CHAPTER 7

BLACK HOLES AIN'T SO BLACK

Before 1970, my research on general relativity had concentrated mainly on the question of whether or not there had been a big bang singularity. However, one evening in November that year, shortly after the birth of my daughter, Lucy, I started to think about black holes as I was getting into bed. My disability makes this rather a slow process, so I had plenty of time. At that date there was no precise definition of which points in space-time lay inside a black hole and which lay outside. I had already discussed with Roger Penrose the idea of defining a black hole as the set of events from which it was not possible to escape to a large distance, which is now the generally accepted definition. It means that the boundary of the black hole, the event horizon, is formed by the light rays that just fail to escape from the black hole, hovering forever just on the edge Figure 7:1. It is a bit like running away from the police and just managing to keep one step ahead but not being able to get clear away!

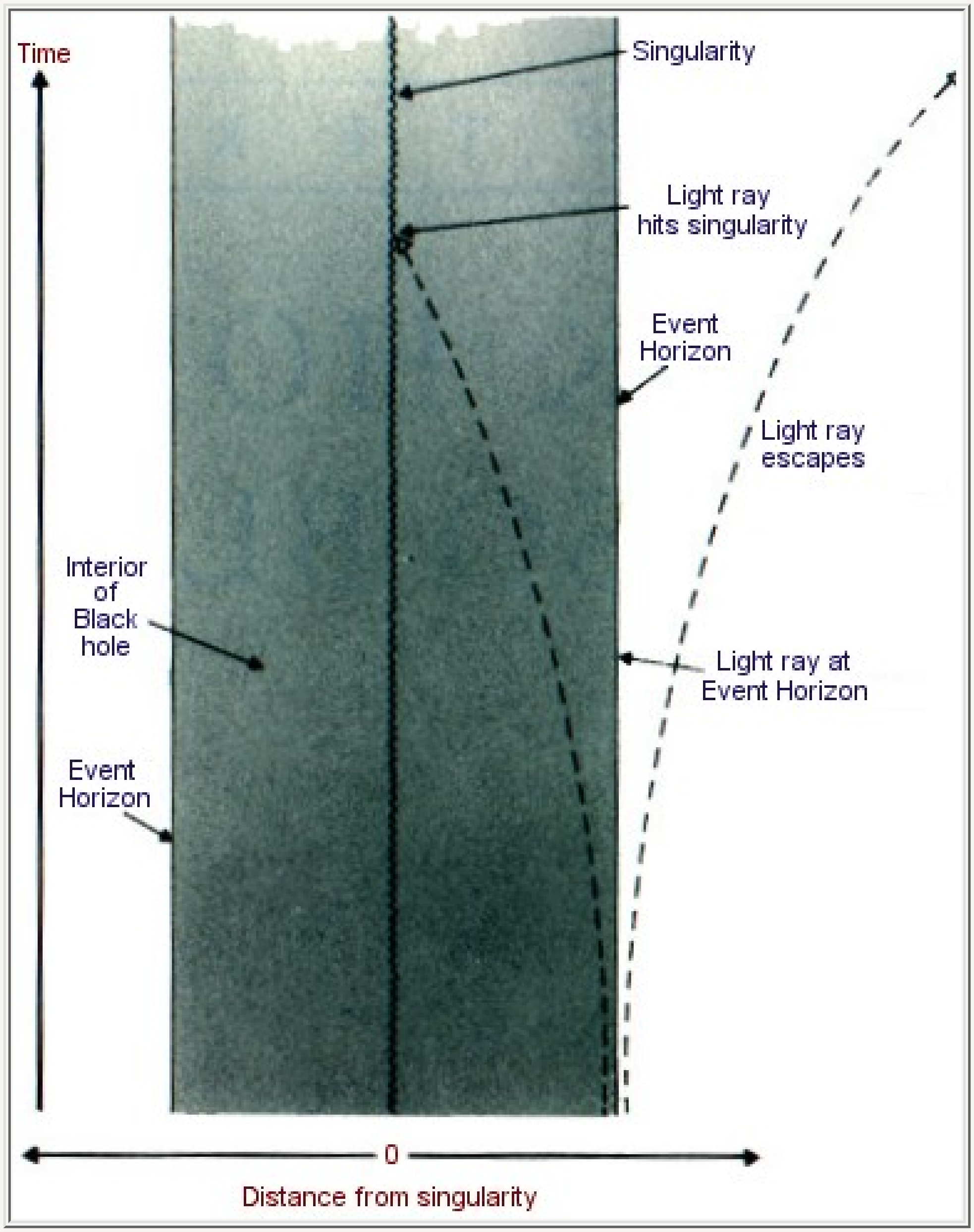
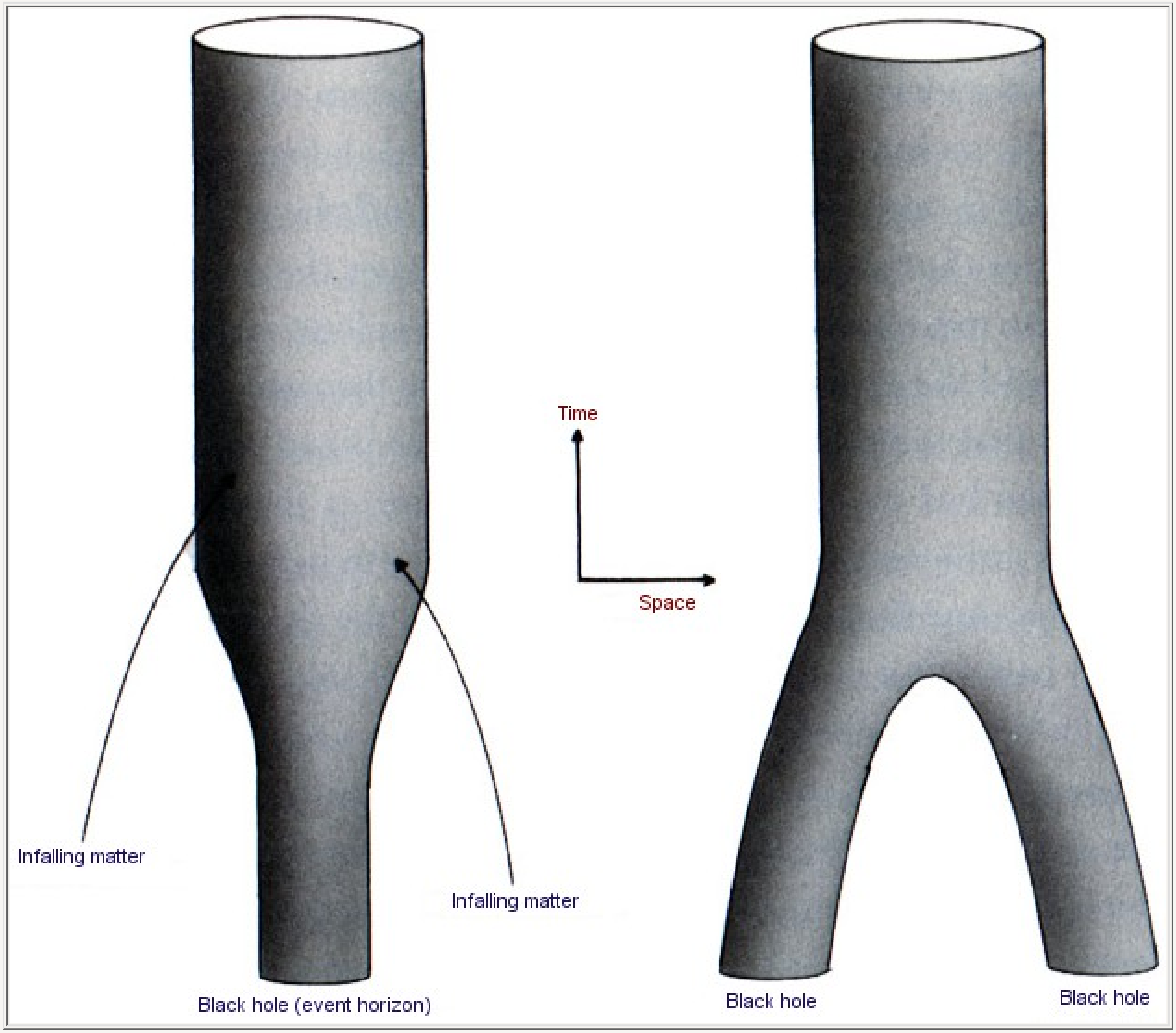


Figure 7:1

Suddenly I realized that the paths of these light rays could never approach one another. If they did they must eventually run into one another. It would be like meeting someone else running away from the police in the opposite direction – you would both be caught! (Or, in this case, fall into a black hole.) But if these light rays were swallowed up by the black hole, then they could not have been on the boundary of the black hole. So the paths of light rays in the event horizon had always to be moving parallel to, or away from, each other. Another way of seeing this is that the event horizon, the boundary of the black hole, is like the edge of a shadow – the shadow of impending doom. If you look at the shadow cast by a source at a great distance, such as the sun, you will see that the rays of light in the edge are not approaching each other.

