they were over a few billion tons (the mass of a mountain), they would still be around today and would be very difficult to detect.

The only way we could detect dark matter that was uniformly distributed throughout the universe would be by its effect on the expansion of the universe. One can determine how fast the expansion is slowing down by measuring the speed at which distant galaxies are moving away from us. The point is that we are observing these galaxies in the distant past, when light left them on its journey to us. One can plot a graph of the speed of the galaxies against their apparent brightness or magnitude, which is a measure of their distance from us. Different lines on this graph correspond to different rates of slowing of the expansion. A graph that bends up corresponds to a universe that will recollapse. At first sight the observations seem to indicate recollapse. But the trouble is, the apparent brightness of a galaxy is not a very good indication of its distance from us. Not only is there considerable variation in the intrinsic brightness of galaxies, but there is also evidence that their brightness is varying with time. Since we do not know how much to allow for the evolution of brightness, we can't yet say what the rate of slowing down is: whether it is fast enough for the universe to recollapse eventually, or whether it will continue to expand forever. That will have to wait until we develop better ways of measuring the distances of galaxies. But we can be sure that the rate of slowing down is not so rapid that the universe will collapse in the next few billion years.

Neither expanding forever nor recollapsing in a hundred billion years or so is a very exciting prospect. Isn't there something we can do to make the future more interesting? One way that would certainly do that would be to steer ourselves into a black hole. It would have to be a fairly big black hole, more than a million times the mass of the sun. But there is a good chance there's a black hole that big at the center of our galaxy.

We are not quite sure what happens inside a black hole. There are solutions of the equations of general relativity that would allow one to fall into a black hole and come out of a white hole somewhere else. A white hole is the time reverse of a black hole. It is an object that things can come out of but nothing can fall into. The white hole could be in another part of the universe. This would seem to offer the possibility of rapid intergalactic travel. The trouble is it might be too rapid. If travel through black holes were possible, there would seem nothing to prevent you from arriving back before you set off. You could then do something, like kill your mother, that would have prevented you from going in the first place.

Perhaps fortunately for our survival (and that of our mothers), it seems that the laws of physics do not allow such time travel. There seems to be a Chronology Protection Agency that makes the world safe for historians by preventing travel into the past. What seems to happen is that the effects of the uncertainty principle would cause there to be a large amount of radiation if one traveled into the past. This radiation would either warp space-time so much that it would not be possible to go back in time, or it would cause space-time to come to an end in a singularity like the big bang and the big crunch. Either way, our past would be safe from evil-minded persons. The Chronology Protection Hypothesis is supported by some recent calculations that I and other people have done. But the best evidence we have that time travel is not possible, and never will be, is that we have not been invaded by hordes of tourists from the future.

To sum up: Scientists believe that the universe is governed by well-defined laws that in principle allow one to predict the future. But the motion given by the laws is often chaotic. This

means that a tiny change in the initial situation can lead to change in the subsequent behavior that rapidly grows large. Thus, in practice, one can often predict accurately only a fairly short time into the future. However, the behavior of the universe on a very large scale seems to be simple, and not chaotic. One can therefore predict whether the universe will expand forever or whether it will recollapse eventually. This depends on the present density of the universe. In fact, the present density seems to be very close to the critical density that separates recollapse from indefinite expansion. If the theory of inflation is correct, the universe is actually on the knife edge. So I am in the well-established tradition of oracles and prophets of hedging my bets by predicting both ways.