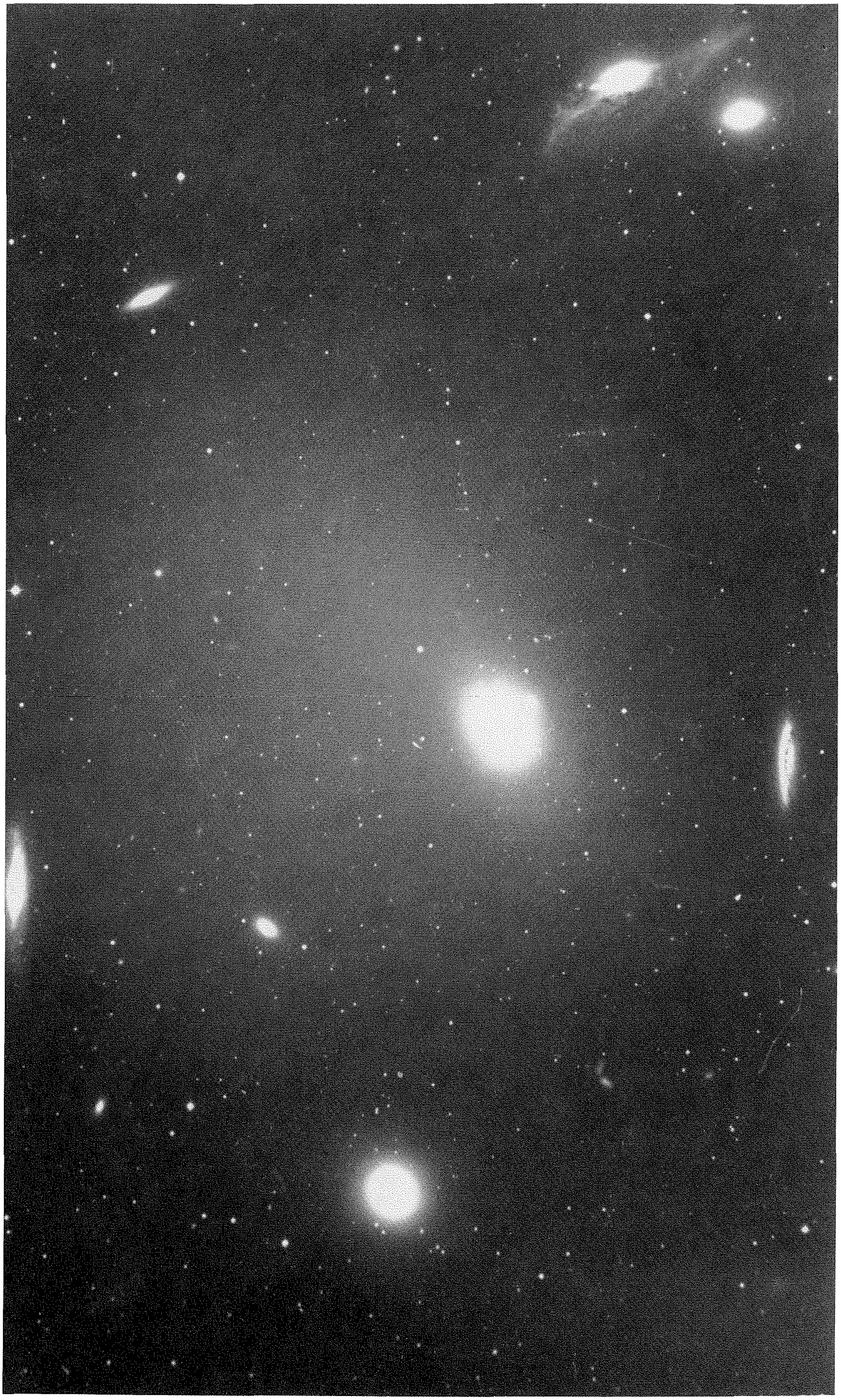

The Future of the Universe

by Stephen W. Hawking

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.

Gravity attracts some galaxies into groups like the Virgo Cluster, whose central region is shown here. The galaxies are moving within the clusters at such high speeds, however, that they would fly apart unless there were some extra mass, greater than the masses of the galaxies, keeping the cluster together. What is not known is whether this unseen dark matter exists in great enough quantities to cause the universe to collapse in a Big Crunch.

In this lecture I'm supposed to tell you about 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 would like to have written 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 been very wide of the mark. But I don't suppose it would have sold as well as my history of the past.