If the rays of light that form the event horizon, the boundary of the black hole, can never approach each other, the area of the event horizon might stay the same or increase with time, but it could never decrease because that would mean that at least some of the rays of light in the boundary would have to be approaching each other. In fact, the area would increase whenever matter or radiation fell into the black hole Figure 7:2.



Figures 7:2 & 7:3

Or if two black holes collided and merged together to form a single black hole, the area of the event horizon of the final black hole would be greater than or equal to the sum of the areas of the event horizons of the original black holes Figure 7:3. This nondecreasing property of the event horizon's area placed an important restriction on the possible behavior of black holes. I was so excited with my discovery that I did not get much sleep that night. The next day I rang up Roger Penrose. He agreed with me. I think, in fact, that he had been aware of this property of the area. However, he had been using a slightly different definition of a black hole. He had not realized that the boundaries of the black hole according to the two definitions would be the same, and hence so would their areas, provided the black hole had settled down to a state in which it was not changing with time.

The nondecreasing behavior of a black hole’s area was very reminiscent of the behavior of a physical quantity called entropy, which measures the degree of disorder of a system. It is a matter of common experience that disorder will tend to increase if things are left to themselves. (One has only to stop making repairs around the house to see that!) One can create order out of disorder (for example, one can paint the house), but that requires expenditure of effort or energy and so decreases the amount of ordered energy available.

A precise statement of this idea is known as the second law of thermodynamics. It states that the entropy of an isolated system always increases, and that when two systems are joined together, the entropy of the combined system is greater than the sum of the entropies of the individual systems. For example, consider a system of gas molecules in a box. The molecules can be thought of as little billiard balls continually colliding with each other and bouncing off the walls of the box. The higher the temperature of the gas, the faster the molecules move, and so the more frequently and harder they collide with the walls of the box and the greater the outward pressure they exert on the walls. Suppose that initially the molecules are all confined to the left-hand side of the box by a partition. If the partition is then removed, the molecules will tend to spread out and occupy both halves of the box. At some later time they could, by chance, all be in the right half or back in the left half, but it is overwhelmingly more probable that there will be roughly equal numbers in the two halves. Such a state is less ordered, or more disordered, than the original state in which all the molecules were in one half. One therefore says that the entropy of the gas has gone up. Similarly, suppose one starts with two boxes, one containing oxygen molecules and the other containing nitrogen molecules. If one joins the boxes together and removes the intervening wall, the oxygen and the nitrogen molecules will start to mix. At a later time the most probable state would be a fairly uniform mixture of oxygen and nitrogen molecules throughout the two boxes. This state would be less ordered, and hence have more entropy, than the initial state of two separate boxes.

The second law of thermodynamics has a rather different status than that of other laws of science, such as Newton's law of gravity, for example, because it does not hold always, just in the vast majority of cases. The probability of all the gas molecules in our first box

found in one half of the box at a later time is many millions of millions to one, but it can happen. However, if one has a black hole around there seems to be a rather easier way of violating the second law: just throw some matter with a lot of entropy such as a box of gas, down the black hole. The total entropy of matter outside the black hole would go down. One could, of course, still say that the total entropy, including the entropy inside the black hole, has not gone down - but since there is no way to look inside the black hole, we cannot see how much entropy the matter inside it has. It would be nice, then, if there was some feature of the black hole by which observers outside the black hole could tell its entropy, and which would increase whenever matter carrying entropy fell into the black hole. Following the discovery, described above, that the area of the event horizon increased whenever matter fell into a black hole, a research student at Princeton named Jacob Bekenstein suggested that the area of the event horizon was a measure of the entropy of the black hole. As matter carrying entropy fell into a black hole, the area of its event horizon would go up, so that the sum of the entropy of matter outside black holes and the area of the horizons would never go down.

