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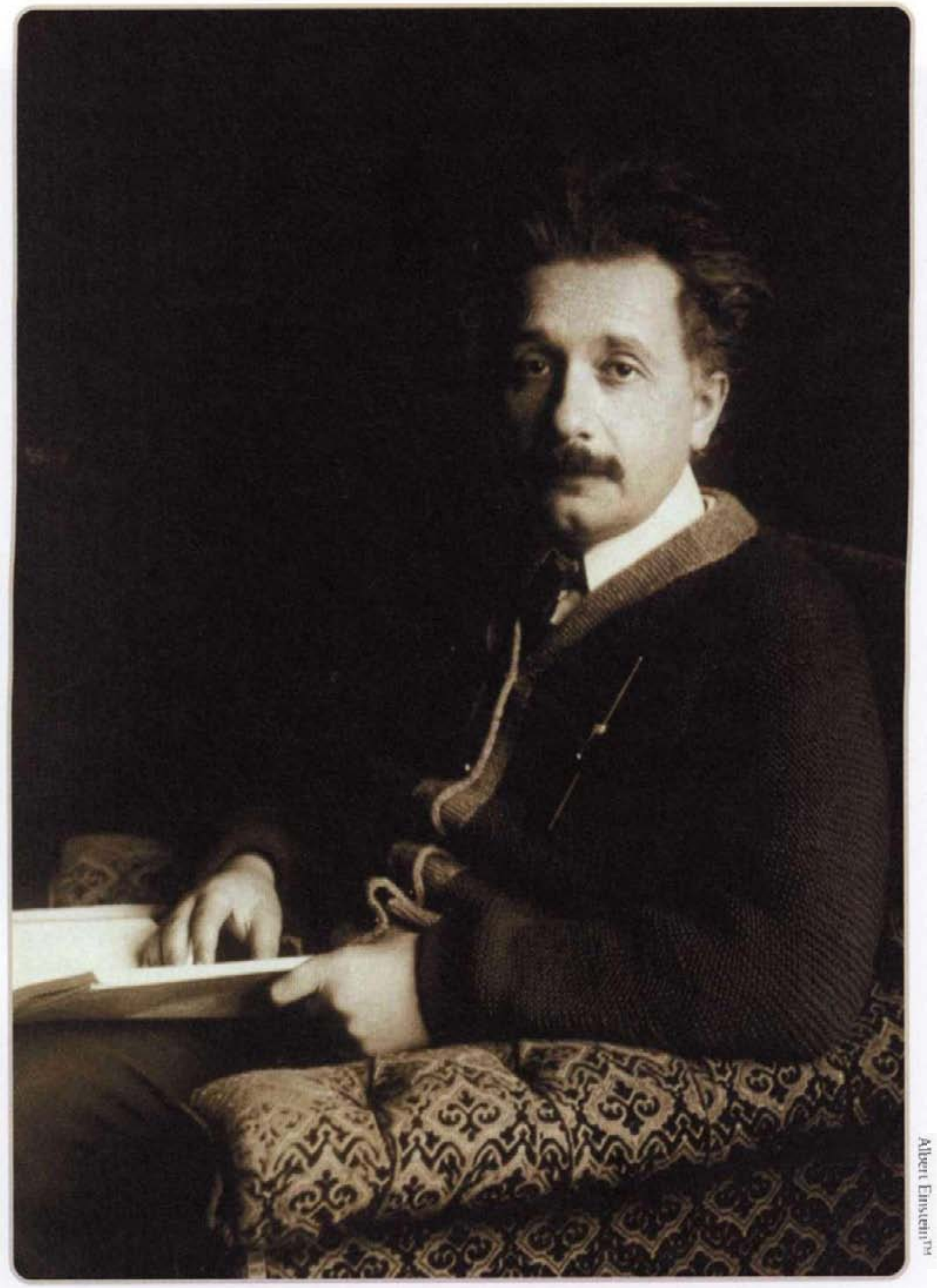
The Universe in a Nutshell