Foretelling the future was the job of oracles or sibyls. These were often women who would be put into a 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 actually happened, the Spartans would be so grateful to the god 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 would 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 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.

A number of dates have been set for the end of the world. So far they have all passed without incident. But the prophets have often had an explanation of 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 apparent 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 for the rest of us, this 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 only has to think of the example 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 300 years we have discovered the scientific laws that govern matter in all normal situations. We still don't know the exact laws

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that govern matter under very extreme conditions. These 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, that we have to spend large amounts of money to build giant particle accelerators to test them.

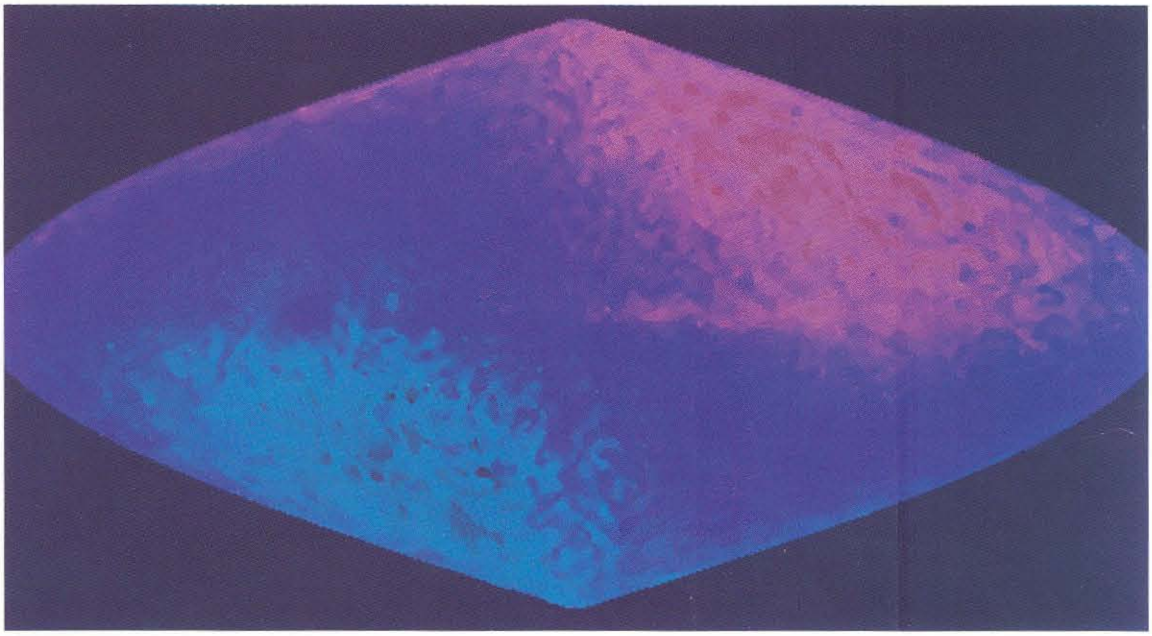
Even though we may know the relevant laws that govern the universe, we may not be able to use them to predict very far into the future. This is because the solutions to the equations of physics may exhibit a property known as chaos. What this means is that a slight change in the starting conditions may make the equations unstable. Change 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 change slightly 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 make a fortune at casinos.

With unstable and chaotic systems there is generally a certain time scale on which a small change in the initial state will grow into a change that is twice as big. In the case of Earth's atmosphere, this time scale is of the order of five days, about the time it takes for air to blow all the way 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 society, or even whether it *has* any future. The danger is that our power to damage or destroy the environment, or each other, 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 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 the motion of the galaxy in the Local Group of galaxies, is also chaotic. In contrast, the motion of the universe on very large scales seems to be uniform and not chaotic. We observe that other galaxies are moving away from



This full-sky microwave map from the Cosmic Background Explorer (COBE) satellite shows a smooth variation between hot and cold spots on opposite sides of the sky. This variation is caused by a Doppler shift due to the Earth's motion through the universe. When the Doppler shift is removed, the intensity of the radiation is the same from every direction, indicating that the universe's expansion on very large scales is highly uniform and not chaotic, and can be predicted far into the future.

