THE LAST

THREE MINUTES

Conjectures about the Ultimate Fate of the Universe

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CHAPTER 2

THE DYING UNIVERSE

In the year 1856, the German physicist Hermann von Helmholtz made what is probably the most depressing prediction in the history of science. The universe, Helmholtz claimed, is dying. The basis of this apocalyptic pronouncement was the so-called second law of thermodynamics. Originally formulated in the early nineteenth century as a rather technical statement about the efficiency of heat engines, the second law of thermodynamics (now often termed simply "the second law") was soon recognized as having universal significance—indeed, literally cosmic consequences.

In its simplest version, the second law states that heat flows from hot to cold. This is, of course, a familiar and obvious property of physical systems. We see it at work whenever we cook a meal or let a hot cup of coffee cool: the heat flows from the region with the higher temperature to that with the lower temperature. There is no mystery about this. Heat manifests itself in matter in the form of molecular agitation. In a gas, such as air, the molecules rush around chaotically and collide. Even in a solid body the atoms jiggle vigorously about. The hotter the body, the more energetic the molecular agitation will be. If two bodies of different temperature are brought into contact, the

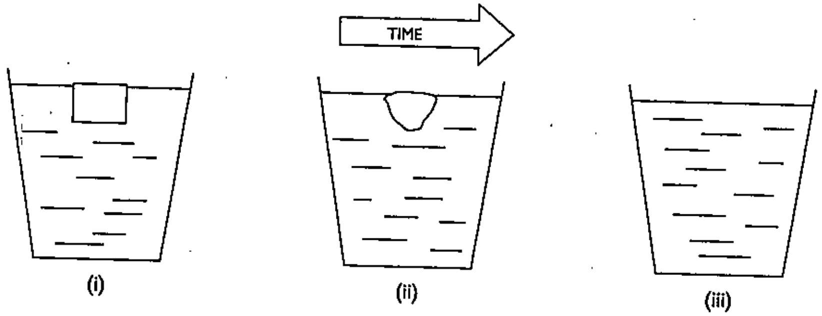

FIGURE 2.1

The arrow of time. The melting ice cube defines a directionality in time: heat flows from the warm water into the cold ice. A movie showing the sequence (iii), (ii), (i) would soon be recognized as a trick. This asymmetry is characterized by a quantity called entropy, which rises as the ice melts.

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more vigorous molecular agitation in the hot body soon spreads to the molecules of the cooler body.

Because heat flow is unidirectional, the process is lopsided in time. A movie showing heat flowing spontaneously from cold to hot would look as silly as a river flowing uphill or raindrops rising to the clouds. So we can identify a fundamental directionality to heat flow, often represented by an arrow pointing from past to future. This "arrow of time" indicates the irreversible nature of thermodynamic processes and has fascinated physicists for a hundred and fifty years. (See figure 2.1).

The work of Helmholtz, Rudolf Clausius, and Lord Kelvin led to the recognition of the significance of a quantity called entropy for characterizing irreversible change in thermodynamics. In the simple case of a hot body in contact with a cold body, the entropy can be defined as heat energy divided by temperature. Consider a small quantity of heat flowing from the hot body into the cold body. The hot body will lose some entropy and the cold body will gain some. Because the same quantity of heat energy is involved but the temperatures differ, the entropy gained by the cold body will be greater than that lost by the hot body. Thus the total entropy of the whole system—hot body plus cold body—rises. One statement of the second law of thermodynamics is then that the entropy of such a system should never fall, for to do so would imply that some heat had gone spontaneously from cold to hot.

A more thoroughgoing analysis enables this law to be generalized to all closed systems: the entropy never falls. If the system includes a refrigerator, which *can* transfer heat from cold to hot, totaling the entropy of the whole system must take into account the energy expended in running the refrigerator. The process of expenditure will itself increase the entropy. It is then always the case that the entropy created by running the refrigerator more than offsets the reduction in entropy resulting from the transfer of heat from cold to hot. In natural systems, too, such as those involving biological organisms or the formation of crystals, the entropy of one part of the system often falls, but this fall is always paid for by a compensatory rise in entropy in another part of the system. Overall, the entropy never goes down.

If the universe as a whole can be considered as a closed system, on the basis that there is nothing "outside" it, then the second law of thermodynamics makes an important prediction: the total entropy of the universe never decreases. In fact, it goes on rising remorselessly. A good example lies right on our cosmic doorstep—the sun, which continuously pours heat into the cold depths of space. The heat goes off into the universe, never to return; this is a spectacularly irreversible process.

An obvious question is, Can the entropy of the universe go on rising forever? Imagine a hot body and a cold body brought into contact inside a thermally sealed container. Heat energy flows from hot to cold and the entropy rises, but eventually the cold body will warm up and the hot body will cool down so that they reach the same temperature. When that state is achieved, there will be no further heat transfer. The system inside the container will have reached a uniform temperature—a stable state of maximum entropy referred to as thermodynamic equilibrium. No further change is expected, as long as the system remains isolated; but if the bodies are disturbed in some way—say, by introducing more heat from outside the container—then further thermal activity will occur, and the entropy will rise to a higher maximum.