This suggestion seemed to prevent the second law of thermodynamics from being violated in most situations. However, there was one fatal flaw. If a black hole has entropy, then it ought to also have a temperature. But a body with a particular temperature must emit radiation at a certain rate. It is a matter of common experience that if one heats up a poker in a fire it glows red hot and emits radiation, but bodies at lower temperatures emit radiation too; one just does not normally notice it because the amount is fairly small. This radiation is required in order to prevent violation of the second law. So black holes ought to emit radiation. But by their very definition, black holes are objects that are not supposed to emit anything. It therefore seemed that the area of the event horizon of a black hole could not be regarded as its entropy. In 1972 I wrote a paper with Brandon Carter and an American colleague, Jim Bardeen, in which we pointed out that although there were many similarities between entropy and the area of the event horizon, there was this apparently fatal difficulty. I must admit that in writing this paper I was motivated partly by irritation with Bekenstein, who, I felt, had misused my discovery of the increase of the area of the event horizon. However, it turned out in the end that he was basically correct, though in a manner he had certainly not expected.

In September 1973, while I was visiting Moscow, I discussed black holes with two leading Soviet experts, Yakov Zeldovich and Alexander Starobinsky. They convinced me that, according to the quantum mechanical uncertainty principle, rotating black holes should create and emit particles. I believed their arguments on physical grounds, but I did not like the mathematical way in which they calculated the emission. I therefore set about devising a better mathematical treatment, which I described at an informal seminar in Oxford at the end of November 1973. At that time I had not done the calculations to find out how much would actually be emitted. I was expecting to discover just the radiation that Zeldovich and Starobinsky had predicted from rotating black holes. However, when I did the calculation, I found, to my surprise and annoyance, that even non-rotating black holes should apparently create and emit particles at a steady rate. At first I thought that this emission indicated that one of the approximations I had used was not valid. I was afraid that if Bekenstein found out about it, he would use it as a further argument to support his ideas about the entropy of black holes, which I still did not like. However, the more I thought about it, the more it seemed that the approximations really ought to hold. But what finally convinced me that the emission was real was that the spectrum of the emitted particles was exactly that which would be emitted by a hot body, and that the black hole was emitting particles at exactly the correct rate to prevent violations of the second law. Since then the calculations have been repeated in a number of different forms by other people. They all confirm that a black hole ought to emit particles and radiation as if it were a hot body with a temperature that depends only on the black hole's mass: the higher the mass, the lower the temperature.

How is it possible that a black hole appears to emit particles when we know that nothing can escape from within its event horizon? The answer, quantum theory tells us, is that the particles do not come from within the black hole, but from the "empty" space just outside the black hole's event horizon! We can understand this in the following way: what we think of as "empty" space cannot be completely empty because that would mean that all the fields, such as the gravitational and electromagnetic fields, would have to be exactly zero. However, the value of a field and its rate of change with time are like the position and velocity of a particle: the uncertainty principle implies that the more accurately one knows one of these quantities, the less accurately one can know the other. So in empty space the field cannot be fixed at exactly zero, because then it would have both a precise value (zero) and a precise rate of change (also zero). There must be a certain minimum amount of uncertainty, or quantum fluctuations, in the value of the field. One can think of these fluctuations as pairs of particles of light or gravity that appear together at some time, move apart, and then come together again and annihilate each other. These particles are virtual particles like the particles that carry the gravitational force of the sun: unlike real particles, they cannot be observed directly with a particle detector. However, their indirect effects, such as small changes in the energy of electron orbits in atoms, can be measured and agree with the theoretical predictions to a remarkable degree of accuracy. The uncertainty principle also predicts that there will be similar virtual pairs of matter particles, such as electrons or quarks. In this case, however, one member of the pair will be a particle and the other an antiparticle (the antiparticles of light and gravity are the same as the particles).

Because energy cannot be created out of nothing, one of the partners in a particle/antiparticle pair will have positive energy, and the other partner negative energy. The one with negative energy is condemned to be a short-lived virtual particle because real particles always have positive energy in normal situations. It must therefore seek out its partner and annihilate with it. However, a real particle close to a massive body has less energy than if it were far away, because it would take energy to lift it far away against the gravitational attraction of the body. Normally, the energy of the particle is still positive, but the gravitational field inside a black hole is so strong that even a real particle can have negative energy there. It is therefore possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle or antiparticle. In this case it no longer has to annihilate with its partner. Its forsaken partner may fall into the black hole as well. Or, having positive energy, it might also escape from the vicinity of the black hole as a real particle or antiparticle Figure 7:4.