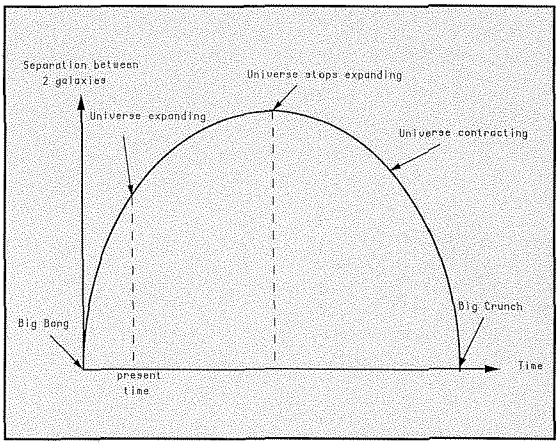
Whatever happens on Earth, the rest of the universe will carry on regardless.

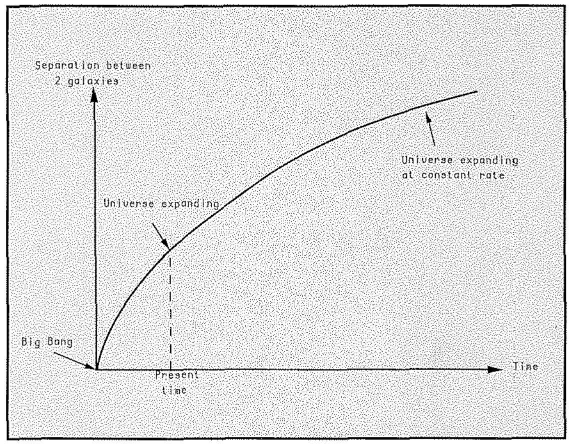
us, and the farther they are from us, the faster they are moving away. This means that the universe is expanding in our neighborhood: the distances between different galaxies are increasing with time.

We also observe a background of microwave radiation coming from outer space. You can actually observe this radiation yourself by turning your television to an empty channel. A few 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 2.7 degrees above absolute zero, so it is not much good for warming up your take-out 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 the same from every direction. This radiation has been measured very accurately by the Cosmic Background Explorer satellite. The map of the sky above was made from these observations. Different intensities of radiation are indicated by different colors. As you can see, the color is the same in every direction. What differences there are, are consistent with the noise in the experiment. There is no evidence of any variation in the background with direction, to a level of one part in 10,000.

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. However, since the time of Copernicus, 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 we can see. We are now so modest that we wouldn't 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, we can describe it in terms of a single number—the distance between two galaxies. This is increasing at the present time, but we 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





Expansion of the universe can be described by the separation between two galaxies. Gravitational attraction should slow down the expansion and eventually, if the average density of the universe is above a certain critical value, cause it to collapse to a Big Crunch. If the density is less than the critical value, the universe will continue to expand forever, the gravitational attraction having less and less of an effect on slowing it down.

Even if the universe is going to recollapse, I can confidently predict that it will not stop expanding for at least 10 billion years. I don't expect to be around to be proved wrong.

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 events that occurred "after" were part of another, separate universe. It's 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.