What do these basic thermodynamic ideas tell us about astronomical and cosmological change? In the case of the sun and most other stars, the outflow of heat can continue for many billions of years, but it is not inexhaustible. A normal star's heat is generated by nuclear processes in its interior. As we shall see, the sun will eventually run out of fuel, and unless overtaken by events it will cool until it reaches the same temperature as the surrounding space.

Although Hermann von Helmholtz knew nothing of nuclear reactions (the source of the sun's immense energy was a mystery at that time), he understood the general principle that all physical activity in the universe tends toward a final state of thermodynamic equilibrium, or maximum entropy, following which nothing of value is likely to happen for all eternity. This one-way slide toward equilibrium became known to the early thermodynamicists as the "heat death" of the universe. Individual systems, it was conceded, might be revitalized by external disturbances, but the universe itself had no "outside" by definition, so nothing could prevent an all-encompassing heat death. It seemed inescapable.

The discovery that the universe was dying as an inexorable consequence of the laws of thermodynamics had a profoundly depressing effect on generations of scientists and philosophers. Bertrand Russell, for example, was moved to write the following gloomy assessment in his book *Why I Am Not a Christian*:

> All the labours of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius, are destined to extinction in the vast death of the solar system, and . . . the whole temple of man's achievement must inevitably be buried beneath the debris of a universe in ruins—all these things, if not quite beyond dispute, are yet so nearly certain that no philosophy which rejects them can hope to stand. Only within the scaffolding of these truths, only on the firm foundation of unyielding despair, can the soul's habitation henceforth be safely built.

Many other writers have concluded from the second law of thermodynamics and its implication of a dying universe that the universe is pointless and human existence ultimately futile. I shall return to this bleak assessment in later chapters and discuss whether or not it is misconceived.

The prediction of a final cosmic heat death not only says something about the future of the universe but also implies something important about the past. It is clear that if the universe is irreversibly running down at a finite rate, then it cannot have existed forever. The reason is simple: if the universe were infinitely old, it would have died already. Something that runs down at a finite rate obviously cannot have existed for eternity. In other words, the universe must have come into existence a finite time ago.

It is remarkable that this profound conclusion was not properly grasped by the scientists of the nineteenth century. The idea of the universe originating abruptly in a big bang had to await astronomical observations in the 1920s, but a definite genesis at some moment in the past seems to have been strongly suggested already, on purely thermodynamic grounds.

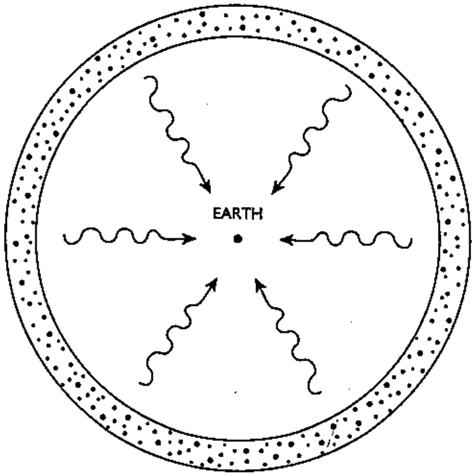

FIGURE 2.2

Olbers' paradox. Imagine an unchanging universe populated by randomly scattered stars at a uniform average density. Shown is a selection of stars occupying a thin spherical shell of space centered on Earth. (The stars outside the shell have been omitted from the picture.) Light from the stars in this shell contributes to the total flux of starlight falling on Earth. The intensity of light from a given star will diminish as the square of the shell's radius. However, the total number of stars in the shell will grow in proportion to the square of the shell's radius. Therefore these two factors cancel each other out, and the total luminosity of the shell is *independent* of its radius. In an infinite universe, there will be an infinity of shells and—apparently—an infinite flux of light reaching Earth.

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Because this obvious inference was not made, however, nineteenth-century astronomers were baffled by a curious cosmological paradox. Known as Olbers' paradox, after the German astronomer who is credited with its formulation, it poses a simple yet deeply significant question: Why is the sky dark at night?

At first, the problem seems trivial. The night sky is dark because the stars are situated at immense distances from us and so appear dim. (See figure 2.2.) But suppose that space has no limit. In this case, there could well be an infinity of stars. An infinite number of dim stars would add up to a lot of light. It is easy to calculate the cumulative starlight from an infinity of unchanging stars distributed more or less uniformly throughout space. The brightness of a star diminishes with distance, according to an inverse-square law. This means that at twice the distance the star is one-quarter as bright, at three times the distance it is one-ninth as bright, and so on. On the other hand, the number of stars increases the farther away you look. In fact, simple geometry shows that the number of stars, say, two hundred light-years away is four times the number one hundred light-years away, while the number three hundred light-years away is nine times the latter. So the number of stars goes up as the square of the distance, while the brightness goes down as the square of the distance. The two effects cancel each other out, and the result is that the total light coming from all the stars at a given distance does not depend on the distance. The same total light comes from stars two hundred light-years away as from those one hundred light-years away.