Albert Einstein in **1920.**

FIG. 1.10

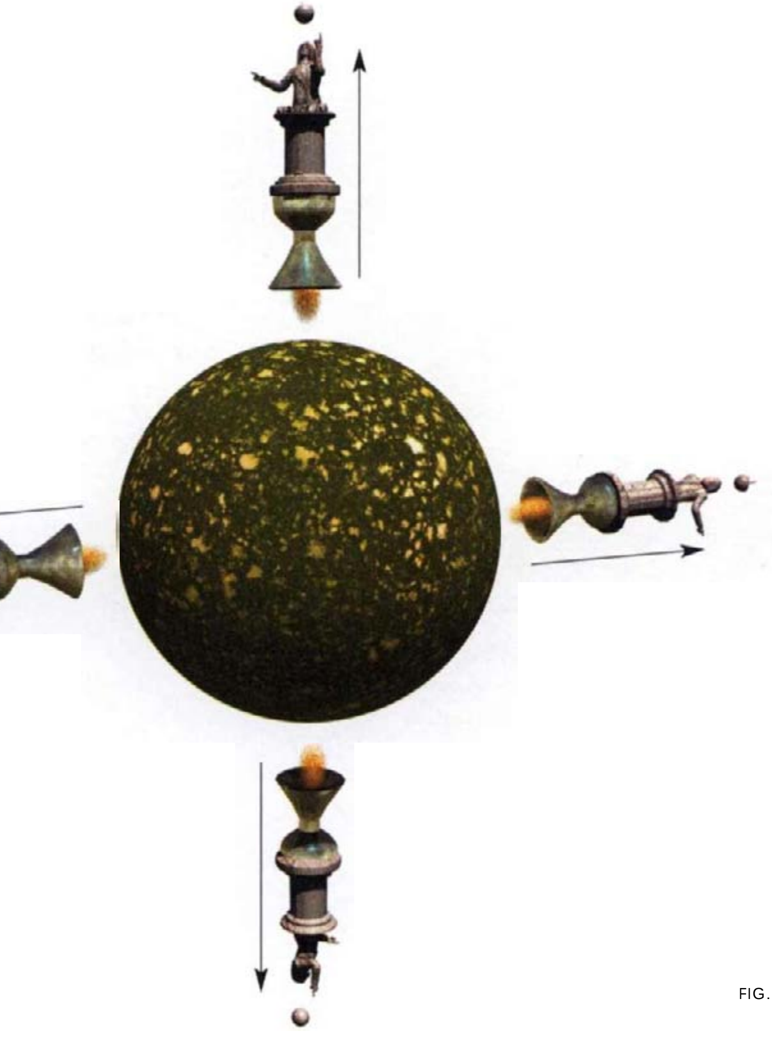


FIG. I.II

If the Earth were flat, one could equally well say that the apple fell on Newton's head because of gravity or because Newton and the surface of the Earth were accelerating upward (Fig. 1.10). This equivalence between acceleration and gravity didn't seem to work for a round Earth, however—people on the opposite sides of the world would have to be accelerating in opposite directions but staying at a constant distance from each other (Fig. 1.11).

But on his return to Zurich in 1912 Einstein had the brain wave of realizing that the equivalence would work if the geometry of spacetime was curved and not flat, as had been assumed hitherto.

If the Earth were flat (FIG. 1. 10) one could say that either the apple fell on Newton's head because of gravity or that the Earth and Newton were accelerating upward. This equivalence didn't work for a spherical Earth (FIG. I. I I) because people on opposite sides of the world would be getting farther away from each other Einstein overcame this difficulty by making space and time curved.

CHAPTER 2

THE SHAPE OF TIME

Einstein's general relativity gives time a shape.
How this can be reconciled with quantum theory.

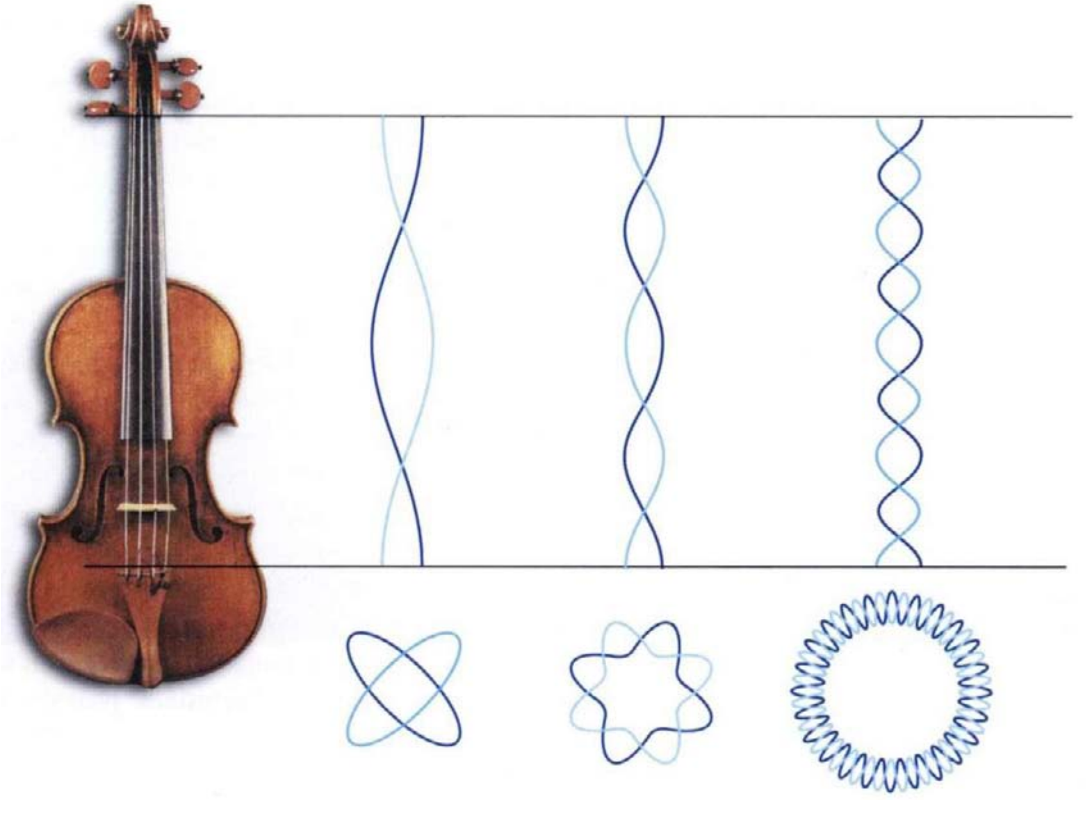
As one goes back in time, the cross sections of our past light cone reach a maximum size and begin to get smaller again. Our past is pear-shaped (Fig. 2.8).