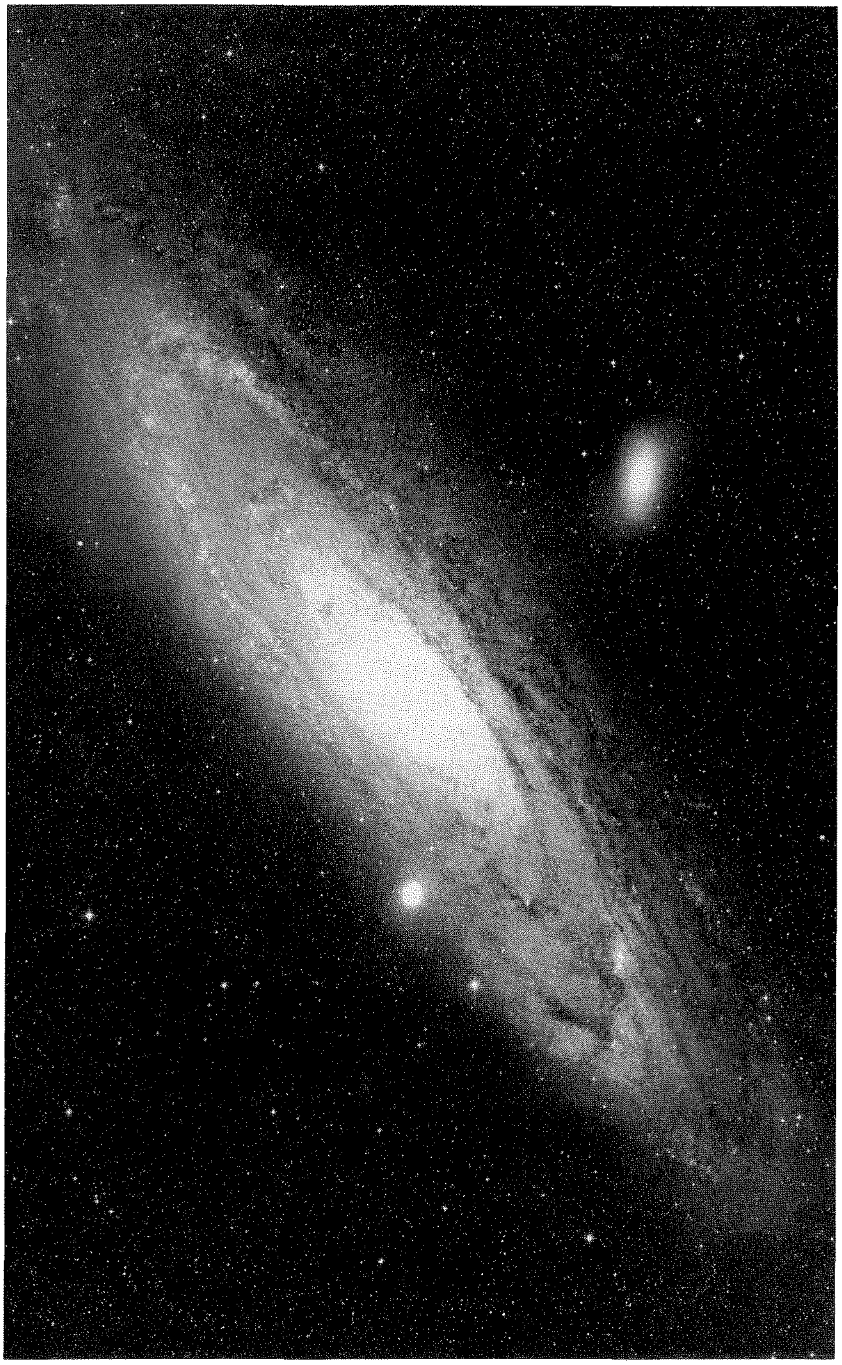
If the average density of the universe is less than a critical value, it will not recollapse but will continue to expand forever. After a certain time, the density will become so low that gravitational attraction will not have any significant effect on slowing down the expansion. The galaxies will continue 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 10 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 we can see and add up their masses, we get less than 1 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 only brings the total up to about 1 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 so 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, but 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. We can, however, 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 the 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, besides the galaxies that we see.

We can make a fairly reliable estimate of the amount of the dark matter in galaxies and clusters for which we have definite evidence. But this estimate is still only about 10 percent of the



Spiral galaxies, such as the great galaxy in Andromeda, offer evidence of the presence of dark matter in the universe, which can't be observed directly. If the stars and gas that can be seen rotating around the galaxy's center were all that it contained, it would fly apart. The gravitational attraction of some other form of matter must be holding it intact.

critical density needed to cause the universe to collapse again. Thus, if one went just by the observational evidence, one would predict that the universe would continue to expand forever. But our solar system won't last forever. After another 5 billion years or so, the sun will reach the end of its nuclear fuel. It will swell up as a red giant star until it has swallowed up Earth and the other nearer planets. It will then settle down to be a white dwarf, 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. Anyway, by the time the sun blows up we should have mastered the art of interstellar travel, if we have not already destroyed ourselves.

After 10 billion years or so, most of the stars in the universe will have burnt out. Stars with masses like that of the sun will become white dwarfs, or neutron stars which are even smaller and more dense. More massive stars can become black holes, which are still smaller, and which have such 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.

A large black hole at the center of a galaxy could take 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 years to evaporate away and disappear completely.

