THE FIRST THREE MINUTES,

by Steven Weinberg (1977, 1988, 1993)

A Modern View of the Origin of the Universe

I

INTRODUCTION: THE GIANT AND THE COW

THE ORIGIN of the universe is explained in the *Younger Edda,* a collection of Norse myths compiled around 1220 by the Icelandic magnate Snorri Sturleson. In the beginning, says the *Edda,* there was nothing at all. "Earth was not found, nor Heaven above, a Yawning-gap there was, but grass nowhere." To the north and south of nothing lay regions of frost and fire, Niflheim and Muspelheim. The heat from Muspelheim melted some of the frost from Niflheim, and from the liquid drops there grew a giant, Ymer. What did Ymer eat? It seems there was also a cow, Audhumla. And what did *she* eat? Well, there was also some salt. And so on.

I must not offend religious sensibilities, even Viking religious sensibilities, but I think it is fair to say that this is not a very satisfying picture of the origin of the universe. Even leaving aside all objections to hearsay evidence, the story raises as many problems as it answers, and each answer requires a new complication in the initial conditions.

We are not able merely to smile at the *Edda*, and forswear all cosmogonical speculation—the urge to trace the history of the universe back to its beginnings is irresistible. From the start of modern science in the sixteenth and seventeenth centuries, physicists and astronomers have returned again and again to the problem of the origin of the universe.

However, an aura of the disreputable always surrounded such research. I remember that during the time that I was a student and then began my own research (on other problems) in the 1950s, the study of the early universe was widely regarded as not the sort of thing to which a respectable scientist would devote his time. Nor was this judgment unreasonable. Throughout most of the history of modern physics and astronomy, there simply has not existed an adequate observational and theoretical foundation on which to build a history of the early universe.

Now, in just the past decade, all this has changed. A theory of the early universe has become so widely accepted that astronomers often call it "the standard model." It is more or less the same as what is sometimes called the "big bang" theory, but supplemented with a much more specific recipe for the contents of the universe. This theory of the early universe is the subject of this book.

To help see where we are going, it may be useful to start with a summary of the history of the early universe, as presently understood in the standard model. This is only a brief run-through—succeeding chapters will explain the details of this history, and our reasons for believing any of it.

In the beginning there was an explosion. Not an explosion like those familiar on earth, starting from a definite center and spreading out to engulf more and more of the circumambient air, but an explosion which occurred simultaneously everywhere, filling all space from the beginning, with every particle of matter rushing apart from every other particle. "All space" in this context may mean either all of an infinite universe, or all of a finite universe which curves back on itself like the surface of a sphere. Neither possibility is easy to comprehend, but this will not get in our way; it matters hardly at all in the early universe whether space is finite or infinite.

At about one-hundredth of a second, the earliest time about which we can speak with any confidence, the temperature of the universe was about a hundred thousand million (10^{11}) degrees Centigrade. This is much hotter than in the center of even the hottest star, so hot, in fact, that none of the components of ordinary matter, molecules, or atoms, or even the nuclei of atoms, could have held together. Instead, the matter rushing apart in this explosion consisted of various types of the so-called elementary particles, which are the subject of modern high-energy nuclear physics.

We will encounter these particles again and again in this book—for the present it will be enough to name the ones that were most abundant in the early universe, and leave more detailed explanations for Chapters III and IV. One type of particle that was present in large numbers is the electron, the negatively charged particle that flows through wires in electric currents and makes up the outer parts of all atoms and molecules in the present universe. Another type of particle that was abundant at early times is the positron, a positively charged particle with precisely the same mass as the electron. In the present universe positrons are found only in high-energy laboratories, in some kinds of radioactivity, and in violent astronomical phenomena like cosmic rays and supernovas, but in the early universe the number of positrons was almost exactly equal to the number of electrons. In addition to electrons and positrons, there were roughly similar numbers of various kinds of neutrinos, ghostly particles with no mass or electric charge whatever. Finally, the universe was filled with light. This does not have to be treated separately from the particles—the quantum theory tells us that light consists of particles of zero mass and zero electrical charge known as photons. (Each time an atom in the filament of a light bulb changes from a state of higher energy to one of lower energy, one photon is emitted. There are so many photons coming out of a light bulb that they seem to blend together in a continuous stream of light, but a photoelectric cell can count individual photons, one by one.) Every photon carries a definite amount of energy and momentum depending on the wavelength of the light. To describe the light that filled the early universe, we can say that the number and the average energy of the photons was about the same as for electrons or positrons or neutrinos.