As one follows our past light cone back still further, the positive energy density of matter causes the light rays to bend toward each other more strongly. The cross section of the light cone will shrink to zero size in a finite time. This means that all the matter inside our past light cone is trapped in a region whose boundary shrinks to zero. It is therefore not very surprising that Penrose and I could prove that in the mathematical model of general relativity, time must have a beginning in what is called the big bang. Similar arguments show that time would have an end, when stars or galaxies collapse under their own gravity to form black holes. We had sidestepped Kant's antimony of pure reason by dropping his implicit assumption that time had a meaning independent of the universe. Our paper, proving time had a beginning, won the second prize in the competition sponsored by the Gravity Research Foundation in 1968, and Roger and I shared the princely sum of $300. I don't think the other prize essays that year have shown much enduring value.

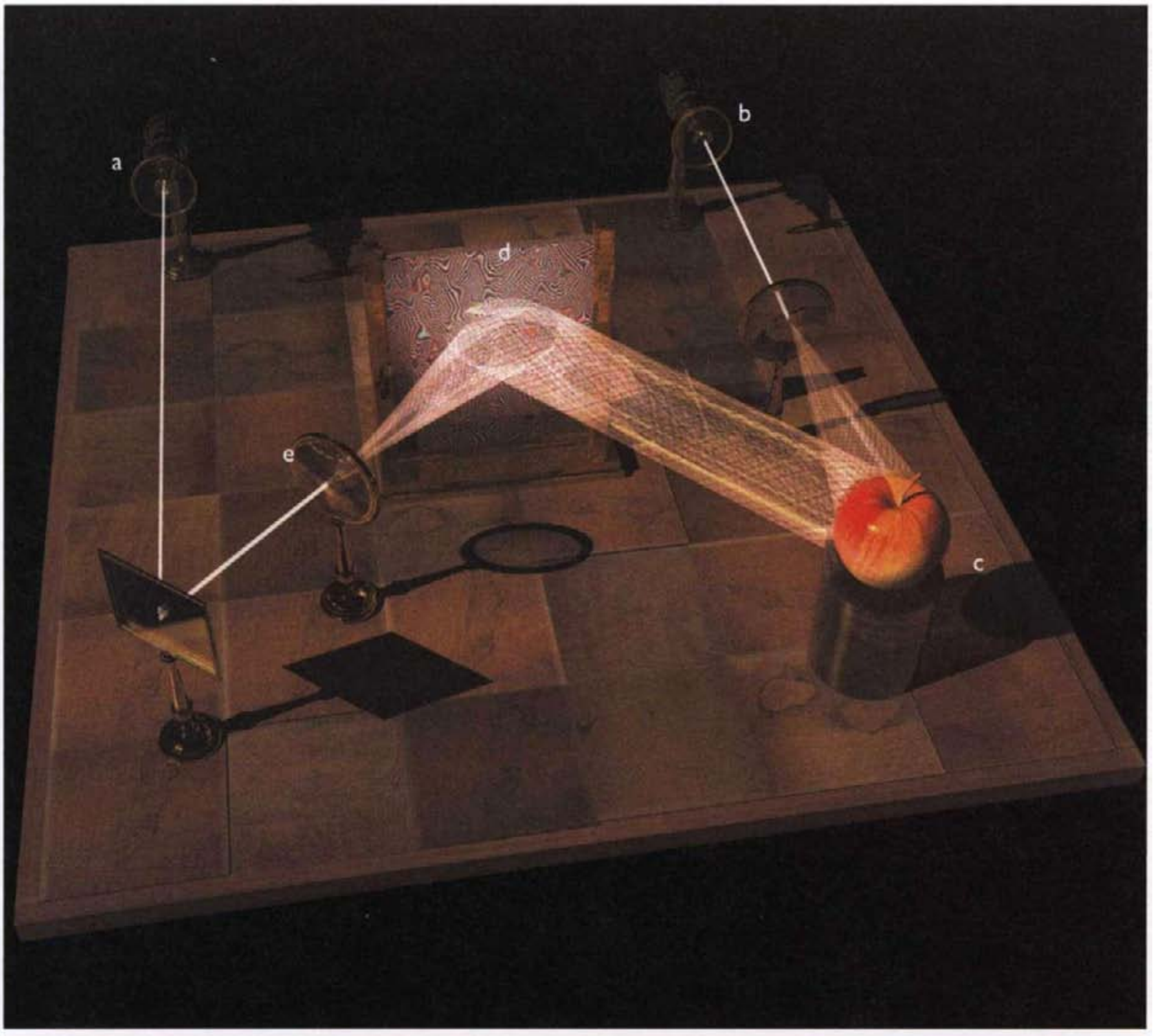
There were various reactions to our work. It upset many physicists, but it delighted those religious leaders who believed in an act of creation, for here was scientific proof. Meanwhile, Lifshitz and Khalatnikov were in an awkward position. They couldn't argue with the mathematical theorems that we had proved, but under the Soviet system they couldn't admit they had been wrong and Western science had been right. However, they saved the situation by finding a more general family of solutions with a singularity, which weren't special in the way their previous solutions had been. This enabled them to claim singularities, and the beginning or end of time, as a Soviet discovery.

(FIG. 2.8) TIME IS PEAR-SHAPED

If one follows our past light cone back in time, it will be bent back by the matter in the early universe. The whole universe we observe is contained within a region whose boundary shrinks to zero at the big bang. This would be a singularity, a place where the density of matter would be infinite and classical general relativity would break down.



less than a billion billion times those of particles in a TNT explosion. If supergravity was only a low energy approximation, it could not claim to be the fundamental theory of the universe. Instead, the underlying theory was supposed to be one of five possible superstring theories. But which of the five string theories described our universe? And how could string theory be formulated, beyond the approximation in which strings were pictured as surfaces with one space dimension and one time dimension moving through a flat background spacetime? Wouldn't the strings curve the background spacetime?