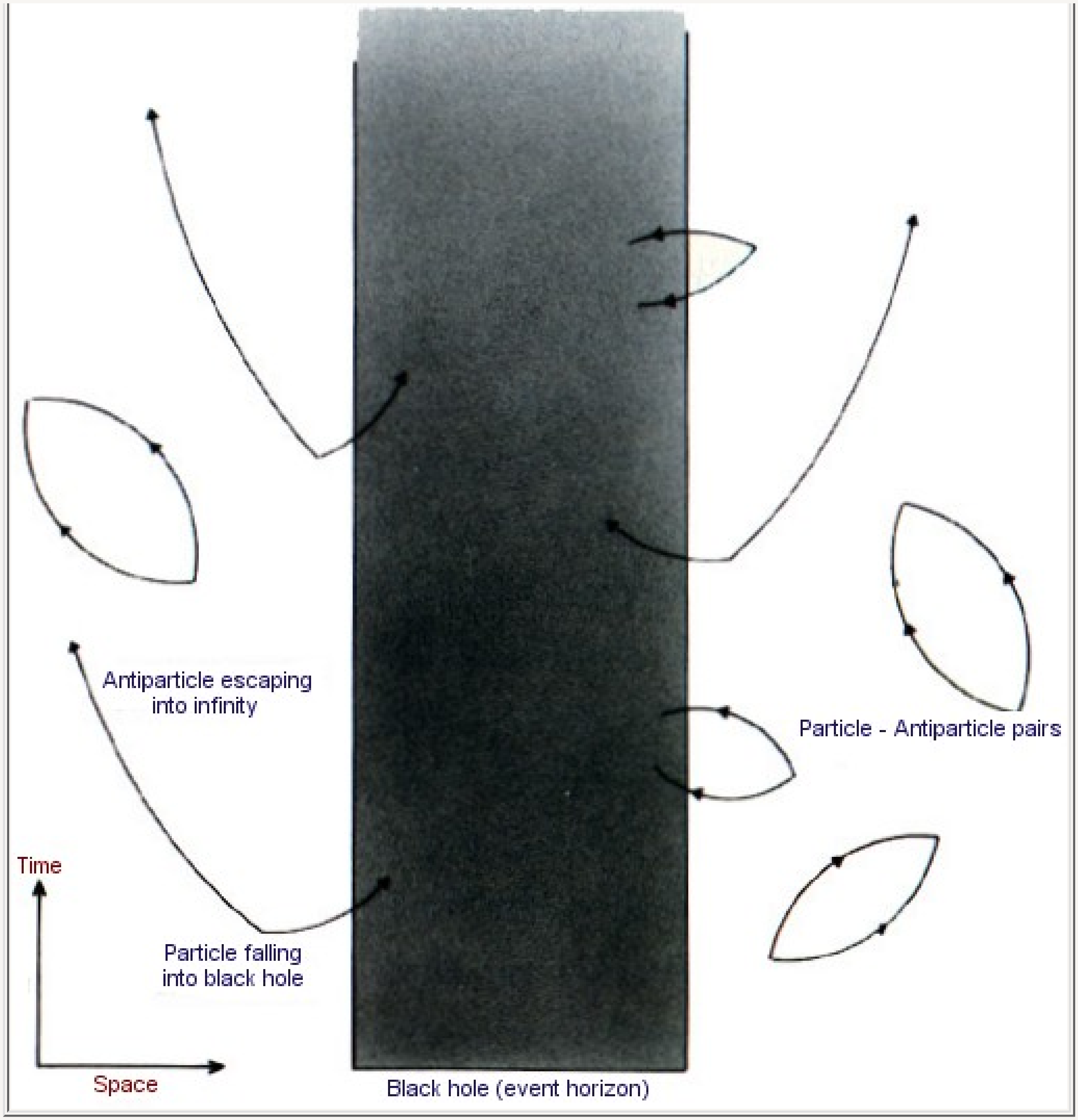


Figure 7:4

To an observer at a distance, it will appear to have been emitted from the black hole. The smaller the black hole, the shorter the distance the particle with negative energy will have to go before it becomes a real particle, and thus the greater the rate of emission, and the apparent temperature, of the black hole.