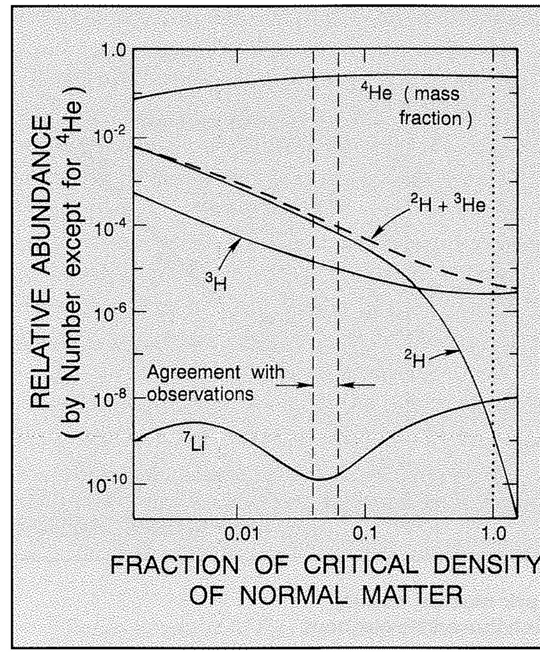
The future of a universe that expanded forever would be rather boring.

One might expect, therefore, that most matter in galaxies and clusters would eventually end up in black holes. However, some time ago I discovered that black holes weren't as black as they had 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 a 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. This 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 1 followed by 90 zeros. This is far longer than the present age of the universe, which is a mere 10^{10}. Still, there will be plenty of time if the universe is going to expand forever.

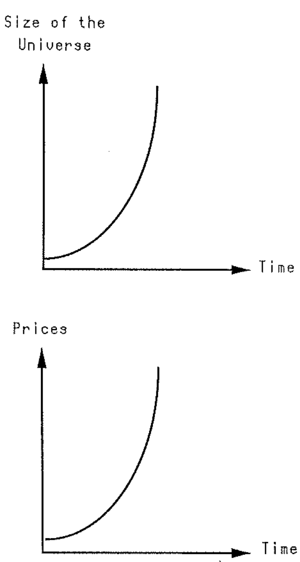
The future of a universe that expanded forever would be rather boring. But it is by no means certain that the universe will expand forever. We have definite evidence only for about a tenth of the density needed to cause the universe to recollapse. But there might be further kinds of dark matter that we have not detected, which 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 on 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 10 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 the time it was about 10 years old. How was 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 universes with different densities. Only those that were very close to the critical density would last for long and contain enough matter



The amounts of various light elements produced in the Big Bang can be calculated, but these abundances depend on the amount of normal matter in the universe. The actual observed abundances of these elements fall within the dashed-line vertical column, at the point where the amount of normal matter is just less than a tenth of the critical density. If the theory of inflation is correct so the total density is critical, then the other nine-tenths cannot be normal matter.



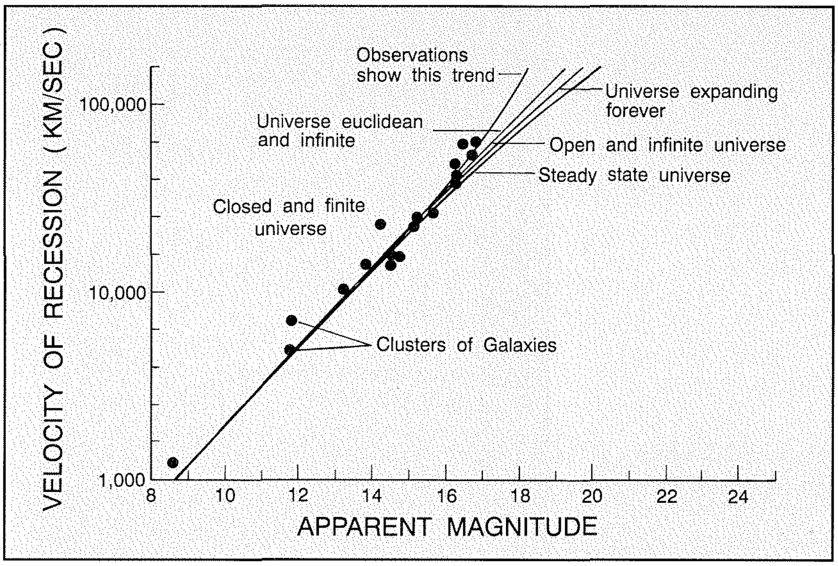
The theory of inflation in the infant universe is much like inflation in the economy, although the early universe would have inflated a bit faster—increasing by a factor of a billion billion billion in a fraction of a second.