(Fig. 2.22) Holography is essentially a phenomenon of interference of wave patterns. Holograms are created when the light from a single laser is split into two separate beams **(a)** and **(b)**. One **(b)** bounces off the object **(c)** onto a photo-sensitized plate **(d)**. The other **(a)** passes through a lens **(e)** and collides with the reflected light of **(b)**, creating an interference pattern on the plate.

When a laser is shone through the developed plate a fully *three-dimensional* image of the original object appears. An observer can move around this holographic image, being able to see all the hidden faces that a normal photo could not show.

The two-dimensional surface of the plate on the left, unlike a normal photo, has the remarkable property that any tiny fragment of its surface contains all the information needed to reconstruct the whole image.

Edwin Hubble at the 100-inch Mount Wilson telescope in 1930.

(FIG. 3.6) HUBBLE'S LAW

By analyzing the light from other galaxies, Edwin Hubble discovered in the 1920s that nearly all galaxies are moving away from us, at a velocity **V** that is proportional to their distance **R** from the Earth, so **V** = **H** × **R**.

This important observation, known as Hubble's law, established that the universe is expanding, with the Hubble constant **H** setting the rate of expansion.

The graph below shows recent observations of the red-shift of galaxies, confirming Hubble's law to vast distances away from us.

The slight upward bend in the graph at large distances indicates that the expansion is speeding up, which may be caused by vacuum energy.

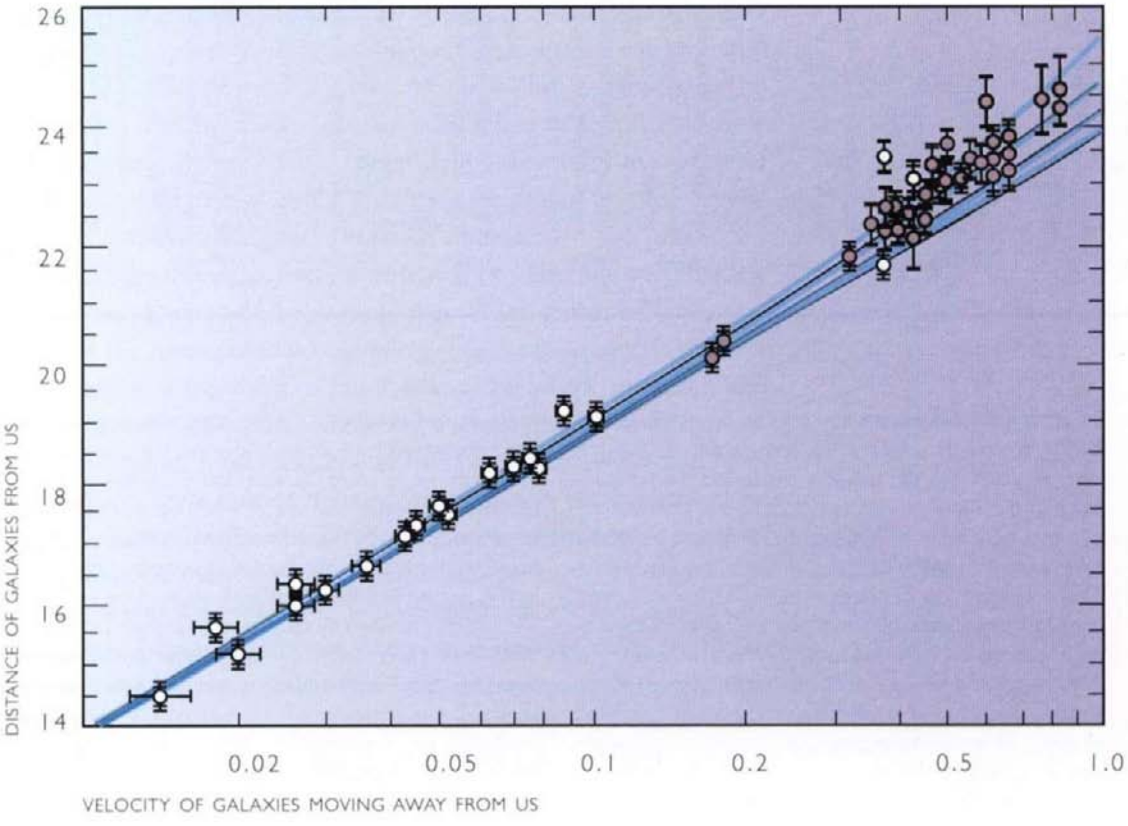
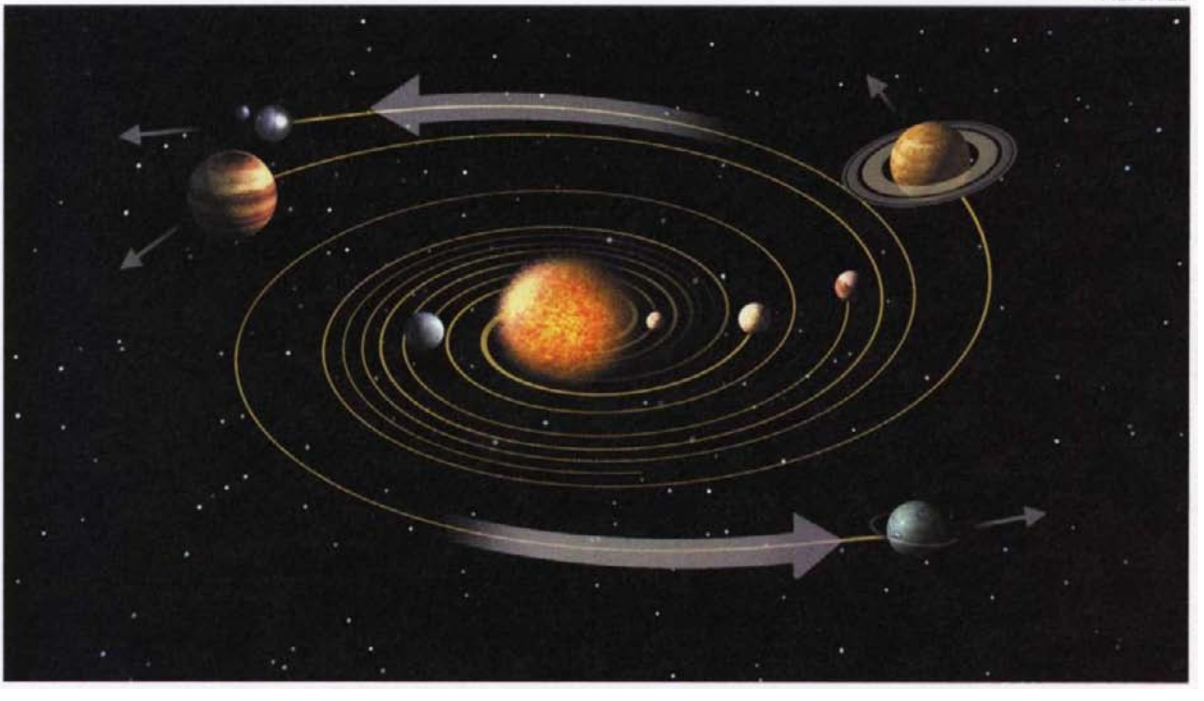