The positive energy of the outgoing radiation would be balanced by a flow of negative energy particles into the black hole. By Einstein's equation $E = mc^2$ (where *E* is energy, *m* is mass, and *c* is the speed of light), energy is proportional to mass. A flow of negative energy into the black hole therefore reduces its mass. As the black hole loses mass, the area of its event horizon gets smaller, but this decrease in the entropy of the black hole is more than compensated for by the entropy of the emitted radiation, so the second law is never violated.

Moreover, the lower the mass of the black hole, the higher its temperature. So as the black hole loses mass, its temperature and rate of emission increase, so it loses mass more quickly. What happens when the mass of the black hole eventually becomes extremely small is not quite clear, but the most reasonable guess is that it would disappear completely in a tremendous final burst of emission, equivalent to the explosion of millions of H-bombs.

A black hole with a mass a few times that of the sun would have a temperature of only one ten millionth of a degree above absolute zero. This is much less than the temperature of the microwave radiation that fills the universe (about

2.7º above absolute zero), so such black holes would emit even less than they absorb. If the universe is destined to go on expanding forever, the temperature of the microwave radiation will eventually decrease to less than that of such a black hole, which will then begin to lose mass. But, even then, its temperature would be so low that it would take about a million million million million million million million million million million million years (1 with sixty-six zeros after it) to evaporate completely. This is much longer than the age of the universe, which is only about ten or twenty thousand million years (1 or 2 with ten zeros after it). On the other hand, as mentioned in Chapter 6, there might be primordial black holes with a very much smaller mass that were made by the collapse of irregularities in the very early stages of the universe. Such black holes would have a much higher temperature and would be emitting radiation at a much greater rate. A primordial black hole with an initial mass of a thousand million tons would have a lifetime roughly equal to the age of the universe. Primordial black holes with initial masses less than this figure would already have completely evaporated, but those with slightly greater masses would still be emitting radiation in the form of X rays and gamma rays. These X rays and gamma rays are like waves of light, but with a much shorter wavelength. Such holes hardly deserve the epithet black: they really are white hot and are emitting energy at a rate of about ten thousand megawatts.

One such black hole could run ten large power stations, if only we could harness its power. This would be rather difficult, however: the black hole would have the mass of a mountain compressed into less than a million millionth of an inch, the size of the nucleus of an atom! If you had one of these black holes on the surface of the earth, there would be no way to stop it from falling through the floor to the center of the earth. It would oscillate through the earth and back, until eventually it settled down at the center. So the only place to put such a black hole, in which one might use the energy that it emitted, would be in orbit around the earth – and the only way that one could get it to orbit the earth would be to attract it there by towing a large mass in front of it, rather like a carrot in front of a donkey. This does not sound like a very practical proposition, at least not in the immediate future.

But even if we cannot harness the emission from these primordial black holes, what are our chances of observing them? We could look for the gamma rays that the primordial black holes emit during most of their lifetime. Although the radiation from most would be very weak because they are far away, the total from all of them might be detectable. We do observe such a background of gamma rays: Figure 7:5 shows how the observed intensity differs at different frequencies (the number of waves per second). However, this background could have been, and probably was, generated by processes other than primordial black holes. The dotted line in Figure 7:5 shows how the intensity should vary with frequency for gamma rays given off by primordial black holes, if there were on average 300 per cubic light-year. One can therefore say that the observations of the gamma ray background do not provide any positive evidence for primordial black holes, but they do tell us that on average there cannot be more than 300 in every cubic light-year in the universe. This limit means that primordial black holes could make up at most one millionth of the matter in the universe.