for stars and planets to form. Only in those universes would 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, however, do not like the anthropic principle because it seems to attach too much importance to our own existence. There has thus been a search for another possible explanation of why the density should be so close to the critical value. This search led to the theory of inflation in the early universe. The idea is that the size of the universe might have kept doubling like the way prices double every few months in some countries. The inflation of the universe, however, would have been much more rapid and extreme: an increase by a factor of at least a billion billion billion in a tiny fraction of a second. This amount of 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 value. But because of the uncertainty principle of quantum mechanics, the universe could not be exactly the same everywhere and could not have the same critical density. This means that the universe would probably recollapse eventually, but not for much longer than the 15 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 the 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 graphs, with the amount of light elements shown 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 really is a critical density of dark matter, and it is not the kind of matter that stars and galaxies are made of, what could it be? The main candidates would be remnants left over from the early stages of the universe. One possibility is elementary particles. There are several hypothetical candidates, particles that we think might exist but which 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. Some recent observations, however, 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



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.

Dark matter, evenly distributed throughout the universe, would slow down the expansion, which can be measured by the speed at which distant galaxies are receding. This speed can be plotted against the galaxies' apparent brightness—the farther away (in distance or back in time) they are, the dimmer they are (which means the larger their "apparent magnitude"), and the faster they move. Brightness, however, has turned out to be an unreliable measure of distance, so this sort of calculation doesn't determine the real rate of slowing, but only indicates that it's not happening very fast.

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 or freezing of water are examples of phase transitions. In a phase transition, an initially uniform medium, such as water, develops irregularities, such as 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 I 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.

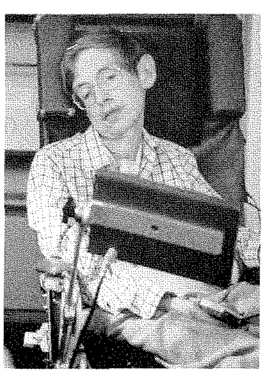
The only way we could detect dark matter that was uniformly distributed throughout the universe would be by its effect on the expansion of the universe. One can determine how fast the expansion is slowing down by measuring the speed at which distant galaxies are moving away from us. The point is that 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 goes straight, or flattens out, corresponds to a universe that will expand forever. And 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 that 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. That should give us time to sort out the Middle East crisis and one or two other problems.

Neither expanding forever nor recollapsing in a hundred billion years or so are very exciting prospects. 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. Otherwise, the difference in the gravitational pull on our head and our feet would tear us into spaghetti before we got inside. But there is a good chance that there's a black hole that big at the center of the 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.

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.

The white hole could be in another part of the universe. Thus, 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 to be 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. You only have to watch *Back to the Future* to see the problems that time travel could cause.



However, 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 cause a large amount of radiation, if one can travel into the past. This radiation would either warp spacetime so much that it would not be possible to go back in time; or it would cause spacetime 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, a change 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 will actually be on the knife edge. So I'm in the well-established tradition of oracles and prophets of hedging my bets by predicting both ways. □

The largest crowd in Beckman Auditorium history, spilling over into Ramo Auditorium for simulcast video and mere audio on the grass outside, came to hear Stephen Hawking give the talk on which this article is based. Hawking, who has suffered from amyotrophic lateral sclerosis since he was 21, delivered his lecture and answered questions afterward using a computer voice machine, which he operates from a keyboard. The lecture was part of a Caltech Centennial symposium—"The Origin and Evolution of Large Scale Structure in the Universe"—in late September, and was arguably the Centennial's biggest hit, at least in numbers.

Hawking is the Lucasian Professor of Mathematics at Cambridge University—Isaac Newton's old chair. He received his undergraduate degree in 1962 from Oxford and PhD in 1965 from Cambridge, where he has remained ever since; he's been a professor in the Department of Applied Mathematics and Theoretical Physics there since 1977. A longtime friend of Kip Thorne, the Feynman Professor of Theoretical Physics, Hawking spent a year at Caltech in the mid-seventies as a Sherman Fairchild Distinguished Scholar and will return as a Fairchild Scholar this January. Widely regarded by physicists as one of the most brilliant theoreticians since Einstein, Hawking also brought cosmology to the masses with his 1988 bestseller, A Brief History of Time.

When asked in 1975 (in an interview published in Caltech News*) whether he believed that humans will ever discover the ultimate laws that control the universe, Hawking replied: "I rather hope not. There may be ultimate answers, but if there are, I would be sorry if we were to find them. For my own sake I would like very much to find them, but their discovery would leave nothing for those coming after me to seek. Each generation builds on the advances of the previous generation, and this is as it should be. As human beings, we need the quest."*