FIG. 3.12A

FIG. 3.12B



CHAPTER 4

PREDICTING THE FUTURE

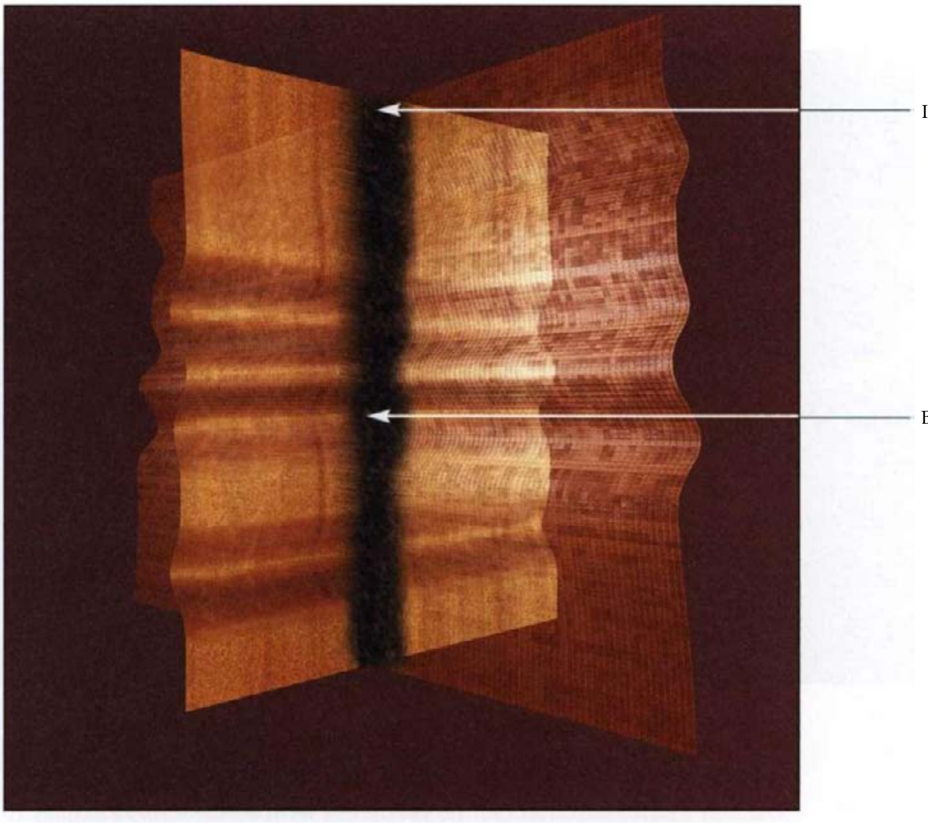
How the loss of information in black boles may reduce our ability to predict the future.

holes, and his attitude was shared by most of the old guard in general relativity. I remember going to Paris to give a seminar on my discovery that quantum theory means that black holes aren't completely black. My seminar fell rather flat because at that time almost no one in Paris believed in black holes. The French also felt that the name as they translated it, *trou noir,* had dubious sexual connotations and should be replaced by *astre occlu,* or "hidden star." However, neither this nor other suggested names caught the public imagination like the term *black bole,* which was first introduced by John Archibald Wheeler, the American physicist who inspired much of the modern work in this field.

The discovery of quasars in 1963 brought forth an outburst of theoretical work on black holes and observational attempts to detect them (Fig. 4.10). Here is the picture that has emerged. Consider what we believe would be the history of a star with a mass twenty times that of the Sun. Such stars form from clouds of gas, like those in the Orion Nebula (Fig. 4.1 1). As clouds of gas contract under their own gravity, the gas heats up and eventually becomes hot enough to start the nuclear fusion reaction that converts hydrogen into helium. The heat generated by this process creates a pressure that supports the star against its own gravity and stops it from contracting further. A star will stay in this state for a long time, burning hydrogen and radiating light into space.