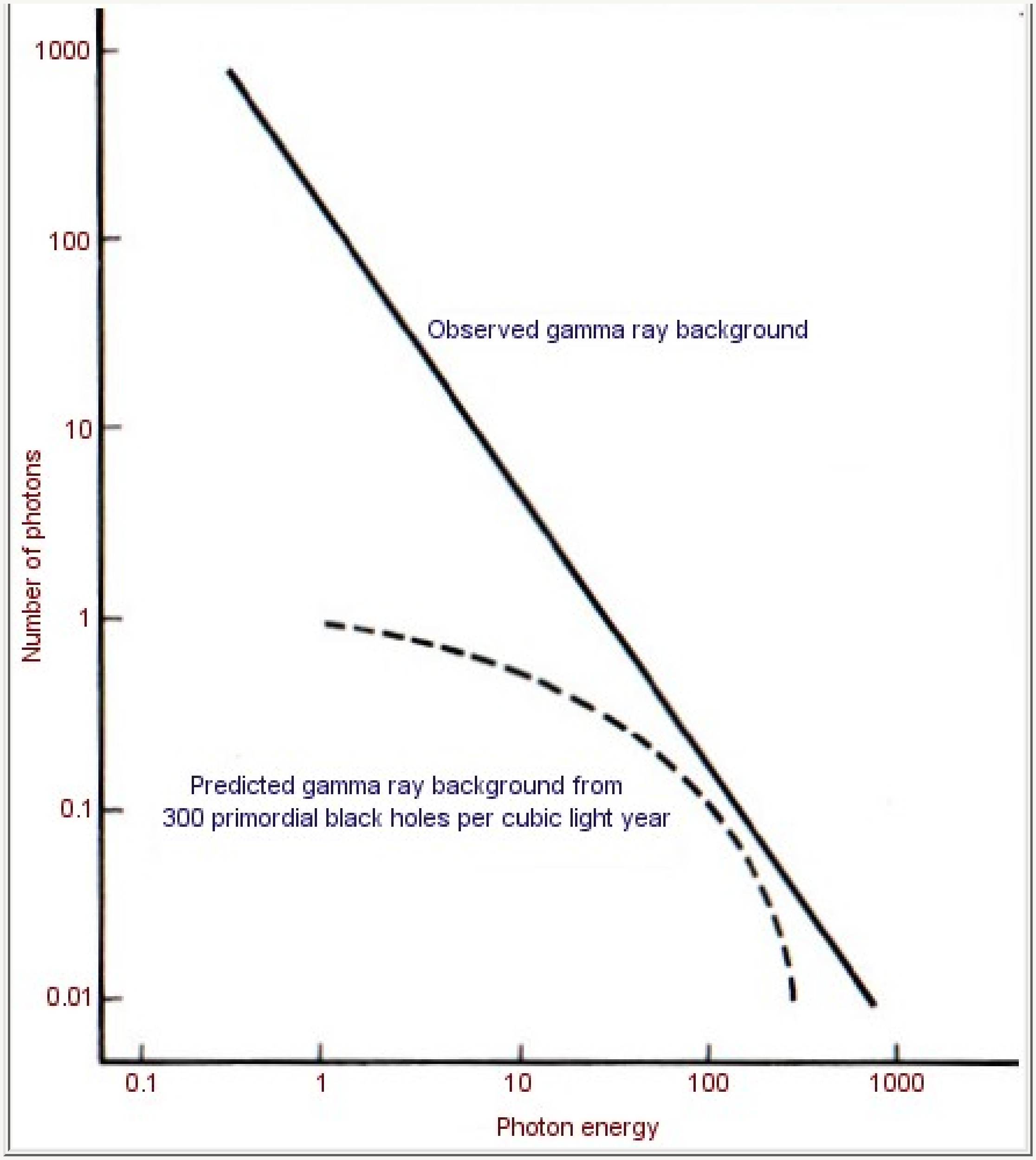


Figure 7:5

With primordial black holes being so scarce, it might seem unlikely that there would be one near enough for us to observe as an individual source of gamma rays. But since gravity would draw primordial black holes toward any matter, they should be much more common in and around galaxies. So although the gamma ray background tells us that there can be no more than 300 primordial black holes per cubic light-year on average, it tells us nothing about how common they might be in our own galaxy. If they were, say, a million times more common than this, then the nearest black hole to us would probably be at a distance of about a thousand million kilometers, or about as far away as Pluto, the farthest known planet. At this distance it would still be very difficult to detect the steady emission of a black hole, even if it was ten thousand megawatts. In order to observe a primordial black hole one would have to detect several gamma ray quanta coming from the same direction within a reasonable space of time, such as a week. Otherwise, they might simply be part of the background. But Planck's quantum principle tells us that each gamma ray quantum has a very high energy, because gamma rays have a very high frequency, so it would not take many quanta to radiate even ten thousand megawatts. And to observe these few coming from the distance of Pluto would require a larger gamma ray detector than any that have been constructed so far. Moreover, the detector would have to be in space, because gamma rays cannot penetrate the atmosphere.