The problem comes when we add up the light from all the stars at all possible distances. If the universe has no boundary, there seems to be no limit to the total amount of light received on Earth. Far from being dark, the night sky ought to be infinitely bright!

The problem is ameliorated somewhat when account is taken of the finite size of stars. The farther away a star is from Earth, the smaller is its apparent size. A nearby star will obscure a more distant star if it lies along the same line of sight. In an infinite universe this will happen infinitely often, and taking it into account changes the conclusion of the previous calculation. Instead of an infinite flux of light arriving on Earth, the flux is merely very large—roughly equivalent to the sun's disk filling the sky, as would be the case if the Earth were located about a million miles from the solar surface. This would be a very uncomfortable location indeed; in fact, the Earth would be rapidly vaporized by the intense heat.

The conclusion that an infinite universe ought to be a cosmic furnace is actually a restatement of the thermodynamic problem I discussed earlier. The stars pour heat and light into space, and this radiation slowly accumulates in the void. If the stars have been burning forever, it seems at first sight that the radiation must have an infinite intensity. But some radiation, while traveling through space, will strike other stars and be reabsorbed. (This is equivalent to noticing that nearby stars obscure the light from more distant ones.) Therefore the intensity of the radiation will rise until an equilibrium is established at which the rate of emission just balances the rate of absorption. This state of thermodynamic equilibrium will occur when the radiation in space reaches the same temperature as the surfaces of the stars—a few thousand degrees. Thus the universe should be full of heat radiation with a temperature of several thousand degrees, and the night sky, instead of being dark, should glow at this temperature.

Heinrich Olbers proposed a resolution to his own paradox. Noting the existence of large amounts of dust in the universe, he suggested that this material would absorb most of the starlight and thus darken the sky. Unfortunately, his idea, though imaginative, was fundamentally flawed: the dust would eventually heat up and start to glow with the same intensity as the radiation it absorbed.

Another possible resolution is to abandon the assumption that the universe is infinite in extent. Suppose the stars are many but finite in number, so that the universe consists of a huge assemblage of stars surrounded by an infinite dark void; then most of the starlight will flow away into the space beyond, and be lost. But this simple resolution, too, has a fatal flaw—one that was, in fact, already familiar to Isaac Newton in the seventeenth century. The flaw concerns the nature of gravitation: Every star attracts every other star with a force of gravity, therefore all the stars in the assemblage would tend to fall together, congregating at the center of gravity. If the universe has a definite center and edge, it seems that it must collapse in on itself. An unsupported, finite, static universe is unstable, and subject to gravitational collapse.

This gravitational problem will crop up again later in my story. Here we need simply note the ingenious way in which Newton attempted to sidestep it. The universe can collapse to its center of gravity, Newton reasoned, only if it *has* a center of gravity. If the universe is both infinite in extent and (on average) uniformly populated with stars, then there will be no center and no edge. A given star will be pulled every which way by its many neighbors, like a gigantic tug-of-war in which ropes bristle in all directions. On average, all these tugs will cancel one another, and the star won't move.

So if we accept Newton's resolution of the collapsing-cosmos paradox, we are back with an infinite universe again, and the problem of Olbers' paradox. It seems that we must face either one or the other. But with the benefit of hindsight we can find a way between the horns of the dilemma. It is not the assumption that the universe is infinite in *space* that is wrong but the assumption that it is infinite in *time*. The paradox of the flaming sky arose because astronomers assumed that the universe was unchanging, that the stars were static and had been burning with undiminished intensity for all eternity. But we now know that both these assumptions were wrong. First, as I shall shortly explain, the universe is not static but expanding. Second, the stars cannot have been burning forever, because they would have long since run out of fuel. The fact that they are burning now implies that the universe must have come into existence at a finite time in the past.

If the universe has a finite age, Olbers' paradox goes away immediately. To see why, consider the case of a very distant star. Because light travels at a finite speed (300,000 kilometers a second, in a vacuum) we do not see the star as it is today but as it was when the light left it. For example, the bright star Betelgeuse is about six hundred and fifty light-years away, so it appears to us now as it was six hundred and fifty years ago. If the universe came into existence, say, ten billion years ago, then we would not see any stars located more than ten billion light-years away from Earth. The universe *may* be infinite in spatial extent, but if it has a finite age we cannot in any case see beyond a certain finite distance. So the cumulative starlight from an infinite number of stars of finite *age* will be finite, and possibly insignificantly small.

The same conclusion follows from thermodynamic considerations. The time taken for the stars to fill space with heat radiation and reach a common temperature is immense, because there is so much empty space in the universe. There has simply been insufficient time since the beginning for the universe to have reached thermodynamic equilibrium by now.

All the evidence points, then, to a universe that has a limited life span. It came into existence at some finite time in the past, it is currently vibrant with activity, but it is inevitably degenerating toward a heat death at some stage in the future. A host of questions immediately arises. When will the end come? What form will it take? Will it be slow or sudden? And is it conceivable that the heat-death conclusion, as scientists currently understand it, might turn out to be wrong?