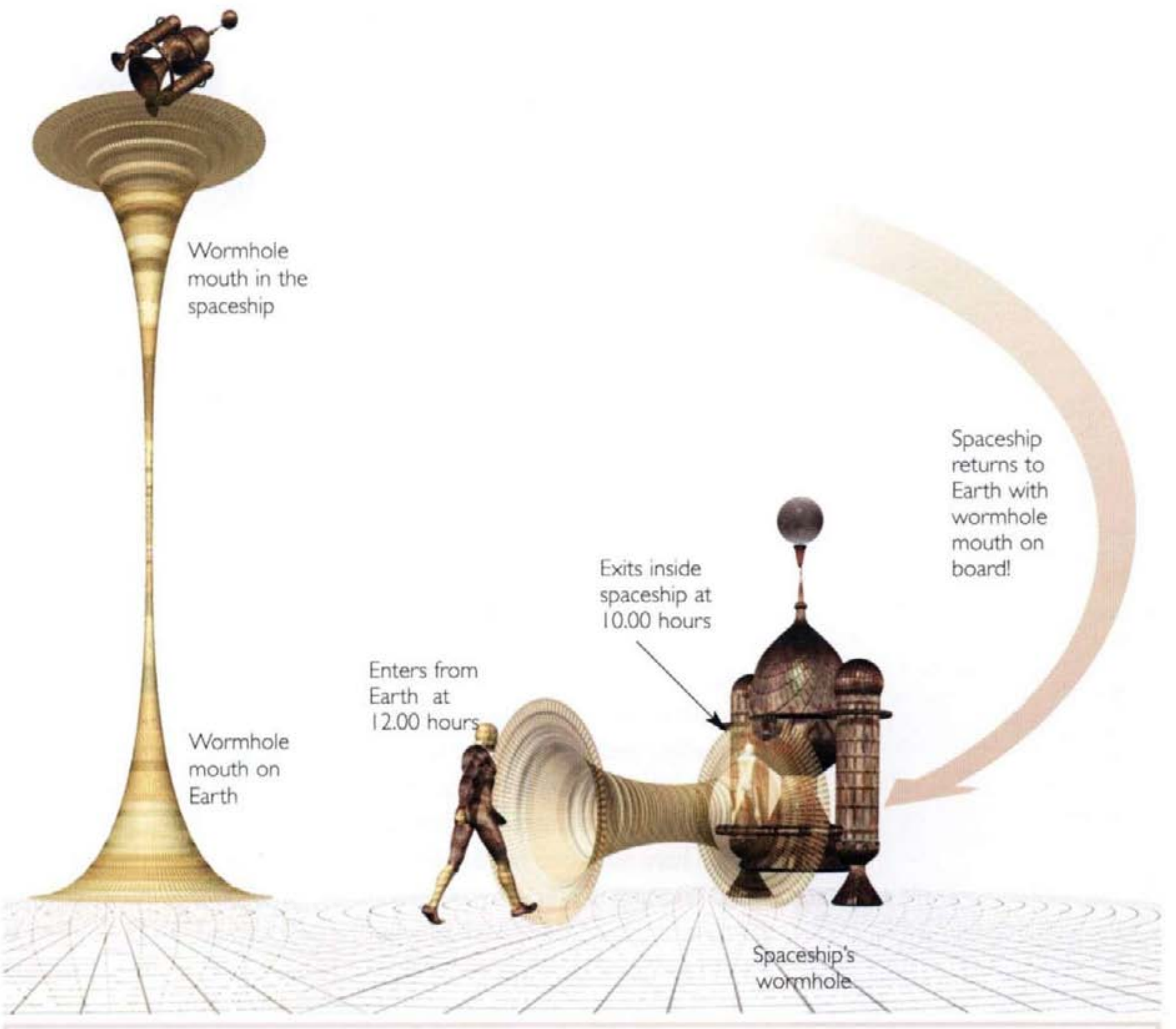
(FIG.4.1 1)
Stars form in clouds of gas and dust like the Orion Nebula.

The gravitational field of the star will affect the paths of light rays coming from it. One can draw a diagram with time plotted upward and distance from the center of the star plotted horizontally (see Fig. 4.12, page 114). In this diagram, the surface of the star is represented by two vertical lines, one on either side of the center. One can choose that time be measured in seconds and distance in light-seconds—the distance light travels in a second. When we use these units, the speed of light is 1; that is, the speed of light is 1 light-second per second. This means that far from the star and its gravitational field, the path of a light ray on the diagram is a line at a 45-degree angle to the vertical. However, nearer the star, the curvature of space-time produced by the mass of the star will change the paths of the light rays and cause them to be at a smaller angle to the vertical.



(FIG. 4.22)
Black holes can be thought of as the intersections of p-branes in the extra dimensions of spacetime. Information about the internal states of black holes would be stored as waves on the p-branes.

measured. Because of this, it is not possible to predict the spin or the wave function of the particle that escapes. It can have different spins and different wave functions, with various probabilities, but it doesn't have a unique spin or wave function. Thus it would seem that our power to predict the future would be further reduced. The classical idea of Laplace, that one could predict both the positions and the velocities of particles, had to be modified when the uncertainty principle showed that one could not accurately measure both positions and velocities. However, one could still measure the wave function and use the Schrodinger equation to predict what it should be in the future. This would allow one to predict with certainty one combination of position and velocity—which is half of what one could predict according to Laplace's ideas. We can predict with certainty that the particles have opposite spins, but if one particle falls into the black hole, there is no prediction we can make with certainty about the



(2)
One can imagine taking one end of the wormhole on a long journey on a spaceship while the other end remains on Earth.