Of course, if a black hole as close as Pluto were to reach the end of its life and blow up, it would be easy to detect the final burst of emission. But if the black hole has been emitting for the last ten or twenty thousand million years, the chance of it reaching the end of its life within the next few years, rather than several million years in the past or future, is really rather small! So in order to have a reasonable chance of seeing an explosion before your research grant ran out, you would have to find a way to detect any explosions within a distance of about one light-year. In fact bursts of gamma rays from space have been detected by satellites originally constructed to look for violations of the Test Ban Treaty. These seem to occur about sixteen times a month and to be roughly uniformly distributed in direction across the sky. This indicates that they come from outside the Solar System since otherwise we would expect them to be concentrated toward the plane of the orbits of the planets. The uniform distribution also indicates that the sources are either fairly near to us in our galaxy or right outside it at cosmological distances because otherwise, again, they would be concentrated toward the plane of the galaxy. In the latter case, the energy required to account for the bursts would be far too high to have been produced by tiny black holes, but if the sources were close in galactic terms, it might be possible that they were exploding black holes. I would very much like this to be the case but I have to recognize that there are other possible explanations for the gamma ray bursts, such as colliding neutron stars. New observations in the next few years, particularly by gravitational wave detectors like LIGO, should enable us to discover the origin of the gamma ray bursts.

Even if the search for primordial black holes proves negative, as it seems it may, it will still give us important information about the very early stages of the universe. If the early universe had been chaotic or irregular, or if the pressure of matter had been low, one would have expected it to produce many more primordial black holes than the limit already set by our observations of the gamma ray background. Only if the early universe was very smooth and uniform, with a high pressure, can one explain the absence of observable numbers of primordial black holes.

The idea of radiation from black holes was the first example of a prediction that depended in an essential way on both the great theories of this century, general relativity and quantum mechanics. It aroused a lot of opposition initially because it upset the existing viewpoint: “How can a black hole emit anything?” When I first announced the results of my calculations at a conference at the Rutherford-Appleton Laboratory near Oxford, I was greeted with general incredulity. At the end of my talk the chairman of the session, John G. Taylor from Kings College, London, claimed it was all nonsense. He even wrote a paper to that effect. However, in the end most people, including John Taylor, have come to the conclusion that black holes must radiate like hot bodies if our other ideas about general relativity and quantum mechanics are correct. Thus, even though we have not yet managed to find a primordial black hole, there is fairly general agreement that if we did, it would have to be emitting a lot of gamma rays and X rays.

The existence of radiation from black holes seems to imply that gravitational collapse is not as final and irreversible as we once thought. If an astronaut falls into a black hole, its mass will increase, but eventually the energy equivalent of that extra mass will be returned to the universe in the form of radiation. Thus, in a sense, the astronaut will be “recycled.” It would be a poor sort of immortality, however, because any personal concept of time for the astronaut would almost certainly come to an end as he was torn apart inside the black hole! Even the types of particles that were eventually emitted by the black hole would in general be different from those that made up the astronaut: the only feature of the astronaut that would survive would be his mass or energy.

The approximations I used to derive the emission from black holes should work well when the black hole has a mass greater than a fraction of a gram. However, they will break down at the end of the black hole’s life when its mass gets very small. The most likely outcome seems to be that the black hole will just disappear, at least from our region of the universe, taking with it the astronaut and any singularity there might be inside it, if indeed there is one. This was the first indication that quantum mechanics might remove the singularities that were predicted by general relativity. However, the methods that I and other people were using in 1974 were not able to answer questions such as whether singularities would occur in quantum gravity. From 1975 onward I therefore started to develop a more powerful approach to quantum gravity based on Richard Feynrnan’s idea of a sum over histories. The answers that this approach suggests for the origin and fate of the universe and its contents, such as astronauts, will be de-scribed in the next two chapters. We shall see that although the uncertainty principle places limitations on the accuracy of all our predictions, it may at the same time remove the fundamental unpredictability that occurs at a space-time singularity.

PREVIOUS NEXT