These particles—electrons, positrons, neutrinos, photons—were continually being created out of pure energy, and then after short lives being annihilated again. Their number therefore was not preordained, but fixed instead by a balance between processes of creation and annihilation. From this balance we can infer that the density of this cosmic soup at a temperature of a hundred thousand million degrees was about four thousand million (4×10^9) times that of water. There was also a small contamination of heavier particles, protons and

neutrons, which in the present world form the constituents of atomic nuclei. (Protons are positively charged; neutrons are slightly heavier and electrically neutral.) The proportions were roughly one proton and one neutron for every thousand million electrons or positrons or neutrinos or photons. This number—a thousand million photons per nuclear particle—is the crucial quantity that had to be taken from observation in order to work out the standard model of the universe. The discovery of the cosmic radiation background discussed in Chapter III was in effect a measurement of this number.

As the explosion continued the temperature dropped, reaching thirty thousand million (3×10^{10}) degrees Centigrade after about one-tenth of a second; ten thousand million degrees after about one second; and three thousand million degrees after about fourteen seconds. This was cool enough so that the electrons and positrons began to annihilate faster than they could be recreated out of the photons and neutrinos. The energy released in this annihilation of matter temporarily slowed the rate at which the universe cooled, but the temperature continued to drop, finally reaching one thousand million degrees at the end of the first three minutes. It was then cool enough for the protons and neutrons to begin to form into complex nuclei, starting with the nucleus of heavy hydrogen (or deuterium), which consists of one proton and one neutron. The density was still high enough (a little less than that of water) so that these light nuclei were able rapidly to assemble themselves into the most stable light nucleus, that of helium, consisting of two protons and two neutrons.

At the end of the first three minutes the contents of the universe were mostly in the form of light, neutrinos, and antineutrinos. There was still a small amount of nuclear material, now consisting of about 73 percent hydrogen and 27 percent helium, and an equally small number of electrons left over from the era of electron-positron annihilation. This matter continued to rush apart, becoming steadily cooler and less dense. Much later, after a few hundred thousand years, it would become cool enough for electrons to join with nuclei to form atoms of hydrogen and helium. The resulting gas would begin under the influence of gravitation to form clumps, which would ultimately condense to form the galaxies and stars of the present universe. However, the ingredients with which the stars would begin their life would be just those prepared in the first three minutes.

The standard model sketched above is not the most satisfying theory imaginable of the origin of the universe. Just as in the *Younger Edda*, there is an embarrassing vagueness about the very beginning, the first hundredth of a second or so. Also, there is the unwelcome necessity of fixing initial conditions, especially the initial thousand-million-to-one ratio of photons to nuclear particles. We would prefer a greater sense of logical inevitability in the theory.

For example, one alternative theory that seems philosophically far more attractive is the so-called steady-state model. In this theory, proposed in the late 1940s by Herman Bondi, Thomas Gold, and (in a somewhat different formulation) Fred Hoyle, the universe has always been just about the same as it is now. As it expands, new matter is continually created to fill up the gaps between the galaxies. Potentially, all questions about why the universe is the way it is can be answered in this theory by showing that it is the way it is because that is the only way it can stay the same. The problem of the early universe is banished; there was no early universe.

How then did we come to the "standard model?" And how has it supplanted other theories, like the steady-state model? It

is a tribute to the essential objectivity of modern astrophysics that this consensus has been brought about, not by shifts in philosophical preference or by the influence of astrophysical mandarins, but by the pressure of empirical data.

The next two chapters will describe the two great clues, furnished by astronomical observation, which have led us to the standard model—the discoveries of the recession of distant galaxies and of a weak radio static filling the universe. This is a rich story for the historian of science, filled with false starts, missed opportunities, theoretical preconceptions, and the play of personalities.

Following this survey of observational cosmology, I will try to put the pieces of data together to make a coherent picture of physical conditions in the early universe. This will put us in a position to go back over the first three minutes in greater detail. A cinematic treatment seems appropriate: frame by frame, we will watch the universe expand and cool and cook. We will also try to look a little way into an era that is still clothed in mystery—the first hundredth of a second, and what went before.

Can we really be sure of the standard model? Will new discoveries overthrow it and replace the present standard model with some other cosmogony, or even revive the steady-state model? Perhaps. I cannot deny a feeling of unreality in writing about the first three minutes as if we really know what we are talking about.

However, even if it is eventually supplanted, the standard model will have played a role of great value in the history of cosmology. It is now respectable (though only in the last decade or so) to test theoretical ideas in physics or astrophysics by working out their consequences in the context of the standard model. It is also common practice to use the standard model as a theoretical basis for justifying programs of astronomical observation. Thus, the standard model provides an essential common language which allows theorists and observers to appreciate what each other are doing. If some day the standard model is replaced by a better theory, it will probably be because of observations or calculations that drew their motivation from the standard model.

In the last chapter I will say a bit about the future of the universe. It may go on expanding forever, getting colder, emptier, and deader. Alternatively, it may recontract, breaking up the galaxies and stars and atoms and atomic nuclei back into their constituents. All the problems we face in understanding the first three minutes would then arise again in predicting the course of events in the last three minutes.