(3)
Because of the twins paradox effect, when the spaceship returns, less time has elapsed for the mouth it contains than for the mouth that stays on earth. This would mean that if you step into the Earth mouth, you could come out of the spaceship at an earlier time.

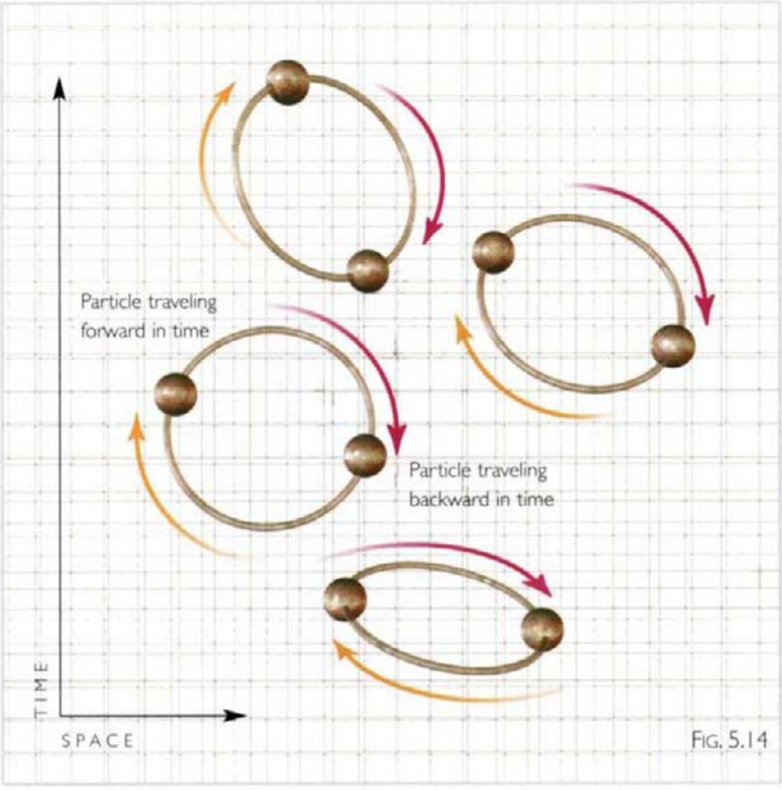
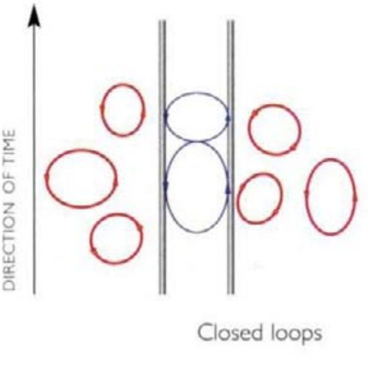


FIG. 5.14

light given out by hydrogen atoms, caused by electrons moving in closed loops. Another is a small force between parallel metal plates, caused by the fact that there are slightly fewer closed-loop histories that can fit between the plates compared to the region outside—another equivalent interpretation of the Casimir effect. Thus the existence of closed-loop histories is confirmed by experiment (Fig. 5.15).

One might dispute whether closed-loop particle histories have anything to do with the warping of spacetime, because they occur even in fixed backgrounds such as flat space. But in recent years we have found that phenomena in physics often have dual, equally valid descriptions. One can equally well say that a particle moves on a closed loop in a given fixed background, or that the particle stays fixed and space and time fluctuate around it. It is just a question of whether you do the sum over particle paths first and then the sum over curved spacetimes, or vice versa.

FIG. 5.15



On the other hand, we already know the laws that hold in all but the most extreme situations: the laws that govern the crew of the *Enterprise,* if not the spaceship itself. Yet it doesn't seem that we will ever reach a steady state in the uses we make of these laws or in the complexity of the systems that we can produce with them. It is with this complexity that the rest of this chapter will be concerned.

By far the most complex systems that we have are our own bodies. Life seems to have originated in the primordial oceans that covered the Earth four billion years ago. How this happened we don't know. It may be that random collisions between atoms built up macromolecules that could reproduce themselves and assemble themselves into more complicated structures. What we do know is that by three and a half billion years ago, the highly complicated DNA molecule had emerged.

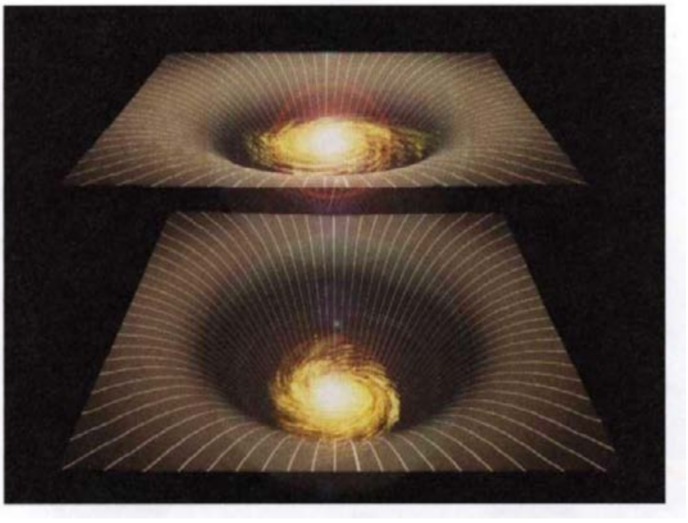
DNA is the basis for all life on Earth. It has a double helix structure, like a spiral staircase, which was discovered by Francis Crick and James Watson in the Cavendish lab at Cambridge in 1953. The two strands of the double helix are linked by pairs of bases, like the treads in a spiral staircase. There are four bases in DNA: adenine, guanine, thymine, and cytosine. The order in which they occur along the spiral staircase carries the genetic information that enables the DNA to assemble an organism around it and reproduce itself. As it makes copies of itself, there are occasional errors in the proportion or order of the bases along the spiral. In most cases, the mistakes in copying make the DNA either unable or less likely to reproduce itself, meaning that such genetic errors, or mutations, as they are called, will die out. But in a few cases, the error or mutation will increase the chances of the DNA surviving and reproducing. Such changes in the genetic code will be favored. This is how the information contained in the sequence of DNA gradually evolves and increases in complexity (see Fig. 6.4, page 162).

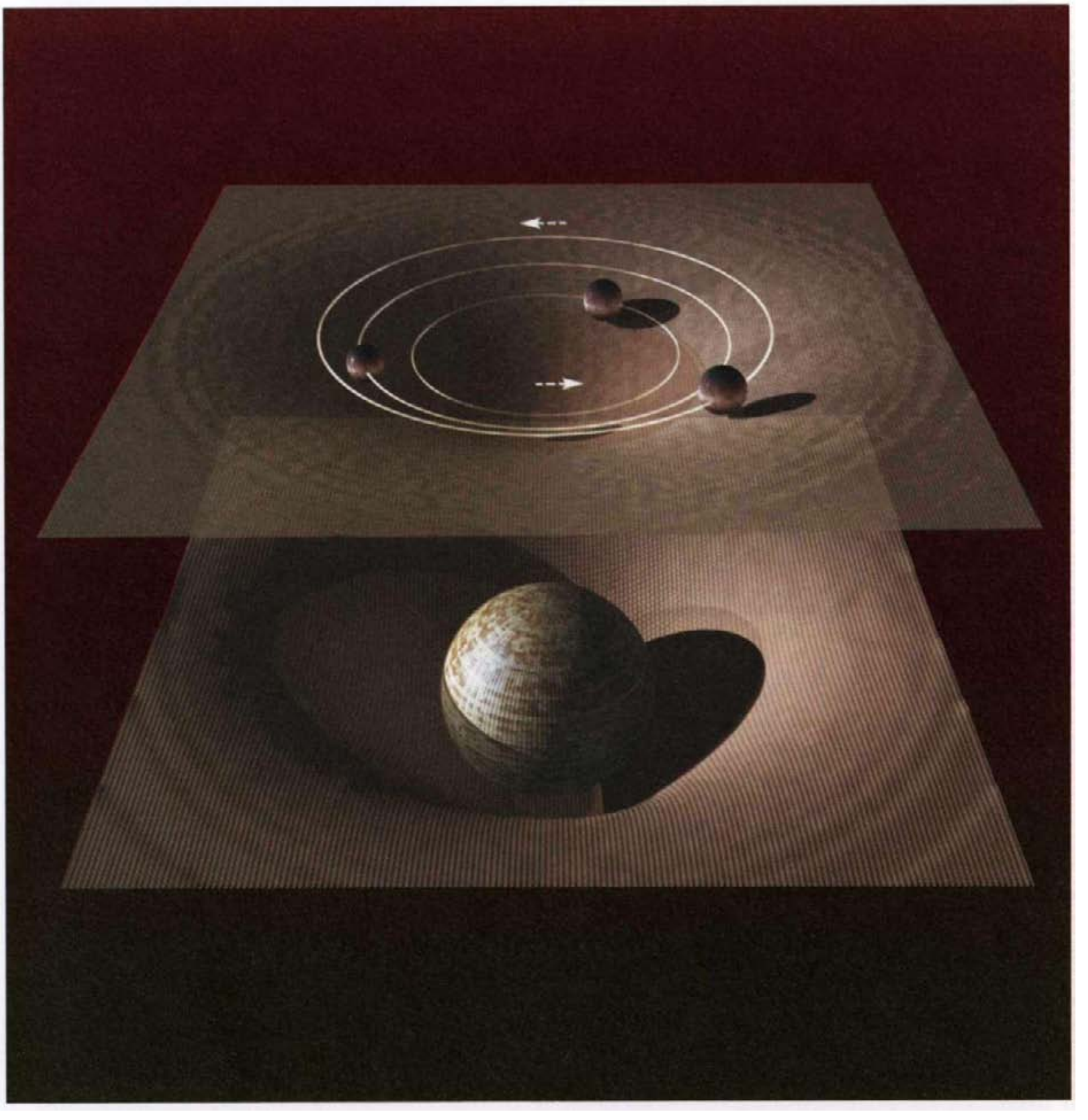
Because biological evolution is basically a random walk in the

CHAPTER 7

BRANE NEW WORLD

Do we live on a brane or are we just holograms?





(FIG. 7.12) In the brane world scenario, planets may orbit a dark mass on a shadow brane because the gravitational force propagates into the extra dimensions.

(FIG. 7.18)

The brane world picture of the origin of the universe differs from that discussed in Chapter 3, because the slightly flattened four-dimensional sphere, or nutshell, is no longer hollow but is filled by a fifth dimension.